Digital Image Processing

Unit 1: Introduction

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What is a Digital Image?

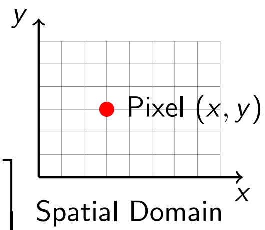
Definition

An image may be defined as a two-dimensional function, $f(x, y)$, where x and y are **spatial** (plane) coordinates.

- The amplitude of f at any pair of coordinates (x, y) is called the **intensity** or **gray level**
- When x, y, and the intensity values are all finite, discrete quantities, we call it a **digital image**
- A digital image is composed of a finite number of elements called:
  - Picture elements
  - Image elements
  - Pels
  - **Pixels** (most widely used term)

Spatial Domain:

- 2D array of pixels
- Each pixel has coordinates (x, y)
- Each pixel has an intensity value



Matrix Form:

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

Fundamental Steps in Digital Image processing

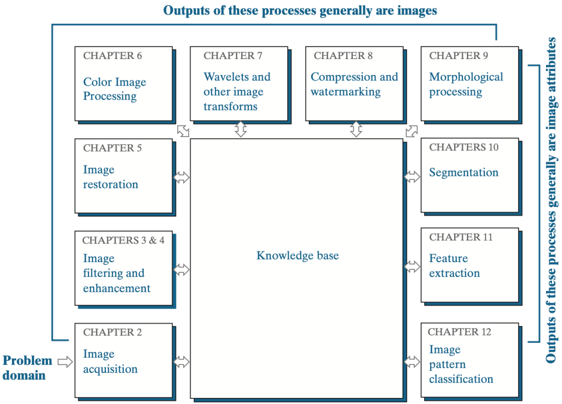
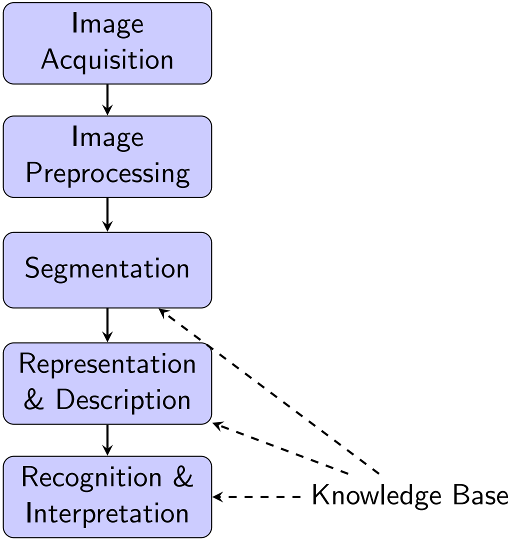


Figure: Fundamental steps in digital image processing. The chapter(s) indicated in the boxes is where the material described in the box is discussed.

Block Diagram of Image Processing System



Two Broad Categories of Image Processing

Category 1: Image-to-Image

Input: Images
Output: Images

- Image Enhancement
- Image Restoration
- Color Processing
- Image Compression
- Morphological Processing

Category 2: Image-to-Attributes

Input: Images
Output: Attributes/Descriptors

- Segmentation
- Feature Extraction
- Feature Description
- Pattern Classification
- Object Recognition

Important Note

Not all processes are applied to every image. The choice depends on the application and objectives.

Image Acquisition

Definition

The first process in image processing pipeline - obtaining a digital image for processing.

Acquisition Methods:

- Direct digital capture (digital cameras, scanners)
- Conversion from analog to digital
- Receiving pre-digitized images
- Medical imaging devices (CT, MRI, X-ray)
- Remote sensing satellites
- Synthetic image generation

Preprocessing during Acquisition:

- Scaling and resizing
- Format conversion
- Initial noise reduction
- Geometric corrections

Image Enhancement

Definition

The process of manipulating an image so the result is more suitable than the original for a **specific application**.

Key Characteristics:

- **Subjective** - depends on viewer
- **Problem-oriented** - no universal solution
- **Application-specific** - what works for X-rays may not work for satellites
- No general "theory" exists

Common Techniques:

- Contrast adjustment
- Brightness modification
- Noise reduction
- Sharpening
- Edge enhancement
- Histogram equalization

Important

Enhancement is evaluated by human visual interpretation - the viewer is the ultimate judge!

Enhancement vs. Restoration

Aspect	**Enhancement**	**Restoration**
Nature	Subjective	Objective
Basis	Human preferences	Mathematical/probabilistic models
Goal	Visual appeal	Recovery from degradation
Evaluation	Human judgment	Quantitative metrics
Approach	Heuristic methods	Model-based techniques
Applications	Display, visualization	Quality improvement, deblurring

Example:

- Enhancement: Making an image "look better" for presentation
- Restoration: Removing blur caused by camera motion using a degradation model

Enhancement Applications

Enhancement techniques vary widely based on application domain:

Medical Imaging:

- X-ray contrast enhancement
- MRI feature highlighting
- Tumor boundary clarification

Satellite/Remote Sensing:

- Infrared band processing
- Cloud removal
- Vegetation index enhancement

Consumer Photography:

- Color correction
- Red-eye removal
- Auto-enhancement

Industrial Inspection:

- Defect highlighting
- Surface analysis
- Quality control

What works for one domain may not work for another!

Image Restoration

Definition

Improving the appearance of an image using **objective**, mathematical or probabilistic models of image degradation.

Restoration vs. Enhancement:

- Restoration is **objective** - based on mathematical models
- Enhancement is **subjective** - based on human preferences

Common Restoration Problems:

- Motion blur removal and Out-of-focus correction
- Atmospheric turbulence compensation
- Noise reduction (Gaussian, salt-and-pepper)
- Geometric distortion correction

Typical Approach: Model the degradation process, then apply inverse operations

$$g(x, y) = h(x, y) * f(x, y) + n(x, y)$$

where g = degraded image, f = original, h = degradation function, n = noise

Color Image Processing

Growing Importance

Significant increase in digital image use over the Internet has made color processing increasingly important.

Key Topics in Color Processing:

- Color models (RGB, HSV, CMYK, YCbCr, etc.)
- Color space transformations, enhancement and correction
- Color balancing and histogram equalization
- Pseudocolor and full-color processing
- Color-based segmentation

Applications:

- Web image processing and Digital photography
- Medical imaging (false color for emphasis)
- Feature extraction using color information
- Object recognition based on color

Wavelets and Multi-resolution Processing

Purpose

Foundation for representing images in various degrees of resolution.

Key Applications:

- **Image compression** - efficient storage and transmission
- **Pyramidal representation** - successive subdivision into smaller regions
- **Multi-scale analysis** - examining images at different resolutions
- Feature extraction at multiple scales

Comparison with Fourier Transform:

- Fourier: frequency domain, global analysis
- Wavelets: time-frequency localization, local analysis
- Wavelets better for non-stationary signals
- Better edge and discontinuity preservation

Other Transform Methods: DCT, Hadamard, Haar, Slant transforms, and others are used routinely in image processing

Image Compression

Definition

Techniques for reducing the storage required to save an image, or the bandwidth required to transmit it.

Why Compression?

- Storage capacity improved
- Transmission bandwidth still limited
- Internet has significant pictorial content
- Cost-effective distribution

Common Standards:

- **JPEG** - lossy, photos
- **PNG** - lossless, graphics
- **GIF** - limited colors
- **JPEG2000** - wavelet-based
- **HEIF** - modern standard

Compression Types:

- **Lossless:** Perfect reconstruction possible (PNG, GIF)
- **Lossy:** Some information lost, higher compression (JPEG)

Most users interact with compression through file extensions (.jpg, .png, etc.)

Morphological Processing

Definition

Tools for extracting image components that are useful in the representation and description of **shape**.

Primary Operations:

- **Erosion** - shrinks objects
- **Dilation** - expands objects
- **Opening** - erosion followed by dilation
- **Closing** - dilation followed by erosion

Applications:

- Shape analysis and description
- Boundary extraction
- Region filling
- Noise removal
- Skeletonization
- Object separation

Transition Point

This marks the beginning of transition from processes that **output images** to processes that **output image attributes**.

Image Segmentation

Definition

Partitioning an image into its constituent parts or objects.

Importance:

- One of the most **difficult** tasks in DIP
- Autonomous segmentation is challenging
- Critical for object identification
- Gateway to higher-level processing

Common Techniques:

- Threshold-based
- Region-based (growing, splitting)
- Edge-based
- Clustering methods
- Graph-based methods

Critical Success Factor

Rugged segmentation $\rightarrow$ High probability of success
Weak/erratic segmentation $\rightarrow$ Almost guaranteed failure

The more accurate the segmentation, the more likely automated classification will succeed!

Feature Extraction

Definition

Process that follows segmentation - extracting meaningful information from raw pixel data.

Two Main Components:

1. **Feature Detection:** Finding features in an image, region, or boundary
2. **Feature Description:** Assigning quantitative attributes to detected features

Example:

- **Detection:** Finding corners in a region
- **Description:** Describing corners by orientation (45°) and location ($x=100$, $y=200$)

Input to Feature Extraction:

- Raw pixel data from segmentation
- Boundary pixels (separating regions)
- All points within a region

Feature Categories and Properties

Three Principal Categories:

1. **Boundary Features:** Shape descriptors, Fourier descriptors, signatures
2. **Region Features:** Texture, moments, color histograms
3. **Whole Image Features:** Global statistics, transforms

Desirable Feature Properties (Invariance):

- **Scale invariance** - same feature at different sizes
- **Translation invariance** - independent of position
- **Rotation invariance** - same under rotation
- **Illumination invariance** - robust to lighting changes
- **Viewpoint invariance** - consistent across viewing angles

Goal

Features should be as **insensitive as possible** to parameter variations while remaining **discriminative** for classification.

Image Pattern Classification

Definition

The process that assigns a **label** (e.g., "vehicle", "face", "cat") to an object based on its feature descriptors.

Classical Approaches:

- Minimum distance classifier
- Correlation-based methods
- Bayes classifier
- K-nearest neighbors (KNN)
- Support Vector Machines (SVM)
- Decision trees

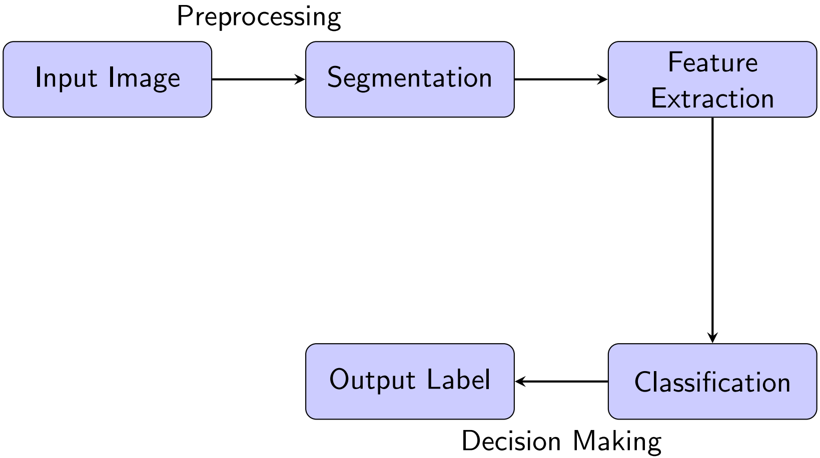
Modern Approaches:

- Deep neural networks
- **Convolutional Neural Networks (CNNs)**
- Transfer learning
- Ensemble methods
- Deep learning architectures

Deep CNNs

Convolutional Neural Networks are **ideally suited** for image processing work - they can learn hierarchical features directly from raw pixels!

Classification Pipeline



Role of Knowledge Base

Purpose

Prior knowledge about the problem domain coded into the image processing system.

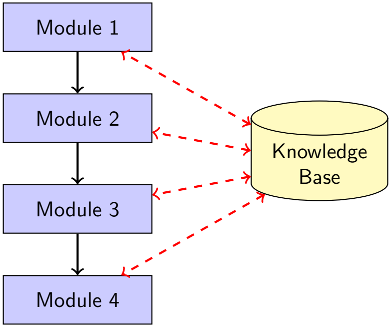
Types of Knowledge:

- **Simple:** Regions of interest locations, limiting search areas
- **Complex:**
  - Interrelated lists of possible defects (materials inspection)
  - High-resolution satellite image databases (change detection)
  - Expert system rules and heuristics
  - Domain-specific constraints

Knowledge Base Functions:

1. **Guides operation** of each processing module
2. **Controls interaction** between modules
3. Provides context and constraints
4. Enables intelligent decision-making

System Integration and Interaction



Double-headed arrows:
Knowledge base
controls modules

Single-headed arrows:
Data flow between
processing modules

Practical Considerations: Image Display and Visualization

Important Note

Viewing results can take place at the **output of any stage** in the processing pipeline!

Why Display at Different Stages?

- Debug and verify processing steps
- Understand algorithm behavior
- Quality control and validation
- Interactive parameter adjustment
- Comparative analysis
- Presentation and communication

Display Considerations:

- Appropriate color mapping for visualization
- Scaling and normalization for viewing
- False color for emphasizing features
- Side-by-side comparisons

System Complexity and Application Requirements

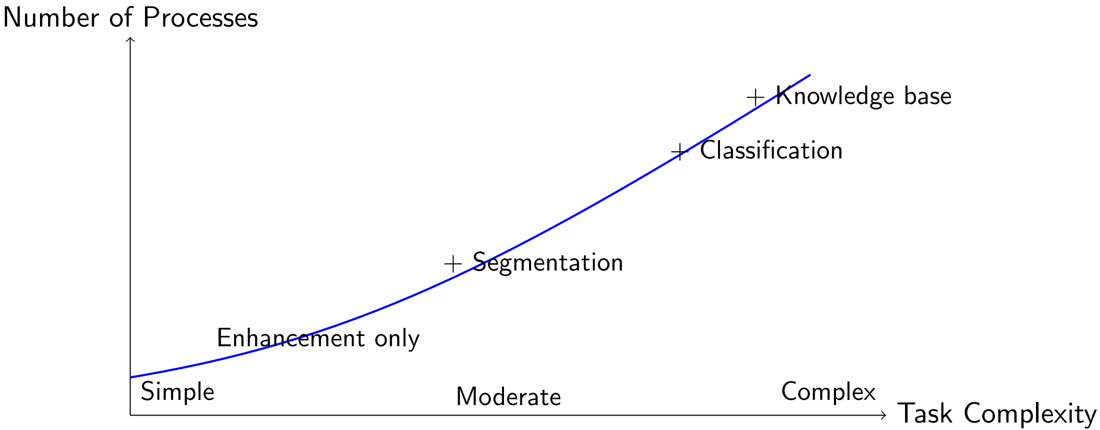
Key Principle

Not all image processing applications require the complexity of all modules!

Complexity Levels:

1. **Simple Applications:**
   - Example: Image enhancement for human viewing
   - May only need: Acquisition $\rightarrow$ Enhancement $\rightarrow$ Display
   - No segmentation, classification, or other advanced stages needed
2. **Moderate Applications:**
   - Example: Quality control inspection
   - Need: Acquisition $\rightarrow$ Enhancement $\rightarrow$ Segmentation $\rightarrow$ Feature Extraction
3. **Complex Applications:**
   - Example: Autonomous vehicle vision
   - Need: All stages plus knowledge base integration

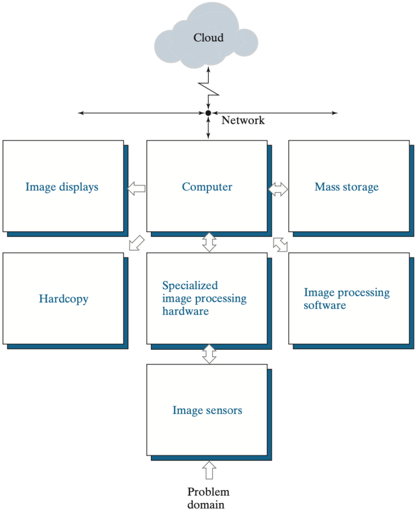
Scalability and Task Complexity



General Rule:

As the **complexity of an image processing task increases**, *so does the* **number of processes required** *to solve the problem.*

Elements of the Digital Image Processing System



Components of a general-purpose image processing system

1. **Image Sensors**: Convert optical images into electronic signals
2. **Image Digitizer**: Converts analog signals to digital form
3. **Computer**: Performs processing operations
4. **Mass Storage**: Stores images and intermediate results
5. **Display**: Shows processed images
6. **Communication Networks**: Transfer images between systems
7. **Software**: Algorithms for image manipulation

Structure of the Human Eye

Key Components:

- **Cornea**: Front transparent layer
- **Iris**: Controls light entering
- **Lens**: Focuses light on retina
- **Retina**: Contains light receptors
- **Rods**: 100 million, low light vision
- **Cones**: 6-7 million, color vision
- **Optic Nerve**: Transmits signals to brain

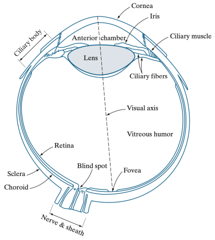


Figure: Simplified diagram of a cross section of the human eye.

Image Formation in the Eye

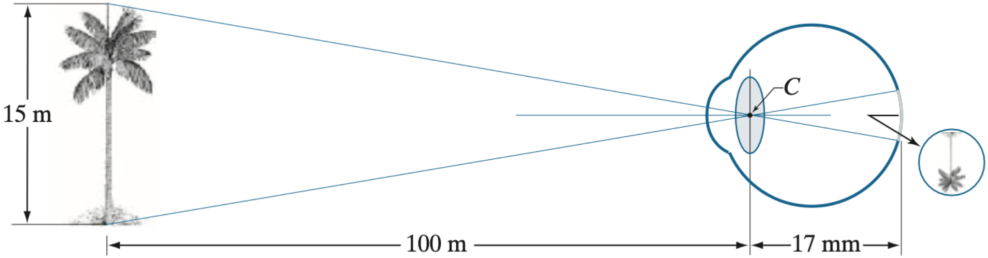


Figure: Image formation in eye

Image Formation in the Eye

- Light enters through the cornea and is focused by the lens
- The image is formed on the retina (inverted and reversed)
- Photoreceptors (rods and cones) convert light to electrical signals
- Signals are transmitted through the optic nerve to the brain
- The brain interprets and "corrects" the image

Electromagnetic Spectrum:

- Humans perceive only the **visible spectrum**: 400-700 nm
- Imaging machines can work across the entire EM spectrum:
  - Gamma rays, X-rays, UV, Visible, IR, Microwave, Radio waves

Brightness Adaptation and Discrimination

- Human visual system adapts to enormous range of intensities (10^{10})
- **Subjective brightness**: logarithmic function of incident light intensity
- Visual system cannot operate over full range *simultaneously*

Brightness Adaptation

Visual system varies overall sensitivity by changing adaptation level

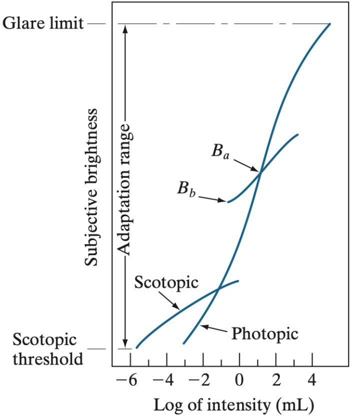


Figure: Range of subjective brightness sensations showing a particular adaptation level, Ba.

Brightness Discrimination

Classic experiment: Uniformly illuminated field + incremental flash

- Background illumination: I
- Increment: ΔI
- Subject responds when change is detectable

Weber Ratio

$$\frac{\Delta I_c}{I}$$

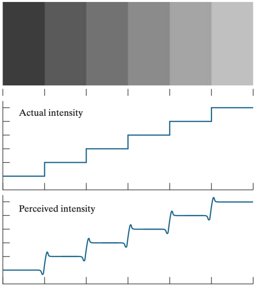
where ΔI_c is increment discriminable 50% of the time

- Small ratio = good discrimination (small % change detectable)
- Large ratio = poor discrimination (large % change needed)

Key finding: Discrimination improves as background illumination increases

Perceived brightness is not simply physical intensity

1. **Mach Bands**
   - Visual system under/overshoots at intensity boundaries
   - Perceived scalloping despite constant actual intensity



2. **Simultaneous Contrast**
   - Perceived brightness depends on surroundings
   - Same intensity appears darker with lighter background

Figure: Examples of simultaneous contrast. All the inner squares have the same intensity, but they appear progressively darker as the background becomes lighter.

The eye fills in or misperceives geometric properties

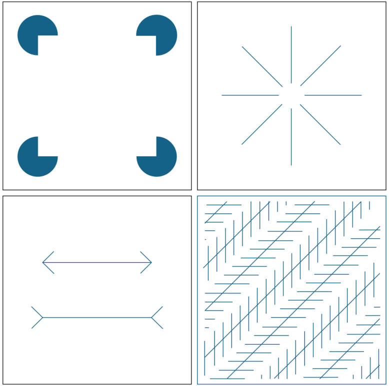


Figure: Some well-known optical illusions.

- Square outline perceived despite no defining lines
- Circles completed from partial line segments
- Equal-length lines appear different
- Parallel lines appear non-parallel due to crosshatching

Implication: Visual perception involves complex processing beyond raw intensity

Comparison: Brightness Adaptation and Discrimination

Brightness Adaptation:

- Human eye can adapt to light levels ranging from scotopic (dim) to photopic (bright)
- Range: 10^{-6} to 10^{4} lumens/m^2
- Adaptation is not instantaneous
- Achieved through pupil size adjustment

Brightness Discrimination:

- Ability to distinguish between different intensity levels
- Weber's Law: $\frac{\Delta I}{I} = k$
- Humans can distinguish 2 million colors
- Simultaneous contrast affects perception

Key Point

The eye does not function as a measuring instrument; perception depends on context and adaptation state.

Summary: Image Processing Methods Overview

Image-to-Image Processes:

- Acquisition, Enhancement (subjective), Restoration (objective)
- Color Processing, Wavelets, Compression, Morphology

Image-to-Attributes Processes:

- Segmentation (critical step), Feature Extraction & Description
- Pattern Classification (classical and deep learning)

Key Principles:

1. Enhancement is **subjective**, Restoration is **objective**
2. Segmentation quality critically affects final results
3. Features should be **invariant** to transformations
4. Deep CNNs are ideal for image processing
5. Knowledge base guides and controls processing
6. Complexity scales with application requirements

Learning Objectives Achieved

After this overview, you should understand:

- ✓ Two broad categories of image processing methods
- ✓ Complete image processing system architecture
- ✓ Distinction between enhancement and restoration
- ✓ Role of segmentation in the processing pipeline
- ✓ Feature extraction and description principles
- ✓ Modern classification approaches (especially CNNs)
- ✓ Importance of knowledge base integration
- ✓ How system complexity scales with application needs
- ✓ Where visualization can occur in the pipeline

This overview provides the foundation for understanding detailed algorithms in each area!