Introduction to Visual Perception & the EM Spectrum

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

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?
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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

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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

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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...)

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
  - 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 $\Delta I$ in the form of short duration pulse appears

Brightness Adaptation & Discrimination (5):
- Discriminating Between Changes in Light Intensity (cont...)
  - If $\Delta I$ isn't bright enough, subject says "no" indicating no perceivable change
  - As $\Delta I$ is increased, subject will eventually say "yes" indicating a perceivable change
  - When $\Delta I$ is large enough, subject will say "yes" always
  - Weber ratio
    - The quantity $\Delta I / I$ where $\Delta I_c$ is the increment of illumination discriminable 50% of the time

Brightness Adaptation & Discrimination (6):
- Weber ratio (cont...)
  - Large Weber ratio $\rightarrow$ indicates large percentage change in intensity required to discriminate change
  - Small Weber ratio $\rightarrow$ 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

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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

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Introduction (1):
- Intensity of an Image Arises from Two Potential Sources
  - Emitted from a 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

1D sampled output

2D sampled output

Single 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
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Sensor Strip Image Acquisition (2):
- Sensor Strip (cont...)
  3D reconstruction

Sensor Strip Image Acquisition (3):
- 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 (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

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Image Sampling and Quantization

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 $0 \leq f(x,y) \leq \infty$
  - 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 $f(x,y) = i(x,y) \times r(x,y)$
- $0 < i(x,y) < \infty$ denotes the energy arising from the source
- $0 \leq r(x,y) \leq 1$ 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 $l = f(x,y)$ and $L_{\min} \leq l \leq L_{\max}$
  - 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
    - $l = 0$ → black
    - $l = L - 1$ → white
    - All intermediate values are shades of gray

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**
  - Sampling in 2D is similar to sampling in 1D, but now we sample this "extra" dimension.
  - To simplify the problem, we sample a 2D function one "row" at a time. Each "row" represents a 1D function.
  - We sample this 2D function one "row" at a time to reduce the problem of 2D sampling to repeated 1D sampling.
  - We 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 a 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.
  - We need to "map" these "continuous" values to a (typically) much smaller discrete set of values.

Basic Concept (4):
- **Quantization (cont...)**
  - Quantization refers to the 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: discrete = round(continuous) (e.g., if continuous = 4.55, then quantized to 5).

Basic Concept (5):
- **Graphical Illustration of “One Row” Sampling**
  - Continuous intensity of the 1D portion of image where white = max intensity & black = min intensity.
  - Continuous values quantized into set of discrete values.

Basic Concept (6):
- **Graphical Illustration of “One Row” Sampling**
  - Continuous intensity of the 1D portion of image where white = max intensity & black = min intensity.
  - Function sampled at evenly spaced intervals.

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.

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**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 \rightarrow \text{denotes row index ranging from 0 to } M - 1
    - y \rightarrow \text{denotes column index ranging from 0 to } N - 1
  - Examples:
    - (0,0) \rightarrow \text{first row, first column (known as the origin)}
    - (0,1) \rightarrow \text{first row, second column}
    - (M-1, N-1) \rightarrow \text{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

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

**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

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