

# Chapter 12: Computers in Nuclear Medicine

Set of 140 slides based on the chapter authored by  
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of the IAEA publication (ISBN 78–92–0–143810–2):  
*Nuclear Medicine Physics:*  
*A Handbook for Teachers and Students*

## Objective:

To familiarize the student with the fundamental concepts of computers and their application to nuclear medicine.



**IAEA**  
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- 12.1. Phenomenal increase in computing capabilities
- 12.2. Storing images on a computer
- 12.3. Image processing
- 12.4. Data acquisition
- 12.5. File format
- 12.6. Information system

# 12.1 PHENOMENAL INCREASE IN COMPUTING CAPABILITIES

## 12.1.1 Moore's Law

### Moore's Law

- ❑ 'New memory chips have twice the capacity of prior chips, and new chips are released every 18 to 24 months'.  
*Gordon Moore, co-founder of Intel, 1965.*
- ❑ Moore's law predicted an exponential growth in computer memory size, a prediction that has proved remarkably accurate.
- ❑ At the same time price has steadily decreased.

# 12.1 PHENOMENAL INCREASE IN COMPUTING CAPABILITIES

## 12.1.2 Hardware vs 'Peopleware'

### Hardware vs 'Peopleware'

- ❑ The rapid growth in the capability of computers has implications for the management of a nuclear medicine department.
- ❑ The growth in productivity of people (staff) is much slower.
- ❑ This is altering decisions about the balance between staff and computers
- ❑ Since hardware is relatively cheap, it is always better to assign more computer power and less people power to a new task.

# 12.1 PHENOMENAL INCREASE IN COMPUTING CAPABILITIES

## 12.1.3 Future trends

### Future trends

#### □ Multiple processor chips (cores)

- Increasing the number of processor cores is likely to be the main contributor to personal computer capability in the near future.
- However existing applications are often unable to make efficient use of the available cores.
- Multi-threaded programming, that allows subtasks to be computed independently in parallel, is needed.
- Image processing algorithms are well suited to acceleration using multi-threaded programming.
- Increasingly, new software releases include multi-threading.

# 12.1 PHENOMENAL INCREASE IN COMPUTING CAPABILITIES

## 12.1.3 Future trends

### Future trends

#### □ Graphical Processing Units (GPUs)

- Were originally developed to accelerate graphics processing for computer games, but new software tools allow them to be programmed to perform other tasks suited to parallelization.
- They comprise hundreds or thousand of cores, each which can perform the same task on a different piece of data at the same time. For example each core could operate the data in one pixel of an image.
- The main bottleneck is the overhead of transferring data from the host computer to GPU memory, and returning results from GPU memory to the host. If this is required frequently there may be no net gain in processing time.

# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.1 Number systems

### Decimal, binary, hexadecimal, and base 256

- ❑ The decimal number system with which we are all familiar, has 10 digits, 0-9.
- ❑ Computers are best at dealing with two values, on or off. The binary number system has two digits, 0 and 1.
- ❑ Converting between the two number systems is quite straightforward. Consider the decimal number  $124_{10}$ . It is equivalent to  $4 \times 10^0 + 2 \times 10^1 + 1 \times 10^2$ .
- ❑ By analogy, we can convert any binary number, e.g.  $1011_2$ , to its decimal equivalent as  $1 \times 2^0 + 1 \times 2^1 + 0 \times 2^2 + 1 \times 2^3$ , or  $11_{10}$ . Note that only the base changes (from 10 to 2).

# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.1 Number systems

### Decimal, binary, hexadecimal, and base 256

- ❑ The hexadecimal number system has 16 symbols, 0-9 and A-F, and its base is 16.
- ❑ Here is a table showing the value of each hexadecimal symbol in decimal.

Hexadecimal (base 16)	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
Decimal (base 10)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

- ❑ To convert a hexadecimal number, e.g.  $5A3_{16}$ , to decimal we write  $3 \times 16^0 + A \times 16^1 + 5 \times 16^2 = 3 + (10 \times 16) + (5 \times 256) = 1443_{10}$ .



# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.1 Number systems

### Decimal, binary, hexadecimal, and base 256

- ❑ The internet addressing scheme (for IP addresses) uses a base 256 number system.
- ❑ As can be seen in the table below this makes IP addresses more human-friendly than binary or hexadecimal.

← 32 binary digits →								
<b>Binary</b>	0001	1000	0000	1001	1111	0011	0100	1110
<b>Hexadecimal</b>	1	8	0	9	F	3	4	E
<b>IP address</b>	24.		9.		243.		78	

## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.1 Number systems

#### Kilo, mega, giga, tera

- ❑ In the decimal system, kilo, mega, giga and tera are used to represent 1000, 1 000 000, 1 000 000 000 and 1 000 000 000 000, respectively.
- ❑ Using scientific notation, these numbers are  $10^3$ ,  $10^6$ ,  $10^9$  and  $10^{12}$ , respectively.
- ❑ Quantities of similar magnitude in the binary system are  $2^{10}$ ,  $2^{20}$ ,  $2^{30}$  and  $2^{40}$ , or  $1024_{10}$  (kilo),  $1\,048\,576_{10}$  (mega),  $1\,073\,741\,824_{10}$  (giga), and  $1\,099\,511\,627\,776_{10}$  (tera), respectively.

# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.1 Number systems

kilo, mega, giga, tera

Symbol	Prefix	Power of 2	Value	Power of 10
k	kilo	$2^{10}$	1024	$\sim 10^3$
M	mega	$2^{20}$	1 048 567	$\sim 10^6$
G	giga	$2^{30}$	1 073 741 824	$\sim 10^9$
T	tera	$2^{40}$	1 099 511 627 776	$\sim 10^{12}$

## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.2 Data representation

- ❑ Digital images are composed of individual picture elements, pixels, which represent a single point in the image. Each pixel is represented by a number or a series of numbers. There are several methods of representing each number.

# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.2 Data representation

### Integer numbers

- A group of binary digits (bits) can be interpreted in several different ways. The simplest is as a positive integer, numbers 0, 1, 2, 3, etc.

Binary	Decimal
000	0
001	1
010	2
011	3
100	4
101	5

# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.2 Data representation

### Integer numbers

- ❑ The number of bits determines how large a number can be stored.
- ❑ If we are only concerned with representing positive integers (e.g. if we are counting photons in pixel) we can use all the bits to represent the size of the number.
- ❑ In general, the largest positive (or ‘unsigned’) integer that can be represented in N bits is  $2^N - 1$ .  
e.g. If  $N=4$ , the largest integer is  $1111_2$ , or  $2^4 - 1 = 15$ .
- ❑ A group of 8 bits is called a byte, and can represent unsigned integers up to 255.

# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.2 Data representation

### Integer numbers

- As the range of values that can be represented in one byte is limited, it is common to form groups of 2, 4 or bytes to store larger integer values. This is important if the number of counts expected in one pixel is larger than 255.

The Number Of Counts That Can Be Represented In Different Image Formats

	<b>Bits</b>	<b>Range</b>	<b>No of values</b>
1 bit	1	0 – 1	2
1 byte	8	0 – 255	256
2 bytes	16	0 – 65 535	64 k
4 bytes	32	0 – 4 294 967 295	4 G

# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.2 Data representation

### Integer numbers

- ❑ If we need to represent both negative and positive integer values, this is done by dedicating one of the bits to indicate the sign. Such integers are called ‘signed’ integers. This reduces the magnitude of numbers that can be represented by a factor of about 2.
- ❑ If we are storing signed integers in an 8-bit byte, and dedicate the most significant bit (MSB) to represent the sign:
  - MSB = 0 : positive integer
  - MSB = 1 : negative integer

## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.2 Data representation

#### Negative integers

❑ Negative integers are represented as the '2's complement' of their positive counterpart. The 2's complement is obtained by adding 1 to the '1's complement'. This is best illustrated by an example.

❑ A negative integer is represented by first taking the 1's complement (i.e. reversing the value of every bit) of its positive counterpart, and then adding 1.

e.g.    1                    1's complement            2's complement  
          00000001<sub>2</sub>        11111110<sub>2</sub>                11111111<sub>2</sub>

❑ So, -1 is represented as the 8 bit signed integer 11111111<sub>2</sub>.



# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.2 Data representation

### Signed integer numbers

- As shown below 8-bit signed integers can range from -128 to +127.

#### 8-bit signed integers

Binary	Decimal
01111111	+127
01111110	+126
01111101	+125
...	
00000001	+1
00000000	0
11111111	-1
...	
10000010	-126
10000001	-127
10000000	-128

# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.2 Data representation

### Floating point numbers

- ❑ Floating-point representation in a computer is analogous to scientific notation in which a number is represented by a mantissa,  $M$ , with a certain number of significant digits, times  $10^N$ , where  $N$  is the exponent.
- ❑ The computer uses base 2 rather than 10, i.e. a floating point value is given by

$$M \times 2^N$$

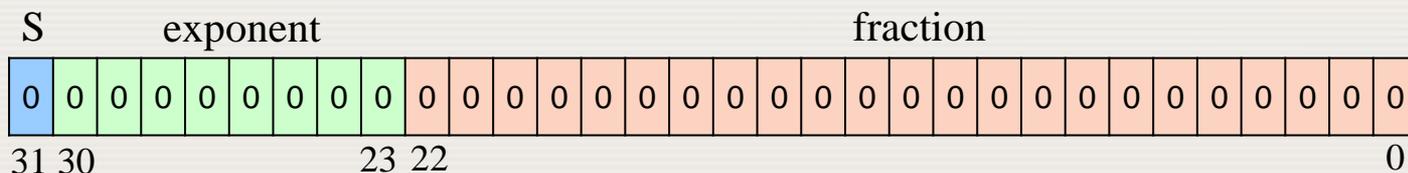
where precision, is determined by the number of bits used to represent  $M$ , and the range is determined by the number of bits used to represent  $N$ . A sign bit sets the sign.

# 12.2 STORING IMAGES ON A COMPUTER

## 12.2.2 Data representation

### Floating point numbers

- ❑ Floating numbers are usually represented in either 32 bits ('single precision') or 64 bits ('double precision').
- ❑ The number of these bits allocated to each of M and N represents a tradeoff between precision and range.
- ❑ The most common single precision standard in use is IEEE 754, in which 8 bits are allocated for the exponent, 23 bits for the significant digits (fraction) and 1 bit for the sign.



## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.2 Data representation

#### Byte order

- ❑ Memory is addressed by byte. When a number is stored using 32 bits (4 bytes), then successive numbers start at memory addresses 0, 4, 8, etc.
- ❑ Confusion can arise because some manufacturers assemble 4-byte numbers using address 0 followed by address 1, e.g. 0123, and others in the order 3210.
- ❑ The former is sometime called 'big-endian', the big address is at the end - the big values come first; the latter is sometimes called 'little-endian'.

## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.3 Images and volumes

- ❑ Images can be represented by 2-D functions. If  $x$  and  $y$  are taken to be horizontal and vertical, a 2-D function,  $f(x, y)$ , gives the value of the image at each point in the image.
- ❑ Ever increasingly, imaging equipment produces not a single image, but a 3-D volume of data, e.g. right to left, anterior to posterior and caudal to cephalic. A volume of data can be represented as a 3-D function,  $f(x, y, z)$ .
- ❑ One of the challenges of data visualization is to facilitate the input of 3-D data using the 2-D channel afforded by the human visual system.

## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.3 Images and volumes

#### Continuous, discrete and digital functions

- The real world is usually modelled as continuous in space and time. Continuous means that space or time can be divided into infinitesimally small increments. A function,  $f(x)$ , is said to be a continuous function if both the independent variable  $x$  and the dependent variable  $f$  are represented by continuous values. The most natural model for the distribution of a radiopharmaceutical in the body is a continuous 3-D function.

## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.3 Images and volumes

#### Continuous, discrete and digital functions

- An image that is divided into pixels is an example of a discrete function. The independent variables  $x$  and  $y$ , which can only take on the values at particular pixel locations, are digital. The dependent variable, intensity, is continuous. A function with independent variable(s) that are digital and dependent variable(s) that are continuous is called a discrete function.

## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.3 Images and volumes

#### Continuous, discrete and digital functions

- ❑ A computer can represent only digital functions, where both the independent and dependent variable(s) are digital. Digital values provide a good model of continuous values if the coarseness of the digital representation is small with respect to the standard deviations of the continuous values. For this reason, digital images often provide very similar representations of the continuous world.
- ❑ Nuclear medicine is intrinsically digital in the sense that nuclear medicine imaging equipment processes scintillation events individually.



## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.3 Images and volumes

#### Matrix representation

- The surface of the gamma camera can be visualized as being divided into tiny squares. An element in a 2-D matrix can represent each of these squares. A 3-D matrix can represent a dynamic series of images or single photon emission computed tomography (SPECT) data collection. A 3-D matrix is equivalent to a 3-D digital function,  $f(x, y, z)$ . Both representations are equivalent to the computer program language representation,  $f[z][y][x]$ .

## 12.2 STORING IMAGES ON A COMPUTER

### 12.2.3 Images and volumes

#### Matrix representation

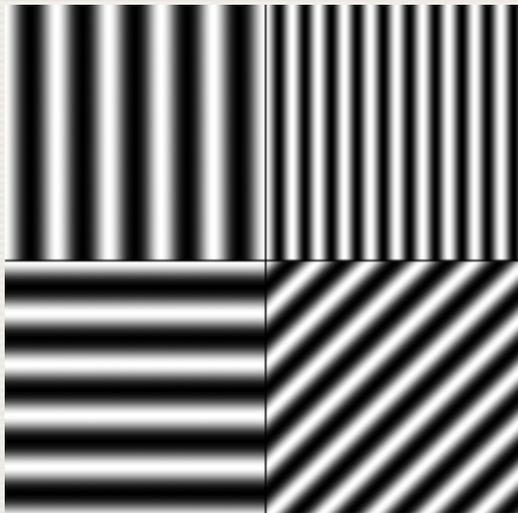
- ❑ It is particularly simple for a computer to represent a matrix when the number of elements in each dimension is a power of two, e.g. 64x64. In this case, the x, y and z values are aligned with the bits in the memory address. Early computer image dimensions were usually powers of two.
- ❑ Modern programming practice has considerably lessened the benefit of this simple addressing scheme. However, where hardware implementation is a large part of the task, there is still a strong tendency to use values that are a power of two.

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Spatial frequency

- A 'pure' spatial frequency corresponds to a sinusoidal function in the spatial domain. Sinusoidal means a sine, a cosine or a combination of the two. Figure 12.1 shows a number of different sinusoidal functions.



*FIG. 12.1. The upper left quadrant is a sinusoid with a single frequency in the x direction; the upper right is a sinusoid with twice the frequency; the lower left is a sinusoid with a single frequency in the y direction; and the lower right is a single sinusoid which varies in both the x and y direction.*

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Spatial frequency

- ❑ Spatial frequency is often given in units of cycles per pixel.
- ❑ A signal that has successive maxima and minima in adjacent pixels will have one complete cycle in two pixels or 0.5 cycles per pixel.
- ❑ The spatial frequency scale is often shown from 0 to 0.5 cycles per pixel, where 0 cycles per pixel represents a constant value in the image domain and 0.5 cycles per pixel represents an image which varies from maximum to minimum in 2 pixels.

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Modulation transfer function

- ❑ The modulation transfer function of an imaging system is measured by imaging a spatial sinusoid and seeing how well the peaks and valleys of the sinusoid (the modulation) are preserved (transferred by the system).
- ❑ If they are completely preserved, the modulation transfer is 1. If the peaks and valleys are only half of the original, the modulation transfer is 0.5. The typical bar phantom is an approximation of a sinusoidal function.

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Basis functions

- A function,  $f(t)$ , can be made up of a sum of other functions, e.g. a constant, a line passing through the origin, a parabola centred at the origin, etc. Such a sum of functions can be written as a polynomial, i.e. the sum of  $K$  powers of  $t$ :

$$f(t) = \sum_{k=0}^{K-1} a_k t^k \quad (12.1)$$

- The terms  $t^k$  are basis functions, with coefficients  $a_k$ . Selecting different coefficients  $a_k$ , a large number of functions can be represented.

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Basis functions

- ❑ To make a new polynomial, the key is to select the coefficients. From this viewpoint, the  $t^k$  terms are just placeholders.
- ❑ Extending this point of view, the coefficients can be thought of as a discrete function  $F[k]$ . The polynomial function could be rewritten:

$$f(t) = \sum_{k=0}^{K-1} F[k]t^k \quad (12.2)$$

- ❑ This polynomial function provides a method of transforming from the function of coefficients to the function of time.

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Basis functions

- For this discussion,  $f(t)$  can be described as a function in the 'time domain'.  $F[k]$  can be described as a discrete function in the 'coefficient domain'. These two very different functions represent the same thing in the sense that using evaluation or interpolation, it is possible to convert back and forth between the representations.

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Fourier transform

- The Fourier transform equations can be written compactly using complex exponentials:

$$F(\omega) = \int f(t)e^{-i\omega t} dt \quad (12.3)$$

$$f(t) = \frac{1}{2\pi} \int F(\omega)e^{i\omega t} d\omega \quad (12.4)$$

where  $i = \sqrt{-1}$

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Fourier transform

- ❑ The first equation (Eq. (12.3)) from the time or space domain to the frequency domain is called Fourier analysis.
- ❑ The second equation (Eq. (12.4)), going from the frequency domain to the time or space domain, is called Fourier synthesis.
- ❑ The relation of these equations to the sine and cosine transforms can be seen by substituting for the complex exponential using Euler's formula:

$$e^{i\omega t} = \cos(\omega t) + i \sin(\omega t) \quad (12.5)$$

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Fourier transform

- These equations have been written in terms of time and frequency. Analogous equations can be written in terms of space and spatial frequency. For the 2-D case:

$$F(k_x, k_y) = \int f(x, y) e^{-i(k_x x + k_y y)} dx dy \quad (12.6)$$

$$f(x, y) = \frac{1}{2\pi} \int F(k_x, k_y) e^{i(k_x x + k_y y)} dk_x dk_y \quad (12.7)$$

- The common use of the letter  $k$  with a subscript for the spatial frequency variable has led to the habit of calling the spatial frequency domain the 'k-space', especially in MRI.

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Fourier transform

- The previous equations refer to continuous functions. The limits of integration of the integrals were not specified, but in fact, the limits are assumed to be  $-\infty$  to  $+\infty$ .
- However, computer representation is digital. Computer representation is often thought of as discrete, not digital, since the accuracy of representation of numbers is often high, so that the quantification effects can be ignored. The Fourier transform equations in discrete form can be written as:

$$F[k] = \sum_{n=0}^{N-1} f[n] e^{-i2\pi kn/N} \quad (12.8) \quad f[n] = \frac{1}{N} \sum_{k=0}^{N-1} F[k] e^{i2\pi kn/N} \quad (12.9)$$

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Fourier transform

- In image processing, the unit of  $n$  is often pixels, and the frequency unit  $k$  is often given as a fraction, cycles/pixel. The space variable  $n$  runs from 0 to  $N - 1$ ; the spatial frequency variable  $k$  runs from  $-0.5$  cycles/pixel to (but not including)  $+0.5$  cycles/pixel in steps of  $1/N$ .

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Fourier transform as a correlation

- Some understanding of how the Fourier transform pair works can be obtained by noting the analogy between these equations and a correlation. The correlation coefficient is written:

$$r = \frac{\sum x_i y_i}{\sqrt{(\sum x_i^2 \sum y_i^2)}} \quad (12.10)$$

where  $x$  and  $y$  are the two variables, and  $i$  indices over the number of samples. The denominator is just normalization, so that  $r$  ranges from  $-1$  to  $1$ .

## 12.3 IMAGE PROCESSING

### 12.3.1 Spatial frequencies

#### Fourier transform as a correlation

- There is an analogy between the correlation equation and the Fourier transform equation. The index  $i$  is analogous to the variable  $t$ ;  $x_i$  is analogous to  $f(t)$ ;  $y_i$  is analogous to the sinusoid. The Fourier transform equation determines how much a function is 'like' the sinusoid, just as the correlation coefficient determines how much two variables are alike.

## 12.3 IMAGE PROCESSING

### 12.3.2 Sampling requirements

#### Sampling requirements

- ❑ Real systems can only handle signal variations up to a particular maximum frequency. Thus, real signals often have a limited frequency content.
- ❑ The sampling theorem says that if a signal only contains frequencies up to a maximum of  $f$ , it can be exactly reproduced from samples acquired at twice the highest frequency.
- ❑ If the sampling is not fast enough, then the high frequencies appear to occur at lower frequencies. This is called aliasing.

## 12.3 IMAGE PROCESSING

### 12.3.3 Convolution

#### Convolution

- ❑ Convolution can be used to describe any linear-time-invariant or linear-shift-invariant system. The input, the system and the output are each described by a function. The system function  $h(t)$  is defined to be the output  $g(t)$  when the input  $f(t)$  is equal to a delta function  $\delta(t)$ .
- ❑ The input  $f(t)$  can be considered a sequence of delta functions,  $\delta(t-\tau)$ , scaled by the input at time  $f(\tau)$ . Each delta function produces a component of the output,  $h(t-\tau)$ , shifted by a time equal to the time of the input and scaled by the magnitude of  $f(\tau)$ .

## 12.3 IMAGE PROCESSING

### 12.3.3 Convolution

#### Convolution

- As the system is time-invariant, the same response  $h(t)$  can be used for an input at any time. As the system is linear, the inputs at different times can be considered separately and the separate outputs can be added. The formula for convolution is:

$$g(t) = \int h(t - \tau) f(\tau) \, d\tau \quad (12.11)$$

## 12.3 IMAGE PROCESSING

### 12.3.3 Shift, scale, add

#### Shift, scale and add

- ❑ Convolution can be summarized as shift, scale, add — shift the system function by an amount equal to the time of the input, scale by the size of the input and add all of the resulting shifted and scaled system functions.
- ❑ Convolution can be used to describe a time–activity curve from a region of interest.
- ❑ The arterial concentration is the input, the system function is the time–activity curve after arterial injection of a bolus of activity, and the time–activity curve after intravenous administration is the convolution of the arterial concentration and the system function.

## 12.3 IMAGE PROCESSING

### 12.3.3.1 Shift, scale, add

#### Shift, scale and add

- Convolution is not limited to 1-D examples. The system function for an Anger camera is the image obtained in response to a point source of activity. A point source can be modelled as a 2-D delta function. The image of a point source will be a blob where the size of the blob is related to the camera's resolution. The blob can be shifted to every point in the field of view (FOV); it can be scaled for the amount of activity at each location; and all of the blobs can be added up. This process — shift, scale, add — will produce the final output image.

## 12.3 IMAGE PROCESSING

### 12.3.3 Shift, scale, add

#### Shift, scale and add

- The formula for 2-D convolution is:

$$g(x, y) = \int h(x - x', y - y', z - z') f(x', y') \, dx' dy' \quad (12.12)$$

- In three dimensions:

$$g(x, y, z) = \int h(x - x', y - y', z - z') f(x', y', z') \, dx' dy' dz' \quad (12.13)$$

## 12.3 IMAGE PROCESSING

### 12.3.3.1 Shift, scale, add

#### Mapping convolution to multiplication

- The Fourier transform of the convolution of two functions is equal to the product of the Fourier transforms of the functions. Symbolically:

$$\int h(t - \tau)f(\tau) d\tau \leftrightarrow F(\omega)H(\omega) \quad (12.14)$$

where the symbol ‘ $\leftrightarrow$ ’ represents Fourier transformation, the left side shows the time domain operations, and the right side shows the Fourier domain operation. The complicated integral in the time domain is transformed into a simple multiplication in the frequency domain.

## 12.3 IMAGE PROCESSING

### 12.3.3 Shift, scale, add

#### Mapping convolution to multiplication

- At first, it may seem that the Fourier transform operation is just as complicated as convolution. However, since the fast Fourier transform algorithm provides an efficient method for calculating the Fourier transform, it turns out that, in general, the most efficient method of performing convolution is to transform the two functions, multiply their transforms and do an inverse transform of the product. Calculation of convolutions is one of the major practical applications of the Fourier transform.

## 12.3 IMAGE PROCESSING

### 12.3.4 Filtering

- ❑ Conceptually, the purpose of filtering is to alter the frequency components of a signal.
- ❑ The data are thought of in terms of their frequency or spatial frequency content, not in terms of their time or space content.
- ❑ The most efficient process in general is (i) Fourier transform, (ii) multiply by a filter and (iii) inverse Fourier transform.
- ❑ Convolution performs this same operation in the time or space domain but, in general, is less efficient.

## 12.3 IMAGE PROCESSING

### 12.3.4 Filtering

- ❑ If, however, a filter can be represented in the time or space domain with only a small number of components that are non-zero, then filter implementation using convolution becomes more efficient.
- ❑ Many image processing filtering operations are implemented by convolution.
- ❑ The non-zero portion of the time or space representation of these filters is called a kernel.
- ❑ Small kernels are often used in image processing.

## 12.3 IMAGE PROCESSING

### 12.3.4 One-dimensional processing

- A 1-D signal  $f(t)$  can be filtered with a frequency domain signal  $H(\omega)$  by transforming  $f(t)$  to  $F(\omega)$ , multiplying the signals to obtain  $G(\omega) = F(\omega)H(\omega)$  and then inverse transforming  $G(\omega)$  to produce the result  $g(t)$ . Alternately, the time domain representation of  $H(\omega)$ ,  $h(t)$ , can be convolved with  $f(t)$ :

$$g(t) = \int h(t - \tau) f(\tau) d\tau \quad (12.15)$$

- A good example of 1-D processing is a graphic equalizer. The sliders on a graphic equalizer represent  $H(\omega)$ . Each slider corresponds to a range of frequencies. The tones in the input signal are multiplied by the values represented by the slider to produce the output signal.

## 12.3 IMAGE PROCESSING

### 12.3.4 Two- and three-dimensional processing

- ❑ Two dimensional processing is exactly analogous to 1-D processing with the 1-D variables  $t$  and  $\omega$  replaced with the 2-D variables  $x, y$  and  $k_x, k_y$ . For 3-D processing,  $t$  is replaced by  $x, y, z$ , and  $\omega$  is replaced by  $k_x, k_y, k_z$ . Four-, five-, six-, etc. dimensional processing can be performed similarly.
- ❑ A property of the Fourier transform equations is separability - the transform with respect to  $x$  can be performed first followed by the transform on  $y$ . A 2-D transform can be performed by first doing the transform on the rows, and then doing the transform on the columns. All that is needed is a 1-D Fourier transform subroutine.

## 12.3 IMAGE PROCESSING

### 12.3.5 Band-pass filters

- ❑ Band-pass filters maintain a range of frequencies while eliminating all other frequencies.
- ❑ An ideal band-pass filter is exactly one for some range of frequencies and exactly zero for the remaining frequencies. There is a very sharp transition between the pass- and the stop-zones.
- ❑ In general a sharp edge in one domain will tend to create ripples in the other domain. Ideal band-pass filtering often creates ripples near sharp transitions in a signal. It is, therefore, common to make the transition from the pass-zone to the stop-zone more gradual.

## 12.3 IMAGE PROCESSING

### 12.3.5 Band-pass filters

#### Low-pass, noise suppression and smoothing filters

- ❑ A low-pass filter is a type of band-pass filter that passes low frequencies and stops high frequencies.
- ❑ In an image, the high spatial frequencies are needed for detail.
- ❑ Zeroing or suppressing the high spatial frequencies compared to the lower frequencies smooths the image, by suppressing the image noise.
- ❑ Low-pass filters both smooth an image and decrease the noise in an image.

## 12.3 IMAGE PROCESSING

### 12.3.5 Band-pass filters

#### Low-pass, noise suppression and smoothing filters

- A common method of implementing a low-pass filter is as a convolution with a small kernel. Below is a 3-by-3 smoothing kernel, also commonly called a 9-point smoothing kernel. Each point in the smoothed image is made up of the scaled sum of nine surrounding points.

3x3 smoothing kernel

1	2	1
2	4	2
1	2	1

- Each point in the smoothed image is made up of the scaled sum of nine surrounding points.

## 12.3 IMAGE PROCESSING

### 12.3.5 Band-pass filters

#### Low-pass, noise suppression and smoothing filters

- Below at left is a 5x5 smoothing kernel. Each point is made up of the scaled sum of 25 surrounding points.

1	2	3	2	1
2	4	8	4	2
4	8	16	8	4
2	4	8	4	2
1	2	3	2	1

Smoothing

-1	-1	-1	-1	-1
-1	-1	-1	-1	-1
-1	-1	25	-1	-1
-1	-1	-1	-1	-1
-1	-1	-1	-1	-1

Sharpening

0	0	-1	0	0
0	-1	-2	-1	0
-1	-2	17	-2	-2
0	-1	-2	-1	0
0	0	-1	0	-0

Unsharp mask

0	-1	0	1	0
0	-1	0	1	0
0	-1	0	1	0
0	-1	0	1	0
0	-1	0	1	0

X gradient

- Three other kernels commonly used in image processing are also shown. The next slide shows the effect of the smoothing filter on an image.

## 12.3 IMAGE PROCESSING

### 12.3.5 Band-pass filters

#### Low-pass, noise suppression and smoothing filters

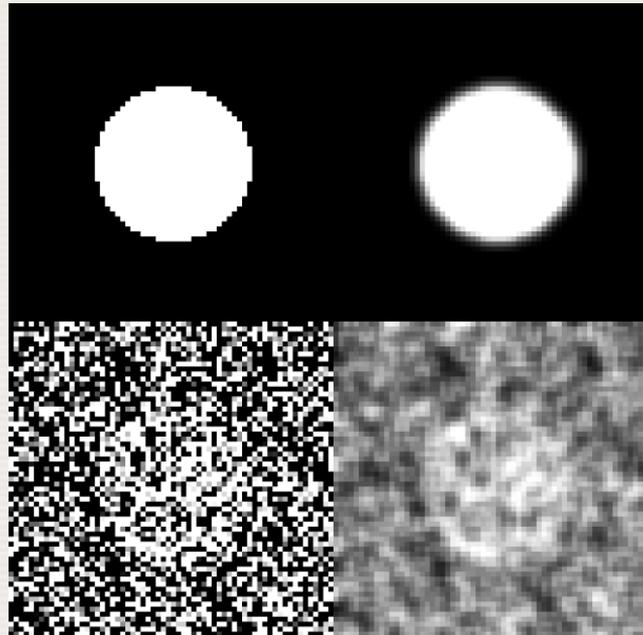


FIG. 12.2. The upper left quadrant shows a circular region of constant intensity; the upper right shows the effect of applying a 5-by-5 smoothing kernel; the lower left shows a very noisy version of the circular region; the bottom right shows the effect of applying a 5-by-5 smoothing kernel.

## 12.3 IMAGE PROCESSING

### 12.3.5 Band-pass filters

#### Low-pass, noise suppression and smoothing filters

- A common method of specifying a low-pass filter in the frequency domain is given by the Butterworth filter:

$$H(k) = \frac{1}{\sqrt{(1 + (k/k_0)^{2n})}} \quad (12.16)$$

- The Butterworth filter has two parameters,  $k_0$  and  $n$ . The parameter  $k_0$  is the cut-off frequency and  $n$  is the order. The filter reaches the value  $2^{-0.5}$  when the spatial frequency  $k$  is equal to  $k_0$ . The parameter  $n$  determines the rapidity of the transition between the pass-zone and the stop-zone.

## 12.3 IMAGE PROCESSING

### 12.3.5 Band-pass filters

#### Low-pass, noise suppression and smoothing filters

- ❑ The filter is sometimes shown in terms of the square of the filter,  $1/(1+(k/k_0)^{2n})$ .
- ❑ In that case, the filter reaches the value of half at the cut-off frequency.
- ❑ The filter is sometimes defined with an exponent of  $n$  instead of  $2n$

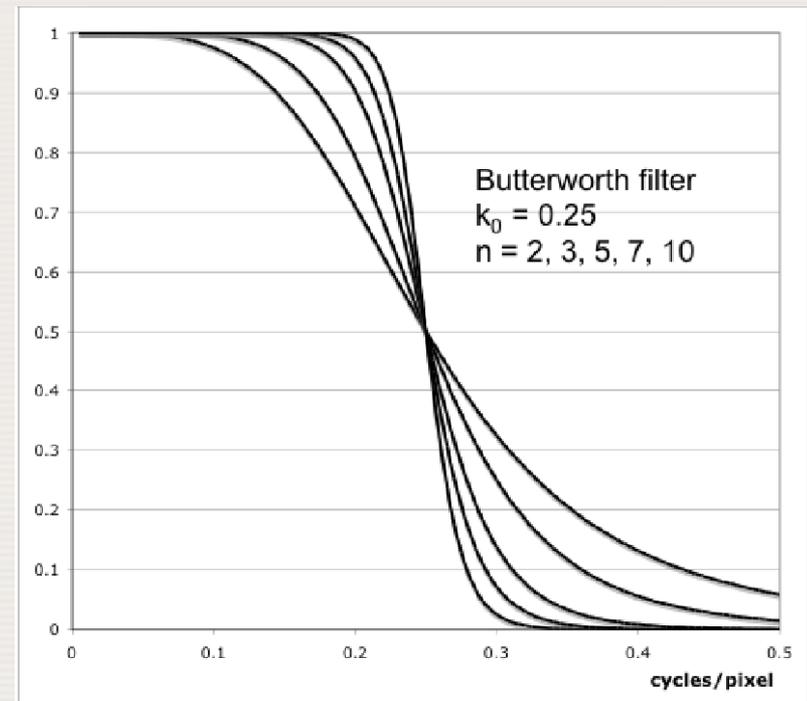


FIG. 12.3. This figure shows the square of the Butterworth filter in the spatial frequency domain with a cut-off equal to 0.25 cycles/pixel and  $n$  equal to 2, 3, 5, 7 and 10.

## 12.3 IMAGE PROCESSING

### 12.3.5 Band-pass filters

#### High-pass and edge-detection

- ❑ Edges, and more generally detail, in an image are encoded with high spatial frequencies. Large regions of constant intensity are coded with low spatial frequencies. Thus, a high-pass filter will tend to emphasize the edges in an image.

## 12.3 IMAGE PROCESSING

### 12.3.5 Band-pass filters

#### High-pass and edge-detection

- Below is the 5x5 sharpening filter kernel from a previous slide and its effect on two images.

-1	-1	-1	-1	-1
-1	-1	-1	-1	-1
-1	-1	25	-1	-1
-1	-1	-1	-1	-1
-1	-1	-1	-1	-1

5x5 sharpening kernel

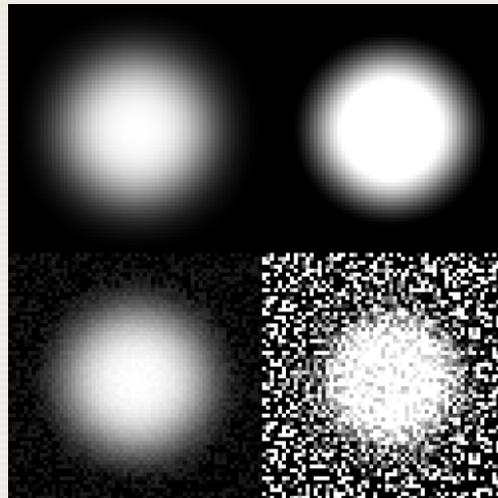


FIG. 12.4. The upper left quadrant shows a smooth circular region; the upper right shows the effect of applying the 5-by-5 sharpening kernel. Note the sharpening effect; the lower left shows a circular region with a small amount of noise; the bottom right shows the tendency of the sharpening kernel to amplify noise.

## 12.3 IMAGE PROCESSING

### 12.3.6 Deconvolution

- Deconvolution is the process of undoing convolution. If we know the input,  $f(t)$ , to a system,  $h(t)$ , and the output,  $g(t)$ , from the system, then deconvolution is the process of finding  $h(t)$  given  $f(t)$  and  $g(t)$ . In the frequency or spatial frequency domain, deconvolution is straightforward - a simple division:

$$H(\omega) = \frac{G(\omega)}{F(\omega)} \quad (12.17)$$

- There is a problem with this simple deconvolution. If  $F(\omega)$  is zero for any  $\omega$ , then  $H(\omega)$  is infinite. Furthermore, any time  $F(\omega)$  is small, then any noise in  $G(\omega)$  is amplified.

## 12.3 IMAGE PROCESSING

### 12.3.6 Deconvolution

- Since signals usually have less power at high frequency or high spatial frequency, the first practical deconvolution was performed by simple high-pass filtering. A Metz filter (described later) can be used to emphasize the mid-frequency range while attenuating the high frequencies. If the statistical properties of the signal and noise are known or can reasonably be approximated, then a Wiener filter can be used.

## 12.3 IMAGE PROCESSING

### 12.3.7 Image restoration filters

- ❑ Some filters attempt to restore degraded images. Degradations can come from many sources, but the most important for this book is degradations caused by imaging instruments such as gamma cameras. If the imaging system is linear-shift-invariant, then it can be modelled by convolution.
- ❑ A restoration filter needs to undo the effect of the imaging system, i.e. to deconvolve for the system function. Even in the case where the system is not linear or shift-invariant, it is often possible to ameliorate the effects of a system with a filter.

## 12.3 IMAGE PROCESSING

### 12.3.7 Image restoration filters

#### Ramp

- The effect of a simple projection/back-projection is to smooth an object. In polar coordinates, the system function is given by the simple equation:

$$H(k, \theta) = \frac{1}{k} \quad (12.18)$$

- Note that the higher frequencies in the image are reduced by a factor proportional to their spatial frequencies. This can be restored with a ramp filter given by:

$$G(k, \theta) = k \quad (12.19)$$

## 12.3 IMAGE PROCESSING

### 12.3.7 Image restoration filters

#### Metz

- If the noise in the detected signal is uniform, then a restoration filter will alter the noise spectrum. For small restorations, the signal to noise may still be favourable, but for frequencies with large restorations, the noise may dominate. The best result is often to restore small effects completely, but restore large effects less. The Metz filter combines these two goals into a single filter.

$$G(k, \theta) = H^{-1}(k, \theta)(1 - (1 - H(k, \theta)^2)^x) \quad (12.20)$$

## 12.3 IMAGE PROCESSING

### 12.3.7 Image restoration filters

#### Metz

- For any system function,  $H(k, \theta)$ , the Metz filter is given by:

$$G(k, \theta) = H^{-1}(k, \theta)(1 - (1 - H(k, \theta)^2)^x) \quad (12.20)$$

- The system function is often written as  $MTF(k, \theta)$  to emphasize that it is a modulation transfer function. The first term in this equation,  $1/H(k, \theta)$ , reverses the effect of the system. When  $H(k, \theta)$  is nearly one, the second term is about equal to one; when  $H(k, \theta)$  is nearly zero, the second term is about equal to zero; at intermediate values, the second term transitions smoothly between these two values.

## 12.3 IMAGE PROCESSING

### 12.3.7 Image restoration filters

#### Metz

- Here a simulated system function is shown (dotted line). Four Metz filters with different  $X$  parameters are shown. At low frequencies, the Metz filter counteracts the effects of the imaging system. At high frequencies, it takes on the character of a low-pass filter. The transition is controlled by the parameter  $X$ .

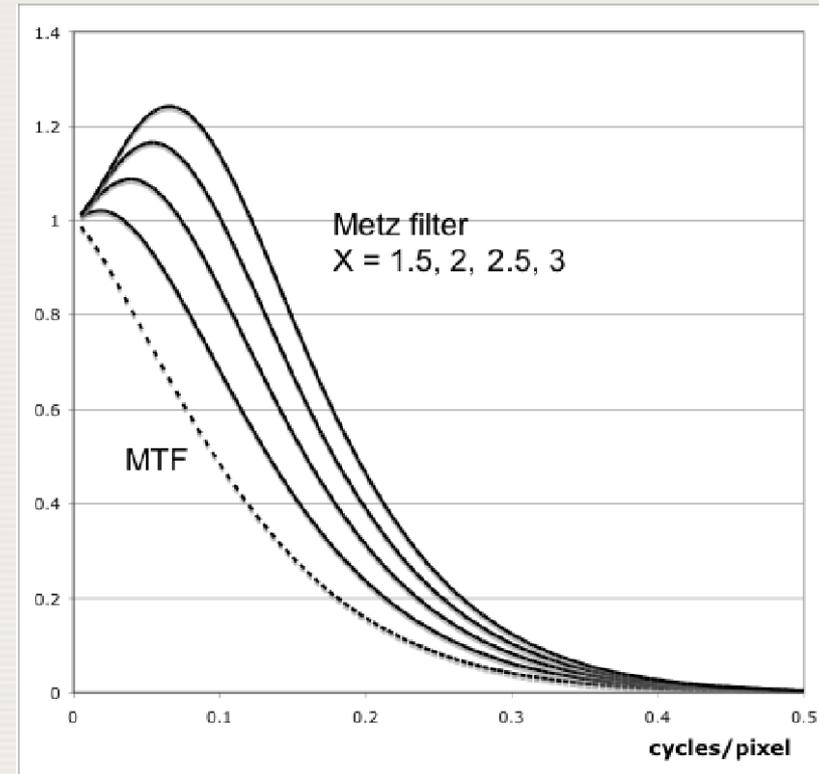


FIG. 12.5. The dotted line shows a simulated modulation transfer function (MTF). The four solid lines show Metz filters for  $X$  equal to 1.5, 2, 2.5 and 3.

## 12.3 IMAGE PROCESSING

### 12.3.7 Image restoration filters

#### Wiener

- Wiener filtering is used when the statistical properties of the signal and of the noise are known. A function known as the power spectral density,  $S(\omega)$ , gives the expected amount of power in a signal as a function of frequency. ‘Power’ means that the function is related to the square of the magnitude of a signal. The Wiener filter is given by:

$$H(\omega) = \frac{S_f(\omega)}{S_f(\omega) + S_n(\omega)} \quad (12.21)$$

where  $S_f(\omega)$  is the power spectral density of the signal  $f(t)$ , and  $S_n(\omega)$  is the power spectral density of the noise  $n(t)$ .

## 12.3 IMAGE PROCESSING

### 12.3.7 Image restoration filters

#### Wiener

- For those frequencies where the signal is much larger than the noise, the Wiener filter is equal to one. For those frequencies where the noise is much larger than the signal, the Wiener filter is equal to zero. The Wiener filter transitions smoothly from the pass-zone to the stop-zone when there is more noise in the data than signal.

## 12.4 DATA ACQUISITION

### 12.4.1 Acquisition matrix size and spatial resolution

- For planar imaging, the FOV of a camera is divided into discrete elements that correspond to the pixels in a digital image. Most commonly, a rectilinear system is used and the digital image is analogous to a matrix. The size of the FOV and the spatial resolution of the camera are important in choosing the size of the matrix to be used. To avoid aliasing, the sampling should be twice the highest frequency that can be recorded by a camera. For example, if the FOV of the camera is 40 cm and the camera can detect frequencies up to 2 cycles/cm, then the matrix should have:

$$2 \text{ samples/cycle} \times 2 \text{ cycles/cm} \times 40 \text{ cm} = 160 \text{ samples.}$$

## 12.4 DATA ACQUISITION

### 12.4.1 Acquisition matrix size and spatial resolution

- ❑ For a normal large FOV Anger camera, a  $256 \times 256$  matrix is more than sufficient for most imaging situations.
- ❑ For clinical imaging, a  $128 \times 128$  matrix is often sufficient. For rapid dynamic images that are often very count limited, a  $64 \times 64$  matrix can be used.
- ❑ For vertex to thigh imaging, a 1:4 matrix, e.g.  $256 \times 1024$ , will cover 160 cm. When including the legs, a non-power-of-two matrix may be most logical.
- ❑ While memory and storage were once expensive and limited, nowadays the selected matrix size should be large enough to ensure that image quality is not compromised.

## 12.4 DATA ACQUISITION

### 12.4.2 Static and dynamic planar acquisition

- Many of the processes of interest in nuclear medicine involve a changing pattern of distribution of a radiopharmaceutical in the body. In matrix mode, a sequence of images collected over time allows visualization and measurement of the biodistribution of the radiopharmaceutical. Each image is often called a frame of data. Collection of a sequence of images over time is called a dynamic acquisition; collection of an image at a single point in time is called a static acquisition.

## 12.4 DATA ACQUISITION

### 12.4.2 Static and dynamic planar acquisition

- ❑ The FOV of the gamma camera is divided into discrete rectangles that are generally square. Each rectangle corresponds to one pixel in the image and each is represented by one memory location.
- ❑ The size of the rectangles puts a limit on the resolution that is achievable, but the rectangle size is not the resolution.
- ❑ The resolution of a gamma camera is the overall ability to resolve adjacent sources of activity. For each scintillation, the gamma camera identifies the rectangle corresponding to the location of the scintillation and increments the corresponding memory location.

## 12.4 DATA ACQUISITION

### 12.4.3 Single photon emission computed tomography

- ❑ SPECT is typically performed by acquiring a sequence of 2-D projection images from multiple different angles around the object. The 2-D projections can be represented by  $p[x', z]$ , where  $z$  is the axial position.
- ❑ The set of projections can be described by a 3-D function,  $p(x', z, \theta)$ , where  $\theta$  is the position of the camera head.

## 12.4 DATA ACQUISITION

### 12.4.3 Single photon emission computed tomography

#### Sinogram

- ❑ The first step in reconstruction is to reformat the data in terms of axial position, described by a function  $p'(x', \theta, z)$ . For each axial position, the set of data,  $p'(x', \theta)$ , has one line of data from each of the projections. Each of the images,  $p'(x', \theta)$ , is called a sinogram.
- ❑ The  $x$  position in the sinogram is the same  $x$  position in the raw projection image. The other position  $\theta$  is the projection angle. A point source will project onto all of the projection images at the same axial position  $z$ . The position of the point source in the  $\theta$  direction will form a sine wave in the sinogram, hence the name sinogram.

## 12.4 DATA ACQUISITION

### 12.4.3 Single photon emission computed tomography

#### Sampling requirements in SPECT

- ❑ Each sinogram  $p'(x', \theta)$  needs to be reconstructed into an image  $f(x, y)$  where  $x$  and  $y$  are coordinates with respect to the patient.
- ❑ In order to reconstruct  $N$  points in a slice,  $N$  data samples are needed. Sampling tangentially to the slice is reasonably straightforward;  $x'$  should have the same sampling rate as  $x$  and  $y$ .
- ❑ Resolution recovery is used in several nuclear medicine applications. Resolution recovery improves 'resolution' using an a priori assumption about, or knowledge of, the spatial resolution of the system.

## 12.4 DATA ACQUISITION

### 12.4.4 Positron emission tomography acquisition

- The detectors in positron cameras detect single photons. However, the key feature of a positron camera is detection of pairs of photons in coincidence. Two photons detected in coincidence define a LOR. The LORs are then reconstructed into a 3-D image set. At that point, PET and SPECT data are the same.

## 12.4 DATA ACQUISITION

### 12.4.4 Positron emission tomography acquisition

#### '2-D' and '3-D' volume acquisition

- ❑ Early (and some not so early) PET cameras had retractable axial collimators and performed '2D' imaging when they were extended. This is a reference to the fact that data were acquired essentially slice-by-slice, and oblique LORs were rejected, either by the collimators or the scanner electronics.
- ❑ Later '3D' scanners were designed without collimators to accept oblique LORs crossing several detector rings. This improved sensitivity, but required a much more computationally demanding reconstruction algorithm than 2D PET.

## 12.4 DATA ACQUISITION

### 12.4.4 Positron emission tomography acquisition

#### Time of flight

- ❑ Time of flight (TOF) imaging measures the difference in arrival time of the two photons at the two detectors. The difference in arrival time provides some (not completely precise) about position of the annihilation event along the LOR.
- ❑ Current detectors can detect differences in arrival of about 0.5 ns which corresponds to a distance of 15 cm at the speed of light.
- ❑ The improvement in signal to noise ratio is most pronounced in large patients, in whom the uncertainty about the location of the annihilation is greatest.

## 12.4 DATA ACQUISITION

### 12.4.5 Gated acquisition

- ❑ Data acquisition can be gated to a physiological signal. Owing to count limitation, if the signal is repetitive, the data from multiple cycles are usually summed together.
- ❑ A gated, static acquisition will have three dimensions - two spatial and one physiological.
- ❑ A gated dynamic acquisition will have four dimensions - two spatial, one time and one physiological.
- ❑ A gated SPECT or PET acquisition will have a different four dimensions - three spatial and one physiological. A gated dynamic SPECT or PET acquisition will have five dimensions - three spatial, one time and one physiological.

## 12.4 DATA ACQUISITION

### 12.4.5 Gated acquisition

#### Cardiac-synchronized

- ❑ Gated cardiac studies were one of the early studies in nuclear medicine. Usually, the electrocardiogram is used to identify cardiac timing.
- ❑ For evaluation of systolic and early diastolic events, it is better to sum cycles using constant timing from the R-wave than to divide different cycles using a constant proportion of the cycle length.
- ❑ However, with constant timing, different amounts of data are collected in later frames. Normalizing the data for the number of cycles contributing to each frame can ameliorate this problem.

## 12.4 DATA ACQUISITION

### 12.4.5 Gated acquisition

#### Respiratory-synchronized

- ❑ Gating to respiration has been used in nuclear medicine both to study respiratory processes and to ameliorate the blurring caused by breathing.
- ❑ Successful synchronization has been based on chest or abdominal position changes, and on image data.
- ❑ Chest and abdominal motion often correlate with the respiratory cycle, although detection of motion and changes in diaphragmatic versus chest wall breathing also pose problems. Although difficult to measure, respiratory gating is becoming more common in PET and CT.

## 12.4 DATA ACQUISITION

### 12.4.6 List mode

- ❑ Instead of collecting data as a sequence of matrixes or frames, the position of each scintillation can be recorded sequentially in a list. Periodically, a special mark is entered into the list, typically every 1 ms, that gives the time and may include physiological data such as the electrocardiogram or respiratory phase.
- ❑ List mode data requires more storage space than matrix mode. For example, a 1 million-count frame of data collected into a 256-by-256 matrix will require 64k memory locations. In list mode, the same data will require 1 million memory locations. However list mode contains some additional information, the order of event arrival.

## 12.4 DATA ACQUISITION

### 12.4.6 List mode

- ❑ List mode data can be easily converted (framed) into matrix mode data.
- ❑ There it offers useful flexibility, in that it can be reframed as many times as desired to create a matrix mode study with any desired matrix size and any desired frame rate. Even the frame rate can be varied during the study if desired.
- ❑ This is useful if the optimum frame rate is not known in advance.

# 12.5 FILE FORMAT

## 12.5.1 File format design

### Interfaces

- ❑ Standards have facilitated the rapid development of computers. Standards can be considered as part of a larger topic, interfaces. In general, an interface is a connection between an entity and the rest of the system. If each entity in the system has an interface and if the interface is the only allowed way for the other parts of the system to interact with an entity, then there is a great simplification of the overall system.
- ❑ Development of one part of a system depends only on that part and the interface. It does not depend on any other part of the system.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Interfaces

- ❑ There was an early problem with development of complex systems. As more resources such as programmers were added to a task, very little additional output resulted. The problem was that as the task grew in complexity, more time was spent on communication between the programmers and less was spent on programming.
- ❑ In a modular system, the details of each portion of the task are hidden from other parts of the task. Modularizing a task tends to linearize the complexity. As a task with complexity  $n$  becomes twice as large, the work becomes about  $2n$ , not  $n^2$  or  $e^{2n}$  times as much.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Interfaces

- File formats are a type of interface. They define how information will be transferred from one system to another. By having a well designed format, the design of each system becomes separate.

# 12.5 FILE FORMAT

## 12.5.1 File format design

### Raster graphics

- ❑ Raster graphics images are made up of a matrix of picture elements or pixels. Each pixel represents one small rectangle in the image. The primary data in nuclear medicine are numbers of counts. Counts are translated into a shade of grey or a colour for display. There are many ways the shade of grey or the colour of a pixel can be encoded. One factor is the number of bits that are used for each pixel. Grey scale images often have 8 bits or 1 byte per pixel. That allows 256 shades of grey, with values from 0 to 255.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Raster graphics

- A common way to encode colour images is in terms of their red, green and blue components. If each of the colours is encoded with 8 bits, 24 bits or 3 bytes are needed per pixel. If each colour is encoded with 10 bits, 30 bits are needed per pixel. Red, green, blue (RGB) encoding is typical in nuclear medicine, but there are other common encodings such as intensity, hue and saturation.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Transparency

- ❑ Graphic user interfaces often allow a composition of images where background images can be seen through a foreground image. In such cases, each pixel in an image may be given a transparency value that determines how much of the background will come through the foreground.
- ❑ A common format is 8 bits for each of the RGB (red, green and blue) colours and an 8-bit transparency value, giving a total of 32 bits per pixel.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Indexed colour

- Typically, an image will include only a small number of the 16 million ( $2^{24}$ ) possible colours in a 24 bit RGB palette. A common method of taking advantage of this is to use indexed colour. Instead of storing the colour in each pixel, an index value is stored. Typically, the index is 8 bits, allowing 256 colours to be specified. In the case where more than 256 colours are used, it is often possible to approximate the colour spectrum using a subset of colours.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Indexed colour

- For indexed colour, a colour palette is stored with the images. The colour palette has 256 colour values corresponding to the colours in the image. The 8 bit index value stored in a pixel is used to locate the actual 24 bit colour in the colour palette, and that colour is displayed in the pixel. Each pixel requires only 8 bits to store the index as opposed to 24 bits to store the actual colour.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Compression

- ❑ The information content of an image is often much smaller than the information capacity of an image format. For example, images often have large blank areas or areas that all have the same colour value. Therefore, it is possible to encode the image using less space.
- ❑ Improving efficiency for one class of images results in decreasing efficiency for another type of image. The trick is to pick an encoding which is a good match for the range of images that are typical of a particular application.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Compression (Run length encoding)

- ❑ One of the simplest and easiest encodings to understand is run-length encoding. This method works well for images where large areas all have the same value, e.g. logos.
- ❑ Instead of listing each pixel value, a value and the number of times it is repeated are listed. If there are 50 yellow pixels in a row, rather than listing the value for yellow 50 times, the value '50' is followed by the value for yellow. Two values instead of 50 values need to be listed.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Compression (LZW)

- ❑ Another common encoding is called Lempel–Ziv–Welch (LZW) after its developers. It was originally under patent, but the patent expired on 20 June 2003, and it may now be used freely. The LZW algorithm is relatively simple but performs well on a surprisingly large class of data.
- ❑ It works well on most images and works particularly well on images with low information content, logos and line drawings.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Compression

- ❑ Both run-length encoding and LZW encoding are form of lossless compression; the original image can be exactly reconstructed from the encoded image.
- ❑ After destructive or irreversible or lossy encoding, the original image cannot be exactly recovered from the encoded image.
- ❑ However, much more efficient encoding can be performed with destructive encoding. While non-destructive encoding results in reduction of the image size by a factor of 2–3, destructive encoding will often result in a reduction of the image size by a factor or 15–25.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Compression (JPEG)

- ❑ The human visual system has decreased sensitivity to low contrast, very high resolution variations. Details, high resolution variations, are conspicuous only at high contrast.
- ❑ Discrete cosine transform (DCT) encoding takes advantage of this property of the visual system.
- ❑ DCT encoding is in the Joint Photographic Experts Group (JPEG) standard. The low spatial resolution content of the image is encoded with high fidelity, and the high spatial resolution content is encoded with low fidelity.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Compression (JPEG)

- Although there are artefacts introduced by the coding, they are relatively inconspicuous for natural scenes. For nuclear medicine images, the artefacts are more apparent on blown up images of text.

## 12.5 FILE FORMAT

### 12.5.1 File format design

#### Compression (Wavelets)

- ❑ Wavelets are a generalized form of sinusoids. Some improvement in compression ratios at the same level of apparent noise can be obtained using wavelet-transform coding.
- ❑ The ‘blocky’ artefacts that degrade DCT images are not seen with wavelet-transform images.
- ❑ The JPEG 2000 standard uses wavelet-transform coding

## 12.5 FILE FORMAT

### 12.5.2 Common image file formats

#### Bitmap

- Bitmap (BMP) is a general term that may refer to a number of different types of data. When used in reference to image formats, it may be used to mean a raster graphic format, but it often refers to a Windows image format. The Windows file format is actually called a device independent bitmap (DIB).

## 12.5 FILE FORMAT

### 12.5.2 Common image file formats

#### Tagged image file format (TIFF)

- ❑ The TIFF format includes many types of images. Most commonly, it is used for 8 bit grey scale, 8 bit indexed colour or 24 bit RGB colour images. Images are typically compressed with the non-destructive LZW algorithm.
- ❑ The TIFF format is often used for high quality single images that are losslessly compressed.

## 12.5 FILE FORMAT

### 12.5.2 Common image file formats

#### Graphics interchange format (GIF)

- GIF is a relatively simple indexed format with up to 8 bits per element. Up to 256 colours are selected from a 24 bit RGB palette. Pixels can be transparent, in which case the background colour is displayed. The 89a specification included multiple images that many be displayed as a cine. Compression is performed with the LZW algorithm.

## 12.5 FILE FORMAT

### 12.5.2 Common image file formats

#### Joint Photographic Experts Group (JPEG)

- ❑ The JPEG standard is a reasonably simple, non-indexed grey scale and colour image format that allows adjustable destructive compression.
- ❑ It tries to match the coding to human vision. It uses more precision for brightness than for hue. It uses more precision for low frequency data than for high frequency detail.

## 12.5 FILE FORMAT

### 12.5.3 Movie formats

- ❑ Multi-track movie formats allow audio and video to be blended together. Often, there are many audio tracks and many video tracks where the actual movie is a blending of these sources of information. A key part of a multi-track format is a timing track, which has information about how the tracks are sequenced and blended in a final presentation.
- ❑ However, in nuclear medicine, there is rarely a need for all of this capacity. Often, all that is needed is a simple sequence of images. A more complex movie format can be used for this type of data, but often a simpler format is easier to implement.

## 12.5 FILE FORMAT

### 12.5.3 Movie formats

#### Image sequence formats

- ❑ Of the image formats described so far, BMP, TIFF and GIF can be used to define an image sequence. An extension of the JPEG format, JPEG 2000, also allows image sequences. As with the multiframe version of BMP and TIFF formats, JPEG 2000 is relatively poorly supported.
- ❑ However, the multiframe version, 89a, of the GIF format is widely supported. It is supported by all web browsers and by almost all image processing and display programs. The GIF format is a logical choice for distribution of cine images.

## 12.5 FILE FORMAT

### 12.5.3 Movie formats

#### Multi-track formats

- ❑ There are several multi-track movie formats available. As newer formats that are still under development, they tend to be controlled by particular vendors.
- ❑ The AVI format is controlled by Microsoft, the QuickTime format is controlled by Apple, the RealVideo format is controlled by RealNetworks and the Flash format is controlled by Adobe.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

- ❑ There are two types of information in a nuclear medicine study - image information and non-image information.
- ❑ The general purpose image and movie formats described above usually lack capabilities that would be optimal for medical imaging.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### Non-image information

- ❑ There is unique nuclear medicine information that must be carried along reliably with the images.
- ❑ This information includes identification data, e.g. name, medical record number; study data, e.g. type of study, pharmaceutical; how the image was acquired, e.g. study date, view; etc. This information is sometimes called meta-information.
- ❑ Most general image formats are not flexible enough to carry this information along with the image.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### American Standard Code for Information Interchange (ASCII)

- ❑ Text information is usually and most efficiently coded in terms of character codes. Each character including punctuation, spacing, etc. is coded as a number of bits. Initially, 7 bits were used; 7 bits allowed  $2^7 = 128$  codes, which were enough codes for the 26 small and 26 capital letters, plus a fairly large number of symbols and control codes.
- ❑ Later it was extended to 8 bits, allowing the addition of 128 new codes. Characters in many of the Latin languages could be encoded using 8 bit ASCII.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### Unicode

- ❑ Computer usage has transcended national boundaries. Internationalization has meant that a single server or client needs to be multilingual.
- ❑ The ASCII code is not adequate for this task, so a multilingual code, Unicode, has superseded it.
- ❑ For example, the Java programming language specifies that programs be written in Unicode. Unicode uses 32 bits, and there are more than 100 000 character codes, including all common languages and many uncommon languages.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### Markup language

- ❑ Markup has the advantage that it can be read by humans and can be edited with any text editor. Hypertext Markup Language (HTML), the language used by the World Wide Web was originally a markup language.
- ❑ When HTML was first developed, text editors were used to write it.
- ❑ A markup language allows other types of information to be included. For example, one of the key features of HTML is that it includes hyperlinks to other HTML pages on the Internet.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### Extensible Markup Language

- ❑ A very popular and increasingly used method for encoding text information is a standard called Extensible Markup Language (XML). It provides a method of producing machine-readable textual data.
- ❑ XML is not a markup language itself, but rather a general format for defining markup languages. It defines how the markup is written. A document is said to be ‘well formed’ if it follows the XML standard.
- ❑ If it is well formed, then the markup can be separated from the rest of the text

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### Extensible Markup Language

- For nuclear medicine file formats, one of the key properties of XML is that it can be used to make text information readable by machine. For example, consider the following section of an XML document:

```
<patient>  
  <name>  
    <last>Parker</last>  
    <first>Tony</first>  
  </name>  
  <medical_record_number>10256892</medical_record_number>  
</patient>
```

- It would be straightforward for a computer to unambiguously determine the name and medical record number from this document.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### Image information

- ❑ The image portion of a nuclear medicine study can be a sequence of static images, a dynamic series, a gated series, multiple dynamics series, raw data from a tomographic collection, reconstructed images, a dynamic series of tomographic collections, a dynamic series of gated tomographic collections, related tomographic datasets, curves from regions of interest, functional datasets derived from calculations on other datasets, etc.
- ❑ Thus, it should be clear that a rather general data format is needed.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### Types of data

- It makes no sense to define a different data format for every type of data mentioned on the previous slide.
- Instead it makes sense to describe the data in the non-image information.
- The interpretation of the data should be part of the non-image information, not part of the data itself.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### Data element

- ❑ The raw data collection bins for a nuclear medicine image will generally be 8 or 16 bit unsigned integers, depending on whether a maximum of 255 or 65 535 counts per pixel are required.
- ❑ For processed results, a larger dynamic range represented by floating-point or complex data may be appropriate.
- ❑ For some analysis, signed integers may be most appropriate.
- ❑ A region of interest can be represented as a single bit raster.

## 12.5 FILE FORMAT

### 12.5.4 Nuclear medicine data requirements

#### Organization

- ❑ A logical first level of organization of the image data is what will be called a 'dataset'. A dataset is an  $n$  dimensional set of data in which each of the data elements is the same format, e.g. 8 bit unsigned integer, 16 bit signed integer or IEEE 32 bit floating-point data.
- ❑ The dimensions do not need to be the same; 7 sets of 100 curves with 256 points is a  $7 \times 100 \times 256$  dataset.
- ❑ The dataset should be the 'atom' of the data; there should not be a lower level of organization. The lower levels of organization will depend on the type of data and the dimensions.

## 12.5 FILE FORMAT

### 12.5.5 Common nuclear medicine data storage formats

#### Interfile

- ❑ The Interfile file format has been used predominantly in nuclear medicine. The final version of Interfile, version 3, was defined in 1992. Although Interfile has been largely replaced by DICOM, it has some interesting properties.
- ❑ The metadata, encoded in ASCII, are readable and editable by any text editor. The lexical structure of the metadata was well defined, so that it is computer readable.

## 12.5 FILE FORMAT

### 12.5.5 Common nuclear medicine data storage formats

#### Digital Imaging and Communications in Medicine (DICOM)

- ❑ DICOM is the most widely accepted radiological imaging format. DICOM began as ACR-NEMA, a collaboration between the American College of Radiology and the National Electrical Manufacturers Association.
- ❑ DICOM is often thought of as a file format; however, the standard covers communication more broadly. It defines a transmission protocol, a query and retrieval standard, and workflow management. Unfortunately, it is overly complex, non-self-describing, and has a heavy 2-D image bias (see Sec. 12.6.4).

## 12.6 INFORMATION SYSTEM

### 12.6.1 Database

- ❑ Databases are one of the most common applications for computers. Web sites frequently depend heavily on a database. For example, Google provides information from a database about the web. Wikipedia, Facebook and YouTube get their content from databases. On-line retailers make extensive use of databases both for product searches and for information about customers and orders.

# 12.6 INFORMATION SYSTEM

## 12.6.1 Database

### Table

- ❑ Almost all of the information in databases is contained in tables. A table is a simple 2-D matrix of information. The rows in a table are called records and the columns are called fields. The rows refer to individual entities.
- ❑ In a patient table, the rows are patients, and the columns are the attributes, e.g. first name, middle name, last name, date of birth, medical record number (MRN), etc.
- ❑ There is usually one field in each table that is unique for each row. That unique field, e.g. MRN, can be used for lookup. As that field allows access to the record, it is called an accession number.

# 12.6 INFORMATION SYSTEM

## 12.6.1 Database

### Index

- ❑ An index provides rapid access to the records (rows) of a table. The index is separate from the table and is sorted to allow easy searching, often using a tree structure. The index provides organization of the records for fast access.
- ❑ Indexes are important for efficiency, but the only information they contain is how to efficiently access the tables.
- ❑ An index can be rebuilt from the tables.

# 12.6 INFORMATION SYSTEM

## 12.6.1 Database

### Relation

- A key element of relational databases is relations. Relations connect one table to another table. Conceptually, the relations form a very important part of a database, and provide much of the complexity. However, the relations themselves are actually very simple. A relation between the patient table and the study table might be written:

$$\text{patient.MRN} = \text{study.MRN}$$

This says that the records in the patient table are linked to the records in the study table by the medical record number (MRN) field.

## 12.6 INFORMATION SYSTEM

### 12.6.2 Hospital Information System

- ❑ A hospital information system is a large distributed database. Data come from clinical laboratories, nuclear medicine and financial systems, etc.

## 12.6 INFORMATION SYSTEM

### 12.6.2 Hospital Information System

#### Admission, discharge transfer

- Most hospital information systems have an admission, discharge, transfer (ADT) database. The ADT system is the master patient identification system. Other systems use the ADT system for institution-wide, reliable, coordinated identification of each patient.

## 12.6 INFORMATION SYSTEM

### 12.6.2 Hospital Information System

#### Information gateway

- Generally, the different departments in a hospital have incompatible databases; even within one department, there may be incompatible systems. One method of ameliorating this problem is the development of Health Level Seven (HL7), a standard message format for communicating between systems in a hospital. However, the connections between systems still differ. If there are  $n$  systems, communication between them becomes a problem that grows proportionally to  $n^2$ .

## 12.6 INFORMATION SYSTEM

### 12.6.2 Hospital Information System

#### Information gateway (continued)

- An information gateway ameliorates this problem. The only task of an information gateway is to connect systems, translating messages so that they can be understood by other systems. Each system only needs to connect to the gateway, and the gateway communicates with all of the systems in the hospital. The growth in complexity tends to increase more like  $n$  than  $n^2$ .

## 12.6 INFORMATION SYSTEM

### 12.6.3 Radiology Information System

- ❑ The radiology information system (RIS) supports scheduling, performing, reporting of procedure results and billing. When nuclear medicine is a division of radiology, the RIS usually also functions as the nuclear medicine information system.
- ❑ However, nuclear medicine procedures have some unique characteristics, such as studies that extend over several days, which may not be well handled by a general purpose RIS.

## 12.6 INFORMATION SYSTEM

### 12.6.4 Picture Archiving and Communication System

- The image information from the imaging equipment is usually stored in a picture archiving and communication system (PACS) that is separate from but coordinated with the radiology/nuclear medicine information system. DICOM is the predominant standard for PACSs.

## 12.6 INFORMATION SYSTEM

### 12.6.4 Picture Archiving and Communication System

#### Study

- The top level of organization in DICOM is the study. This level of organization comes from the organization of the health care system. Health care providers request services from radiology/nuclear medicine by a request for a consultation. Imaging or another service is performed and a report, ideally including image information, is returned to the provider. Each study is linked to a single patient, but a patient can have any number of separate studies.

## 12.6 INFORMATION SYSTEM

### 12.6.4 Picture Archiving and Communication System

#### Sequence

- ❑ Sequence is the next level of organization in DICOM. Sequence comes from a sequence of images; for a volume of image data, sequence is the top level of organization. For example, it is common to collect a sequence of axial images. A more general name for this level of organization would be dataset.

## 12.6 INFORMATION SYSTEM

### 12.6.4 Picture Archiving and Communication System

#### Image

- ❑ Originally, DICOM used a 2-D image as the basic atom. Other data structures are composed of a number of images. Metadata are included with each image, defining the structure of the image, patient information, data collection information and relation of the image to other images. Somewhat more recently, a multiframe format was defined in DICOM. One file may contain information from a volume of data, from a time series, from a gated sequence, from different photopeaks, etc.

## 12.6 INFORMATION SYSTEM

### 12.6.4 Picture Archiving and Communication System

#### Image (continued)

- ❑ Nuclear medicine tends to use the multiframe format much more commonly than other modalities.
- ❑ Describing the organization of a dataset in terms of multiple images is a particularly awkward feature of DICOM.

## 12.6 INFORMATION SYSTEM

### 12.6.4 Picture Archiving and Communication System

#### N-dimensional data

- ❑ It is unfortunate that DICOM selected the image as the basic atom of organization.
- ❑ Even before it was introduced, it was apparent that an N-dimensional data model would be more appropriate. Nuclear medicine and MRI often dealt with 1-D curves, 2-D images, 3-D volumes, 4-D gated or dynamic volumes, etc. However, radiology tended to be film based, and volume data such as CT was anisotropic, so some of the early developers had an image based orientation.

## 12.6 INFORMATION SYSTEM

### 12.6.5 Scheduling

- ❑ Scheduling is a much more complicated task than it may initially seem. Several appointments in different departments may need to be scheduled at the same time. Sequencing of studies may be important, e.g. thyroid imaging should not be performed in proximity to iodinated contrast usage. Some studies require a prior pregnancy test or other laboratory values. Prior data need to be made available prior to performing some studies; for example, a prior electrocardiogram should be available before a myocardial stress study.

## 12.6 INFORMATION SYSTEM

### 12.6.5 Scheduling

- The scheduling system creates a ‘worklist’, a list of studies that need to be performed. Most modern imaging equipment can use a worklist provided by the RIS. When the technologist starts an imaging study, the appropriate patient is picked from the worklist. Selecting a patient from a list results in far fewer errors than re-entering all of the demographic identifier data for each study.

## 12.6 INFORMATION SYSTEM

### 12.6.6 Broker

- A broker is essentially an information gateway. The term ‘information gateway’ is generally used for a hospital-wide system. The term ‘broker’ is generally used when talking about a system within a radiology department. The broker handles incompatible details related to RIS, PACS and imaging devices that are local to radiology.

## 12.6 INFORMATION SYSTEM

### 12.6.7 Security

- Health information is private. Although the privacy of health information is often a relatively minor concern for the general public, it is a major concern for politicians, who make rules about the security needed for medical information. Within the information community, computer security is largely a solved problem, although vigilance is necessary, because there are always hackers trying to exploit any security holes. Furthermore, with aggregation of private health information, the potential extent of a security breach becomes catastrophic. Security depends not only on computer systems, but also on humans who are often the weak link.

## 12.6 INFORMATION SYSTEM

### 12.6.7 Security

- ❑ There needs to be a balance between the damage caused due to a security breach and the expense of the security measures. Often, relatively low damage situations are addressed with overly expensive systems, especially in terms of lost productivity.
- ❑ The dominant effect of security should not be to prevent authorized users from accessing information. Nuclear medicine tends to be a relatively low risk environment, so in most circumstances the balance should favour productivity over security.