Fundamentals of Image Processing

Digital image processing is the technology of applying a number of computer algorithms to process digital images. the outcomes of this process can be either images or a set of representative characteristics or properties of the original images (Figure1).

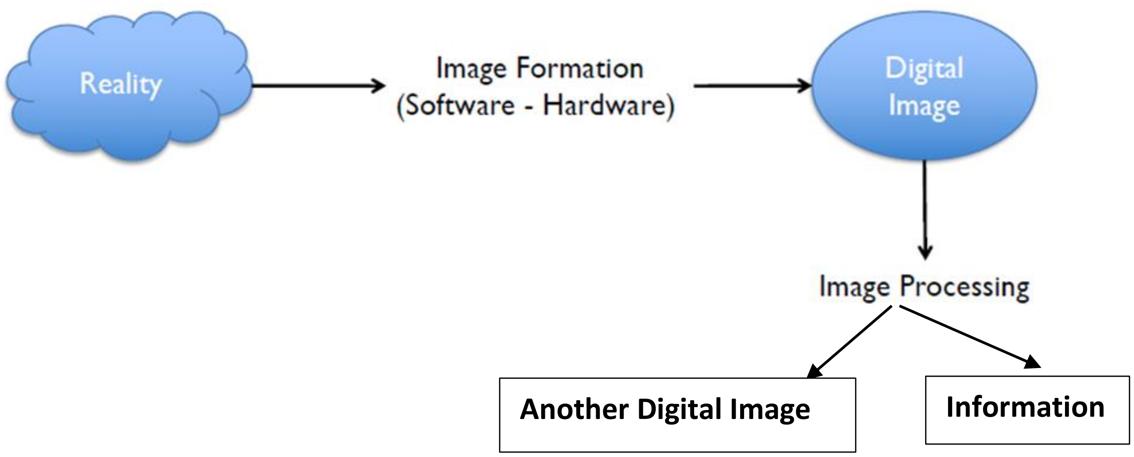

Figure1: digital image processing

An image is a 2-D light intensity function $f(x,y)$. As light is a form of energy:

$$0 < f(x,y) < \infty$$

f(x,y) may be expressed as the product of 2 components:

$$f(x,y)=i(x,y)r(x,y)$$

where:

$i(x,y)$ is the illumination component: $0 < i(x,y) < \infty$,

and $r(x,y)$ is the reflectance component: $0 < r(x,y) < 1$

if $r(x,y)=0$ implies total absorption, and if $r(x,y)=1$ implies total reflectance.

The intensity of a monochrome image f at (x,y) is the *gray level* (l) of the image at that point.

In practice:

$$L_{min} = i_{min} r_{min} \quad and$$

$$L_{max} = i_{max} r_{max}$$

The interval $[L_{min}, L_{max}]$ is called the *gray scale*.

Common practice is to shift the interval to [0,1] where L=0 is considered black and L=1 is considered white.

Digital Image

In digital image processing, two fundamental concepts are image sampling and quantization. These processes are crucial for converting an analog image into a digital form that can be stored, manipulated, and displayed by computers (Figure2). Despite being closely related, sampling and quantization serve distinct purposes and involve different techniques.

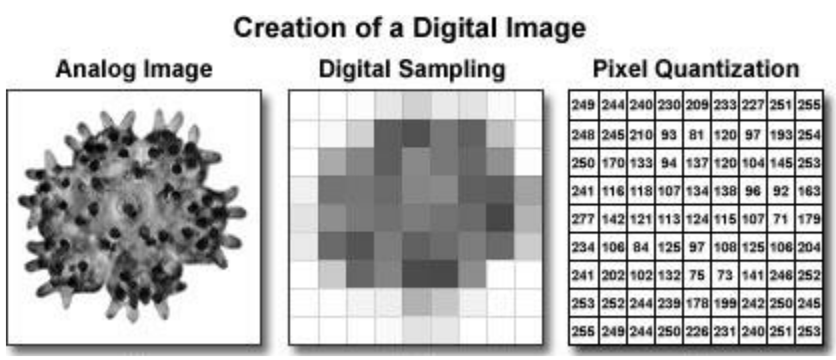

Figure2: Conversion Analog image to digital form

In order to convert this image into a digital image on our computer, the following two main steps are necessary:

Step#1: Sampling

Image sampling is the process of converting a continuous image (analog) into a discrete image (digital) by selecting specific points from the continuous image. This involves measuring the image at regular intervals and recording the intensity (brightness) values at those points (Figure3).

How Image Sampling Works?

- **Grid Overlay:** A grid is placed over the continuous image, dividing it into small, regular sections.
- **Pixel Selection:** At each intersection of the grid lines, a sample point (pixel) is chosen.

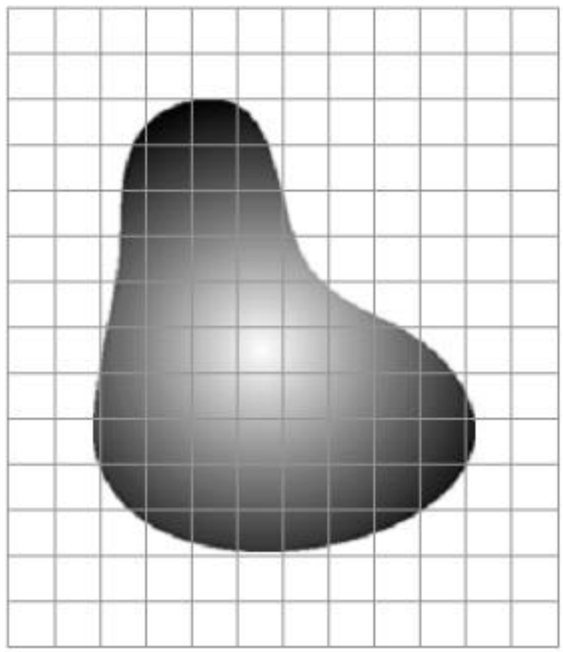

Figure3: Image sampling

Examples of Sampling

- **High Sampling Rate:** A digital camera with a high megapixel count captures more details because it samples the image at more points.
- **Low Sampling Rate:** An old VGA camera with a lower resolution captures less detail because it samples the image at fewer points.

Step#2: Quantization

Image Quantization is the process of converting the continuous range of pixel values (intensities) into a limited set of discrete values. This step follows sampling and reduces the precision of the sampled values to a manageable level for digital representation (Figure4).

How Image Quantization Works?

- **Value Range Definition:** The continuous range of pixel values is divided into a finite number of intervals or levels.
- **Mapping Intensities:** Each sampled pixel intensity is mapped to the nearest interval value.
- **Assigning Discrete Values:** The original continuous intensity values are replaced by the discrete values corresponding to the intervals.

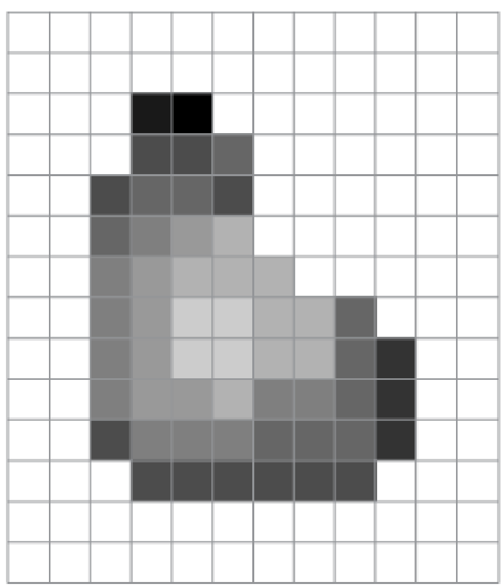

Figure4: Image Quantization

Examples of Quantization

- **High Quantization Levels:** An image with 256 levels (8 bits per pixel) can represent shades of gray more accurately.
- **Low Quantization Levels:** An image with only 4 levels (2 bits per pixel) has much less detail and appears more posterized.

Key Differences Between Image Sampling and Quantization

Feature	Image Sampling	Image Quantization
Definition	Conversion of a continuous image into a discrete set of points by selecting specific pixel positions	Conversion of continuous pixel intensity values into discrete levels
Process Focus	Spatial information (locations of pixels)	Intensity values (brightness or color levels)
Outcome	A grid of pixel values representing spatial resolution	A set of discrete intensity values for each pixel
Resolution Aspect	Affects spatial resolution (detail and clarity of the image)	Affects color/gray level resolution (number of shades or colors)
Determined By	Sampling rate (number of pixels sampled)	Quantization levels (number of intensity levels)
Higher Value Effects	Higher sampling rate captures more spatial detail	More quantization levels represent finer intensity variations
Example	High megapixel count in cameras for detailed images	8-bit color depth for more color variations
Application Impact	Crucial for applications needing high spatial detail like medical imaging	Crucial for applications needing high color fidelity like graphic design
Storage Requirement	Increases with higher sampling rates	Increases with more quantization levels
Typical Values	Measured in pixels per inch (PPI) or dots per inch (DPI)	Measured in bits per pixel (bpp)

Advantages and Disadvantages of Image Sampling and Quantization Image

1. **Sampling:**

Advantages:

1. **Data Reduction:** Converts a continuous signal into a finite set of points, making storage and processing more manageable.
2. **Compatibility:** Sampled images are easily processed by digital systems and algorithms.
3. **Resolution Control:** Allows for control over image resolution by adjusting the sampling rate.

Disadvantages:

1. **Information Loss:** Inevitably loses some information by approximating a continuous signal.
2. **Aliasing:** Can cause distortions and artifacts if the sampling rate is too low.
3. **Computationally Intensive:** High-resolution sampling demands significant computational resources and storage space.

2. Image Quantization:

Advantages:

1. **Data Compression:** Reduces the amount of data by limiting the number of possible values for each pixel.
2. **Simplified Processing:** Makes image processing operations simpler and faster with fewer distinct values.
3. **Noise Reduction:** Helps reduce the impact of noise by mapping small variations in intensity to the same value.

Disadvantages:

1. **Loss of Detail:** Reduces the range of colors or intensity levels, leading to a loss of fine detail and potential color banding.
2. **Quantization Error:** Introduces differences between the original and quantized values, which can become noticeable.
3. **Reduced Image Quality:** Overly aggressive quantization can significantly degrade image quality, making the image appear blocky or posterized.

Applications of Digital Image Processing

Some of the major fields in which digital image processing is widely used:

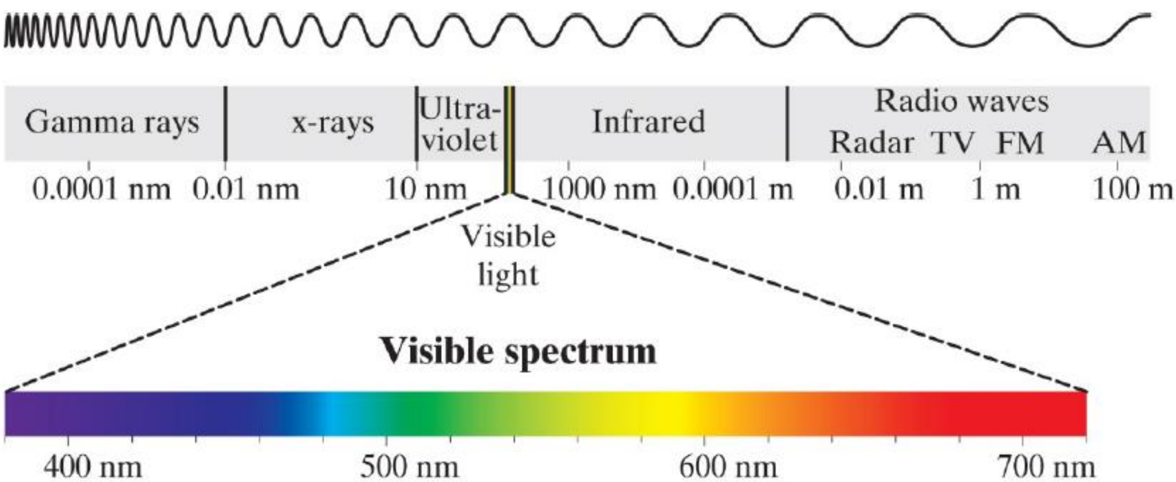

Figure5: The EM spectrum arranged according to wavelength

1. Gamma ray Imaging

Used in nuclear medicine, astronomy: Nuclear medicine: patient is injected with radioactive isotope that emits gamma rays as it decays. Images are produced from emissions collected by detectors (Figure6).

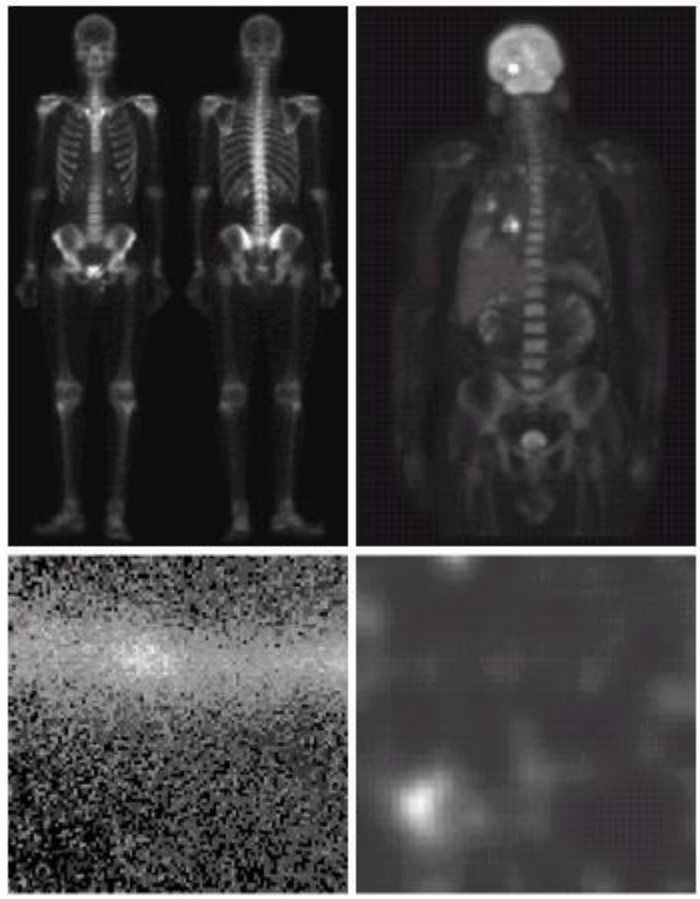

Figure6: Some examples of Gamma ray imaging

2. X-ray imaging:

Oldest source of EM radiation for imaging (figure7).

- X-rays of body
- Used for CAT scans
- Used for angiograms where X-ray contrast medium is injected through catheter to enhance contrast at site to be studied.
- Industrial inspection.

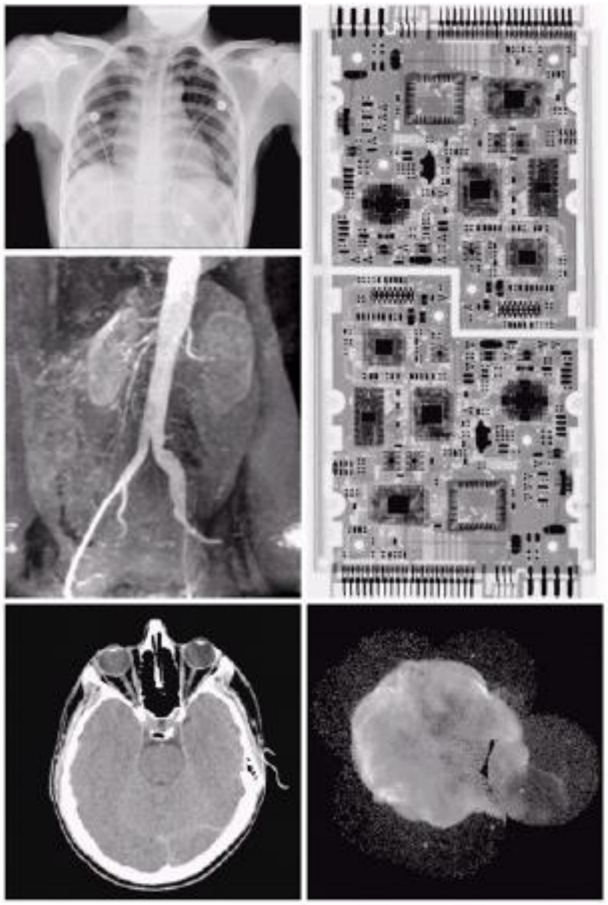

Figure7: Some examples of X-ray imaging

4. Ultra-Violet Imaging

- Used for lithography, industrial inspection, fluorescence microscopy, lasers, biological imaging, and astronomy (Figure8).
- Photon of UV light collides with electron of fluorescent material to elevate its energy. Then, its energy falls and it emits red light.

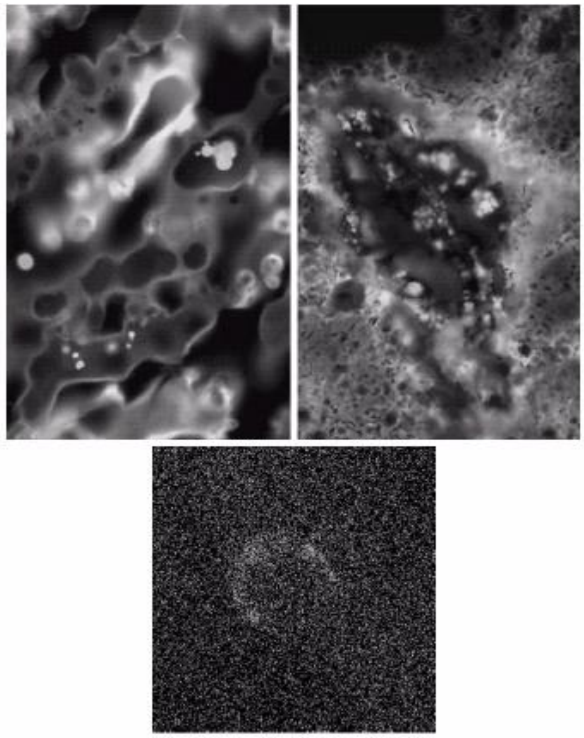

Figure8: Some examples of Ultraviolet imaging

5. Visible and Infrared Imaging

1. Used for astronomy, light microscopy, remote sensing.

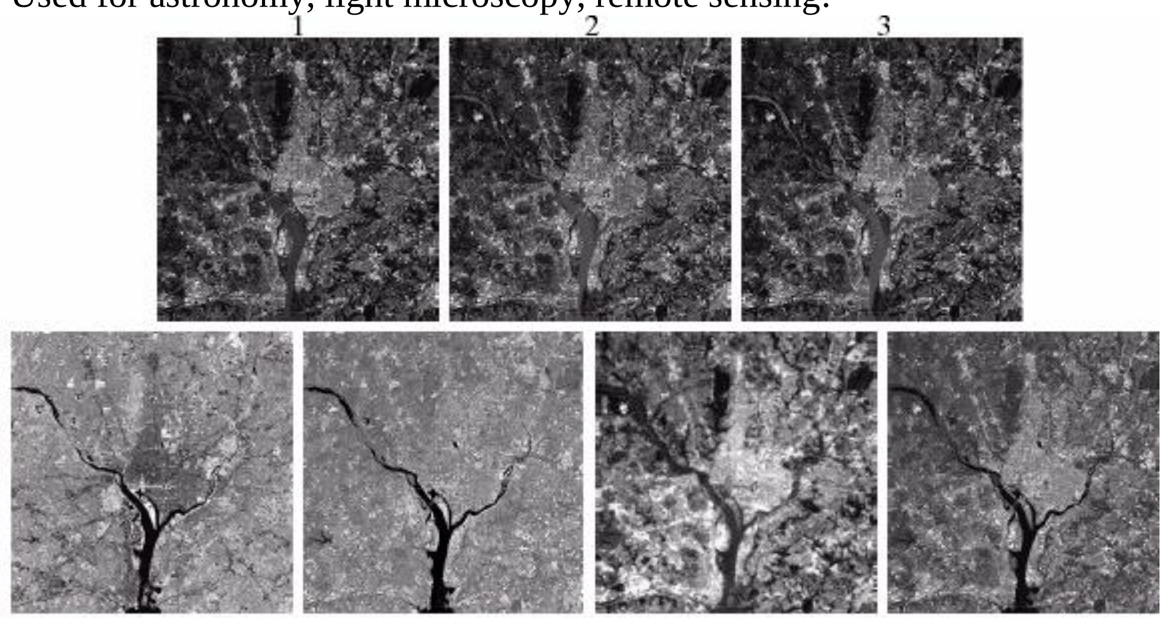

Figure9: LANDSAT satellite images

2. Industrial inspection (Figure10):
   - inspect for missing parts
   - Missing pills

- unacceptable bottle fill
- unacceptable air pockets
- anomalies in cereal color
- incorrectly manufactured replacement lens for eyes

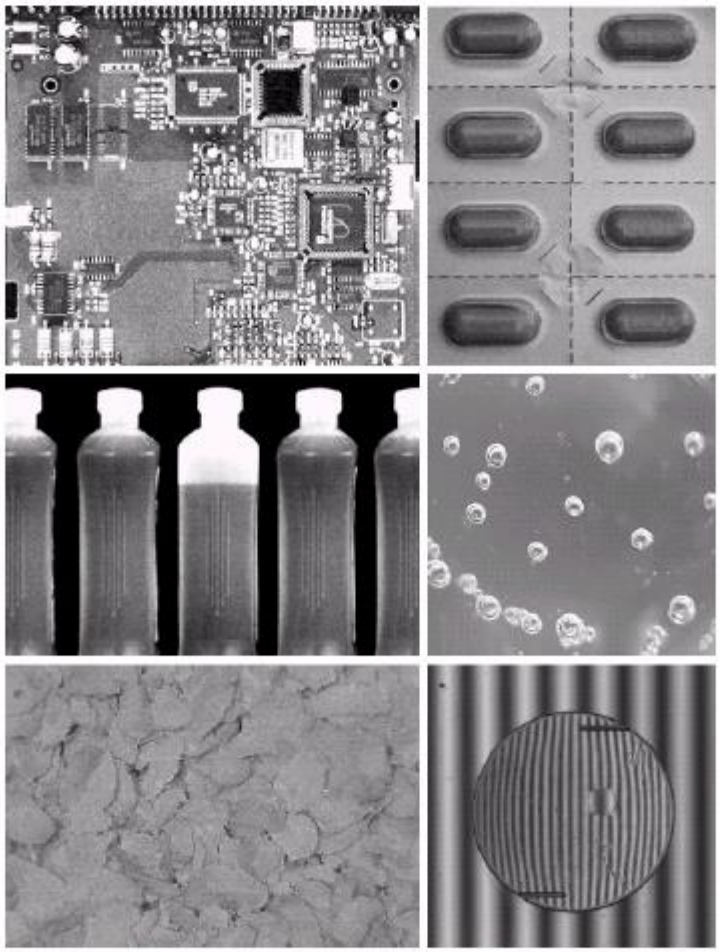

Figure10: Some examples of manufactured goods often checked using digital image processing

6. Microwave Imaging: (Figure11)

• Radar is dominant application
• Microwave pulses are sent out to illuminate scene
• Antenna receives reflected microwave energy

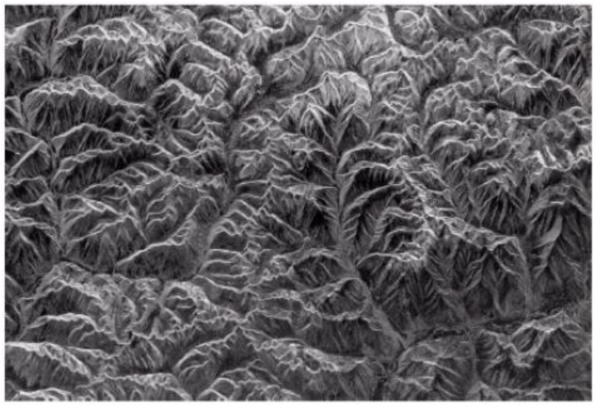

Figure11: Space borne RADAR image of mountains in southeast Tibet

7. **Radio-Band Imaging**

Magnetic resonance imaging (MRI):

-places patient in powerful magnet

-passes radio waves through body in short pulses

-each pulse causes a responding pulse of radio waves to be emitted by patient's issues

-Location and strength of signal is recorded to form image

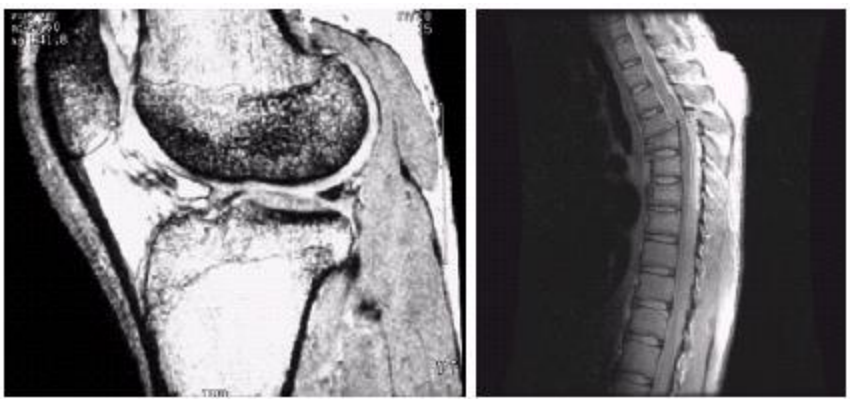

Figure12: MRI images of a human: knee and spine

8. **Non-EM modality: Ultrasound Imaging:**

Used in geological exploration, industry, medicine (Figure13):

-Transmit high-freq. (1-5 MHz) sound pulses into body

-Record reflected waves

-Calculate distance from probe to tissue/organ using the speed of sound (1540 m/s) and time of echo's return

-Display distance and intensities of echoes as a 2D image.

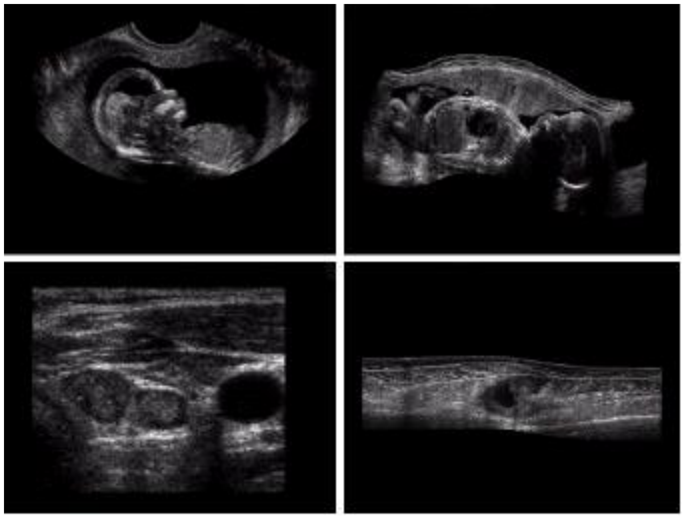

Figure13: Examples of ultrasound imaging

9. **Non-EM modality: Scanning Electron Microscope**

- Stream of electrons is accelerated toward specimen using a positive electrical potential
- Stream is focused using metal apertures and magnetic lenses into a thin beam
- Scan beam; record interaction of beam and sample at each location (dot on phosphor screen)

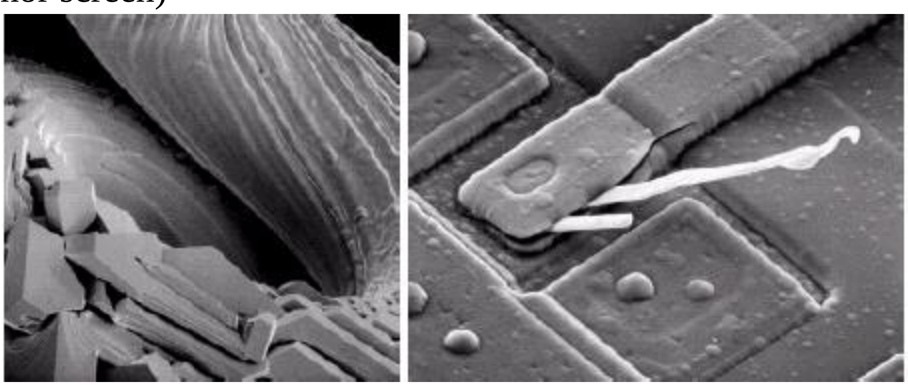

Figure14: Example of electron microscpe

Components of Image Processing System

1) **Image Sensors:** two elements are required to acquire digital image. The first is a physical device that is sensitive to the energy radiated by the object we wish to image and second is specialized image processing hardware.
2) **Specialize image processing hardware:** It consists of the digitizer just mentioned, plus hardware that performs other primitive operations such as

an arithmetic logic unit, which performs arithmetic such addition and subtraction and logical operations in parallel on images

3) **Computer:** It is a general purpose computer and can range from a PC to a suppercomputer depending on the application. In dedicated applications, sometimes specially designed computer are used to achieve a required level of performance.

4) **Software:** It consists of specialized modules that perform specific tasks a well-designed package also includes capability for the user to write code, as a minimum, utilizes the specialized module. More sophisticated software packages allow the integration of these modules.

5) **Mass storage:** This capability is a must in image processing applications. An image of size 1024 x1024 pixels, in which the intensity of each pixel is an 8-bit quantity requires one Megabytes of storage space if the image is not compressed. Image processing applications falls into three principal categories of storage:

a) Short term storage for use during processing
b) On line storage for relatively fast retrieval
c) Archival storage such as magnetic tapes and disks

6) **Image display:** Image displays in use today are mainly color TV monitors. These monitors are driven by the outputs of image and graphics displays cards that are an integral part of computer system.

7) **Hardcopy devices:** The devices for recording image includes laser printers, film cameras, heat sensitive devices inkjet units and digital units such as optical and CD ROM disk.

8) **Networking:** It is almost a default function in any computer system in use today because of the large amount of data inherent in image processing applications. The key consideration in image transmission bandwidth.