COMPUTERS IN MEDICAL IMAGING

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- introduced into medical imaging in the early 1970's
- essential to many modalities
  - X-ray computed tomography (CT)
  - Magnetic resonance imaging (MRI)
  - Single photon emission computed tomography (SPECT)
  - Positron emission tomography (PET)
  - Ultrasound (US)
  - Digital radiology (DR)
  - Picture Archiving and Communication (PACS)

Power of the computer:

- Functional flexibility
  - Data storage
  - Computation
  - Logical evaluation
- Organizational flexibility
  - Data
  - Instructions
  - speed in performing operations

Number systems:

TABLE 4-1. NUMBERS IN DECIMAL AND BINARY FORMS

Decimal	Binary	Decimal	Binary
0	0	8	1000
1	1	9	1001
2	10	10	1010
3	11	11	1011
4	100	12	1100
5	101	13	1101
6	110	14	1110
7	111	15	1111
		16	10000

Data Storage - Number Systems:

- Decimal (Base 10)
  - Uses digits 0,1,2,3,4,5,6,7,8,9
  - Position indicates power of 10 exponent
    - 3506 = $(3 \times 10^{3}) + (5 \times 10^{2}) + (0 \times 10^{1}) + (6 \times 10^{0})$
      - Most significant number or digit
      - Least significant number or digit

Data Storage - Number Systems:

- Decimal (Base 2)
  - Uses digits 0, 1 -> often called binary system
  - Position indicates power of 2 exponent
    - $1101 = (1 \times 2^3) + (1 \times 2^2) + (0 \times 2^1) + (1 \times 2^0)$
      - Most significant number or digit or MSB
      - Least significant number or digit or LSB

Data Storage - Number Systems:

- Conversion between Base 2 and Base 10 (1st base < 2nd base)
  - convert 1st base to individual 2nd base values

  101010(binary) = $(1 \times 2^5) + (0 \times 2^4) + (1 \times 2^3) + (0 \times 2^2) + (1 \times 2^1) + (0 \times 2^0)$
    - $2^5 = 32$
    - $2^4 = 16$
    - $2^3 = 8$
    - $2^2 = 4$
    - $2^1 = 2$
    - $2^0 = 1$
  - Multiply by digit value
  - Sum up to get value in 2nd base

  $(1 \times 32) + (0 \times 16) + (1 \times 8) + (0 \times 4) + (1 \times 2) + (0 \times 1) = 42$ decimal

Data Storage - Number Systems:

- Conversion between Base 10 and Base 2 (1st base > 2nd base)
  - Successively divide by 2nd base and note remainder
    - 42(decimal)/2 21 0 (LSB)
    - 21/2 10 1
    - 10/2 5 0
    - 5/2 2 1
    - 2/2 1 0
    - 1/2 0 1 (MSB)
  - = 101010 binary

Data Storage - Digital Representation of Data:

- Bits – for binary digits
- Bytes – consisting of 8 bits
- Words – 16, 32, and 64 bits

TABLE 4-4. NUMBER OF BITS REQUIRED TO STORE INTEGERS

Number of Bits	Possible Configurations	Number of Configurations	Represent Integers (Decimal Form)
1	0,1	2	0,1
2	00,01,10,11	4	0,1,2,3
3	000,001,010,011,100,101,110,111	8	0,1,2,3,4,5,6,7
8	00000000 to 11111111	256	0 to 255
16	0000000000000000 to 1111111111111111	65,536	0 to 65,535
N		2^N	0 to $2^N - 1$

Data Storage - Digital Representation of Data:

Numeric data – numbers

- 1, 2, 4 and 8 byte positive integers
- 1, 2, 4 and 8 byte signed integers
  - "signed" meaning positive or negative integers
- 4 and 8 byte floating-point numbers
  - 4 byte - single precision
  - 8 byte - double precision

Data Storage - Digital Representation of Data:

Storage of positive integers

- N bits has 2^N possible configurations
- Represent integers from 0 to $2^N - 1$
- One byte can therefore store integers from 0 – 255
- 16-bit word can store integers from 0 – 65,535

Data Storage - Digital Representation of Data:

Storage of signed integers

- Setting the first bit to 0 indicates that the number is positive
- Setting the first bit to 1 indicates that the number is negative
- 11111111 (binary) = -127
- 01111111 (binary) = 127

Data Storage - Digital Representation of Data:

Floating point numbers

- Very large numbers such as Avogadro's number (6.022×10^{23} molecules per gram-mole
- Very small numbers such as the mass of proton (1.673×10^{-27} kilograms)
- 0.11111111 (binary) $\times\ 2^{01001111 (binary)}$

Data Storage - Digital Representation of Data:

Binary representation of text

- American Standard Code for Information Interchange (ASCII)
- "Carriage return" is represented by 00001101
- Upper case "A" is represented by 01000001
- Comma is represented by 00111010
- Digit "2" is represented by 00110010
- 128 characters represented

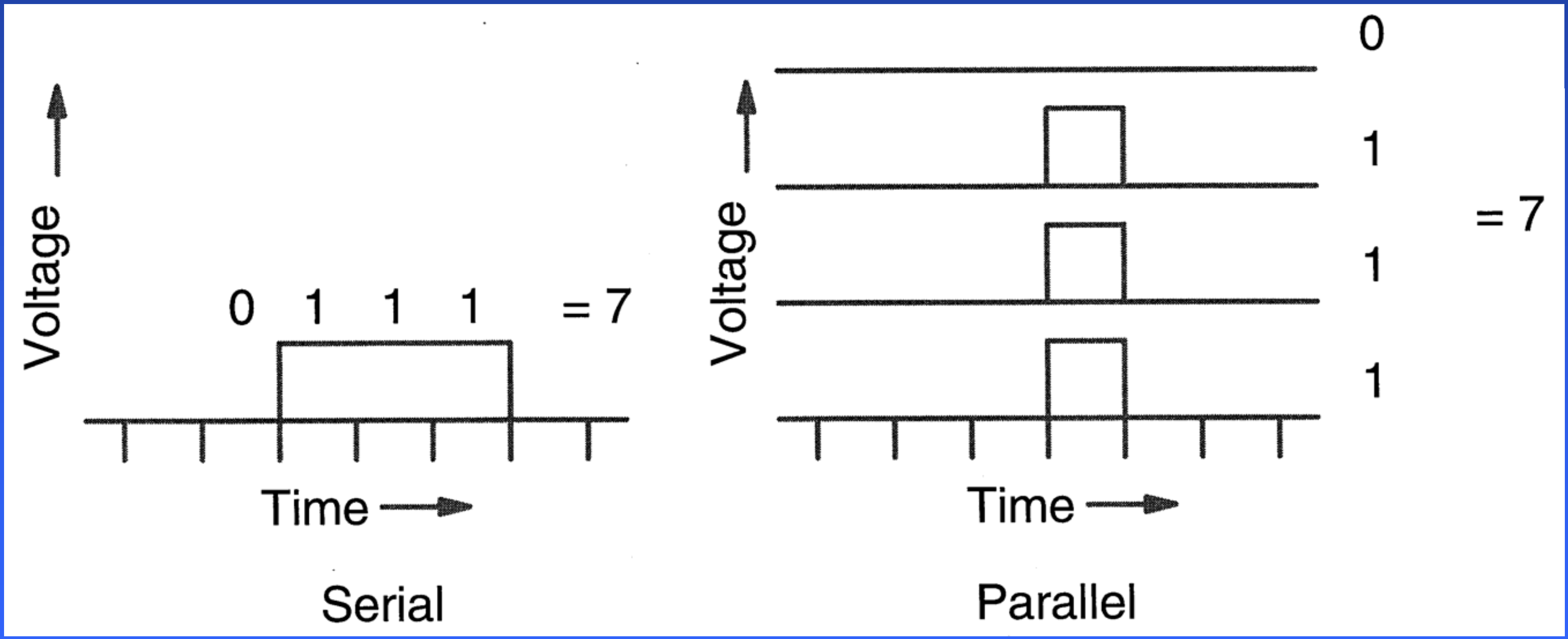
Data Storage - Digital Data Transfer:

Transfer of data in digital form

- Serial form over single wire by transferring each bit value in succession
- Each bit value being transferred over its own wire is called parallel data transfer
- Group of wires used to transfer data between several devices is a data bus
- 32-bit bus transmits 32 bits of data simultaneously

Data Storage - Digital Data Transfer:

Serial and Parallel transfer of digital data - (fig 4.1)



Conversion between Analog and Digital Data:

- Analog representation of data is continuous variable

Advantages of analog data

- Captures small details in signal.
- Data often can be transferred in less time using analog form.

Disadvantages of analog data

- Signals become distorted. Causes of this distortion include inaccuracies when signals are amplified attenuation losses, and electronic noise

Conversion between Analog and Digital Data:

Advantages of digital data

- Data stored or transferred in digital form are remarkably immune to error accumulation
- Most digital circuits make a fresh copy of it
- Redundant information can be sent with each group of bits to permit the receiving device to detect errors or even correct them.
- A simple error detection method uses parity bits. Additional bit is transmitted with each group of bits, typically with each byte. The bit value designates whether an even or an odd number of bits were in the "1" state.

Conversion between Analog and Digital Data:

Disadvantages of digital data

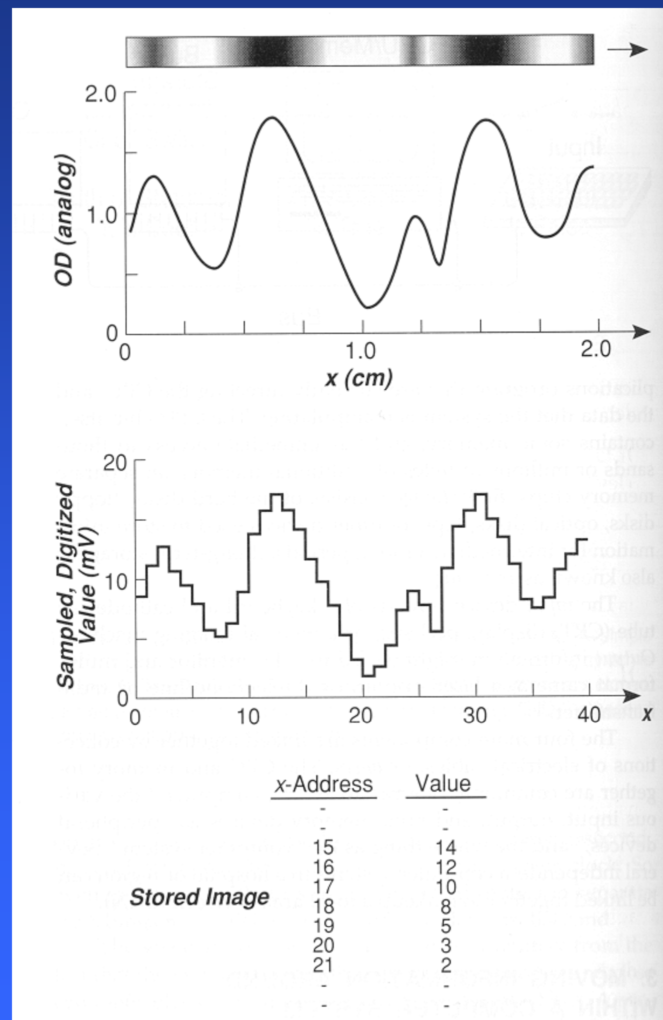
- Fidelity of digitized signal depends on number of bits used.
- More bits mean higher fidelity but more storage and transmission bandwidth required.
- More complex circuitry
- Digitized values only approximate analog signal

Conversion between Analog and Digital Data:

TABLE 4-5. MAXIMAL ERRORS WHEN DIFFERENT NUMBERS OF BITS ARE USED TO APPROXIMATE AN ANALOG SIGNAL

Number of Bits	Number of Values	Maximal Quantization Error (%)
1	2	25
2	4	12.5
3	8	6.2
8	256	0.20
12	4,096	0.012

Conversion between Analog and Digital Data:



Conversion between Analog and Digital Data:

Conversion

- Transducers, sensors, or detectors of most electronic measuring equipment; medical imaging devices, produce analog data
- Devices that perform conversion called analog-to-digital converters (ADCs) or digital-to-analog converters (DACs)
- Most analog signals are continuous in time
- Certain points in time must be selected at which the conversion is to be performed. Process is called sampling
- Each analog sample is then converted into a digital signal. This conversion is called digitization or quantization
- ADC is characterized by its sampling rate and number of bits of output

Conversion between Analog and Digital Data:

Conversion

- Most radiologic applications required very high resolution and sampling rates
- 8-bit ADC, 10-bit ADC, or 12-bit ADC
- Digital representation of data is superior to analog in its resistance to accumulation of errors.
- Disadvantages to digital include the conversion of an analog signal to digital form causes loss of information. This loss is due to both sampling and quantization. ADC samples in put signal, the values of analog signal between moments of sampling are lost. If sampling rate of ADC is sufficiently rapid that analog signal being digitized varies only slightly during intervals between sampling, sampling error will be small. There is minimum sampling rate requirement, Nyquist Limit.that ensures accurate representation of signal.

Conversion between Analog and Digital Data:

Analog and digital representation of numerical data:

A - Three analog voltage pluses, similar to those produced by photomultiplier tube attached to a scintillator. The height of each pulse represents a number.
B - These same numbers represented in digital form.

Conversion between Analog and Digital Data:

Analog and digital representation of numerical data:

C - A continuously varying analog signal, such as that from video camera in fluoroscopy system. Height of signal at each point in time represents a number.
D - Values of this signal, sampled at 3 points, represented in digital form

Conversion between Analog and Digital Data:

Quantization

- Can only approximate value of analog signal
- Causes loss of information.
- e.g., analog voltage signal may be 1.0, 2.5, or 1.7893 V.
- Digital signal is limited to finite number of possible values, determined by number of bits used for signal.
- 1-bit digital signal is limited to two values, 2-bit signal is limited to four values, N-bit signal is restricted to 2^N
- Error is similar to error introduced when number is rounded off

Conversion between Analog and Digital Data:

Quantization

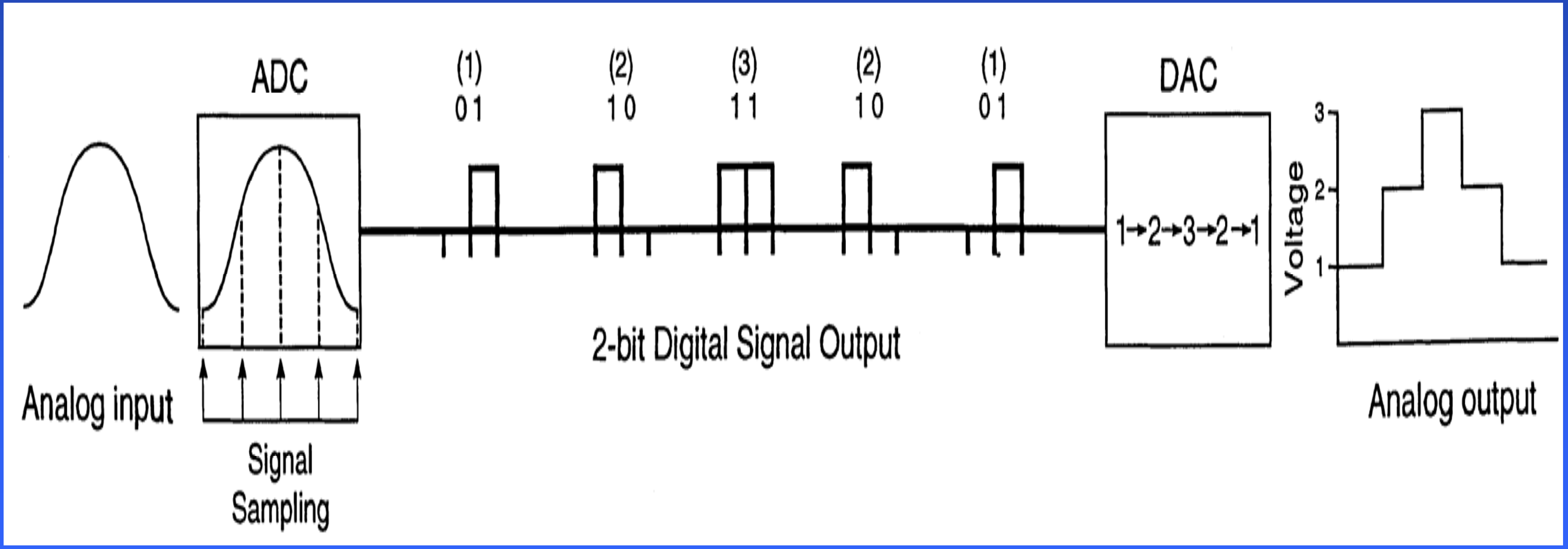
- ADC must sample at sufficiently high rate and provide sufficient number of bits so error is less than uncertainty in analog signal being digitized.
- Analog signal with large signal-to-noise ratio (SNR) requires ADC providing large number of bits to avoid reducing SNR.

Conversion between Analog and Digital Data:

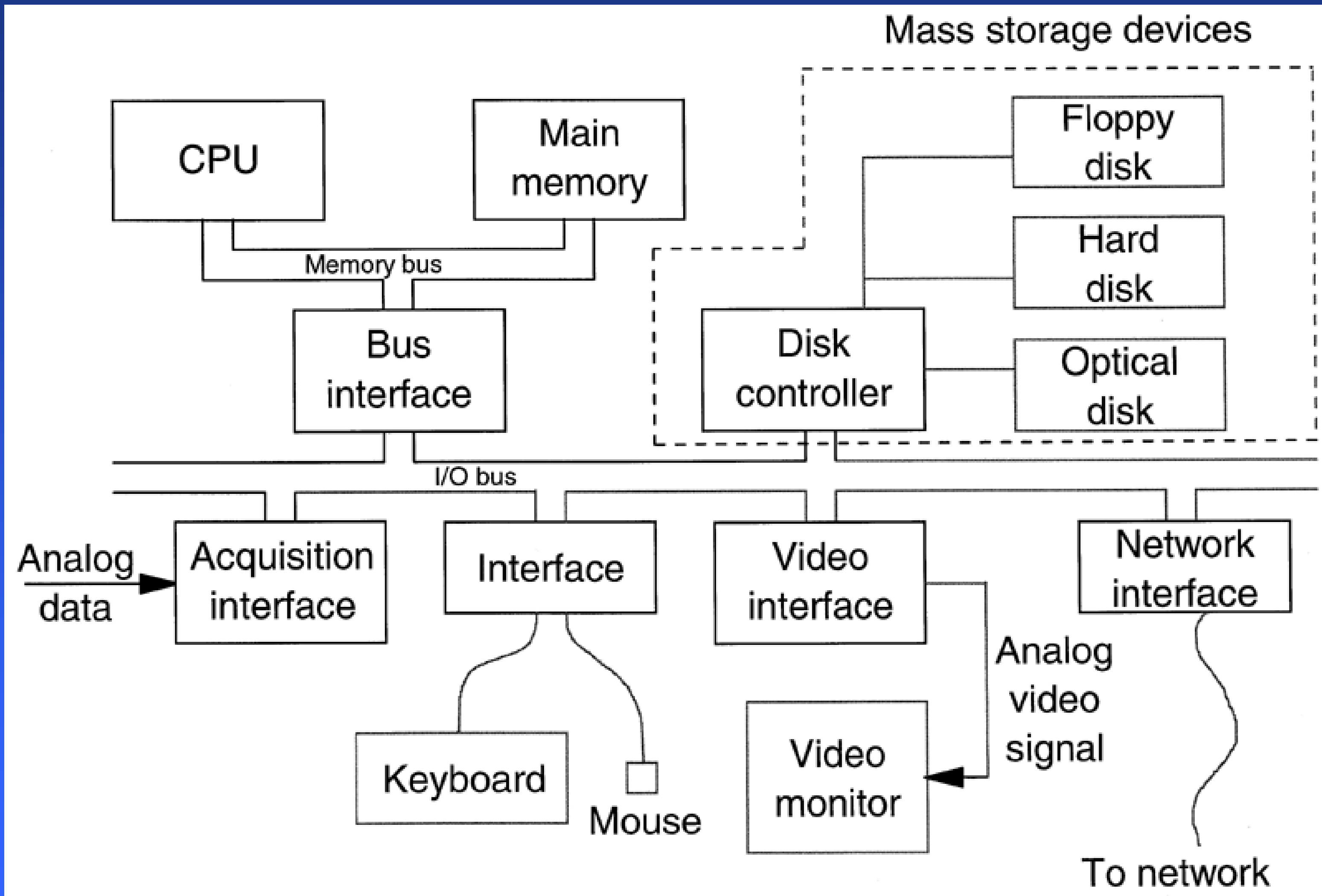
Digital-to-Analog Conversion

- Image information must be converted from digital form to an analog voltage signal. Called Digital-to analog converter (DAC)
- Information lost by analog-to-digital conversion is not restored by sending signal through DAC

Analog-to-digital (ADC) conversion and digital –to-analog (DAC) conversion. In this figure, 2 bit ADC samples input signal 5 times. Note that output signal from DAC is only approximation of input signal to ADC because 2-bit digital numbers produced by ADC can only approximate continuously varying analog signal. (fig 4-3)



Components and Operations of Computers:



Components and Operations of Computers:

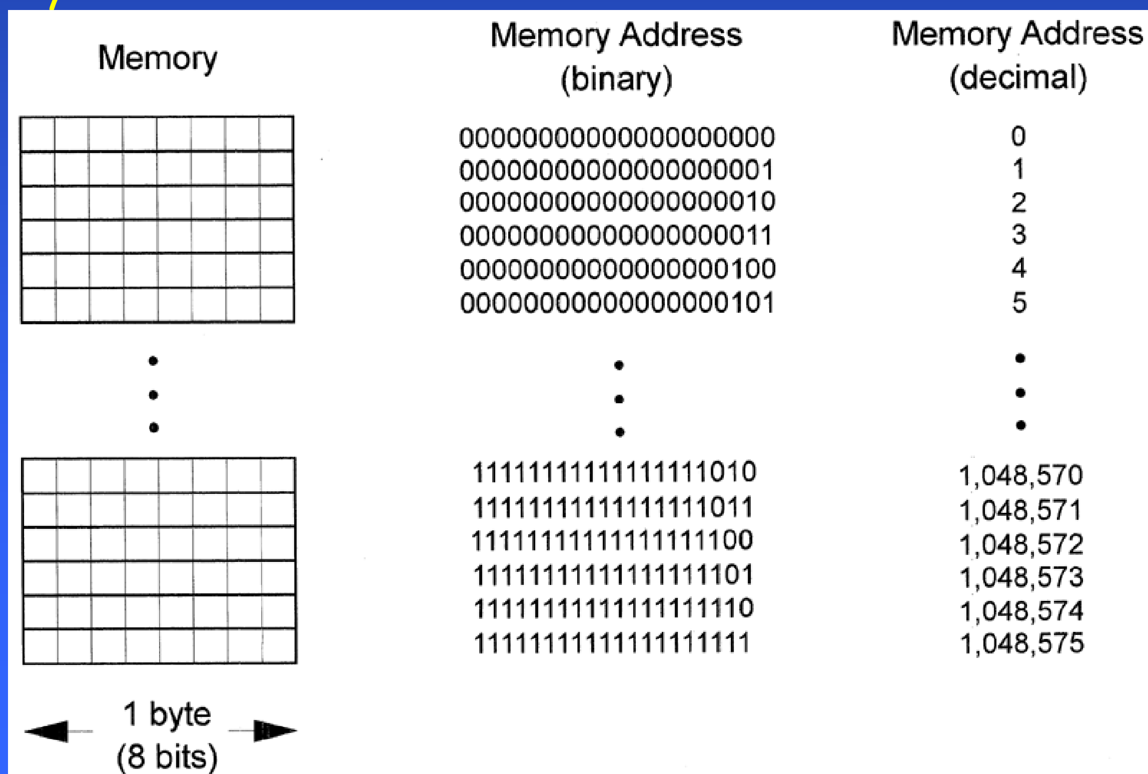
Main Memory

- Data storage locations
- Memory address
- Memory write
- CPU performs memory write, sends both memory address and data to memory
- Random access memory (RAM) also called read-write memory. Disadvantage is volatile, meaning data stored in it are lost when electrical power is turned off.
- Read-only memory (ROM) cannot write or erase data on ROM. Data stored in it are not lost when power lost to computer
- Cache memories - maintain exact copies of memory (multiple reads)

Components and Operations of Computers:

Main Memory

- Data storage locations - Main memory containing 1 megabyte (2^{20} bytes ~ million bytes). Each byte in memory is identified by unique memory address.



Components and Operations of Computers:

Central Processing Unit (CPU)

- CPU fetches and executes instructions in program sequentially
- CPU contained in single computer chip called microprocessor
- An instruction can cause CPU to perform one or more actions
  - Transfer unit of data (e.g., a 16- or 32-bit word) from memory address, CPU storage register, or I/O device to another memory address, register, or I/O device
  - Perform mathematical operation between two numbers in storage registers in CPU (faster) or in memory (slower)
  - Compare 2 numbers or other pieces of data in registers or in memory
  - Change address of next instruction in program to be executed to another location in program which is called branching instruction

Components and Operations of Computers:

Central Processing Unit (CPU)

- CPU is a bottleneck in conventional computer
- One way to improve is to increase speed
- Relieving bottleneck is to design CPU to perform parallel processing

Components and Operations of Computers:

Input/Output Bus & Expansion Slots

- Connect other components together
- – Disks, graphics display, keyboards, etc.
- Generally high-performance 32 or 64 bit connections

Components and Operations of Computers:

Mass Storage Devices

- Mass storage devices include floppy disks drives, hard disk drives (non-removable hard disks are called fixed disks), magnetic tape drives, and optical (laser) disk units
- Magnetic disks are spinning disks coated with material that may be readily magnetized. Above disk is read/write head, to read data senses magnetization of individual locations on disk and , to write data, changes direction of magnetization of individual locations on disk
- Data is stored on disk in concentric rings called tracks
- Read/write heads move radially over disk to access data on different tracks

Components and Operations of Computers:

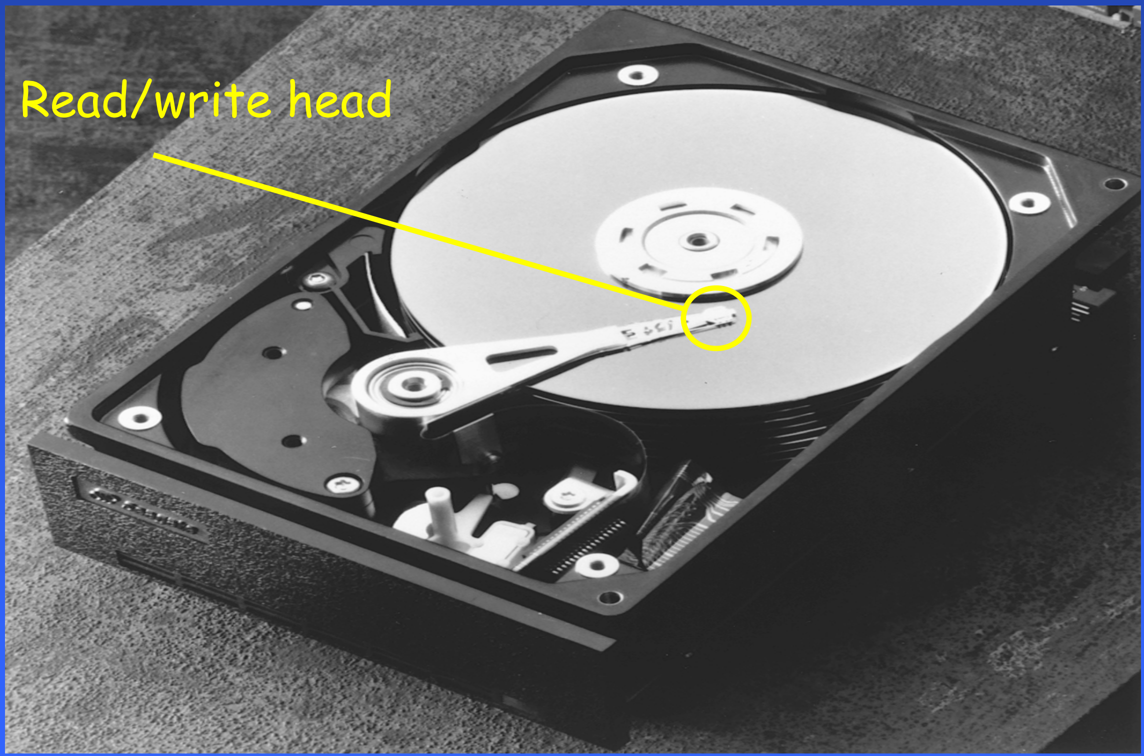
Mass Storage Devices

- Read/write heads move radially over disk to access data on different tracks
- Access time of disk is time required for read/write head to reach proper track (head seek time)
- Data transfer rate is rate which data are read from or written to disk once head and disk are in proper orientation
- Storage capacities of hard disks very large, ranging from 10-500 gigabytes
- Floppy disks are removable plastic disks coated with magnetizable material

Components and Operations of Computers:

Mass Storage Devices

- Hard-disk drive.



Components and Operations of Computers:

Mass Storage Devices

- Magnetic tape is plastic tape coated with magnetizable substance
- Optical disk is removable disk that rotates during data access and from which data are read and written using a laser
- 3 categories of optical disks
  - Read-only – CD-ROMs or DVDs
  - Write-once, Read-many-times (WORM) - CD-ROMs or DVDs
  - Rewritable

Components and Operations of Computers:

Mass Storage Devices

. Phase-change (crystalline to amorphous) when laser heated, changes transparency when read

- Magnetic-optical disk (MOD) contains layer whose magnetization may be changed by magnet if heated above Curie temperature.
- Writing data on MOD uses small electromagnet above disk and laser below. Laser heats small area on recording material above Curie temperature, causing its magnetization to align with that of electromagnet. When domain cools below Curie temperature, magnetism of that domain becomes frozen.
- Magneto-optical disk is read by laser at lower intensity. Polarization of reflected light varies with magnetization of each domain on disk.

Components and Operations of Computers:

Mass Storage Devices

- CD-RWs are common type of rewritable optical disk.
- CD likely to be displaced by DVD, that provides greater storage capacity. DVDs are available in read-only, recordable, and rewritable forms.
- Advantages of optical disks include large storage capacity, on order of 650 megabytes to several gigabytes, and faster data access than magnetic tape.
- Optical disks provide superior data security than most other media because they are not subject to head crashes, as are magnetic disks; are not as vulnerable to wear and damage as magnetic tape and not vulnerable to magnetic fields

Mass Storage Requirments:

TABLE 4-6. COMPARISON OF CHARACTERISTICS OF MASS STORAGE DEVICES AND MEMORY[a]

	Removable	Storage Capacity	Access Time (Average)	Transfer Rate	Cost per Disk/Tape	Media Cost per GB
Floppy disk	Yes	1.2 to 1.4 MB	300 msec	0.03 MB/sec	$0.30	$210
Hard disk	Usually not	10 to 182 GB	6 to 15 msec	3 to 50 MB/sec	NA	
Optical disk, CD-ROM,	Yes	650–700 MB	100 to 150 msec (for 24×)	3.6 MB/sec (for 24×)		
CD-R,					$.50 (CD-R)	$.80 (CD-R)
CD-RW					$1.10 (CD-RW)	$1.70 (CD-RW)
Optical disk,	Yes			8.1 MB/s		
DVD-ROM,		4.7 to 17 GB				
DVD-R,		3.9 GB				
DVD-RAM		5.2 GB			$24 (DVD-RAM)	$4.60 (DVD-RAM)
Magnetic tape (cartridge)	Yes	45 MB to 110 GB	Seconds to minutes	0.125 to 10 MB/sec	$150 (110 GB super DLT)	$1.35 (110 GB super DLT)
Solid-state memory	No	64 MB to 1.5 GB	1 to 80 msec	24 to 250 MB/sec	NA	

[a]Values are typical for 2001-vintage computers. Cost refers to one diskette or tape cartridge.
Storage capacities and transfer rates are for uncompressed data; they would be higher for compressed data.
msec, milliseconds; nsec, nanoseconds (10^6 nsec = 1 msec); MB, megabytes; GB, gigabytes; DLT, digital linear tape.

Components and Operations of Computers:

- Array Processor

- dedicated for mathematical operations

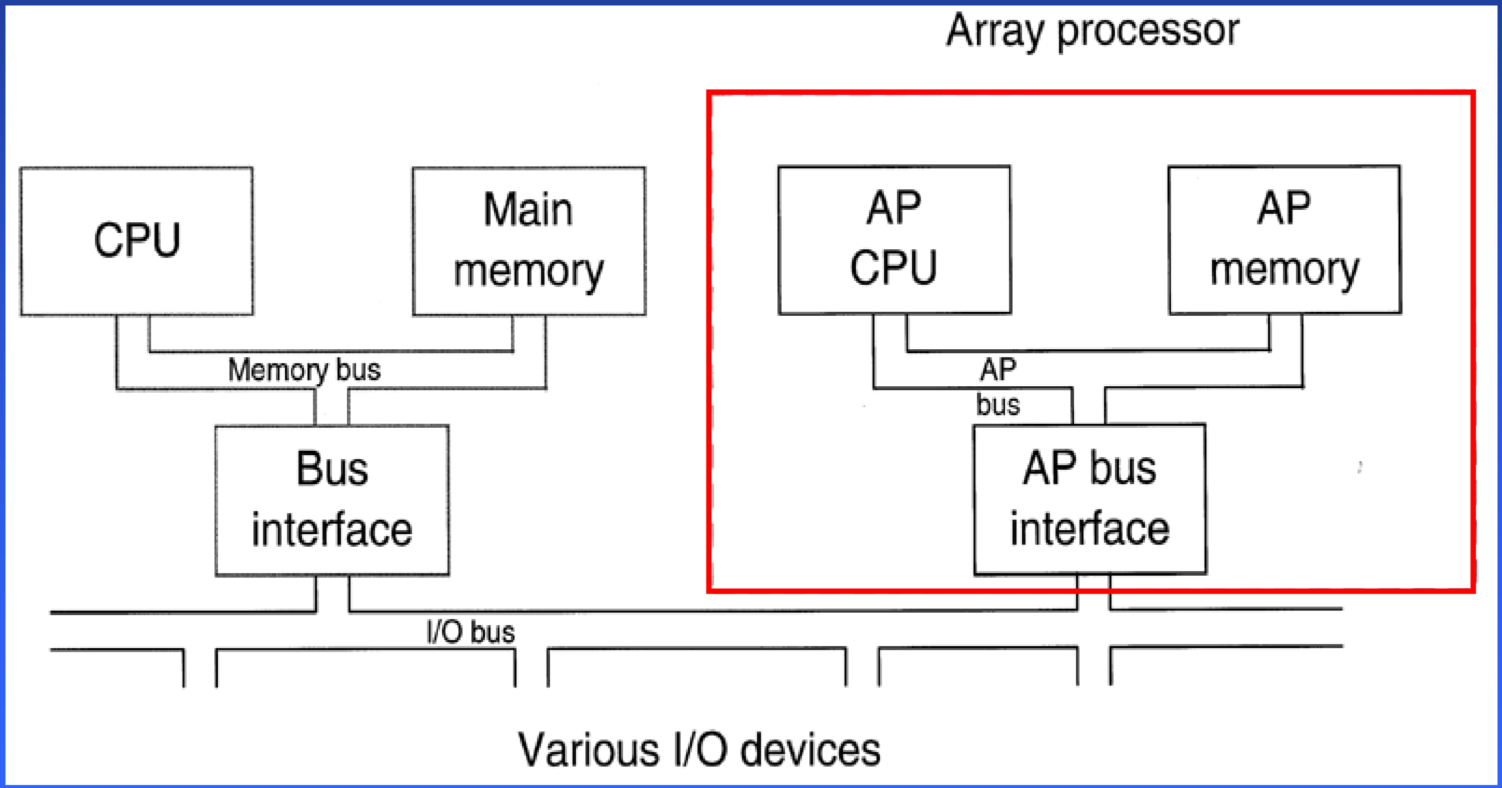
- Keyboard and Pointing Device
- Acquisition Interface
- Communication Interface

– Modem permits computer to transfer information to another computer over network by analog telephone

– Network interface card

Components and Operations of Computers:

Array Processor.

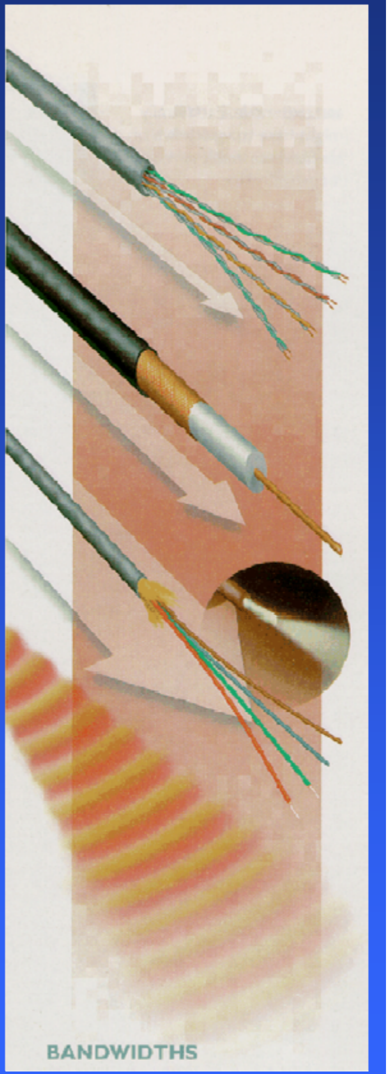


Components and Operations of Computers:

Communication Networks

- Communication Networks
- Modem (500 KBits/sec
- Asynchronous Transfer Mode (ATM)
- (2-500 MB/s)
- Fast Ethernet
- (100 MB/s)
- Ethernet
- (100 MB/s)
- Gigabit
- (1000 MB/s)
- FiberChannel
- (1000 MB/s)

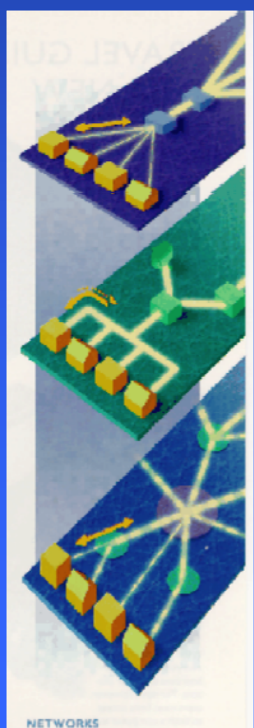
- Network Connection
- Twisted Pair
- Coaxial
- Fiber Optic
- Wireless

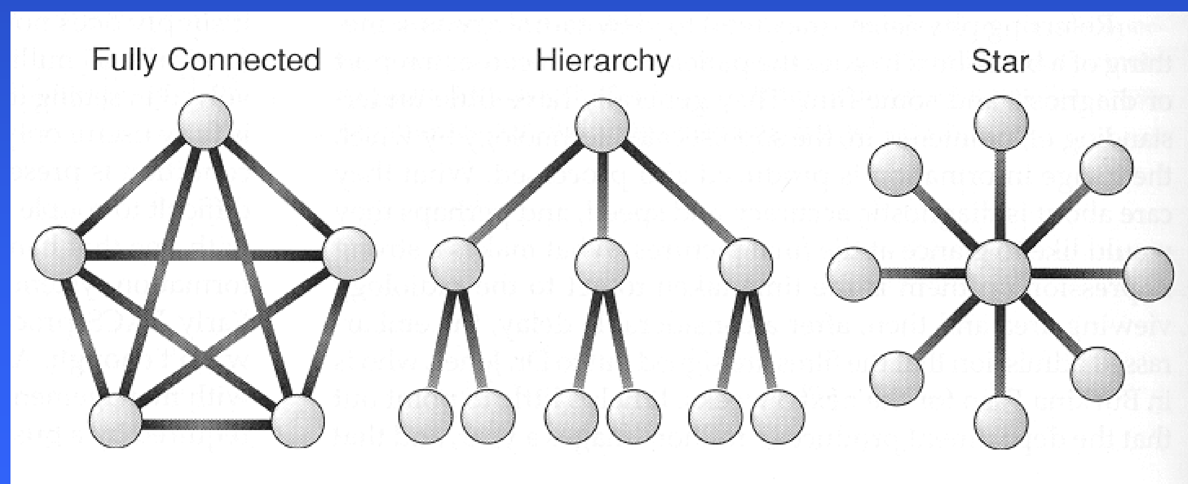


Components and Operations of Computers:

Communication Networks

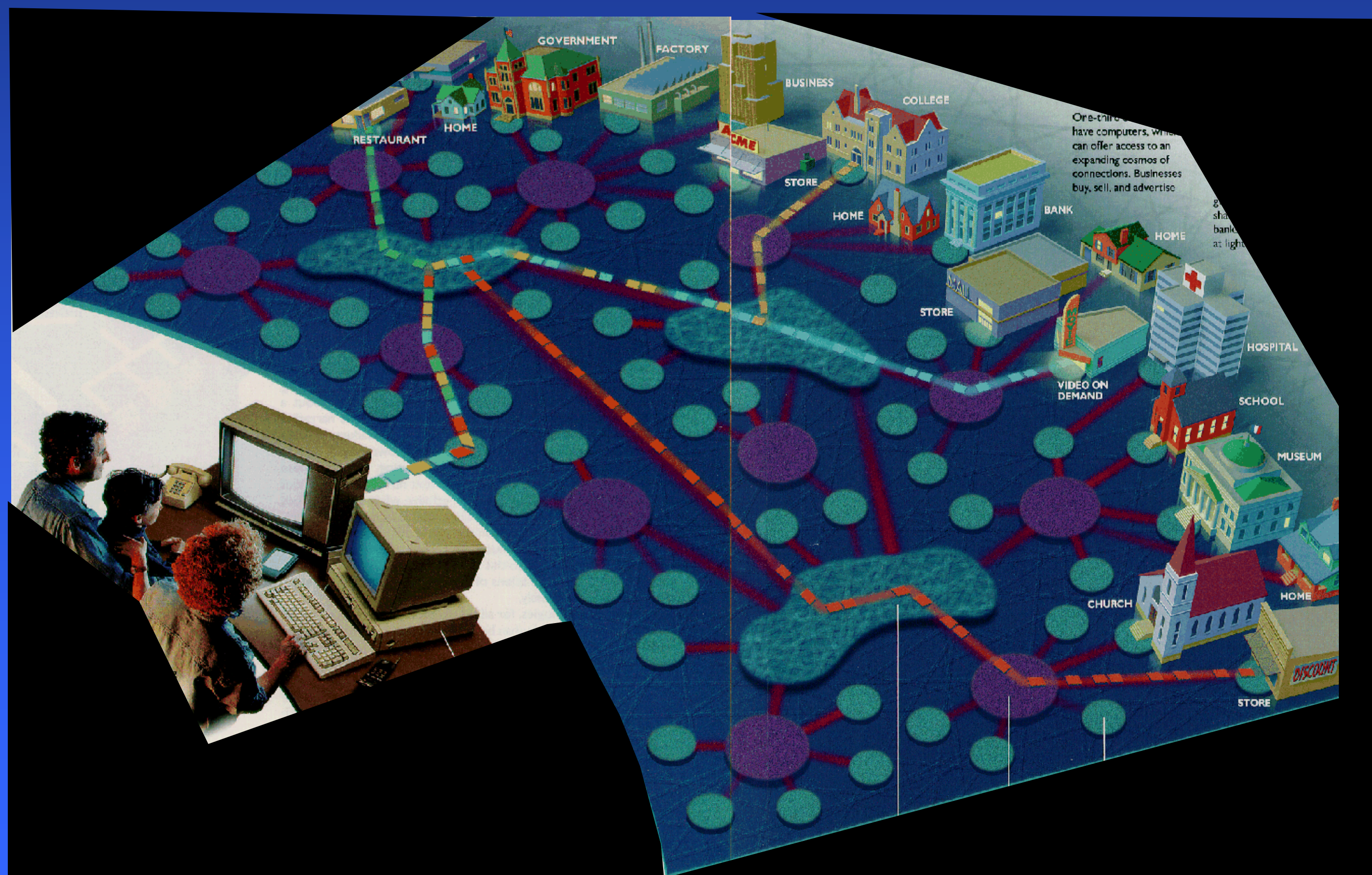
- Network Organization





Components and Operations of Computers:

Communication Networks



Performance of Computers:

- One indicator of CPU speed is speed of its clock
  - e.g. 2.5 GHz Pentium IV
- Speed of CPU may be measured in millions of instructions per second (MIPS)
- Speed of CPU may be measured in millions of floating point operations per second (MFLOPS)
- Programs used for assessing performance are called benchmarks

Computer Software:

- Computer Languages
  - Machine language
  - High-level languages
    - Fortran, Basic
    - C, C++
    - Java
- Applications Programs
- Operating Systems
  - Windows
  - Linux
  - Mac OS on Apple computers
  - Unix for workstations
- Computer security

Computer Software:

- Simple program in language Basic.
- Program prints integers from 1 to 10 on video monitor.

```
10 I = 1
20 PRINT I
30 I = I+1
40 IF I<11 THEN  GOTO  20
50 END
```

Computer Software:

- Computer Security
  - Programs that threaten computers called computer virus. Virus is string of instructions hidden in a program
  - 3 types of viruses
    - Executable file infectors
    - Boot-sector viruses
    - Macroviruses
  - Other types of malicious programs
    - Trojan horses - appear to serve one function but have hidden purpose
    - Worms - automatically spread over computer networks
    - Password grabbers - store passwords of persons logging onto computers for use by unauthorized person
  - Sophisticated computer operating systems, as Unix, provide security features including password protection and ability to grant individual users different levels of access to stored files.

Storage, Processing and Display of Digital Images:

- Storage
- Depends on dynamic range of image (# grey-levels)
- 256 levels = 1 byte is 255 (2^8-1).
- 65536 levels = 2 bytes (16 bits) is 65,535 (2^{16}-1)

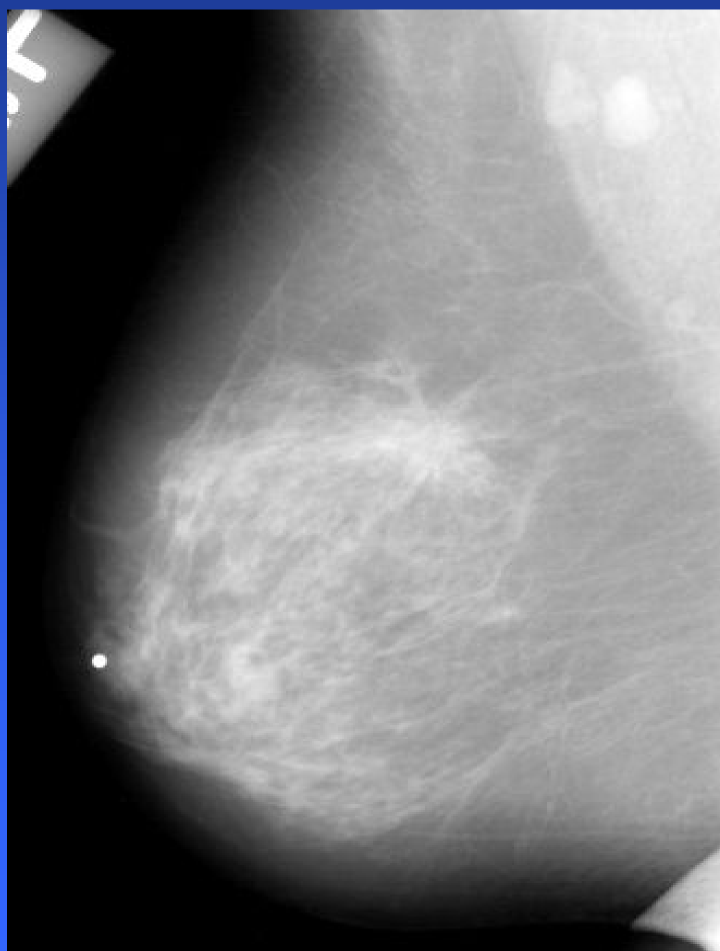
- Pixel size is determined by dividing distance between two points in subject being imaged by number of pixels between these two points
- Example – fluoroscope has 23-cm (9-inch) field of view and images are acquired in 512-by-512 format, then approximate size of pixel is 23 cm/512 = 0.45 mm
- Total number of bytes required to store image is number of pixels in image multiplied by number of bytes per pixel
- (512 x 512 pixels) (1 byte/pixel)/(1,024 bytes/kB) = 256 kB
- (1.4 MB/disk) ($1{,}024^2$ bytes/MB)/[(64 x 64 pixels/image)(2bytes/pixels)] = 179 images/disk

Storage, Processing and Display of Digital Images:

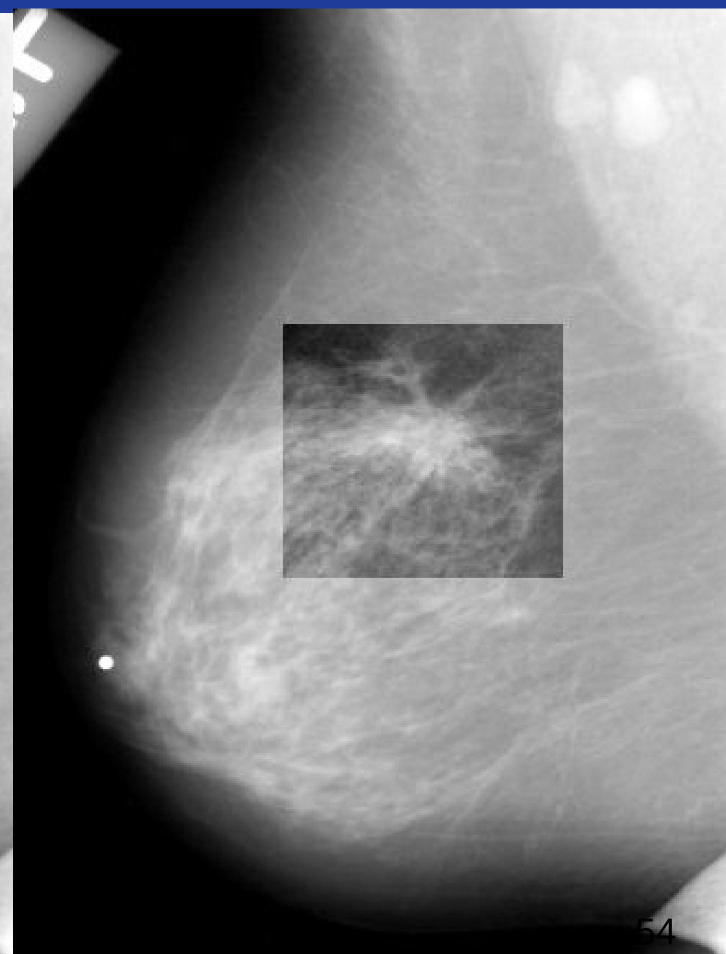
- Processing
  - Spatial filtering is used in many types of medical imaging
  - Quantum mottle is grainy image
  - Smoothing is filtering operation
  - Surface and volume rendering
  - Image co-registration

Processing and Display of Digital Images:

Film-Screen

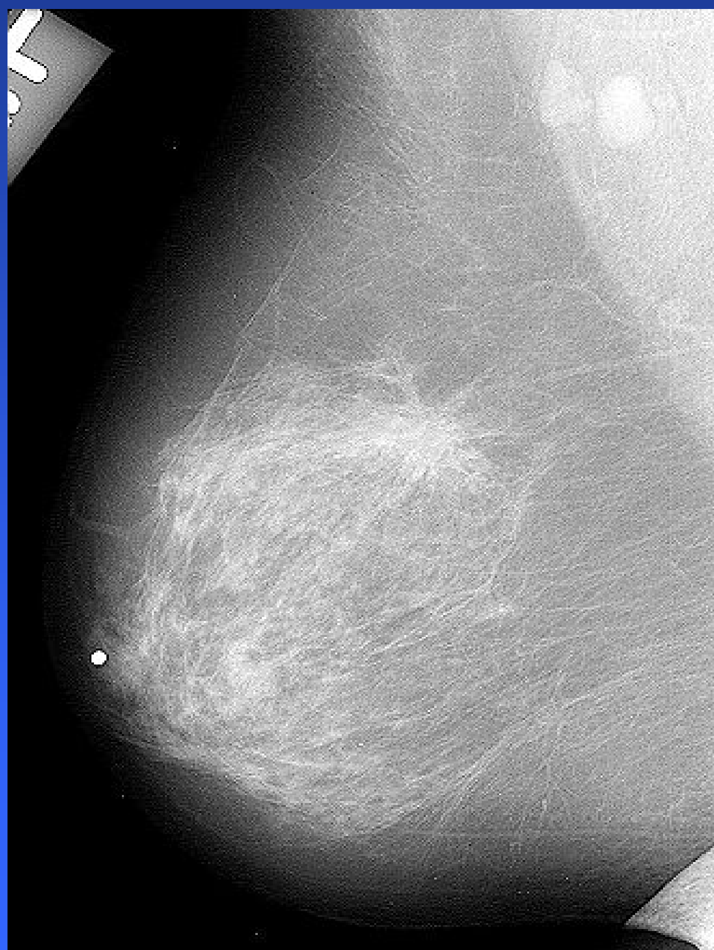


Contrast Enhanced

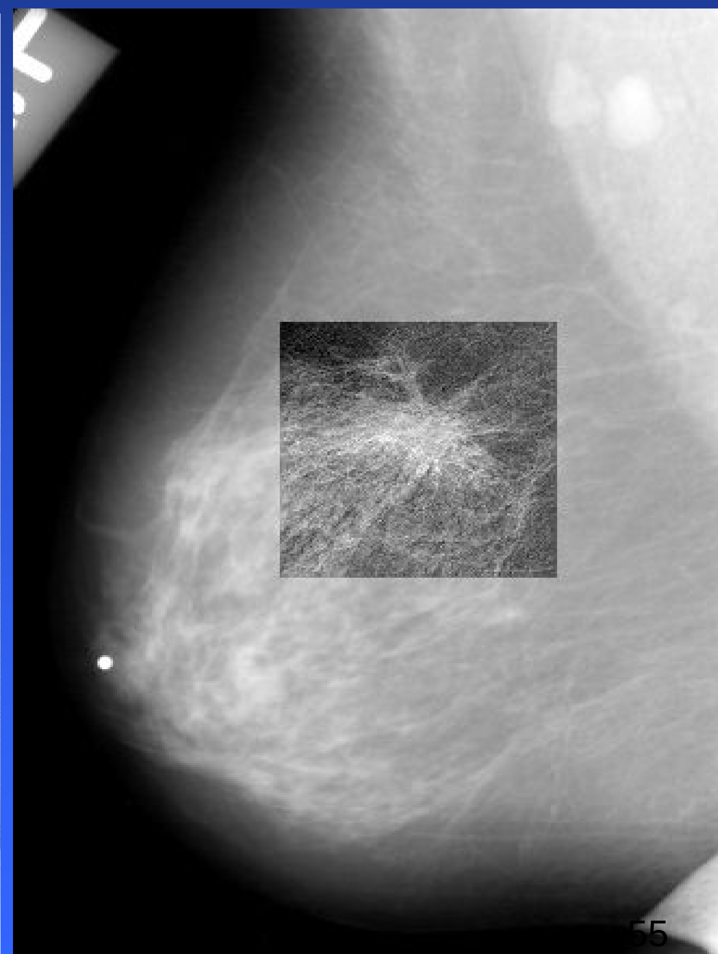


Processing and Display of Digital Images:

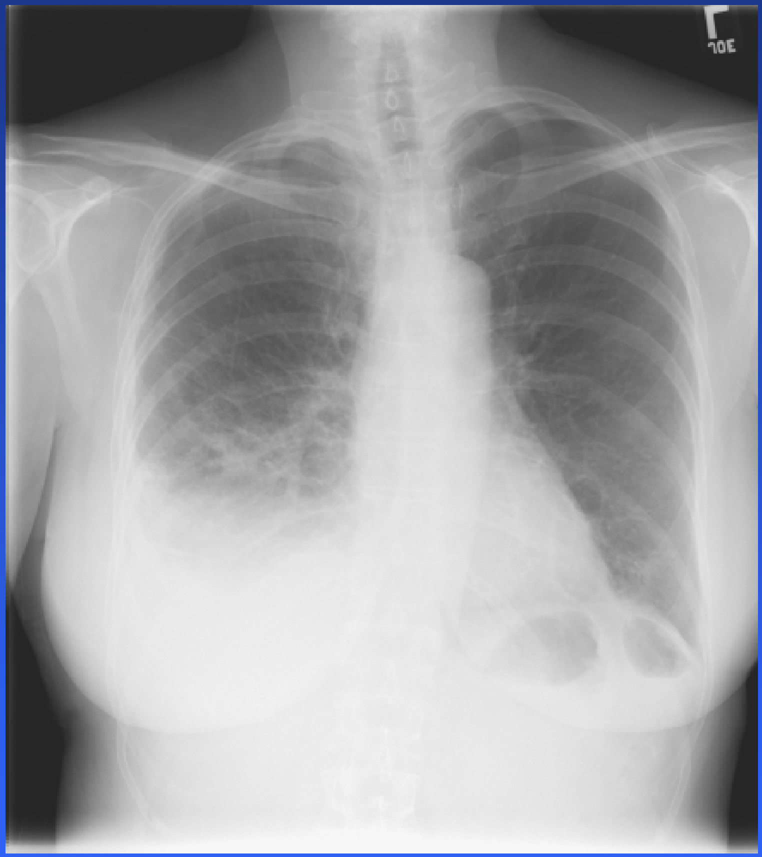
Edge Sharpening



Both



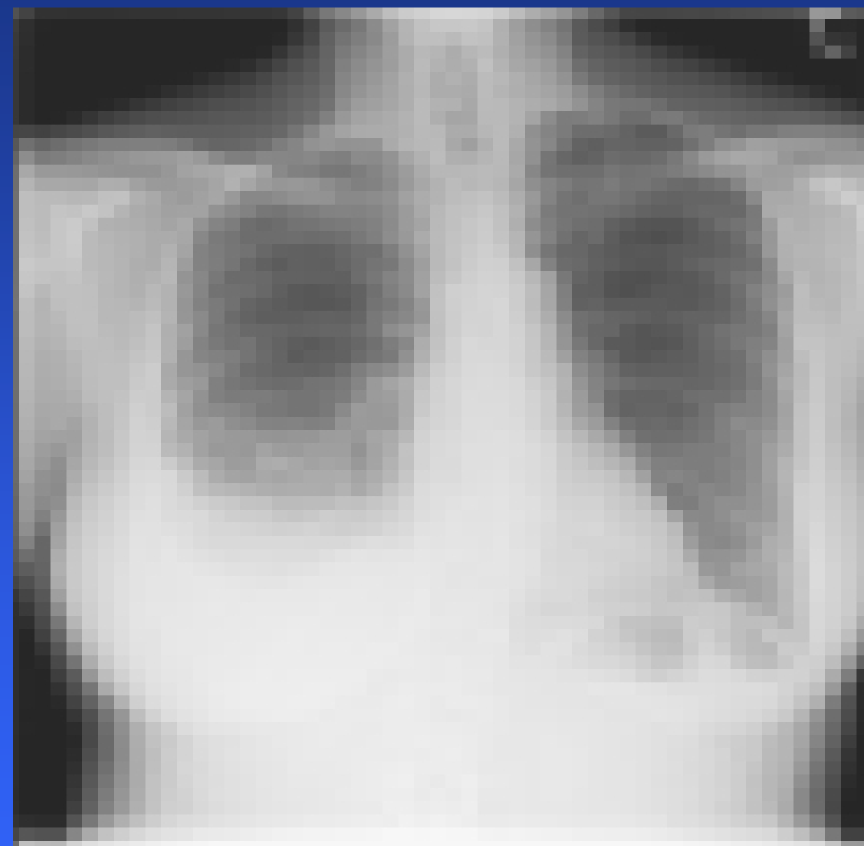
Digital Images Spatial Resolution - Pixels:



1024 x 1024 Pixels

Digital Images Spatial Resolution - Pixels:

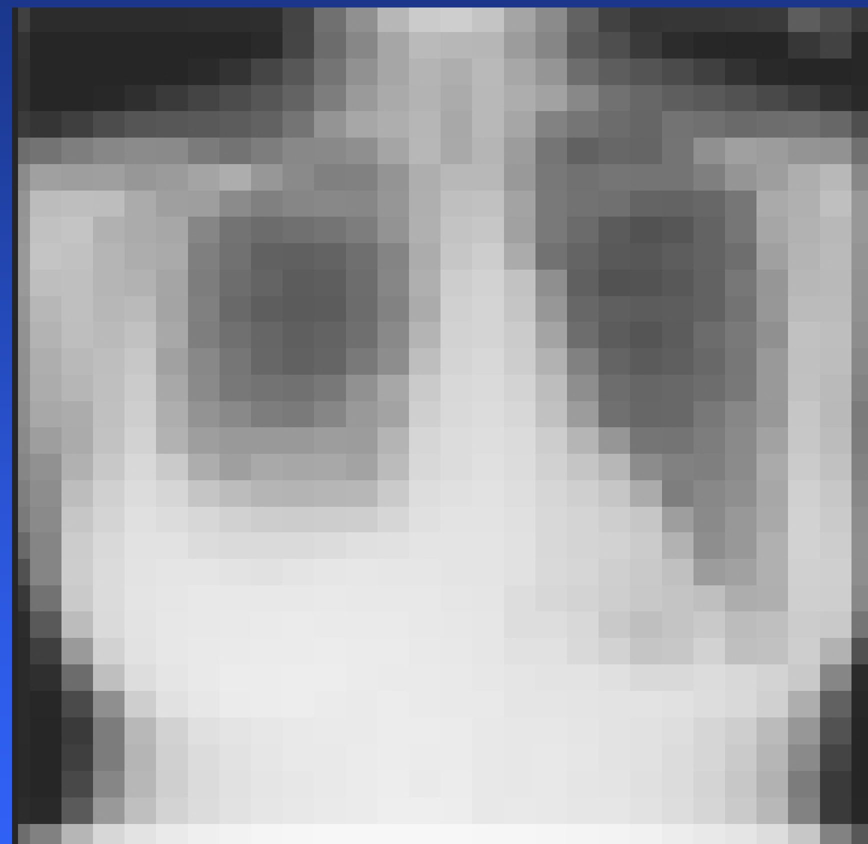
1024 x 1024 Pixels



64 x 64 Pixels

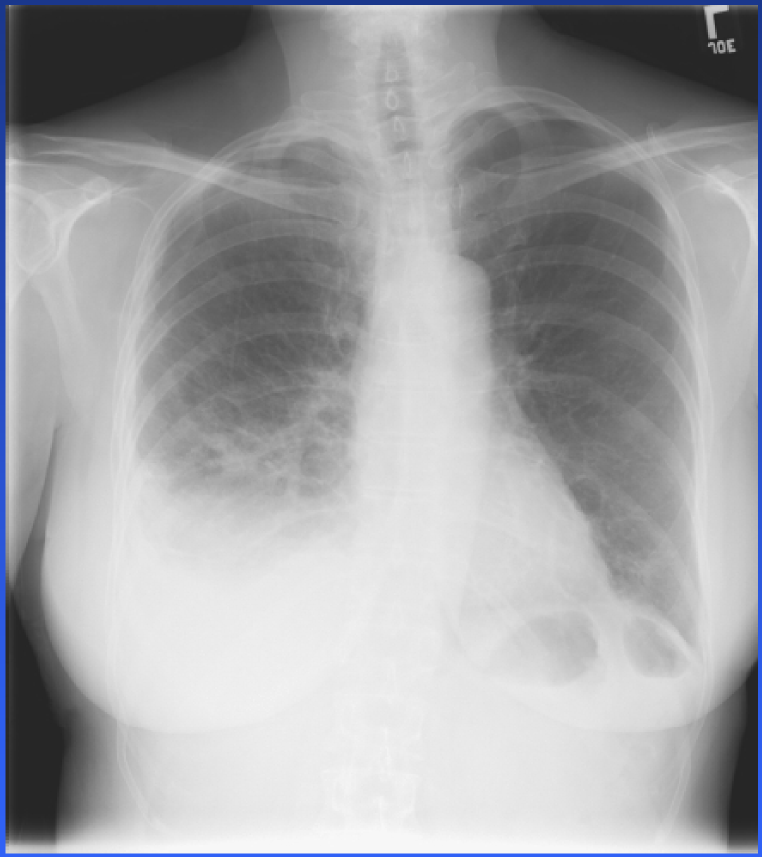
Digital Images Spatial Resolution - Pixels:

1024 x 1024 Pixels



32 x 32 Pixels

Digital Images Spatial Resolution - Pixels:



1024 x 1024 Pixels

16 x 16 Pixels

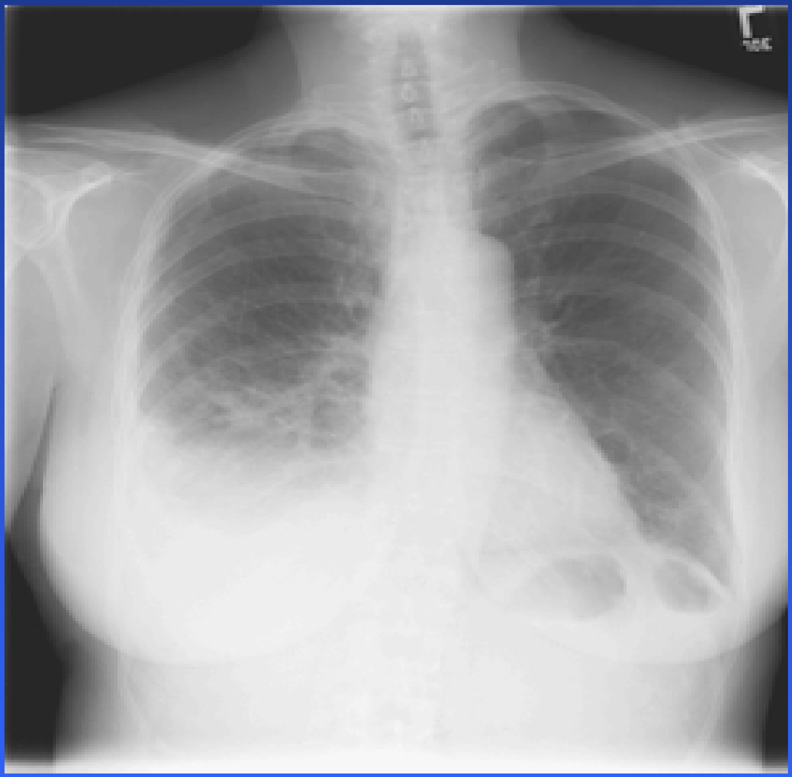
Number systems:

TABLE 4-7. TYPICAL RADIOLOGIC IMAGE FORMATS

Modality	Pixel Format	Bits per Pixel
Scintillation camera planar	64^2 or 128^2	8 or 16
SPECT	64^2 or 128^2	8 or 16
PET	128^2	16
Digital fluoroscopy, cardiac catheter lab	512^2 or 1024^2	8 to 12
Computed radiography, digitized chest films	Typically 2,000 × 2,500	10–12
Mammography (18 × 24 cm) or (24 × 30 cm)	Typically 1,800 × 2,300 to 4,800 × 6,000	12–16
X-ray CT	512^2	12
MRI	64^2 to $1,024^2$	12
Ultrasound	512^2	8

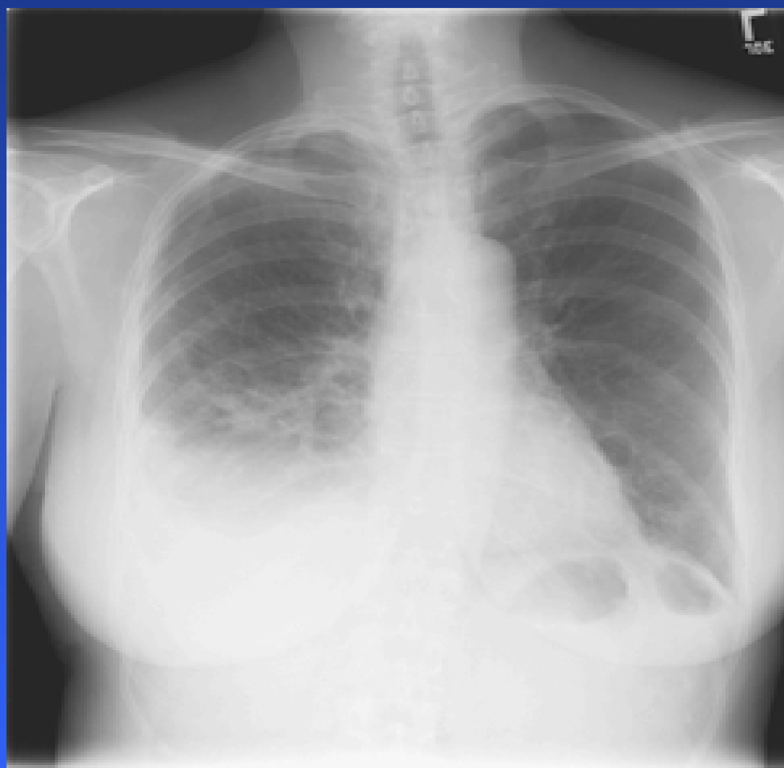
CT, computed tomography; MRI, magnetic resonance imaging; PET, positron emission tomography; SPECT, single photon emission computed tomography.

Digital Images Contrast Resolution - Pixels:

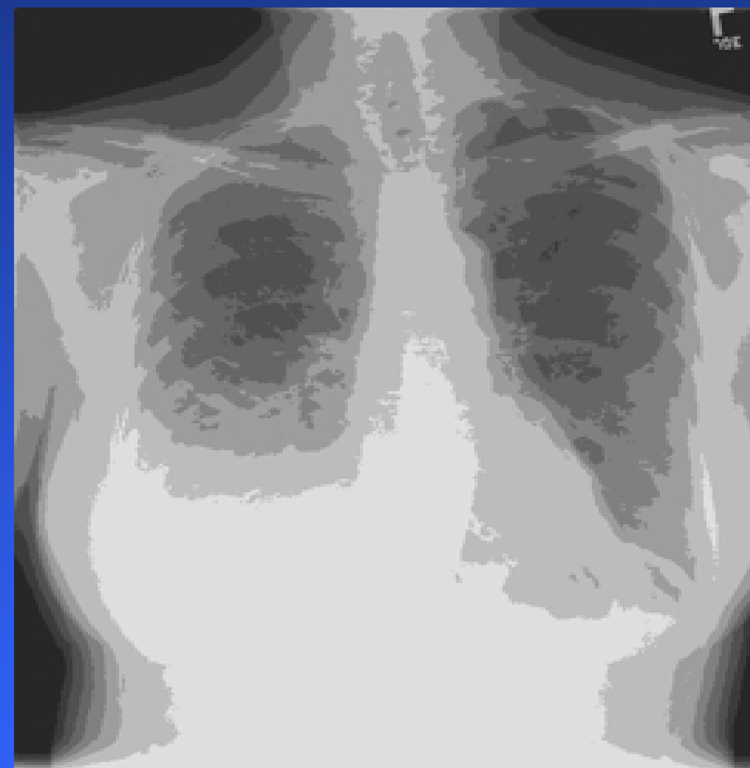


8-bits (256 levels)

Digital Images Contrast Resolution - Pixels:

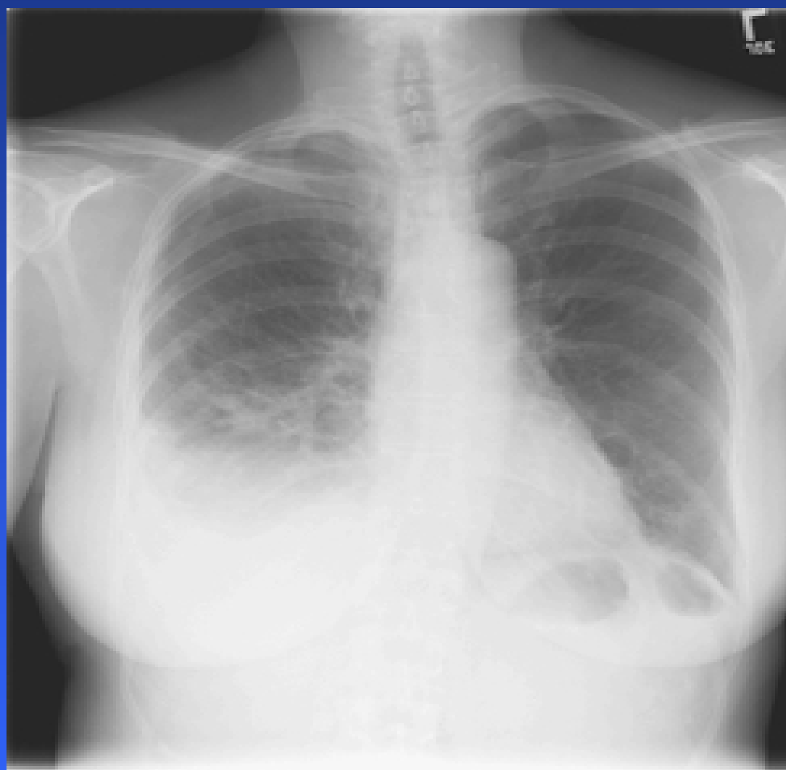


8-bits (256 levels)

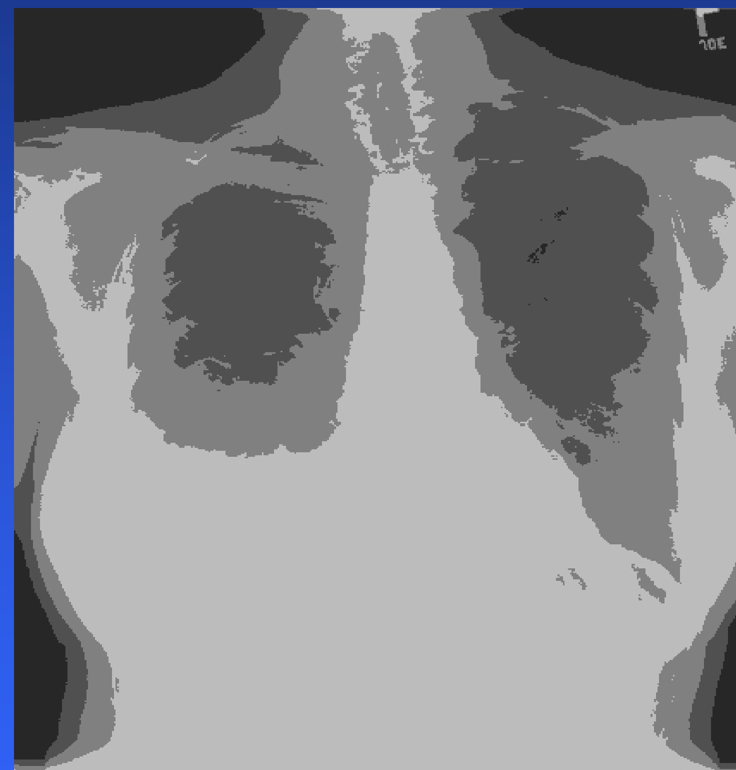


3-bits (8 levels)

Digital Images Contrast Resolution - Pixels:

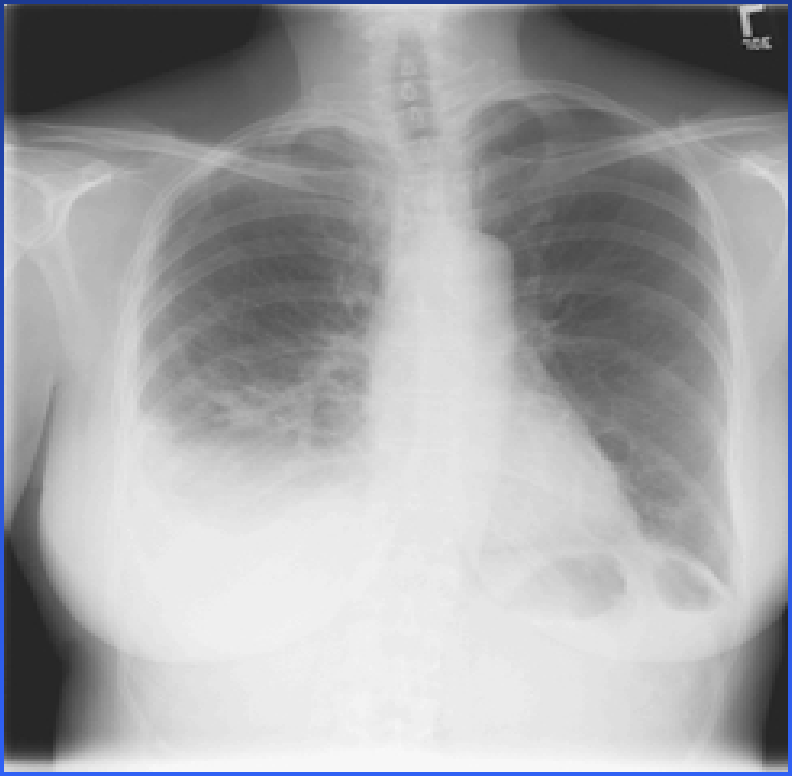


8-bits (256 levels)



2-bits (4 levels)

Digital Images Contrast Resolution - Pixels:



8-bits (256 levels)

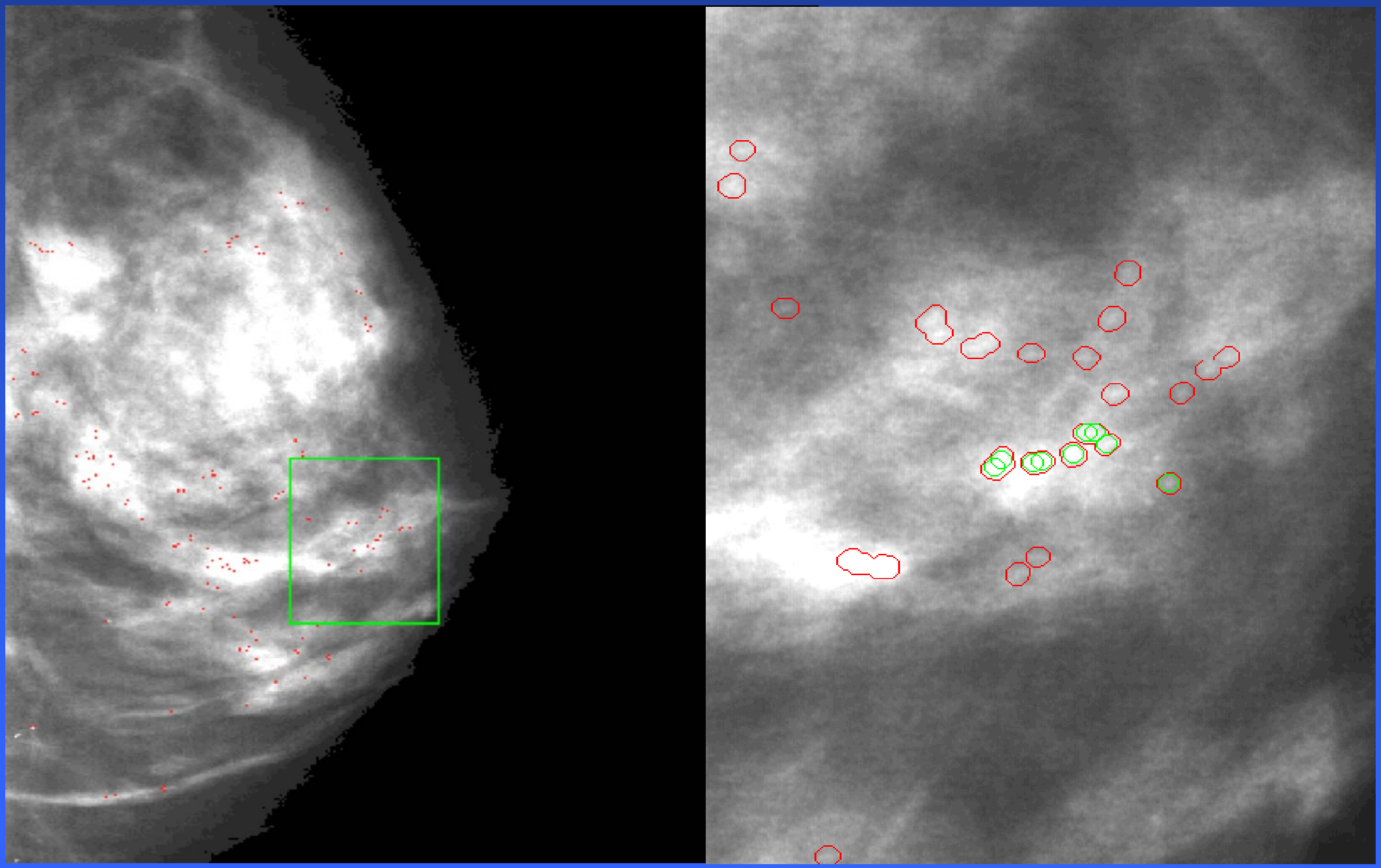
1-bits (2 levels)

Storage, Processing and Display of Digital Images:

- Computer-Aided Detection
  - Computer program to detect features likely to be of clinical significance in images
  - Computer-aided detection improve sensitivity of interpretation, but also may reduce the specificity

Storage, Processing and Display of Digital Images:

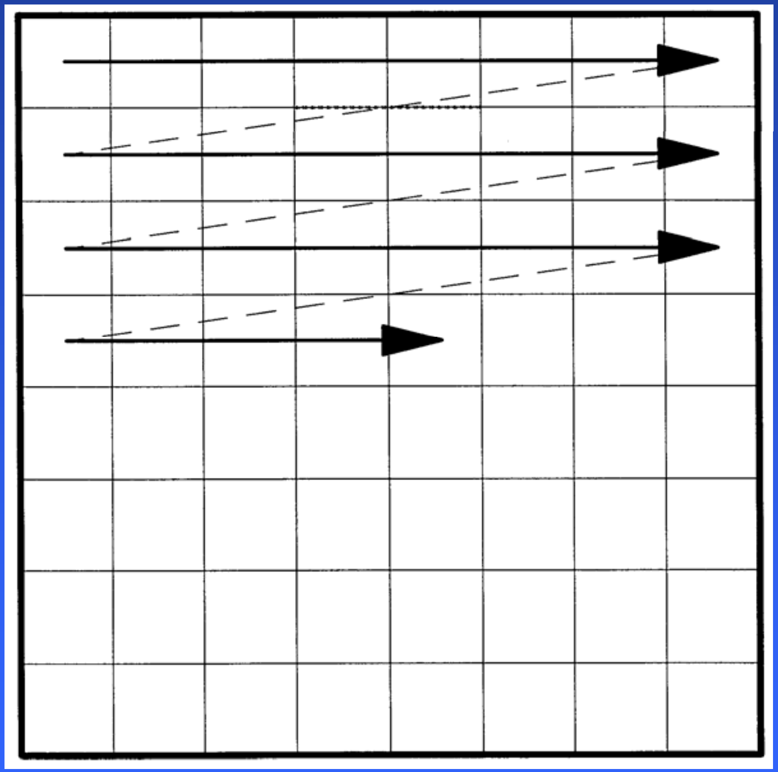
- Computer-Aided Detection



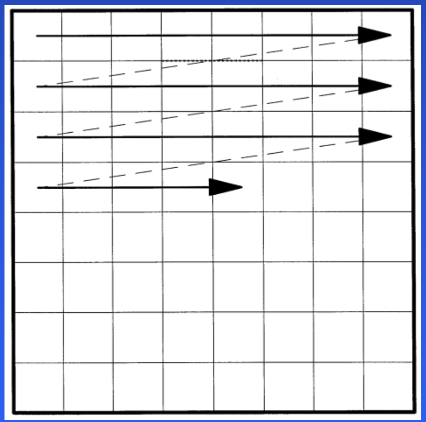
Storage, Processing and Display of Digital Images:

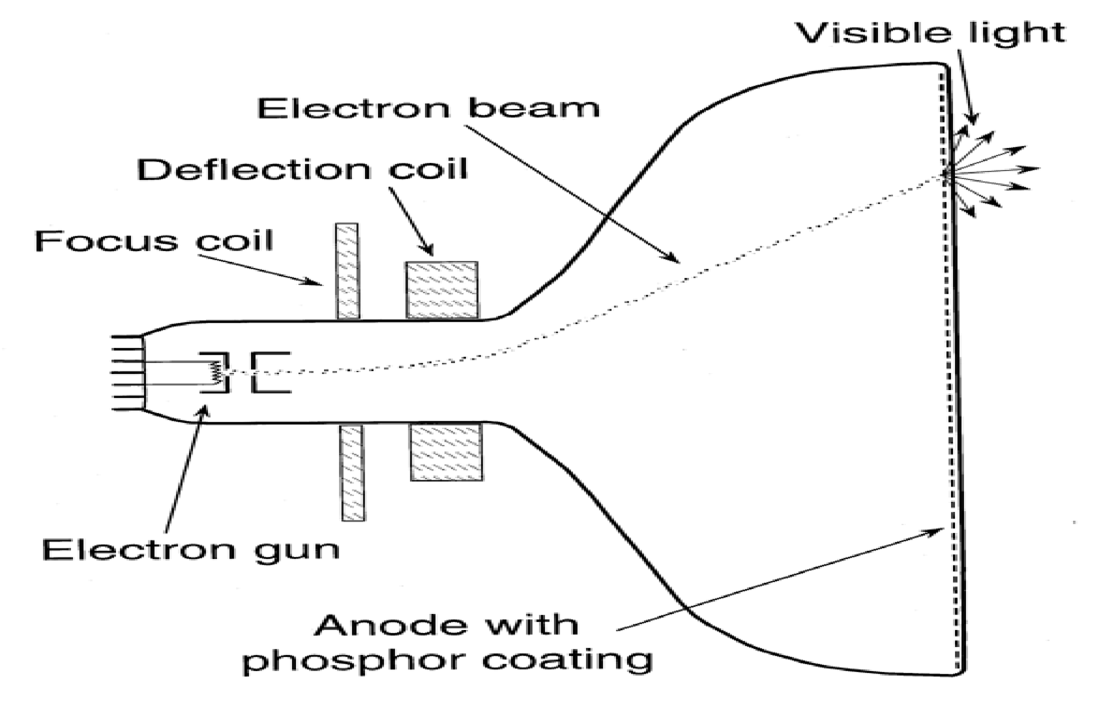
- Display
  - Conversion of Digital Image into an Analog Video Signal
  - Gray-Scale Cathode Ray Tube Monitors
  - Color CRT Monitors
  - Flat-Panel Monitors

Display of Digital Images - conversion to raster:

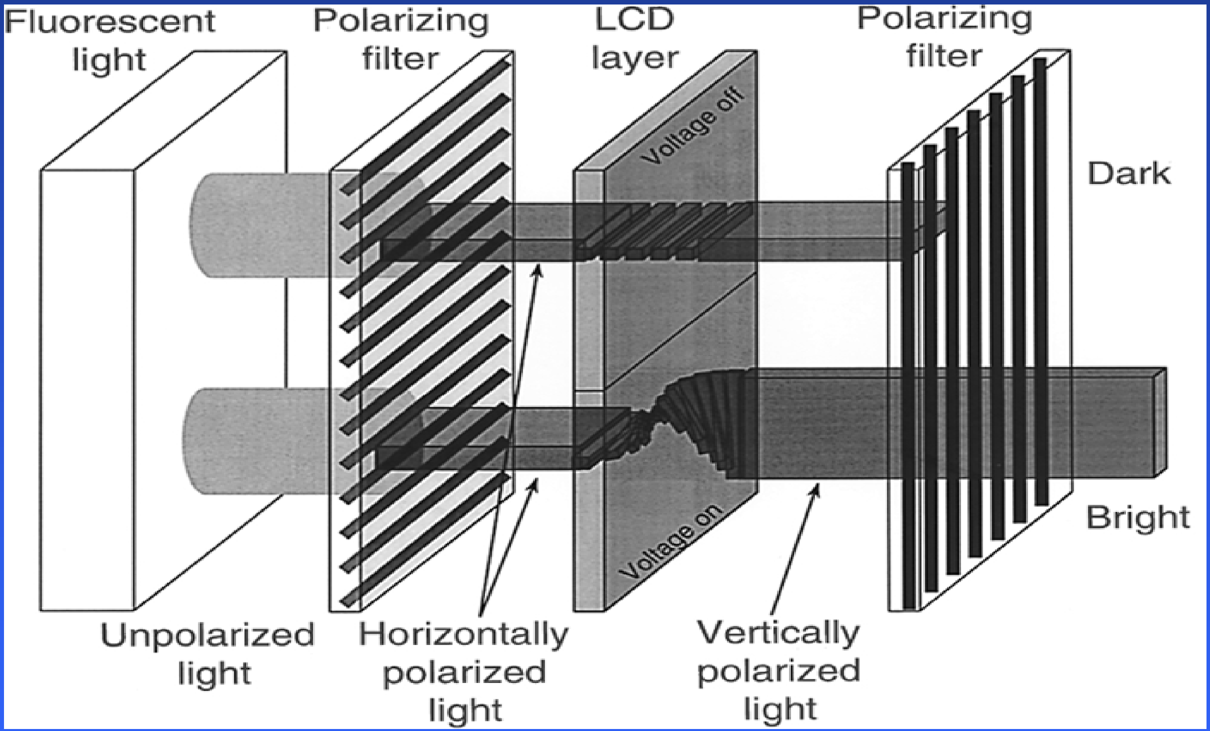


Display of Digital Images - CRT display:





Display of Digital Images - LCD (Liquid Crystal Display):

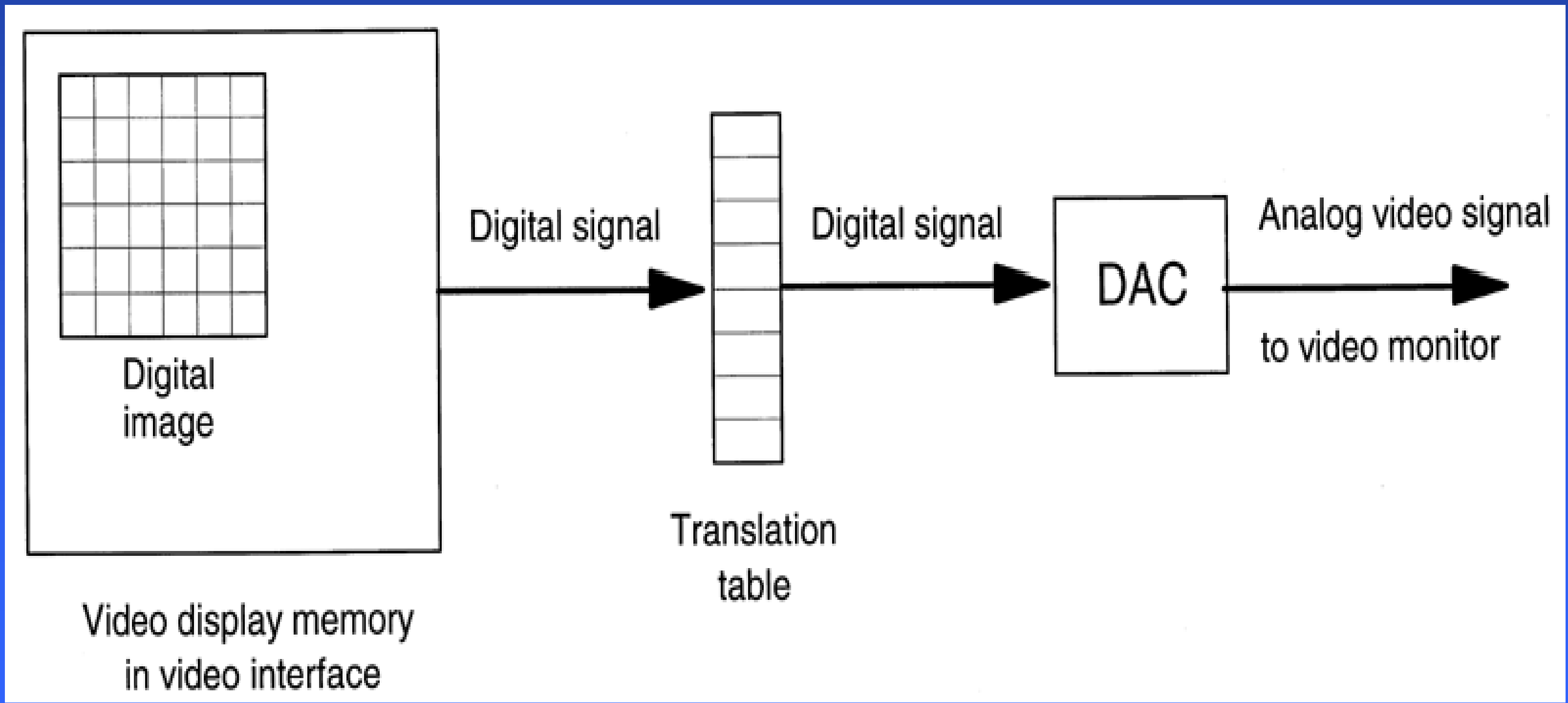


Display of Digital Images:

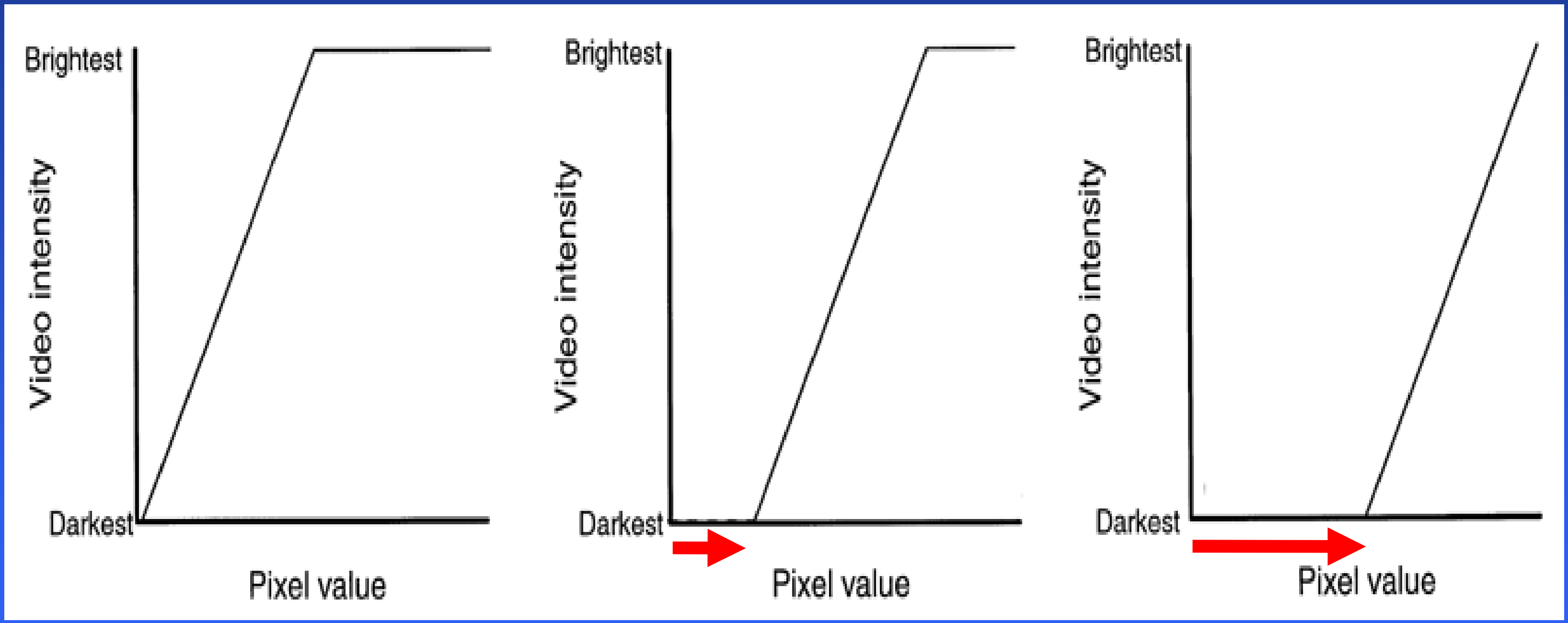
- Contrast Enhancement
  - Amount of choice in how mapping from pixel value to video intensity is to be performed. It is called contrast enhancement
  - Two methods of contrast enhancement on most medical image-processing computers
    - Translation table selection
    - windowing

Display of Digital Images:

- Translation table lookup



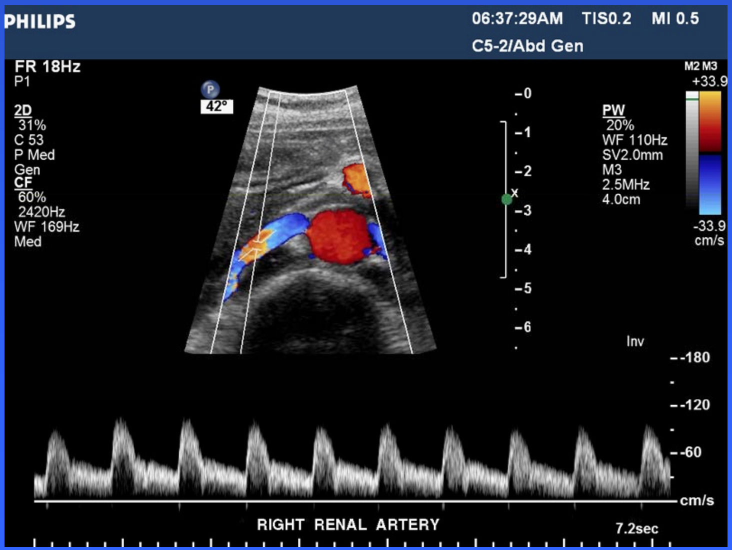
Display of Digital Images - window/level adjustment:



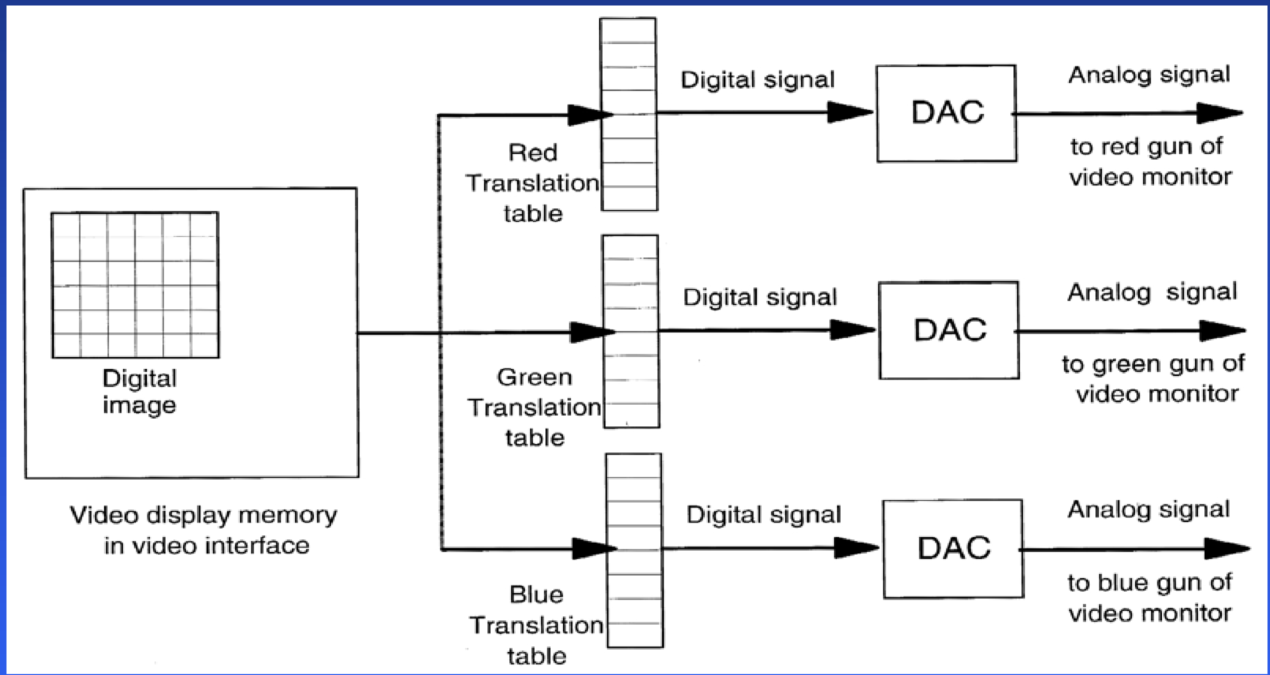
Windowing an image with pixel values from 0 to 200 to enhance contrast in pixels from 0 to 100(left), 50 to 150 (center), and 100-200 (right).

Display of Digital Images:

- Common Uses of False Color include:
  - Nuclear medicine, in which color is often used to enhance perception of contrast
  - ultrasound, in which color is used to superimpose flow information on images displaying anatomic information



Display of Digital Images - false color:



Creation of false color display. Each individual pixel value in image being displayed is used to look up red, green, and blue intensity value. These are simultaneously displayed adjacent to one another within a single pixel of color video monitor. Mix of these three colors creates perception of single color for that pixel.

Display of Digital Images - Hard copy devices:

Digital images recorded on a film with video imager or laser imager.

Video imager focuses image onto the film

Laser imager raster-scans the image onto the film.

Review Question

2. The decimal number 10 is equal to which number in *binary* form?

A. 10
B. 11
C. 111
D. 1010
E. 1100

Review Question

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C. 111
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2. D. One method to convert numbers from decimal to binary form is to repeatedly divide by two and record the remainder from each division:

	remainder	
10/2 = 5	0	(least significant digit)
5/2 = 2	1	
2/2 = 1	0	
1/2 = 0	1	(most significant digit)

Thus 10 (decimal) = 1010 (binary)

Review Question

6. If 16 bits are used for each pixel, a 1.44 megabyte floppy disk can store _______ 128 by 128 pixel digital images.

A. 11
B. 22
C. 46
D. 66
E. 128

Review Question

6. If 16 bits are used for each pixel, a 1.44 megabyte floppy disk can store _______ 128 by 128 pixel digital images.

A. 11
B. 22
C. 46
D. 66
E. 128

6. C. A megabyte is 2^{10} bytes = 1024 x 1024 bytes

Bytes per disk: 1.44 MB x $(1024)^2$ B/MB ≈ 1,510,000 B

Because 16 bits = 2 bytes, there are 128 x 128 x 2 = 32,768 bytes per image:

Thus, one disk can store 1,510,000/32,768 = 46.1 images

If you recognize that a megabyte is about a million bytes, and work the problem using this approximation, you get the answer 44 images, which is close to the correct answer.

Review Question

26. An imaging modality providing better contrast resolution requires ___________.

A. more pixels per image
B. fewer pixels per image
C. more bits per pixel
D. fewer bits per pixel
E. more images

Review Question

26. An imaging modality providing better contrast resolution requires ___________.

A. more pixels per image
B. fewer pixels per image
C. more bits per pixel
D. fewer bits per pixel
E. more images

26. C. An imaging modality providing higher contrast resolution requires more bits per pixel than a modality providing lower contrast resolution. The number of bits per pixel determines the number of values that can be represented by a pixel and thus the number of grayscale levels that can be displayed.