Introduction to Image Processing

ECE 172A: ~~Introduction to Intelligent Systems~~
Course Introduction

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Winter 2025

Outline

- Course Overview and Logistics
- What is **Machine Perception**/**Image Processing**?
  - Definition
  - Digital imaging
- The basic objects: **Images**
  - Continuous/analog images
  - Discrete/sampled images
  - Digital images
- Components of an **image-processing system**
  - Typical image-analysis system
  - Acquisition, storage, and processing
- Conclusion

Course Overview

- **ECE 172A** is an undergraduate class that focuses on the fundamentals of **machine perception** (a.k.a. **image processing**).
- A **tentative** list of topics include
  - Basics of 2D signal processing
  - Continuous vs. discrete vs. digital images
  - Image sampling, acquisition, and quantization
  - Image filtering
  - Morphological processing
  - Image processing tasks (segmentation, preprocessing, feature extraction)
  - Image interpolation
  - Image transforms (DCT, wavelets, etc.) and transform coding
  - Image restoration, reconstruction, and inverse problems
  - Plug-and-play methods

Course Overview

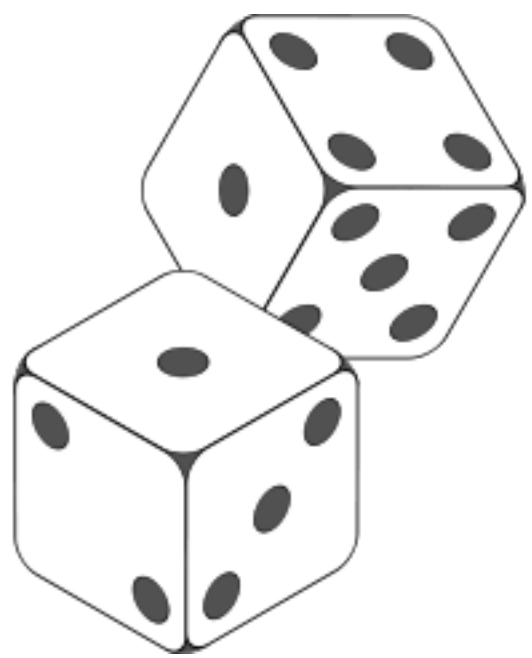
- We will **not follow** any specific textbook, but the following are good references for the subject material.
  - B.K.P. Horn, Robot Vision, New York: McGraw-Hill, 1986.
  - W.K. Pratt, Digital Image Processing, New York: Wiley, 1991.
  - K.R. Castleman, Digital Image Processing, Prentice Hall, Englewood Cliffs, NJ, 1995.
  - A.K. Jain, Fundamentals of Digital Image Processing, Englewood Cliffs, NJ, Prentice-Hall, 1989.
  - B. Jähne, Digital Image Processing, Springer Berlin, Heidelberg, 2005.
  - J.C. Russ, The Image Processing Handbook, CRC Press, 5th edition, 2006.
  - R.C. Gonzalez, R.E. Woods, Digital Image Processing, 4th edition, Pearson, 2017.
  - W. Burger, M.J. Bruge, Digital Image Processing, Springer Cham, MA, 2022.
- The main reference will be **these slides**.

Slides will be posted **immediately** after each lecture.

Prerequisites

- This course assumes basic knowledge of **linear systems fundamentals** at the level of ECE 101. Some background in **probability** will be helpful (e.g., at the level of ECE 109). Familiarity with **Python** will be necessary for the programming components of the course.

Joseph Fourier (1768–1830)



Probability

Python

Logistics

- Course website: `https://sparsity.ucsd.edu/172a/`
- Includes links to:
  - **Canvas:** Course materials, lecture recordings, etc.
  - **Gradescope:** homework submission and grades
  - **Piazza:** Q&A discussions and class announcements
    - check Piazza regularly
- Grading:
  - **5-8 assignments (40%)** (combination of "pen-and-paper" homework and programming lab exercises)
  - **Midterm Exam (20%)** (date is TBD)
  - **Final Exam (40%)** (Thursday, March 20th from 19:00–21:59)
- Late assignment policy:
  - Assignments submitted up to 24 hours late will be penalized by 10%. No late assignments will be accepted after 24 hours beyond the due date.

Lectures and Discussion

- **Lectures:** Tuesdays 17:00–19:50 (CENTR 216)
  - We have **170 minutes** per lecture. (MWF classes are 3×50 minutes)
  - We will have a combination of one or two 10 minute breaks and/or ending class early every lecture.

I want the lectures to be **interactive**.

- **Discussions:** Mondays 17:00–17:50 (CENTR 212)
  - Led by the **TA**
  - These will be **valuable** to attend.
    - Homework and programming advice
    - Addressing any questions from lectures, Piazza, office hours, etc.
    - Opportunity to work with your peers on homework and lab exercises. **(We will release assignments on Mondays.)**

Working together on assignments is a **great way** to learn (and make friends!)

Course Staff

- Rahul Parhi, Assistant Professor, ECE
- I joined UCSD in 2024 after two years of a postdoc at EPFL and a PhD from Univ. of Wisconsin–Madison.
- Office: Jacobs Hall (EBU1), Room 6406
- Office Hours: TBD
- Email: `rahul@ucsd.edu`

`https://schej.it/e/cc3D8`

- Niyas Attasseri, TA
- Office Hours: TBD
- Email: `nattasseri@ucsd.edu`

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What is Image Processing?

Subjective appeal of images

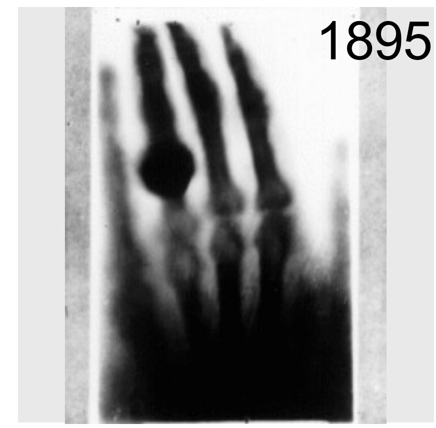
"One picture is worth thousand words"

Guernica, 1937 (Picasso)

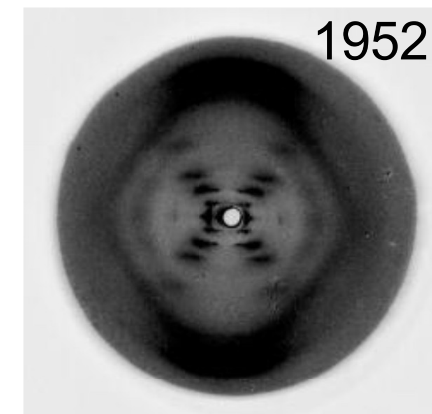
Digital imaging

Any manipulation of image-related data via a computer

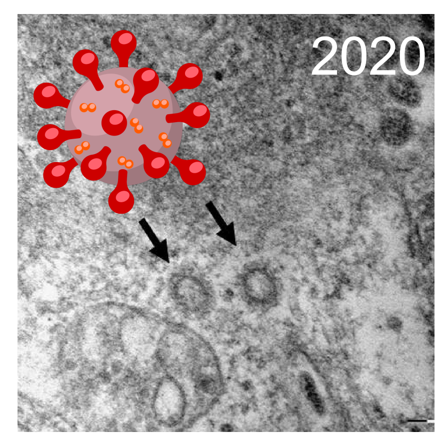
Images in science



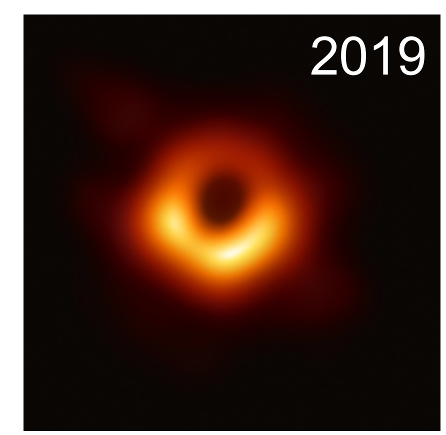
X-rays
Wilhelm Röntgen



Double-helix DNA
Rosalind Franklin



Cryo-electron microscopy
Jacques Dubochet



Black hole image reconstruction
Katie Bouman

History of Image Processing

→ Parallels the development of computers

60-70's → Mainframes

Image processing was pioneered

80-90's → PC

Analog cameras to CCD cameras
Research labs to first real-world
Minicomputers to PC (+grabber) (+DSP)

2000-2015 → PowerPC

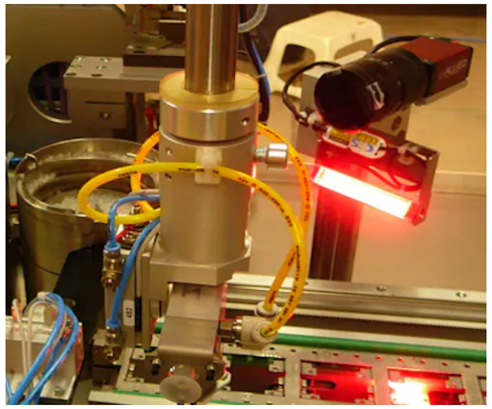
CCD cameras are everywhere
More applications, web/internet
General-purpose processors, software

Present → Parallelization and GPUs

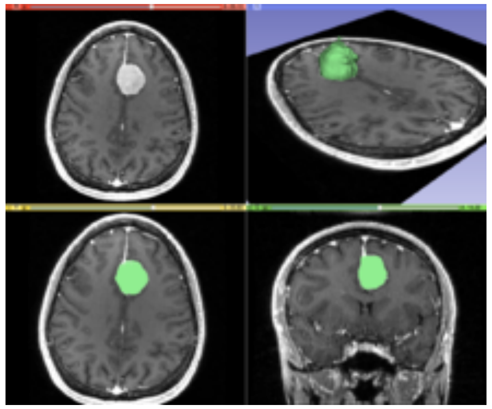
Imaging is everywhere in science and society
High-tech: devices, computer, software
Machine learning and *deep learning*

1957

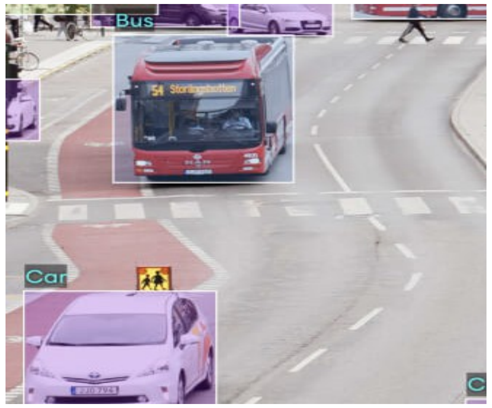
First digital image ever created by Russell Kirsch. Size: 176×176 pixels



Visual control in manufacturing.



Segmentation of **3D** medical images.



Autonomous vehicles.

Disciplines in Digital Imaging

Image processing

Image → Computer → Image

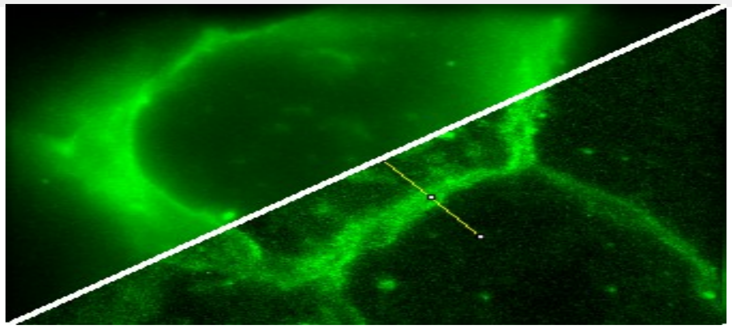
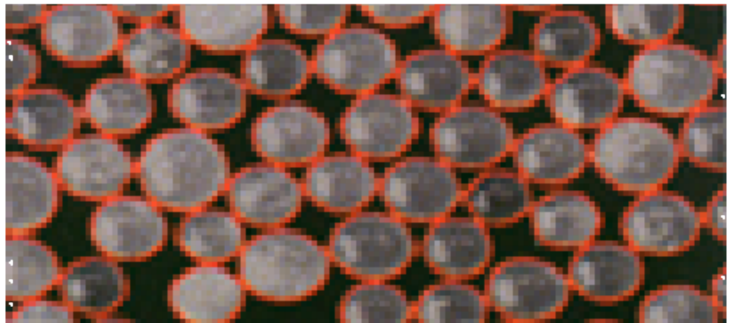


Image analysis

Image → Computer → Features, numbers



Computer vision

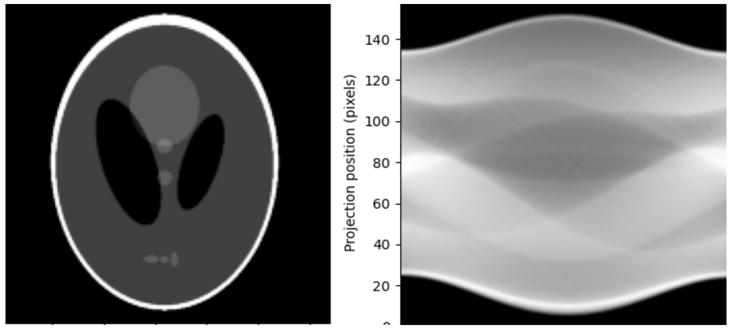
Image → Computer → Objects, 3D scene

Computer graphics

Description → Computer → Image

Image reconstruction

Measure → Computer → Image



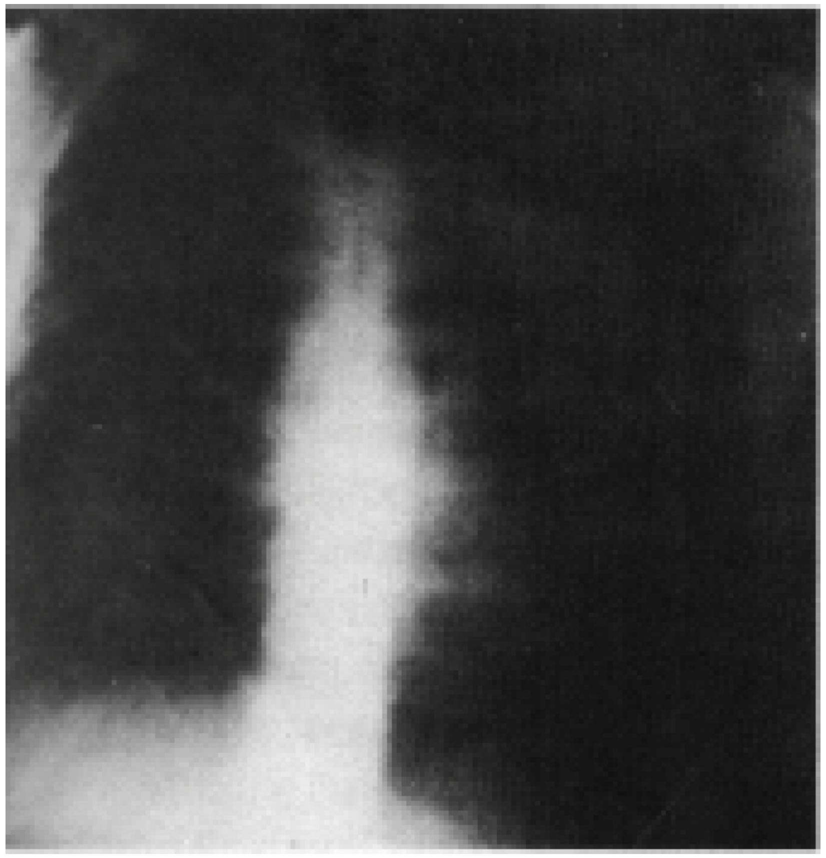
Colloquially, these are all referred to as "image processing"

Image Processing

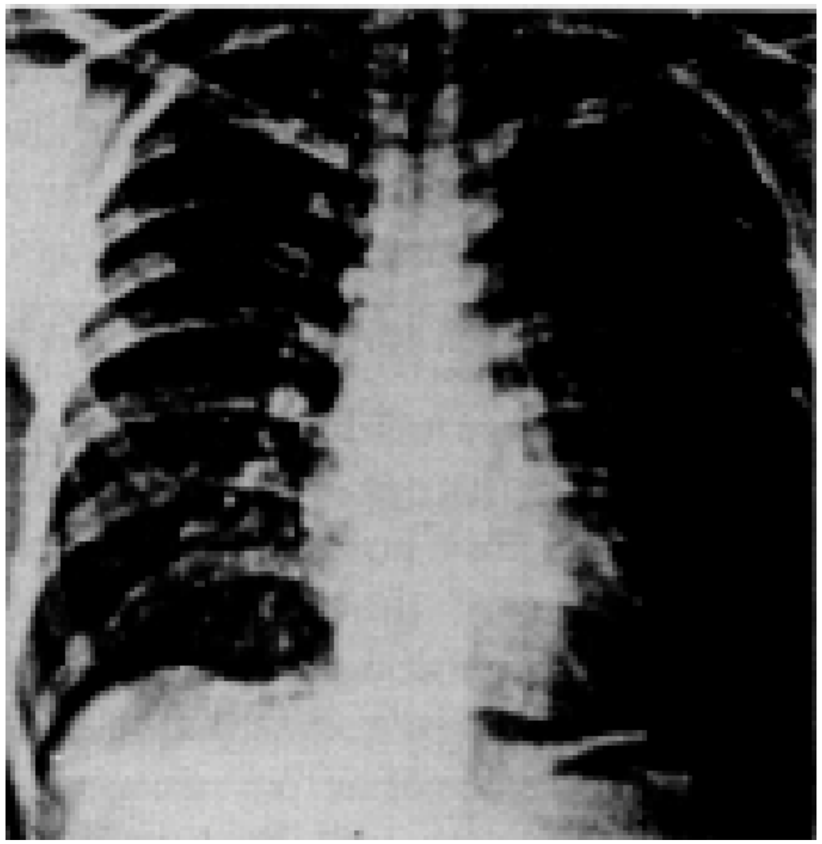
Definition: Transformation of pictorial information

Related fields/concepts: Signal processing, basic components of artificial neural networks (CNNs, in particular)

Example: **enhancement**



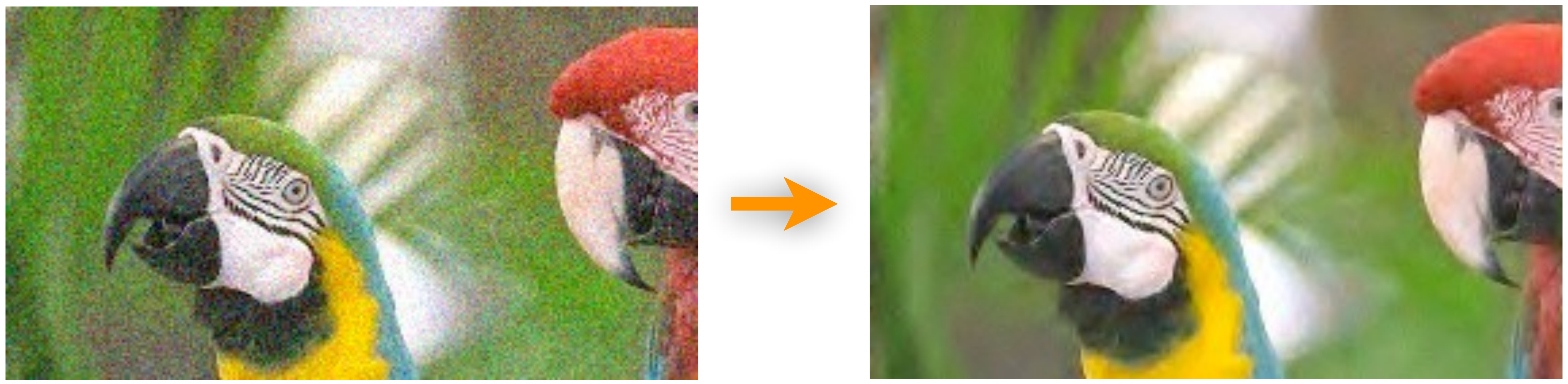
Original X-ray



Enhanced image

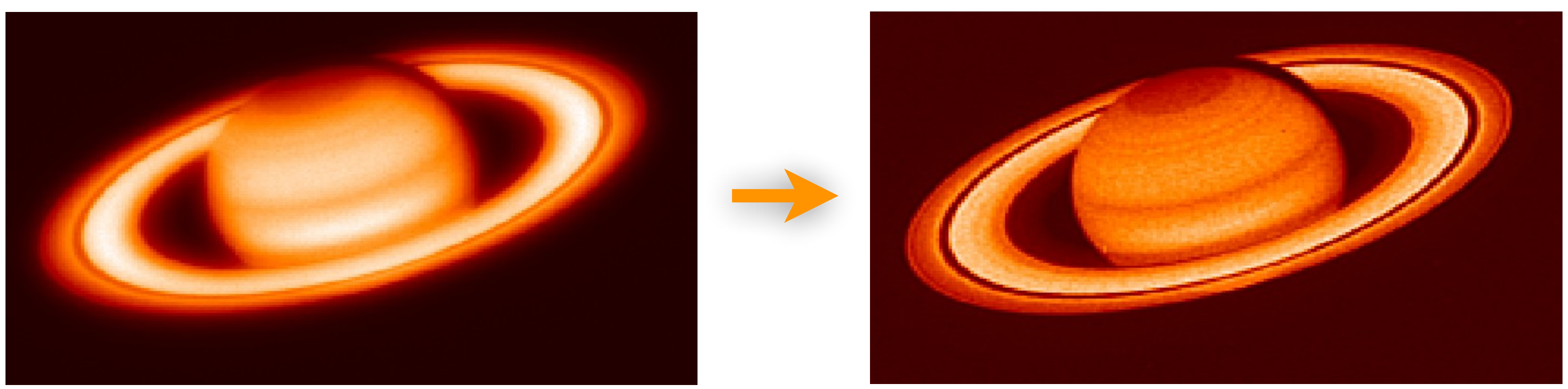
Image Processing (cont'd)

Example: **denoising**



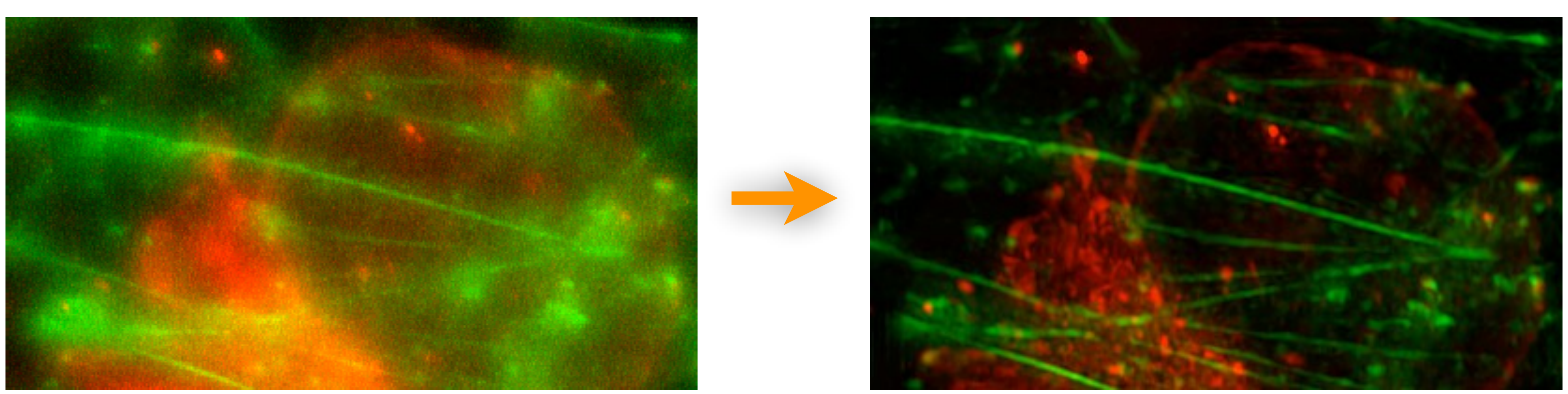
Low-exposure digital photography

Example: **deblurring**



Saturn image (Hubble space telescope)

Example: **deconvolution**



3D fluorescence confocal microscopy

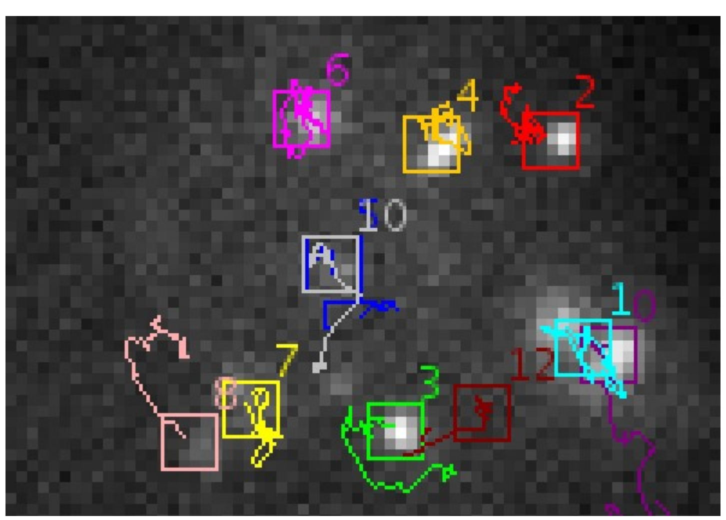
Image Analysis

Definition: Extraction of image features and quantitative information

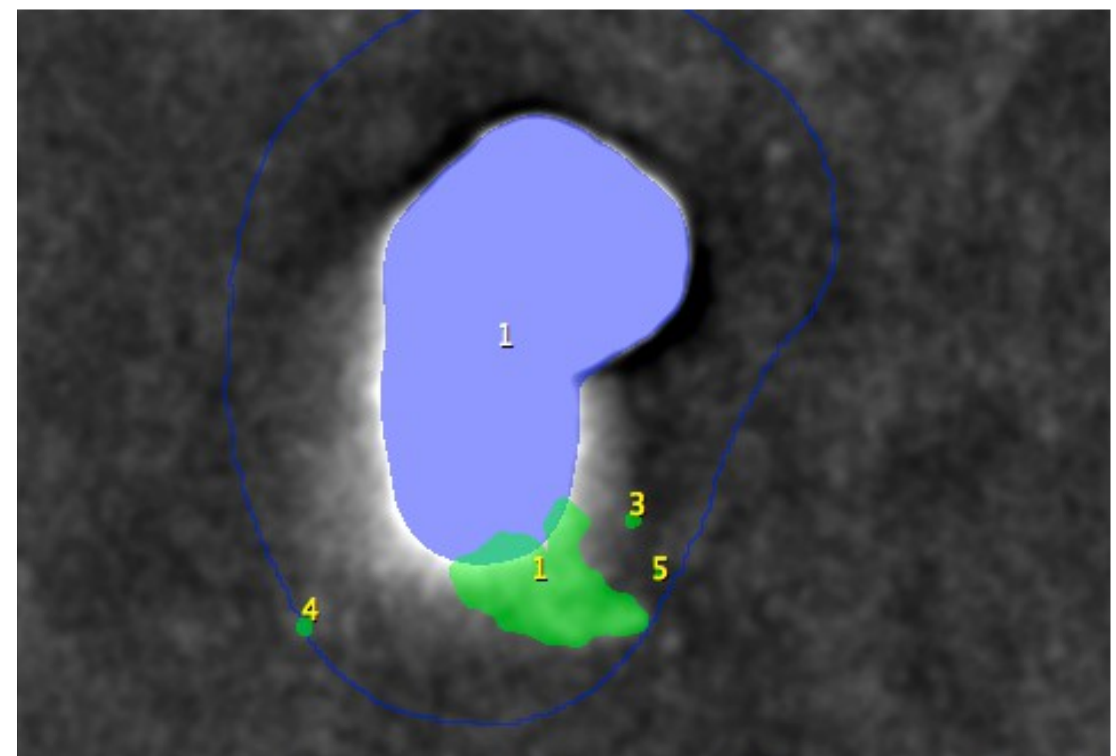
Related fields/concepts: Pattern recognition, machine learning

Example: **bioimage analysis**

- Fluorescence microscopy
- Segmentation of the nucleus
- Segmentation of particles



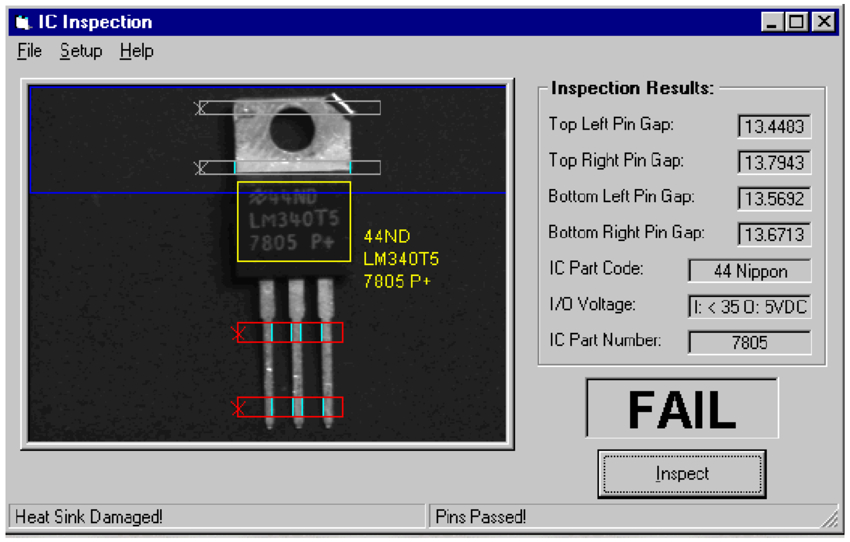
Particle tracking



Channel	Inter [um3]	Inter [%]	Distance [nm]	Label	Vol [um3]
Nucleus				1	174.20
Particle	18.20	0.99	520.00	1	18.30
Particle	0.07	1.00	1715.00	3	0.07
Particle	0.02	0.62	2905.00	4	0.04
Particle	0.09	1.00	2596.00	5	0.09
Extended	18.38	0.02		1	946.61

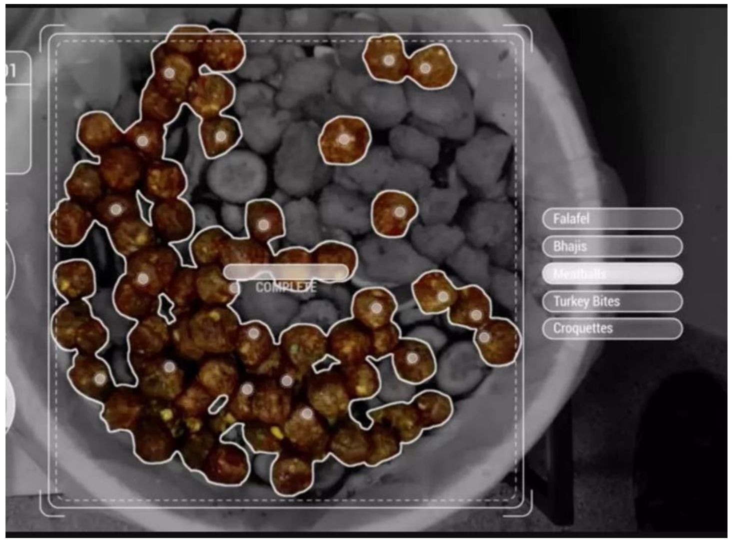
Image Analysis (cont'd)

Example: **industrial vision**

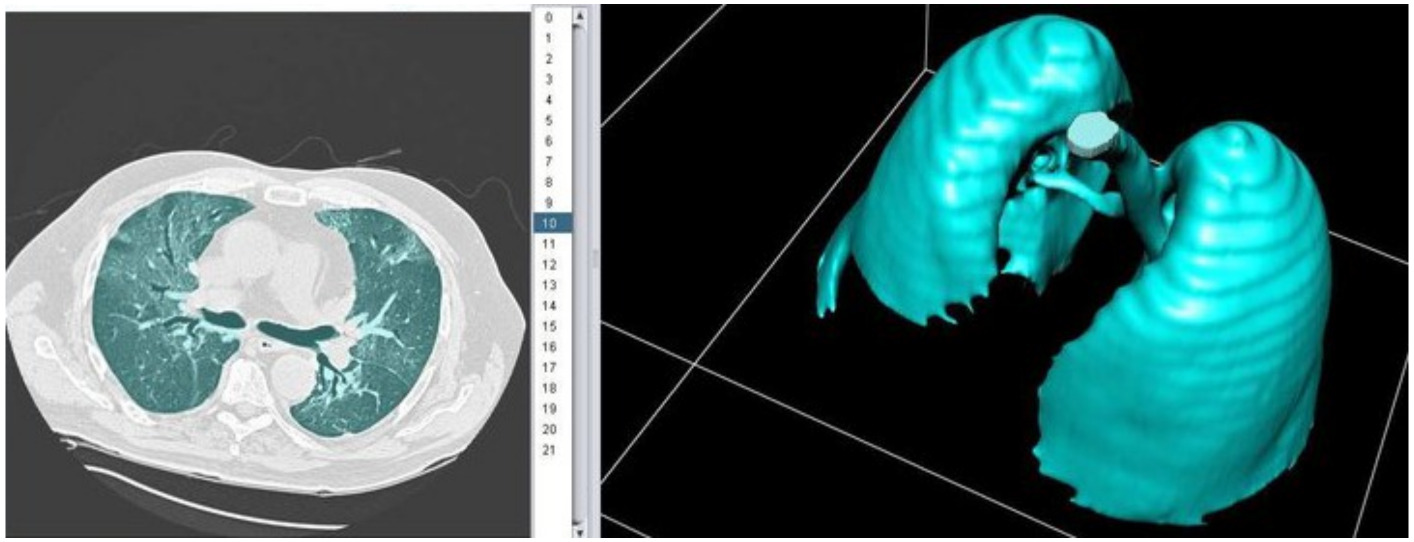


Quality control in production

Check food waste



Example: **medical imaging**



Lung segmentation based on texture information

Where is Image Processing?

Interdisciplinary field

Machine Learning

Mathematics

Photography

Signal Processing

Image Processing

Computer Technology

Optics

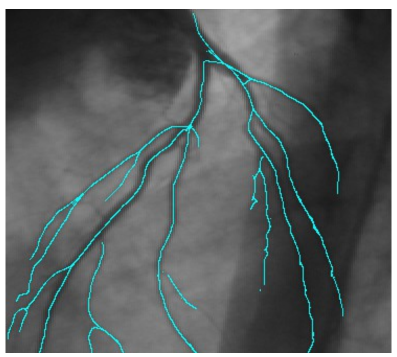
Electronics

↓

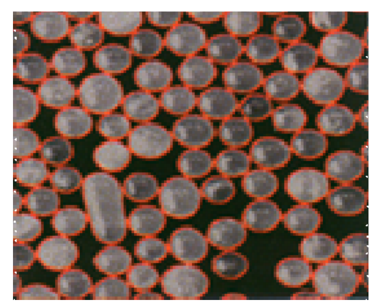
Application Areas

Imaging Applications

- Medical Imaging
  - Contrast enhancement
  - Tomographic reconstruction
  - Screening of X-ray
  - Nuclear medicine, MRI
  - Computer-aided diagnosis
  - Ultrasound imaging



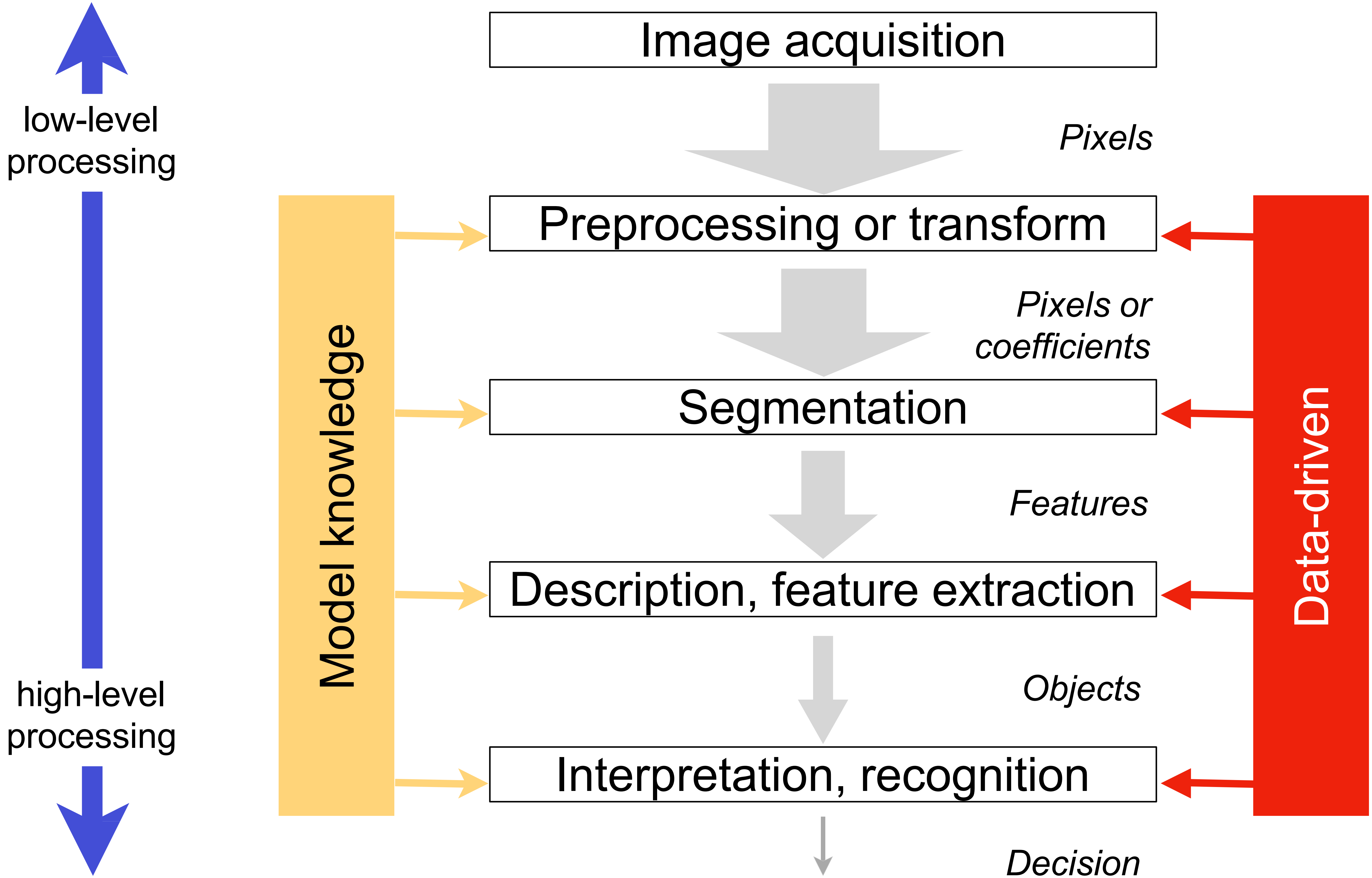
- Aerial/Satellite Imagery
  - Weather prediction
  - Crop assessment
  - Military recognition
  - Remote sensing
  - Geographic information systems
- Banking
  - Optical character recognition (OCR)
- Storage
  - Compression
  - Image archival
- Biology / Microscopy
  - Life cell imaging
  - Micro-array, DNA chip
  - Fluorescence microscopy
  - Super-resolution reconstruction
  - Neuroscience



- Multimedia
  - Digital photography
  - Electronic publishing
  - Watermarking
  - Image database indexing
  - Old-movie restoration
- Astronomy
  - Detection of stars
- Law enforcement
  - Surveillance
  - Biometrics
  - Identification
  - Number-plate recognition

- Industrial vision
  - Inspection
  - Product assembly/monitoring
  - Localization and recognition
  - Robot vision
  - Autonomous vehicles
- Archaeology
  - Restoration of image records
- Physics/Materials
  - Electron microscopy
  - Analysis of materials

Example Image-Analysis Pipeline



The Basic Objects: Images

What even is an image?

- Continuous/analog image

The real world is an analog world

"We are analog beings trapped in a digital world, and the worst part is, we did it to ourselves."
—*Donald A. Norman, 1988, UCSD*

- Discrete/sampled image

How we reason about the images on our computer

- Digital image

The images on our computer

Image Representation: Analog

Analog image (monochrome)

2D light intensity function: $f(x, y)$

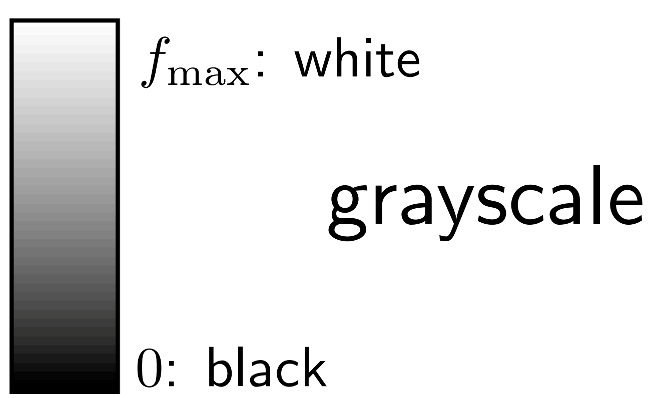
- (x, y) are the spatial coordinates
- The output $f(x, y)$ is the **brightness** (or grayscale level) at (x, y)

Analog images are 2D functions

$f : \mathbb{R} \times \mathbb{R} \to [f_{\min}, f_{\max}] \subset \mathbb{R}$

$f : \mathbb{R}^2 \to [f_{\min}, f_{\max}]$

$f(x, y) \in [f_{\min}, f_{\max}]$ for all (x, y)



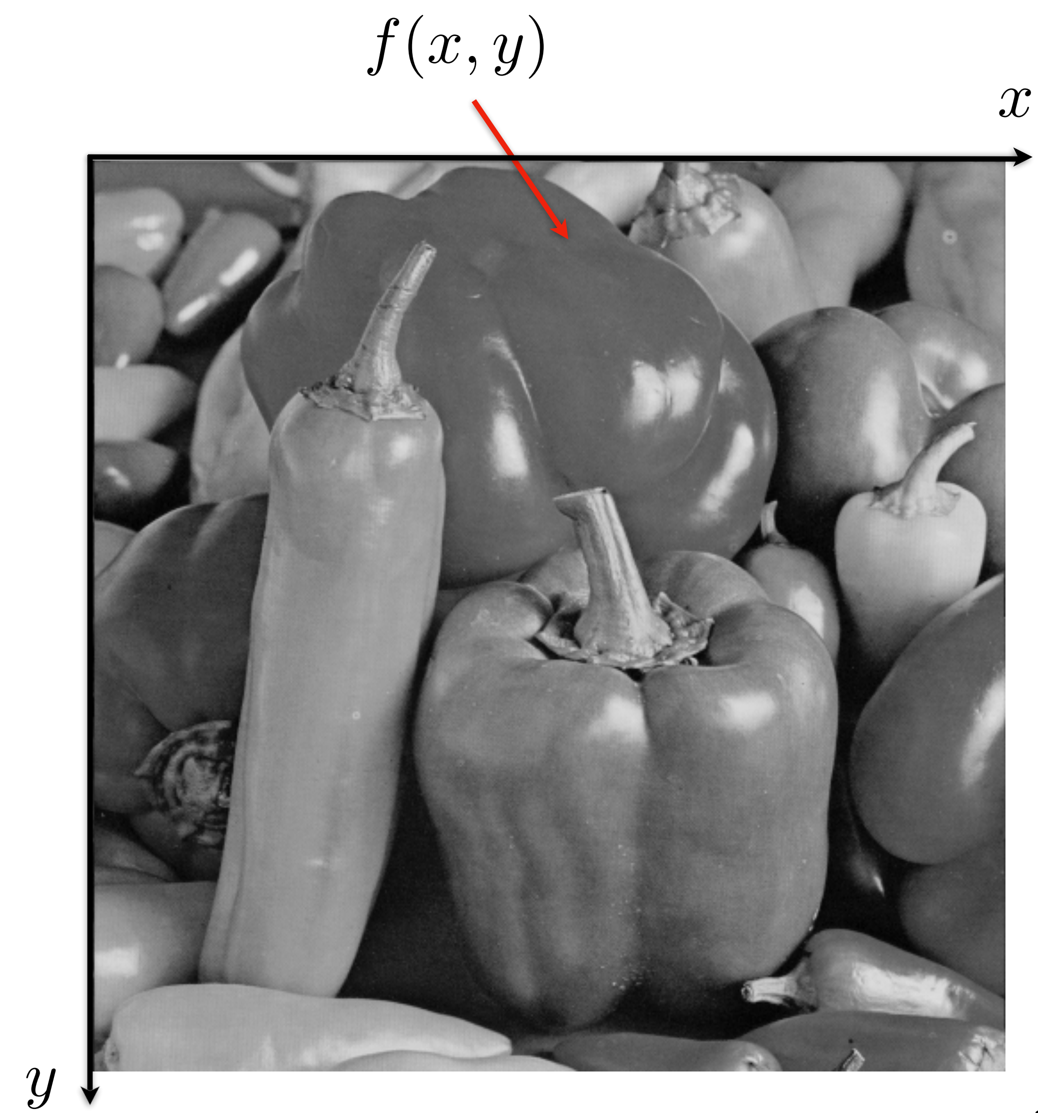
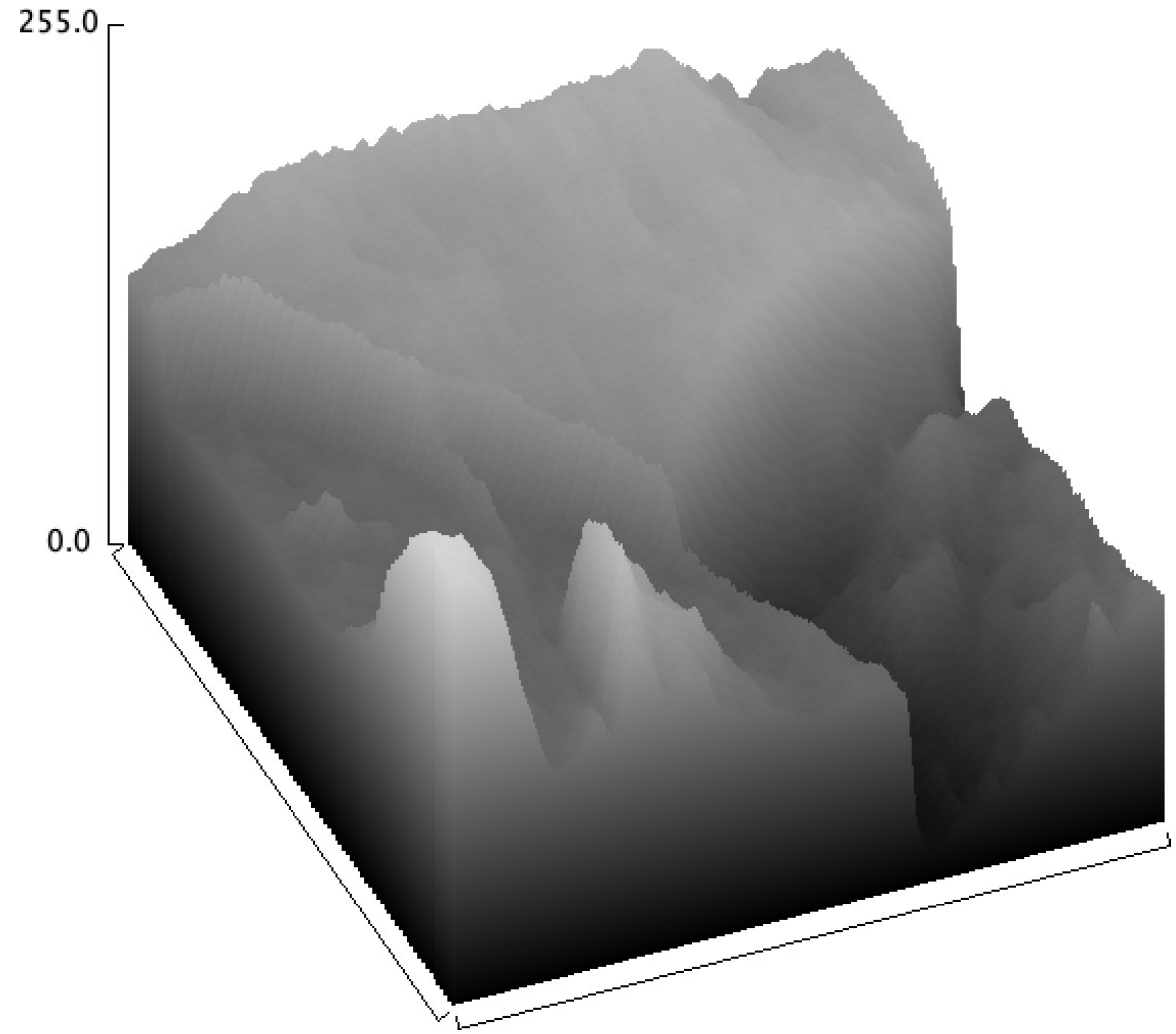


Image Representation: Analog (cont'd)

Analog image (monochrome)

2D light intensity function: $f(x, y)$



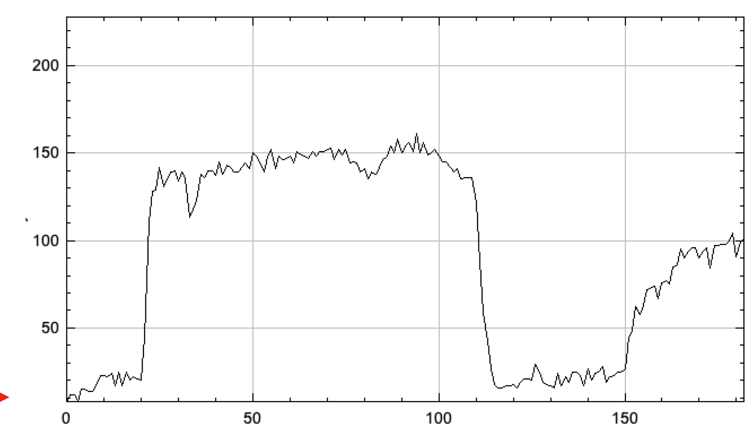
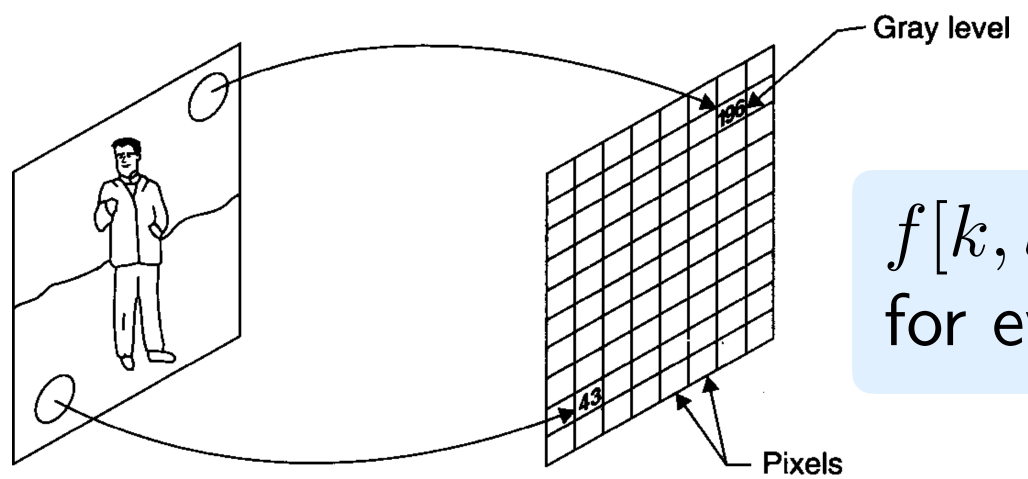


Image Representation: Discrete

Discrete image (monochrome)



Analog image Discrete image

$f[k,l] \in [f_{\text{min}}, f_{\text{max}}] \subset \mathbb{R}$
for every pixel coord. (k,l)

- Set of **pixels** $\rightarrow$ picture elements

  $\{f[k,l]\}$ with $k = 0, \ldots, K-1$ and $l = 0, \ldots, L-1$

  K: number of columns
  L: number of rows

- $K \times L$ **array** or **matrix** of pixels

  $\mathbf{F} = [F_{ij}]$ with $F_{ij} = f[i,j]$

Why is this not digital?

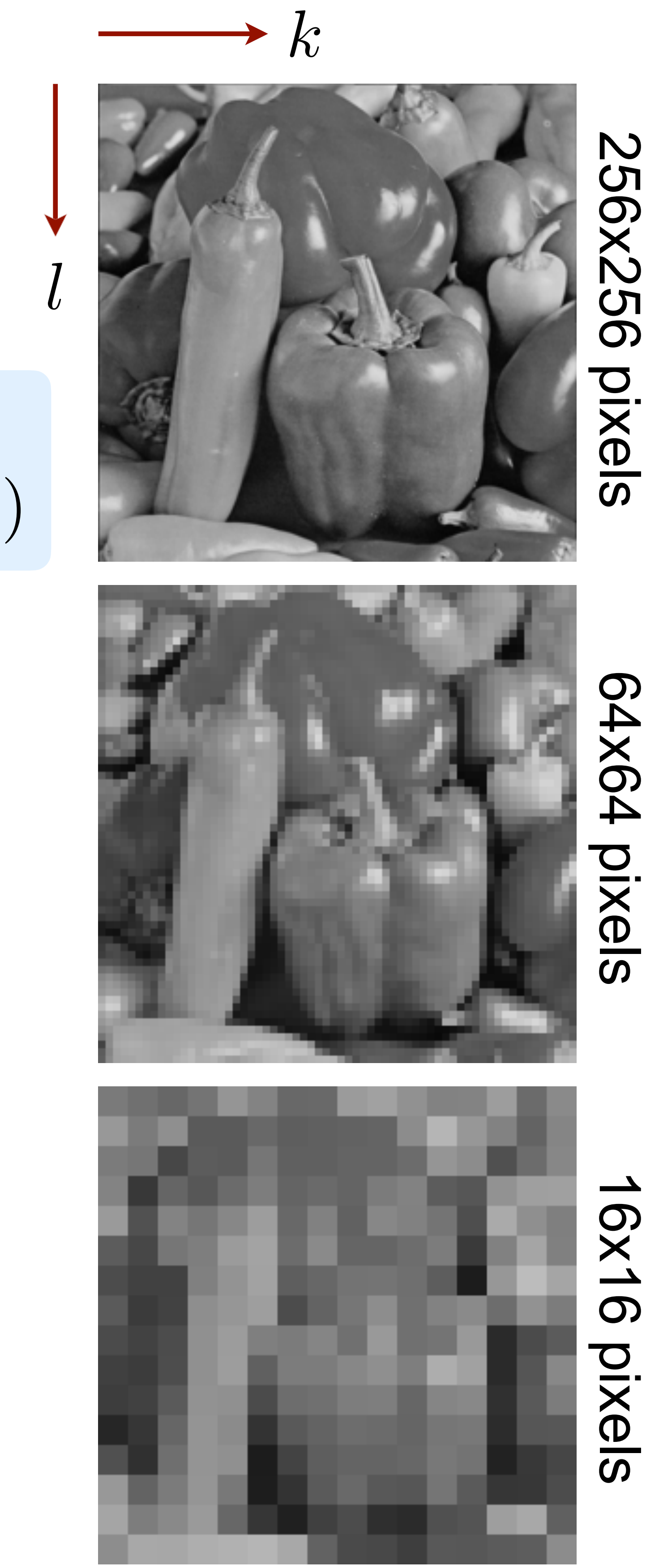
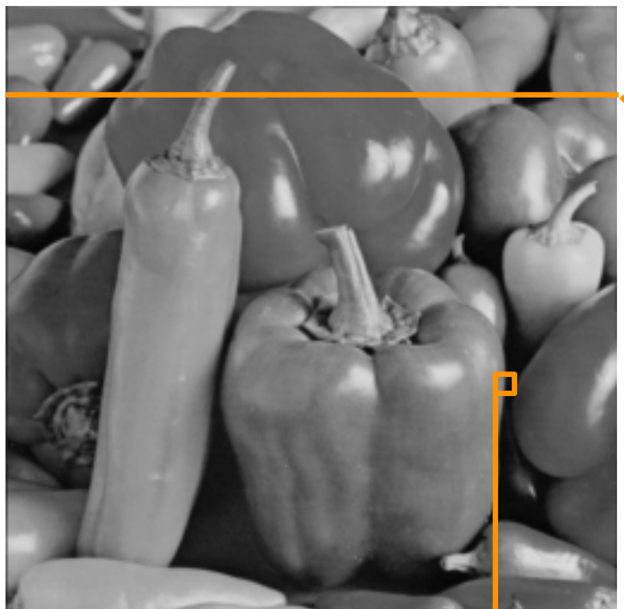


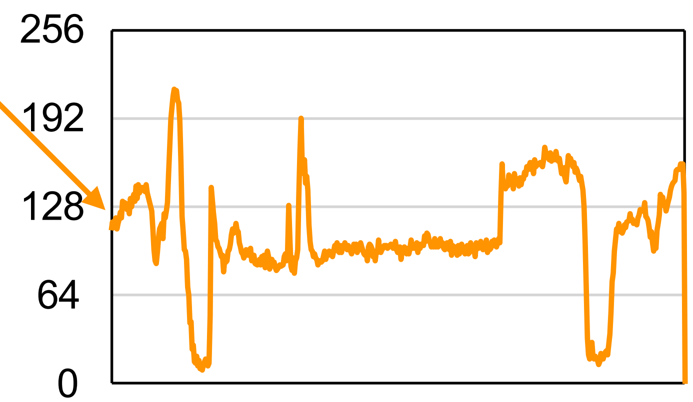
Image Representation: Digital

Digital image (monochrome)

Quantize the gray levels

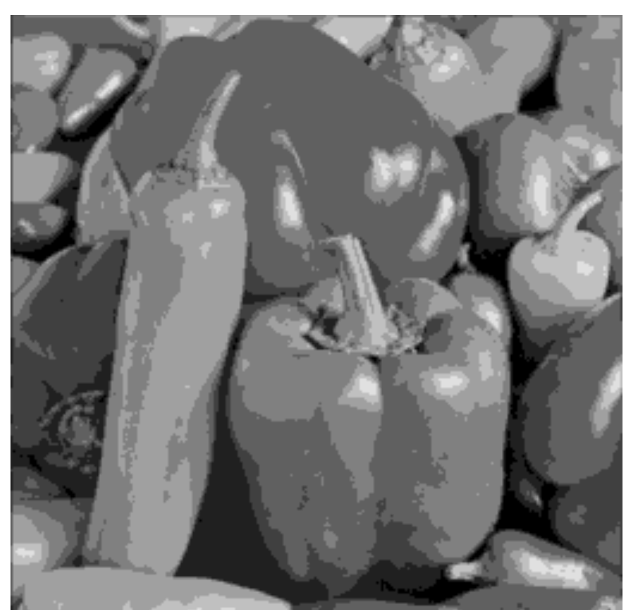


256 gray levels



$$f[k,l] \in \{0, 1, 2, \ldots, 255\}$$

143	149	119	86	75	41	16	11
143	146	134	86	71	41	23	13
144	148	147	85	63	45	18	14
141	149	142	109	50	32	11	15
140	146	152	119	48	31	20	15
150	145	147	137	55	26	10	7
147	143	141	138	74	24	22	11
144	145	137	139	89	19	13	11



8 gray levels

General-purpose

8-bit: 0–255

Science

Sensitive camera: 16-bit

Computation

Floating-point representation

32-bit (float) or 64-bit (double)

Binary

1-bit: 0 or 1

2 gray levels

Beyond 2D? Generalized Images?

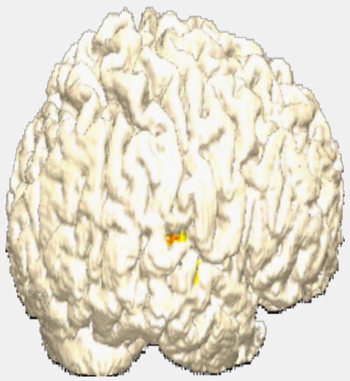
Any kind of higher-dimensional signal

- 3D images or **volumes**: $f(x, y, z)$
- Time or **video** sequence: $f(x, y, t)$
- **Color** or multi-spectral images: $f(x,y) = \begin{bmatrix} f_1(x,y) \\ f_2(x,y) \\ \vdots \\ f_p(x,y) \end{bmatrix}$

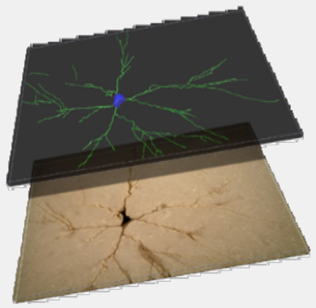
Question: How to get images?

- Devices sensitive to certain EM energy bands
  - X-ray, ultraviolet, visible, infrared, radio-astronomy
- Non-optical imaging
  - MRI, PET, ultrasound, seismic imaging

Examples

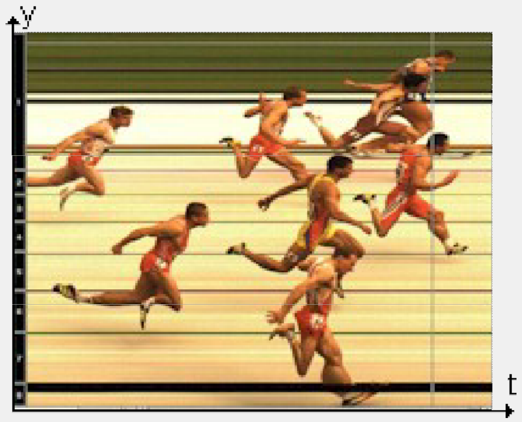


fMRI dataset
150 volumes
$256 \times 256 \times 110$ voxels
$f(x, y, z, t)$



Neuron tracing
Mosaic of micrographs:
90 planes of 2048×2048 pixels

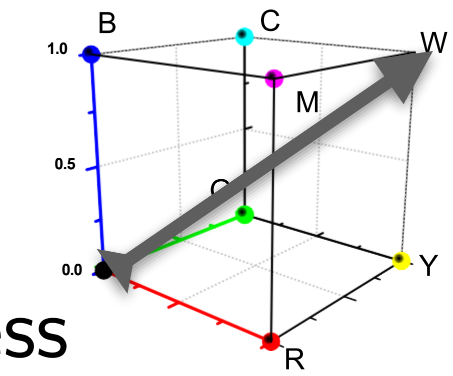
Photofinish with a linear camera
2048 pixels
2000 lines/sec
$f(t, y)$

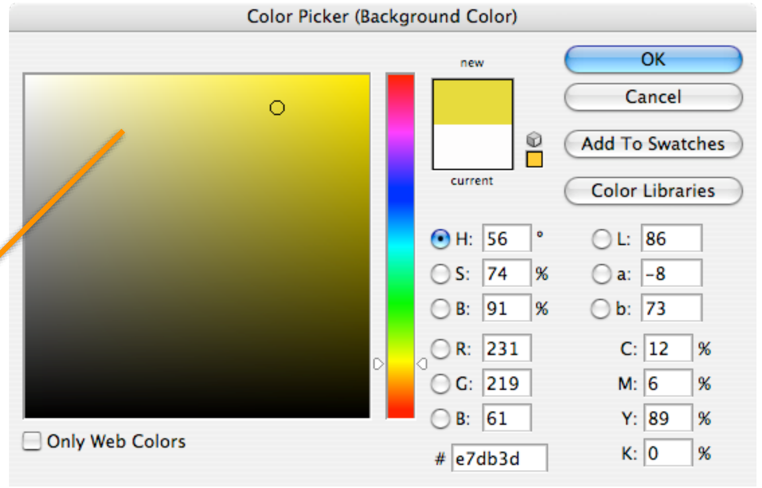


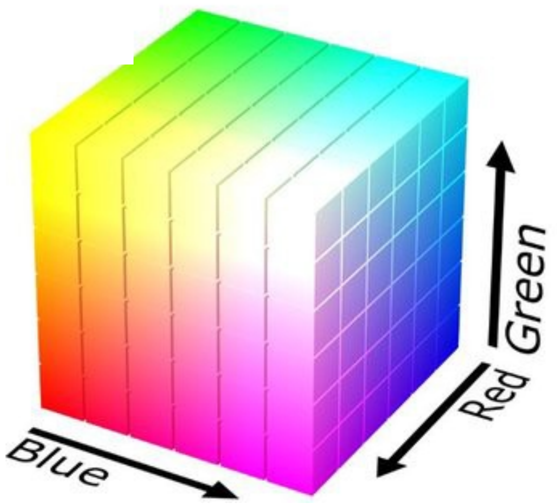
Color Images

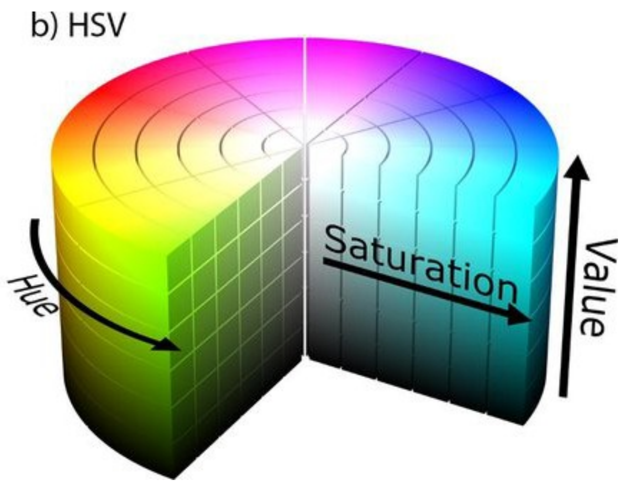
Color-Representation Systems

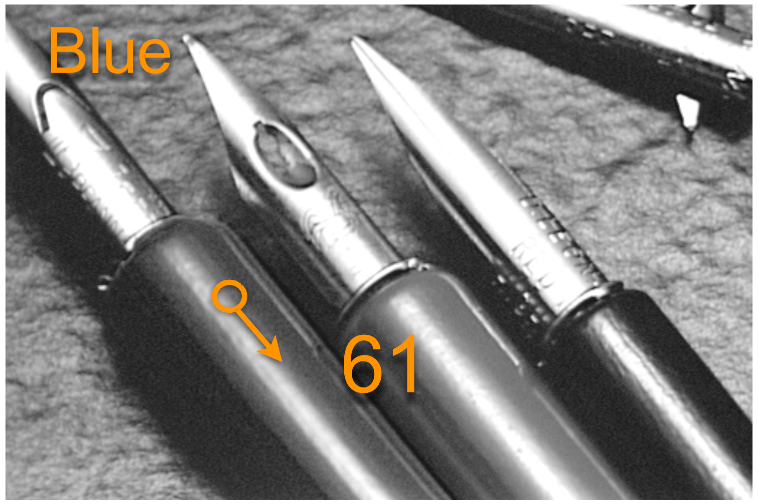
- RGB: Red-Green-Blue
- HSB: Hue-Saturation-Brigthness
- CYMK: Cyan-Yellow-Magenta-Black









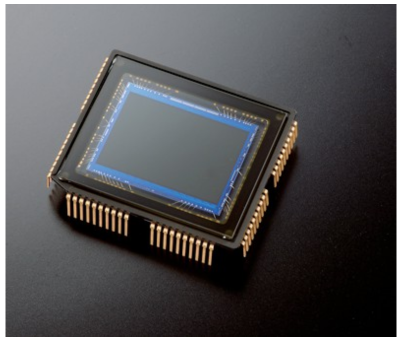


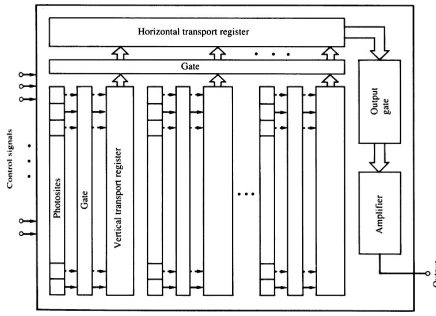
Components of an Imaging System

- Image acquisition
- Storage
- Processing
- Communication
- Display

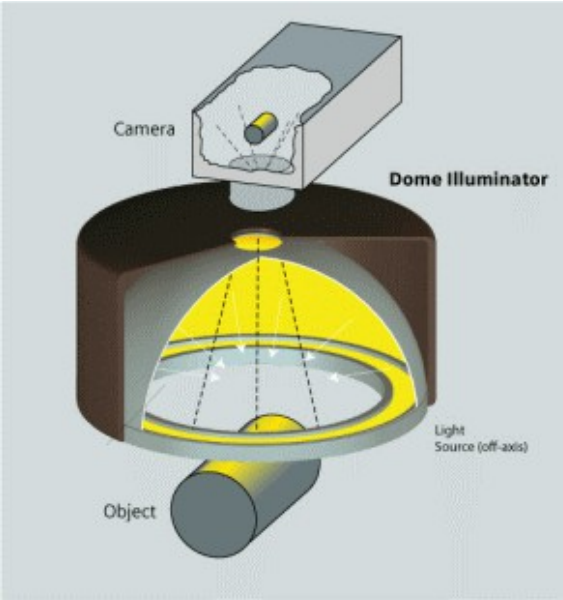
Image Acquisition

- Key elements of an acquisition system
  - Sampling aperture
  - Light sensor: light intensity $\rightarrow$ electric signal
  - Quantizer
- Detector: Charge-coupled devices (CCDs)
  - Single IC device $\rightarrow$ low cost, compact
  - Array of photosensitive cells
  - Low geometric distortions
  - Linear intensity output





- Illumination
  - Optical system / Photography techniques
  - Lighting
  - Depth of field / Aperture
  - Motion control



Digital Image

- Output signal
  - Video signal: TV signal $4{:}3$ (old) $16{:}9$ (modern) aspect ratio
  - Digital output
    - Compressed / uncompressed
    - Processed on chip
- Data
  - Gray-level picture: $512 \times 512 \times 8$ bits $= 262$ KB
  - Photography of smartphone (color): 13 MB
  - Medical imaging CT Scan: $256 \times 256 \times 256 \times 16$ bits $= 32$ MB
  - Whole slide image (digital pathology): $50,000 \times 50,000 \times 24$ bits
- Storage
  - Short-term: RAM (32 GB) vs. long-term: Hard disk (20 TB)
  - Store pixels and metadata (compressed / uncompressed)
    - JPEG, PNG, etc.

Processing Tools

- Powerful computers
  - $<$ 1990 mainframes or specific hardware
  - 1995-2015: General-purpose PCs, CPUs
  - $>$ 2015: CPU + GPU (deep learning) + HPC (servers)
- System integration
  - Smart cameras
    CCD + Processor + RAM

- Image-processing software
  - Desktop: Photoshop, GIMP, etc.
  - Commercial tools: MATLAB, LabView, etc.
  - Programming: Python, Java, etc.

Conclusion

What is the future of image processing? Many indicators of growth.

Highly employable field!

- Economical factors
  - Declining cost of computers
  - Increasing availability of equipment (digitizers and displays)
- New technology trends
  - Processing capacities: Powerful CPUs–Parallelization–GPU
  - Acquisition devices: CCD, CMOS cameras
  - Storage: Large RAM, low-cost, high-capacity **fast** storage
  - High-resolution color display systems
- New applications
  - Consumer products: digital photography, desktop publishing, HDTV
  - Biomedical: digital radiography, ultrasound, fluorescence microscopy, etc.
  - Science: everywhere, from nano-scale to astronomy scale
  - Industry: inspection, and scientific
  - Security: traffic monitoring, biometry