ELIC 629
Digital Image Processing

Winter 2005

Digital Image Fundamentals: Visual Perception & the EM Spectrum, Image Acquisition, Sampling & Quantization

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Overview (1):

- **Review**
  - Some questions to consider
- **Elements of Visual Perception**
  - Structure of the human eye
  - Image formation in the eye
  - Brightness adaptation and discrimination
- **Light and the Electromagnetic Spectrum**
  - Brief review
  - Greater details

Overview (2):

- **Image Sensing and Acquisition**
  - Single sensor acquisition
  - Sensor strip acquisition
  - Sensor array acquisition
  - A simple image formation model
- **Image Sampling and Quantization**
  - Basic concepts
  - Digital image representation
  - Spatial and gray-level resolution
  - Aliasing and Moire patterns

Administrative Details (1):

- **Miscellaneous Notes**
  - No access to the lab and its equipment other than during our regularly scheduled lab hours
    - Even if lab is open, no one else can provide you access to the camera equipment
    - Shouldn't be a problem completing labs during your lab hours
  - Keep in mind that you are responsible for book material as well
    - I will be closely following the material in the book and will provide you with the relevant sections

Review

Some Questions to Consider (1):

- What is a digital image ?
- What is a gray level ?
- What is digital image processing ?
- What are some uses of digital image processing ?
- How is the field of image processing categorized ?
- What is the electromagnetic (EM) spectrum ?
- Can images be generated from non-EM sources ?
- What are the two broad categories of digital image processing ?

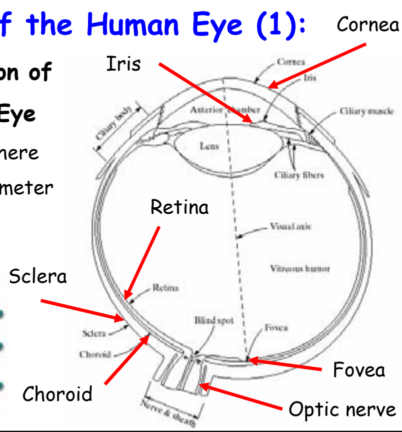
Elements of Visual Perception

Introduction (1):

- **Motivation**
  - Understanding the human visual system is important for digital image processing
  - Although image processing is built upon a strong mathematical/probabilistic foundation, there is also a large subjective component
    - The choice of choosing one technique over another can be subjective
    - My notion of a "good" image may differ from yours

Structure of the Human Eye (1):

- **Cross Section of the Human Eye**
  - Nearly a sphere
  - ~ 20mm diameter



Structure of the Human Eye (2):

- **Major "Components" of the Eye**
  - Cornea
    - Tough, transparent tissue that covers the front surface of the eye
  - Sclera
    - Opaque membrane enclosing remainder of eye
  - Choroid
    - Lies directly below the sclera
    - Contains a network of blood vessels which provide nutrition to the eye

Structure of the Human Eye (3):

- Choroid (cont…)
  - Even minor injuries can lead to severe eye damage
  - Helps reduce the amount of extraneous light entering the eye
  - At the front, choroid is divided into two parts: ciliary body and iris diaphragm
- Iris diaphragm
  - Contracts or expands to control the amount of light entering the eye
  - Dim light → expands to let more light in
  - Bright light or object close-by → contracts

Structure of the Human Eye (4):

- Lens
  - Composed of several layers of fibrous cells
  - Suspended by fibers that attach to the ciliary body
  - Contains 60-70% water, 6% fat
  - Colored by a slight yellow coloration which increases with age → cataracts
  - Absorbs about 8% of visible light spectrum (higher absorption at smaller wavelengths)
  - Absorbs infrared and ultraviolet energy considerably

Structure of the Human Eye (5):

- Retina
  - Inner-most membrane of the eye
  - When eye is properly focused, light from object outside eye is focused on to retina
  - Discrete light receptors are distributed over surface of the retina → cones and rods
- Cones
  - 6 – 7 million in each eye
  - Located primarily in central portion of the retina known as the fovea
  - Each cone is connected to its own nerve end → allows for high resolution/high detail

Structure of the Human Eye (6):

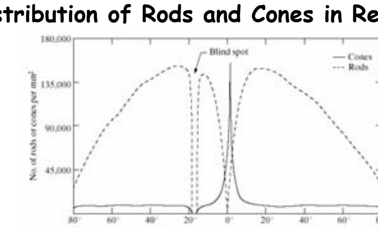
- Cones (cont…)
  - High color sensitivity
  - Eyeball is rotated until the "image" of the object of interest (the object the person is looking at) falls on the fovea
  - Known as photopic vision or bright light vision
- Rods
  - 75 – 150 million distributed over retinal surface
  - Several rods connected to single nerve fiber
  - Less detail → provide general overview of the field of view

Structure of the Human Eye (7):

- Rods (cont…)
  - No color sensitivity
  - Sensitive to low levels of illumination
  - Known as scotopic vision or dim-light vision
- **Recap of Cones and Rods**
  - Cones → color sensitive, high detail, less of them, daylight
  - Rods → non-color sensitivity, less detail, more of them, night time

Structure of the Human Eye (8):

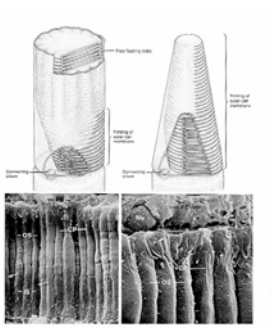
- **Distribution of Rods and Cones in Retina**



- Receptor density measured in degrees from fovea
  - Cones most dense in center area of retina
  - Rods increase in density from center to ~20° then decrease towards periphery

Structure of the Human Eye (9):

- **Rods and Cones in "Real Life"**



Structure of the Human Eye (10):

- **Blind Spot**
  - Absence of receptors in a small portion of the retina
    - Contains the optic nerve; all nerves from the eye receptors exit at the optic nerve
    - No vision in this area → cannot respond to any light falling on this area!
  - But why don't we notice this "blind spot" – shouldn't it be evident to us ?
    - We have two eyes → the blind spot of one eye corresponds to non-blind spot of other eye
    - See web site for example of blind spot

Image Formation in the Eye (1):

- **Eye is Flexible**
  - This actually is a big deal!
  - Primary difference between the eye and regular camera/optical lens
  - Controls the shape of the lens via muscles
    - Allows for focusing of objects close by and distant
    - Distant objects → lens is flattened
    - Close-by objects → lens is "thicker"

Image Formation in the Eye (2):

- ***Graphical Overview***

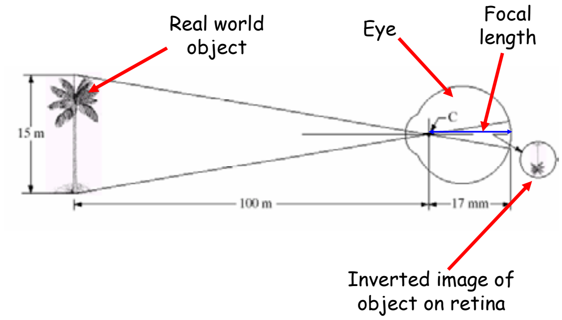


Image Formation in the Eye (3):

- **Focal Length**
  - Distance between center of lens and the retina
  - Varies between 14mm and 17mm as refractive power of lens increases from minimum to maximum
    - Focusing on objects > ~3m → lowest refractive power
    - Focusing on objects close-by → greatest refractive power
    - Simple geometry can be used to calculate the size of retinal image

Image Formation in the Eye (4):

- ***Image of Object on Retina is Inverted!***
  - We are not aware of this however because the inversion is handled by the brain!
- ***"Crossing" of Visual Image Processing***
  - Left (right) visual field processed by right (left) portion of brain

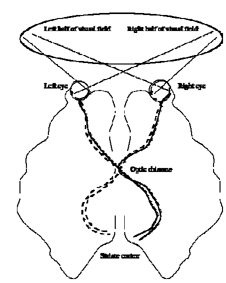
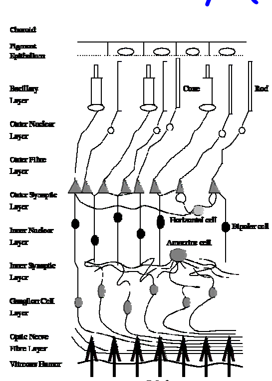


Image Formation in the Eye (5):

- **Overview**

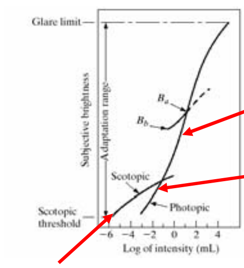


Brightness Adaptation & Discrimination (1):

- **Digital Images are Displayed as a Discrete Set of Intensities**
  - Eye's ability to discriminate between different intensity levels is important for image processing!
- ***Range of Intensities to Which Eye is Sensitive too is Huge!***
  - Order of 10^{10} from scotopic threshold to glare limit

Brightness Adaptation & Discrimination (2):

- **Brightness and & Light Intensity (cont…)**



Range of intensities to which visual system can respond

Photopic

Scotopic

Brightness Adaptation & Discrimination (3):

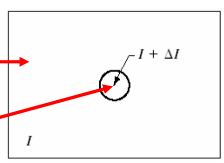
- **Brightness Adaptation**
  - Visual system cannot operate over such a large range simultaneously
  - Total range of distinct intensity levels it can discriminate is small!
  - Brightness adaptation
    - Changes in the overall sensitivity of the visual system to allow for the large range of intensities
  - Brightness adaptation level
    - The current sensitivity level of the visual system

Brightness Adaptation & Discrimination (4):

- **Discriminating Between Changes in Light Intensity**
  - Determined by:
    - Subject views flat uniformly illuminated area illuminated from behind by light source
    - Increment of illumination ΔI in the form of short duration pulse appears

Uniformly illuminated area

Increment of illumination



Brightness Adaptation & Discrimination (5):

- **Discriminating Between Changes in Light Intensity (cont…)**
  - If ΔI isn't bright enough, subject says "no" indicating no perceivable change
  - As ΔI is increased, subject will eventually say "yes" indicating a perceivable change
  - When ΔI is large enough, subject will say "yes" always
  - Weber ratio
    - The quantity $\Delta I_c/I$ where ΔI_c is the increment of illumination discriminable 50% of the time

Brightness Adaptation & Discrimination (6):

- Weber ratio (cont…)
  - Large Weber ratio → indicates large percentage change in intensity required to discriminate change
  - Small Weber ratio → indicates small percentage change in intensity required to discriminate change

Brightness Adaptation & Discrimination (7):

- **Based on these Types of Experiments, we can Distinguish One-Two Dozen Intensity Levels**
  - e.g., in a typical monochrome image, this is the number of different intensities we can "see"
  - This of course doesn't mean we can represent an image by such a small number of intensities!
    - As the eye scans an image, average intensity level background changes
    - Allows different set of incremental changes to be detected at each new adaptation level

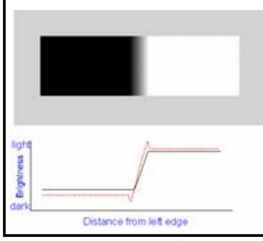
Brightness vs. Intensity (1):

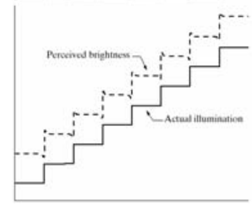
- **Two Phenomena Demonstrate Brightness isn't a Simple Function of Intensity**
  - Mach Bands
    - Visual system tends to overshoot or undershoot around the boundary of regions of different intensities
  - Simultaneous contrast
    - A region's perceived brightness doesn't depend on its intensity only but may also be affected by the intensity of its surroundings

Brightness vs. Intensity (2):

- **Mach Bands**

Scalloping near the boundaries despite the fact that intensity is constant





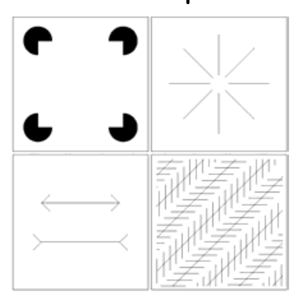
Brightness vs. Intensity (3):

- **Simultaneous Contrast**

  - Intensity of all inner squares is the same but as the background gets lighter, inner square appears darker!

Optical Illusions (1):

- **Eye Fills in Non-Existing Info. or Wrongly Perceives Geometrical Properties of Objects**



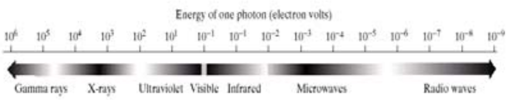
The Electromagnetic Spectrum

Electromagnetic Spectrum-Review(1):

- **Electromagnetic Waves - Review**
  - Conceptualized as:
    - Wave theory → propagating sinusoidal waves of varying wavelength or
    - Particle theory → stream of mass-less particles containing a certain amount of energy, moving at the speed of light (known as a photon)
    - There is also the dual theory in which both forms are present! We won't worry about this !!!

Electromagnetic Spectrum-Review (2):

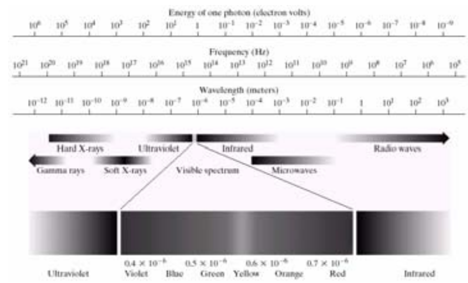
- **Grouping of Spectral Bands of EM Spectrum According to Energy per Photon we Obtain:**



  - Highest energy → gamma rays
  - Lowest energy → radio waves
  - No "smooth transition" between bands of the EM spectrum

Electromagnetic Spectrum (1):

- **Close-up View of the Visible Portion**
  - Small portion of the entire spectrum



Electromagnetic Spectrum (2):

- **Visible Portion (Light) – Colors**
  - Wavelength ranges from
    - 0.43μm (violet – higher energy)
    - 0.79μm (red – lower energy)
  - Color spectrum divided into six broad regions
    - Violet, blue, green, yellow, orange & red
    - Remember → continuous (e.g., no "clear-cut" boundary between colors in the spectrum!)

Electromagnetic Spectrum (3):

- **Visible Portion (Light) – Colors (cont…)**
  - When looking at an object (scene etc.) the colors we actually "see" arise from:
    - The light reflected off of an object
    - A pure blue object reflects blue light while absorbing all other colors completely (e.g., an object's color is determined by its reflection and absorption characteristics)
    - White light → all colors reflected equally
    - Achromatic or monochromatic light → no color, void of any color e.g., gray level: black to white and shades of gray in between

Electromagnetic Spectrum (4):

- **Some Definitions**
  - Radiance
    - Total energy flowing from source (Watts)
  - Luminance
    - Amount of energy the observer perceives from a light source (lumens)
    - Not necessarily all energy emitted is perceived!!
  - Brightness
    - Subjective descriptor of light perception

Image Sensing and Acquisition

Introduction (1):

- **Intensity of an Image Arises from Two Potential Sources**
  - Emitted from an source (e.g., energy emitted from the sun or a light)
  - Reflected from an object which itself does not necessarily emit energy
    - An object can in some cases serve as a source and reflector at the same time!
  - Keep in mind, a source does not have to produce energy restricted to the visual portion of the EM spectrum

Introduction (2):

- **It is this Energy that we Collect ("Sample") and Construct an Image From**
  - Sampling overview
    - Incoming energy is transformed into a voltage by the sensing device (camera, etc…)
    - Output of sensing device is the response of the sensor(s)
    - Digital quantity is obtained by digitizing the sensor's response
    - We will now elaborate on this…

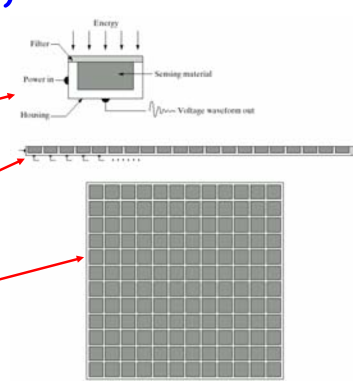
Introduction (3):

- **Overview**

Sensor

1D sampled output

2D sampled output



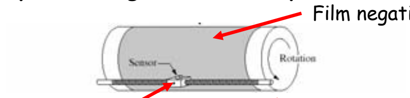
Single Sensor Image Acquisition (1):

- **One Sensor to Sample ("Sense") Energy and Construct Image**
  - Very simple yet very restrictive!
  - Common example is the photodiode
    - Output voltage is proportional to incident light
  - But how do we construct a 2D image using a single sensor when an image is a 2D construct of spatial locations x,y?
    - Must "move" the sensor with respect to both the x and y directions

Single Sensor Image Acquisition (2):

- **Example of Single Sensor Acquisition Device**

Film negative



Sensor Linear motion

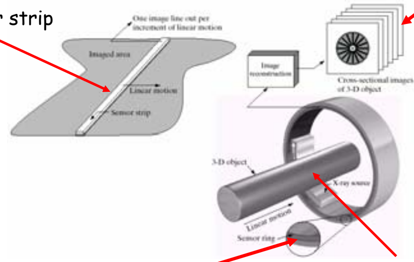
  - Film negative mounted on a drum which rotates allowing for displacement in one direction
  - Single sensor mounted such that it can move in perpendicular direction
  - Allows for high resolution imaging, very inexpensive but too slow!!!

Sensor Strip Image Acquisition (1):

- **Sensor Strip**
  - Rather than using a single sensor, multiple sensors arranged in a line ("strip") are used to image scene
    - Provides one dimensional imaging capability
    - Motion in the other direction allows for imaging in the other direction
    - Typical in flat-bed scanners
    - Air-borne imaging applications where airplane flies over scene to be imaged
    - Can also be arranged in a "ring" as done in medical imaging e.g., CAT scans to give 3D view

Sensor Strip Image Acquisition (2):

- **Sensor Strip (cont…)**



Sensor Array Image Acquisition (1):

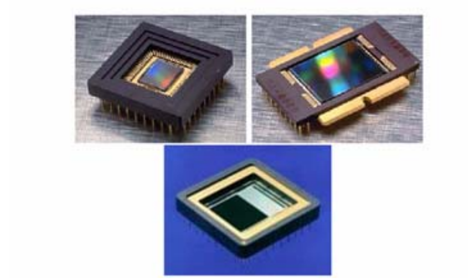
- **Sensors Arranged in a 2D Array**
  - Can now sample in both dimensions
  - No movement of sensor needed to obtain image!
  - More complex and more expensive but no motion!
  - Common arrangement, especially with the current state of technology
    - Sensor arrays are small and are fairly inexpensive
    - Just about all digital cameras/video recorders use a 2D array of sensors → CCD (charged coupled device) with typically 4000 x 4000 elements or more

Sensor Array Image Acquisition (2):

- **Charged Coupled Devices (CCDs)**
  - Invented in 1969 at Bell Labs by George Smith and Willard Boyle
  - Response of each sensor is proportional to the integral of the energy projected onto the surface of the sensor
    - Noise can be reduced by letting the sensor integrate the input energy over some period of time
  - CCDs for various types of energy acquisition not only light!

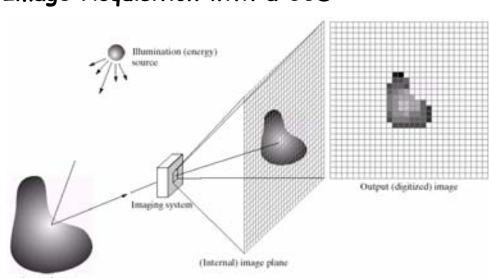
Sensor Array Image Acquisition (3):

- **Example of Typical CCDs**



Sensor Array Image Acquisition (4):

- **Image Acquisition with a CCD**

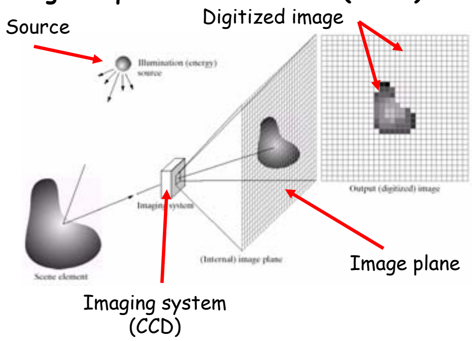


Sensor Array Image Acquisition (5):

- **Image Acquisition with a CCD (cont…)**
  - First function of imaging system is to focus light (energy) onto an image plane - an imaginary plane on which an object is projected
  - If the energy is light, front end of imaging system is a lens and projects the scene being imaged onto the lens focal plane
  - Sensor array is coincident with focal plane & produces output proportional to integral of light incident onto sensor
  - Sensor array output is digitized

Sensor Array Image Acquisition (6):

- **Image Acquisition with a CCD (cont…)**



An Image Formation Model (1):

- **Image Generated by Physical Process**
  - Intensity values at spatial position f(x,y) proportional to the energy radiated by the physical source and

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

  - In other words, intensity values are finite
- **Intensity f(x,y) Characterized by Two Components**
  - Amount of source illumination incident on the scene
  - Amount of illumination being reflected by objects in the scene

An Image Formation Model (2):

- Both components can be combined to give

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

- where
  - → $0 < i(x,y) < \infty$ denotes the energy arising from the source
  - → $0 \le r(x,y) \le 1$ denotes the energy that is reflected off of objects in the scene

An Image Formation Model (3):

- **Note:**
  - When dealing with gray level images, the gray level of a particular pixel is denoted by "$\ell = f(x,y)$" and

$$L_{min} \le \ell \le L_{max}$$

  - The interval $[L_{min}, L_{max}]$ is known as the gray scale
    - Common to shift this interval to the interval [0, L-1] such that, on the gray scale
    - $\ell = 0 \rightarrow$ black
    - $\ell = L - 1 \rightarrow$ white
    - All intermediate values are shades of gray

Image Sampling and Quantization

Basic Concept (1):

- **Goal**
  - Generate digital images from data that has been "sensed" (sampled) by some type of sensor
    - Output of the majority of sensors is some type of continuous voltage waveform but we CANNOT represent a continuous signal on a computer!
    - This continuous voltage waveform data must be converted into digital form
    - The process of digitizing the data involves two processes → sampling and quantization

Basic Concept (2):

- **Sampling in 2D**
  - Same as sampling in 1D but now we sample this "extra" dimension
  - To simplify problem
    - Sample this 2D function one "row" at a time → each "row" is a 1D function and we reduce the problem of 2D sampling to repeated 1D sampling
    - Take ("sample") the values of the continuous intensity function representing this row at equally spaced intervals
    - Sampling period → time between successive samples

Basic Concept (3):

- **Quantization – Converting the "Continuous" Intensity Values to Discrete Values**
  - Although function has been "sampled" at evenly spaced intervals (e.g., discrete), we must still account for the "continuous" intensity values
    - Can be of any value (e.g., theoretically any one of the 10^{10} intensity values we can perceive!)
    - Clearly this is impossible to represent using a computer/machine
    - Need to "map" these "continuous" values to a (typically) much smaller discrete set of values

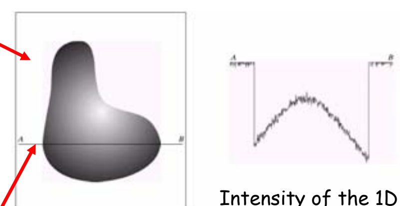
Basic Concept (4):

- **Quantization (cont…)**
  - Quantization → refers to this mapping of the continuous values to a discrete set of values which can be represented on a computer/machine
  - Example
    - Intensity values which range from 1.0 to 10.0 and include any value in-between (e.g., 4.256)
    - Discrete set of values → 1,2,3,4,5,6,7,8,9,10
    - Mapping → discerete = round(continuous) (e.g., if continuous = 4.55, then quantized to 5)

Basic Concept (5):

- **Graphical Illustration of "One Row" Sampling**

Continuous image



"1D"portion of image (one "line" AB of image)

Intensity of the 1D portion of image where white = max intensity & black = min intensity

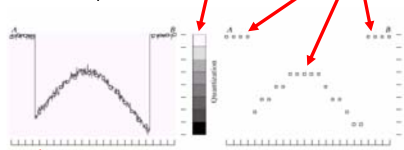
Basic Concept (6):

- **Graphical Illustration of "One Row" Sampling**

Continuous intensity of the 1D portion of image where white = max intensity & black = min intensity

Discrete intensities

Quantized values



Function sampled at evenly spaced intervals

Continuous values quantized into set of discrete value

Basic Concept (7):

- **Sampling and Quantization – Additional Notes**
  - Sampling is typically determined by the sensor arrangement used to generate the image
    - Don't always have the freedom to choose our own sampling interval! e.g., a camera's CCD automatically determines our sampling interval and hence resolution
  - Quantization range is also determined by our machine/computer
  - Remember Nyquist's Theorem

Basic Concept (8):

- **Sensor Array Determines Sampling Interval**

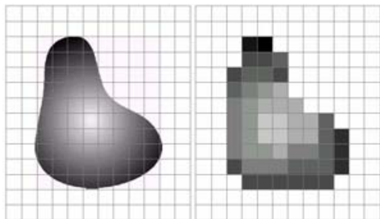


Image Representation (1):

- **Sampling and Quantization Result in a Discrete 2D Function**
  - Recall from first lecture → M x N matrix
  - Spatial coordinates x,y are indices into this matrix
    - x → denotes row index ranging from 0 to M – 1
    - y → denotes column index ranging from 0- N-1
    - Examples:

    (0,0) → first row, first column (known as the origin)

    (0,1) → first row, second column

    (M-1, N-1) → last row, last column

Image Representation (2):

- **Sampling and Quantization Result in a Discrete 2D Function (cont…)**

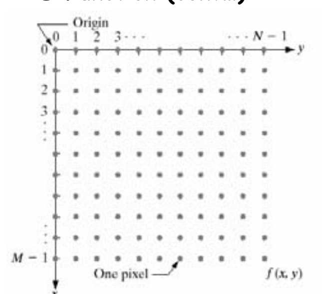


Image Representation (3):

- **M x N Digital Image in Matrix Form**
  - Each element of the matrix is known as a picture element, pel or most commonly pixel

$$f(x, y) = \begin{pmatrix} f(0,0) & f(0,1) & \cdots & f(0,N-1) \\ f(1,0) & f(1,1) & & f(1,N-1) \\ \vdots & & \ddots & \vdots \\ f(M-1,0) & f(M-1,1) & \cdots & f(M-1,N-1) \end{pmatrix}$$

Image Representation (4):

- **Choosing the Range for the Sampling Range Quantization Values**
  - Row and column dimensions (M, N)
    - Must be positive integers
    - Typically begin at "0" and run to M- 1
    - Typically a factor of 2 due to processing, storage and hardware