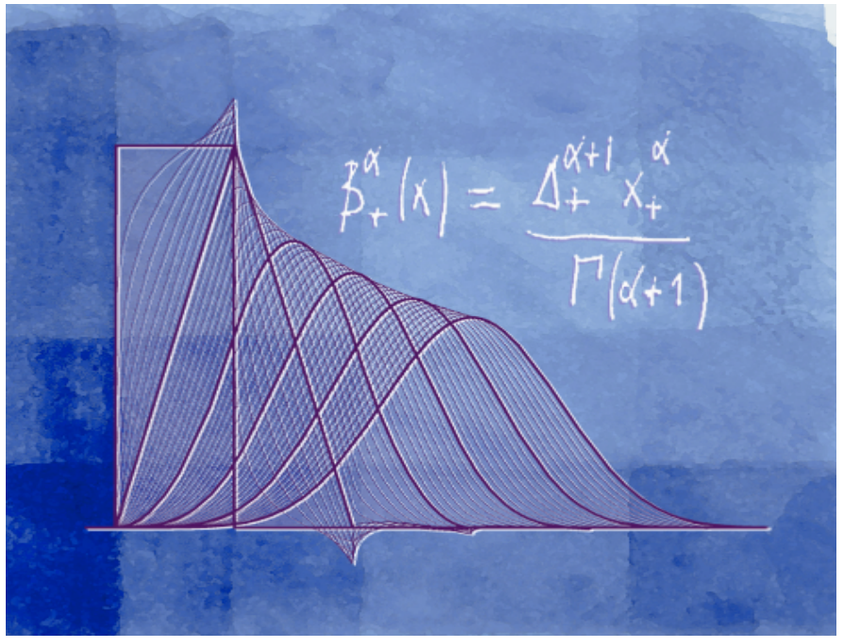
Image Processing

Chapter 0
Introduction

Prof. Michael Unser, LIB



Septembre 2025

CONTENT OF THE CHAPTER 0

- **What is image processing?**
  - Definition
  - Digital imaging
  - Examples
- **The basic objects: images**
  - Continuous images
  - Discrete images
  - Generalized images
- **Components of an image-processing system**
  - Typical image-analysis system
  - Acquisition
  - Storage
  - Processing
- **Conclusion**

WHAT IS IMAGE PROCESSING?

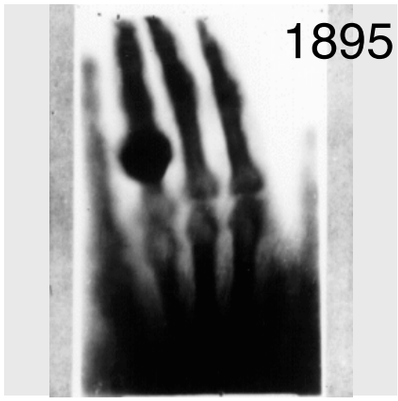
Subjective appeal of images

One picture is worth thousand words

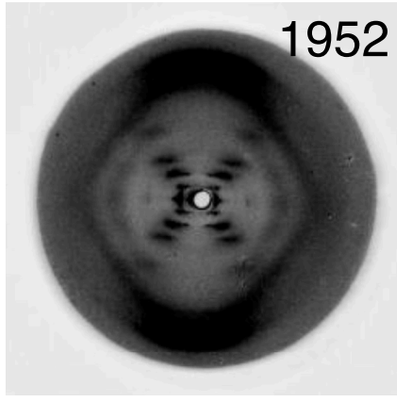
Digital image processing

Any manipulation of image-related data via a computer

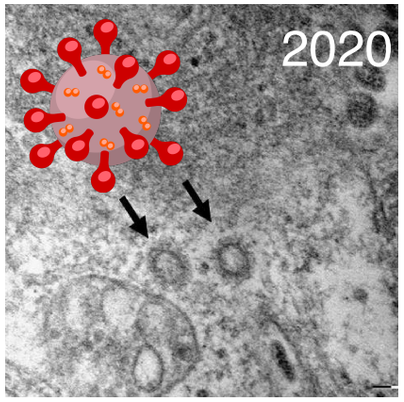
Images in science



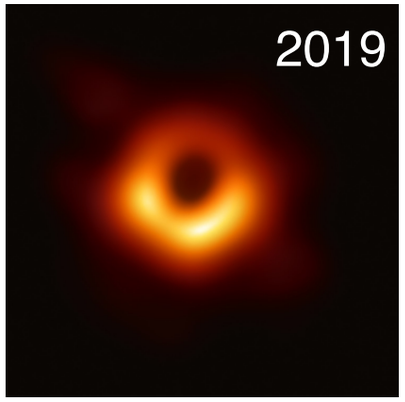
X-rays
Wilhelm Röntgen



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

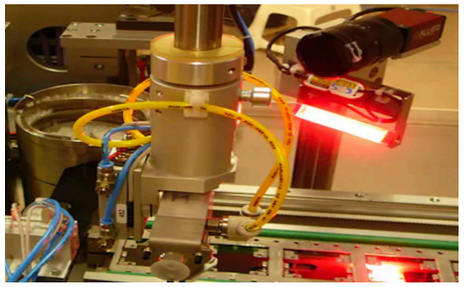
Pioneers of image processing

First digital image 176x176
Russell Kirsch, 1957.

80-90's ➜ PC

Analog camera, low-res, PC (+DSP)

Research labs to first real-world



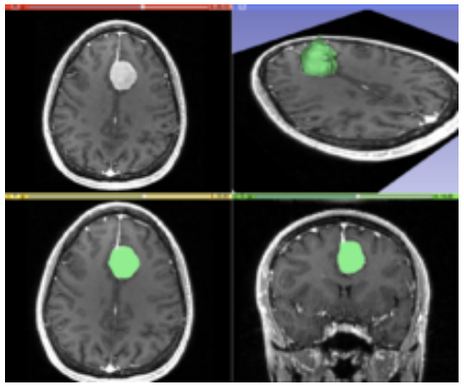
Visual control in manufacture

2000-2015 ➜ PowerPC

CCD camera everywhere

General-purpose CPU, storage, software

More applications, web



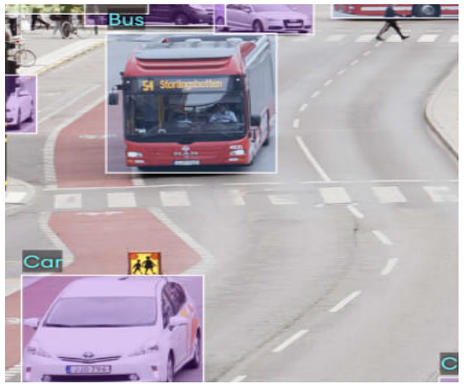
Segmentation of 3D medical images

Present ➜ Parallel / GPU

High-tech: devices, computer, software, data

Imaging everywhere in science and society

Machine learning and artificial intelligence



Autonomous vehicles

Disciplines in digital imaging

Image processing

Image → Computer → Image

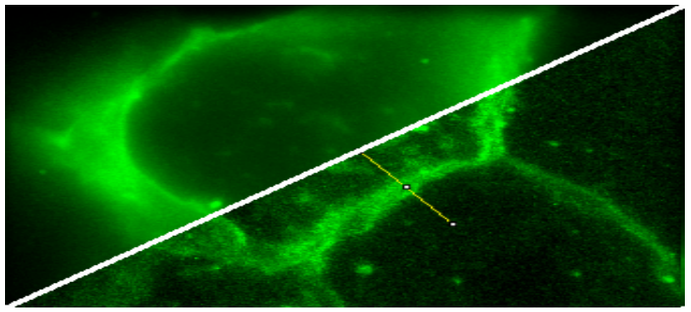
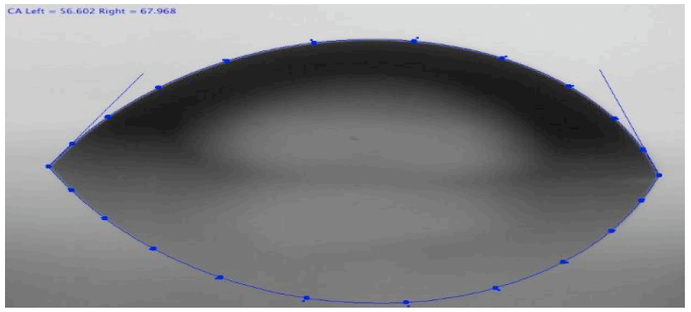


Image analysis

Image → Computer → Features, numbers



Computer vision

Image → Computer → Objects, 3D scene

Computer graphics

Description → Computer → Image

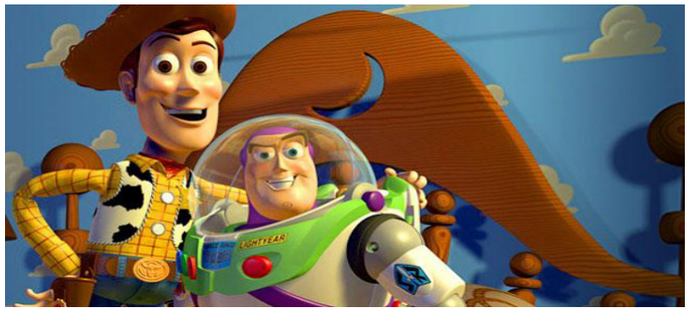


Image reconstruction

Measure → Computer → Image

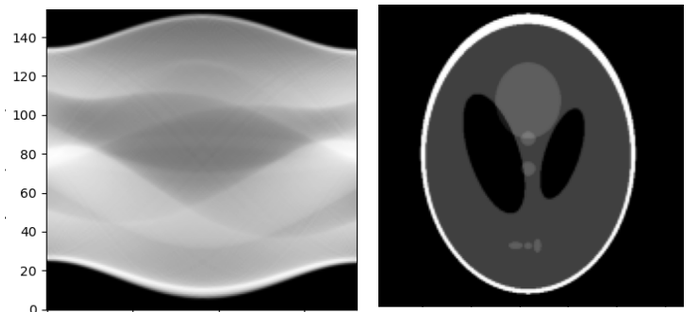
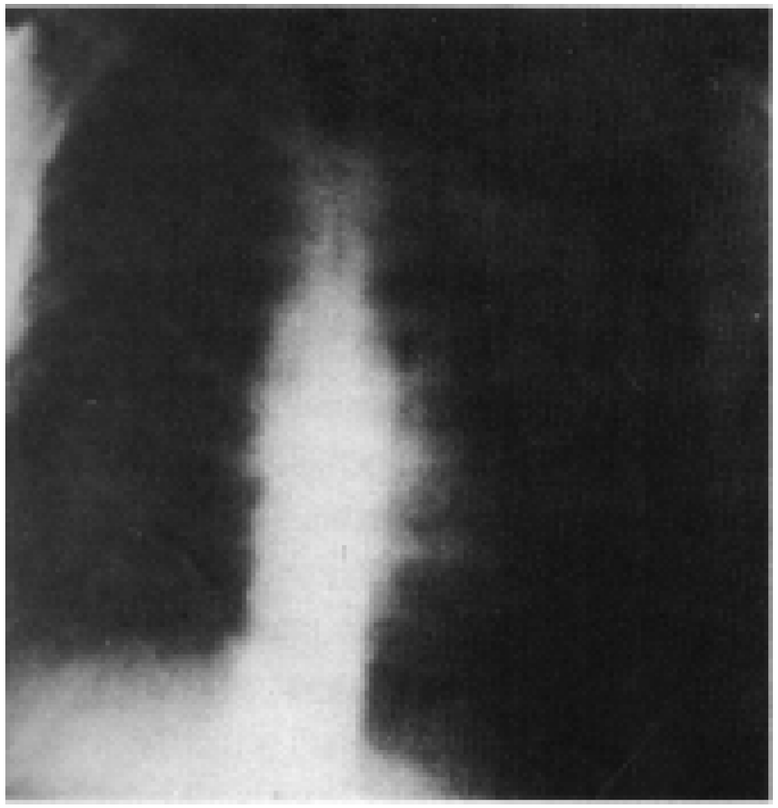


Image processing

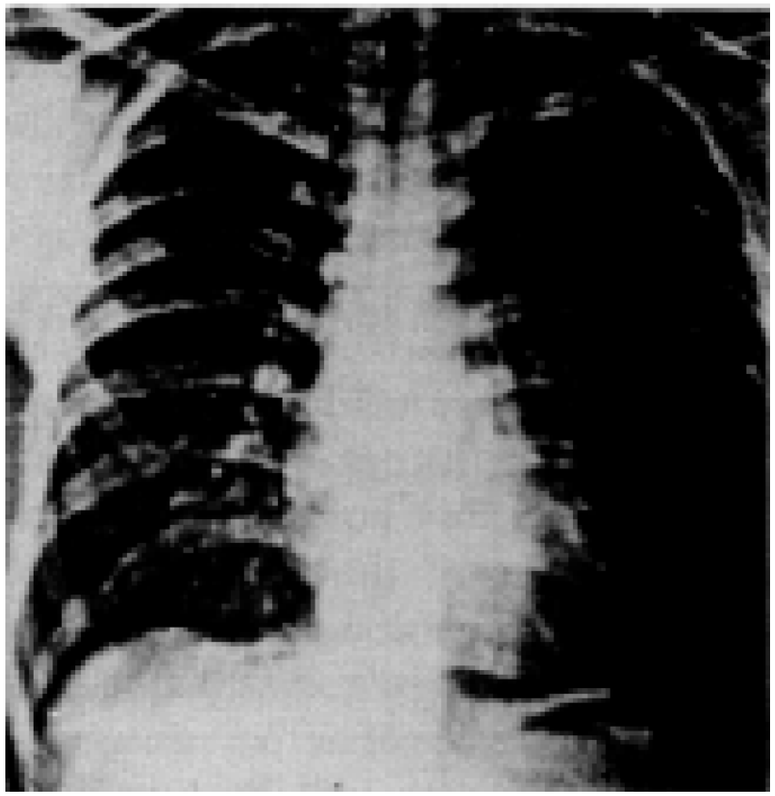
Definition: Transformation of pictorial information

Related field: Signal processing, basic components of artificial neural networks

Example: **enhancement**



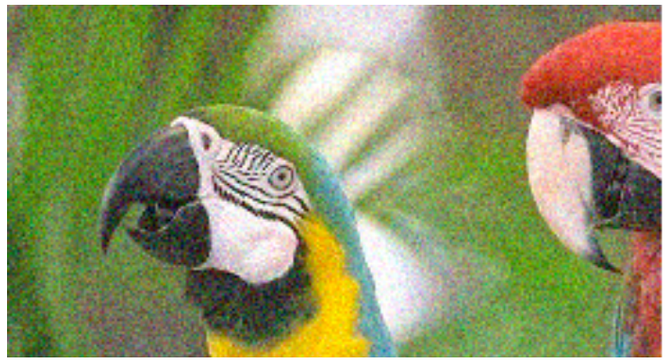
Original radiograph

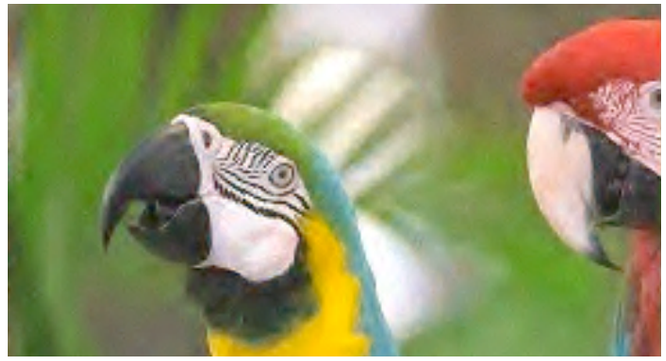


Enhanced image

Image processing (Cont'd)

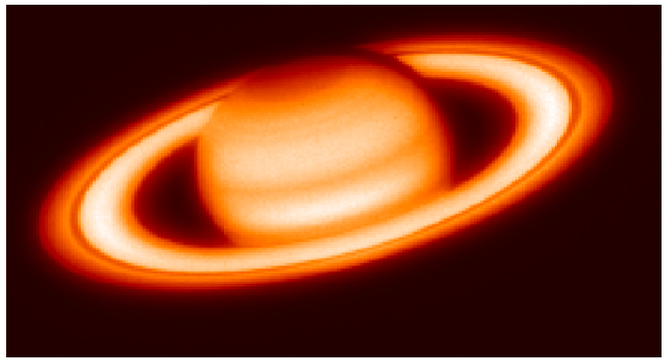
Example: **denoising**

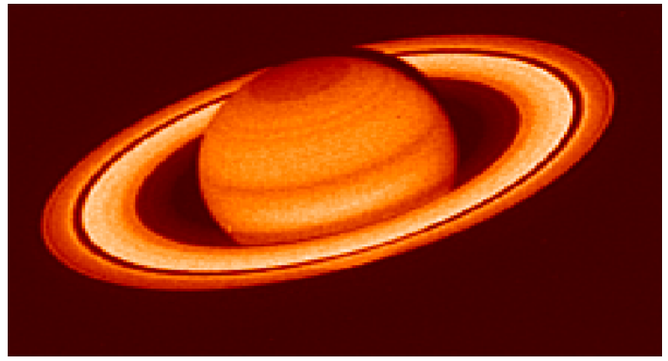




Low exposure
digital photograph

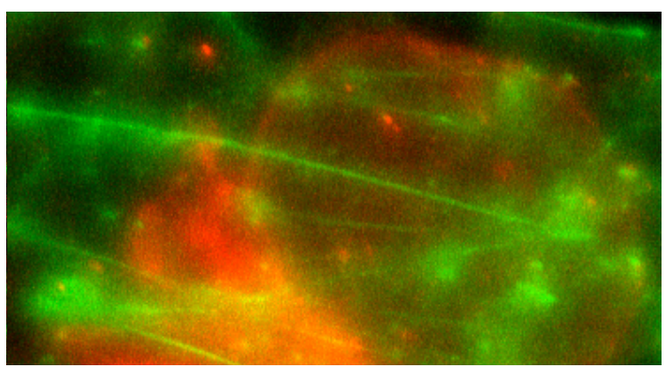
Example: **deblurring**

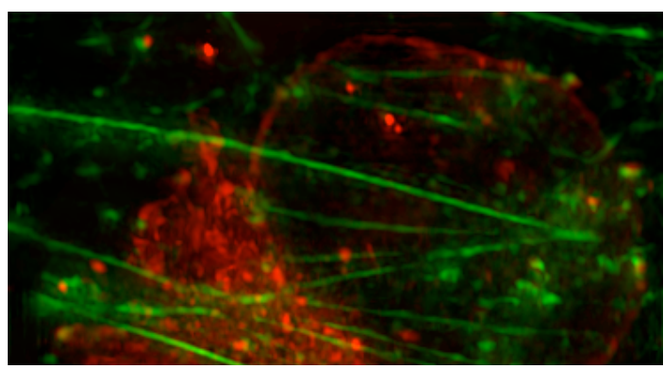




Saturn image
(Hubble Space Telescope)

Example: **deconvolution**





3D fluorescence
confocal microscopy

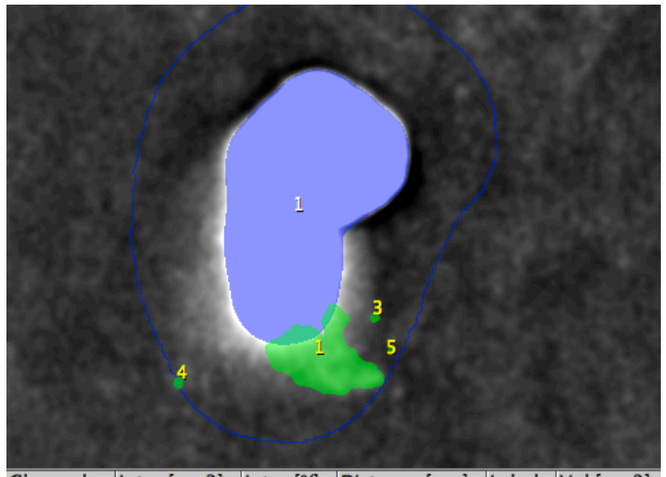
Image analysis

Definition: Extraction of images features and quantitative information (measures)

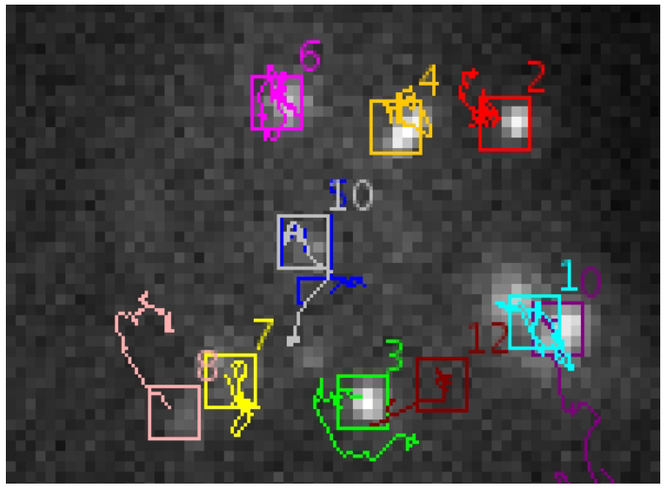
Related field: Pattern recognition, machine learning

Example **Bioimage analysis**

- Fluorescence microscopy, super-resolution, Live cell imaging
- Specific sub-cellular target, segmentation of particles



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



Particle tracking

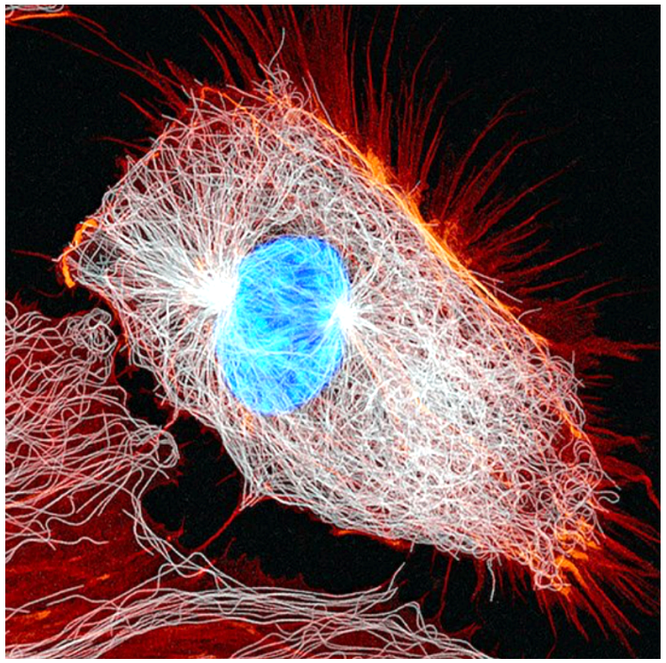
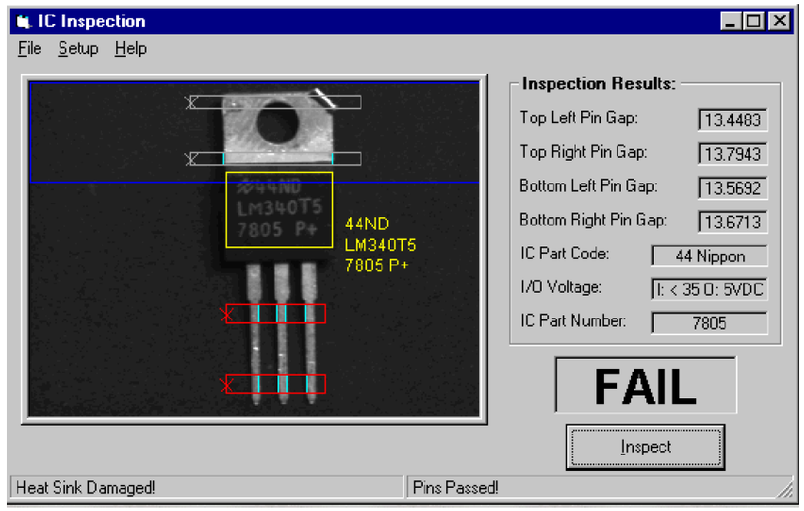


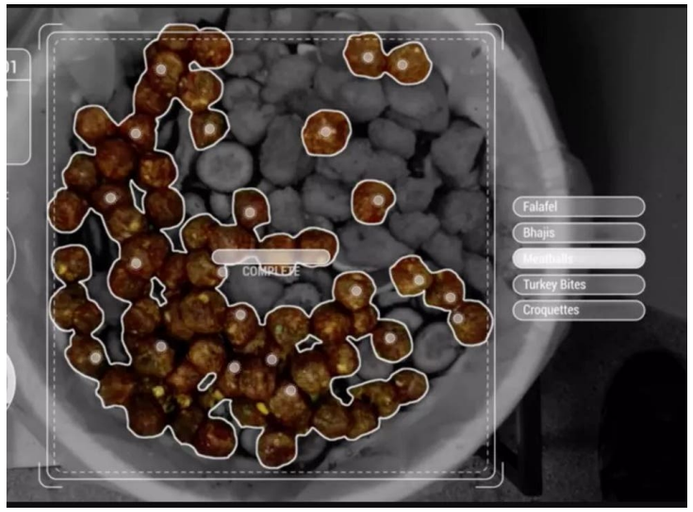
Image analysis (Cont'd)

Example: **industrial vision**

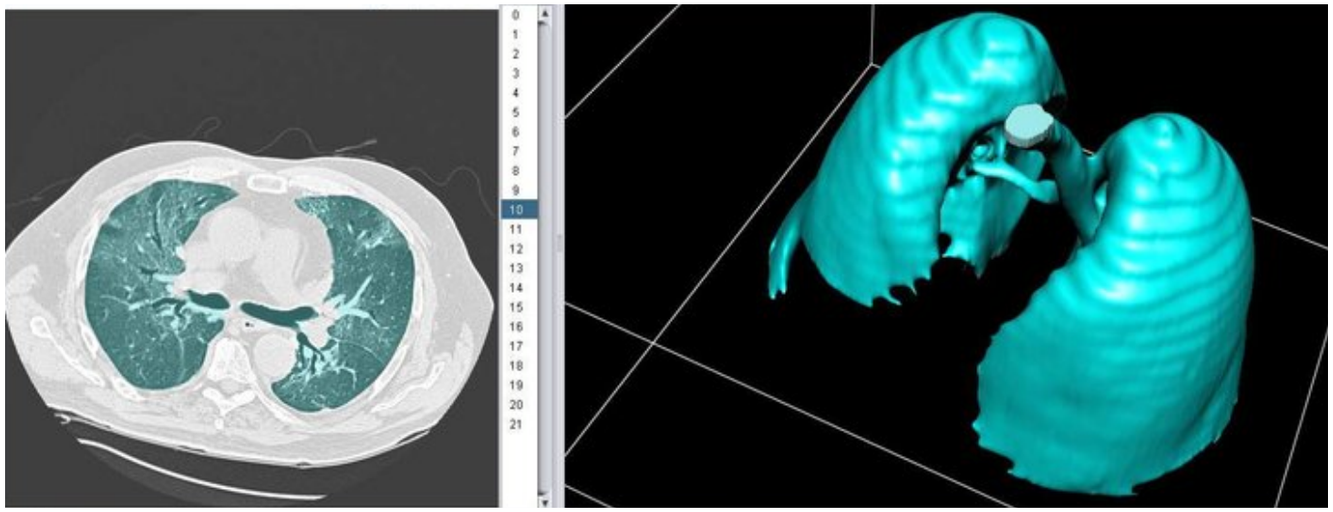


Quality control in production

Check food waste



Example: **medical imaging**



Segmentation of the lung based on texture information

Where is image processing?

Interdisciplinary field

Machine Learning

Mathematics

Photography

Signal processing

Image processing

Computer technology

Optics

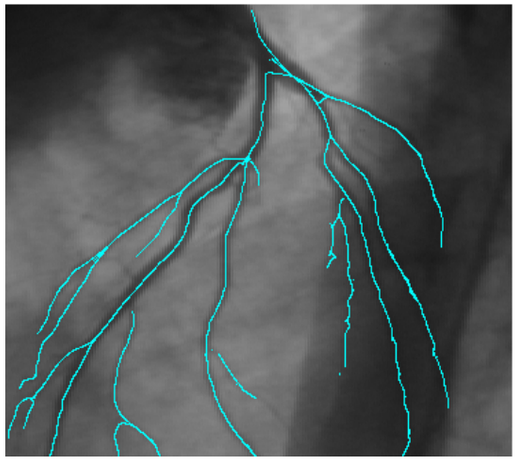
Electronics

↓

Application areas

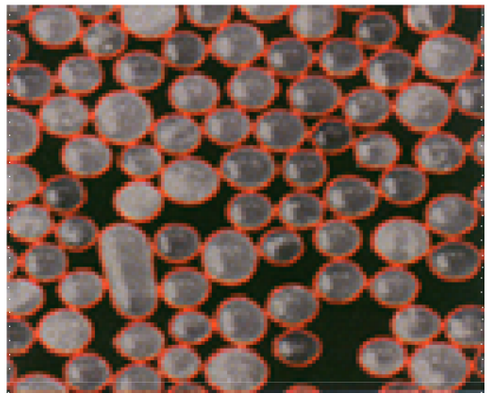
Digital imaging applications

- **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 system
- **Banking**
  - Optical character recognition (OCR)

- **Communication**
  - Compression
  - Image archival
- **Biology / Microscopy**
  - Life Cell imaging
  - Micro-array, DNA chip
  - Fluorescence microscopy
  - Super-resolution reconstruction
  - Neuroscience

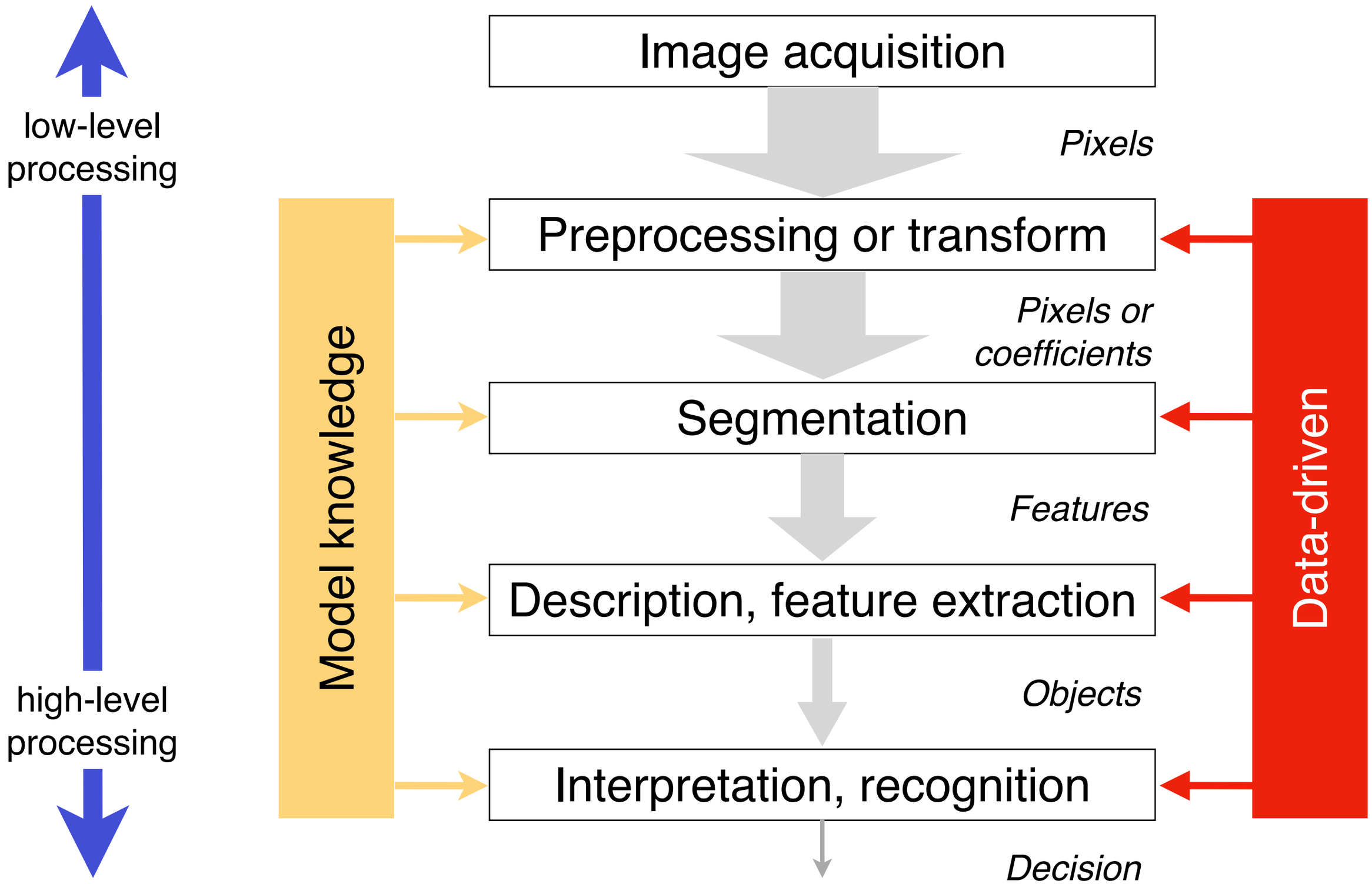


- **Multimedia**
  - Digital photography
  - Electronic publishing
  - Watermarking
  - Image database indexing
  - Old-movie restoration
- **Astronomy**
  - Detection of stars

- **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

Steps in an image-analysis system

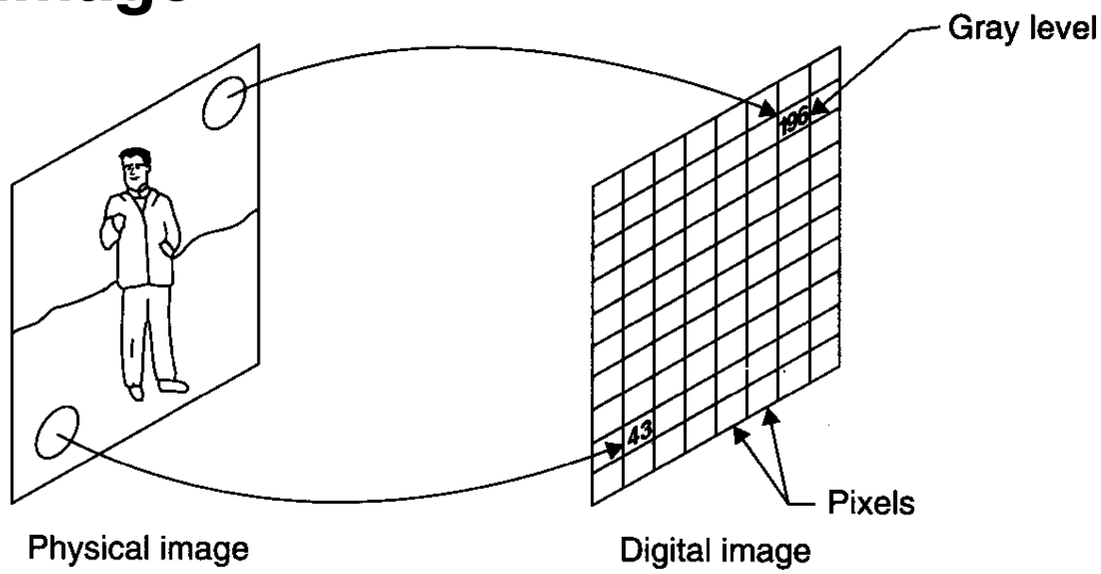


THE BASIC OBJECTS: IMAGES

- **Continuous images**
- **Discrete images**
- **Generalized images**

Digital image representation

Digital image



- Set of *pixels* (picture elements)

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

K : number of columns

L : number of rows (lines)

- Array of pixels $K \times L$

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

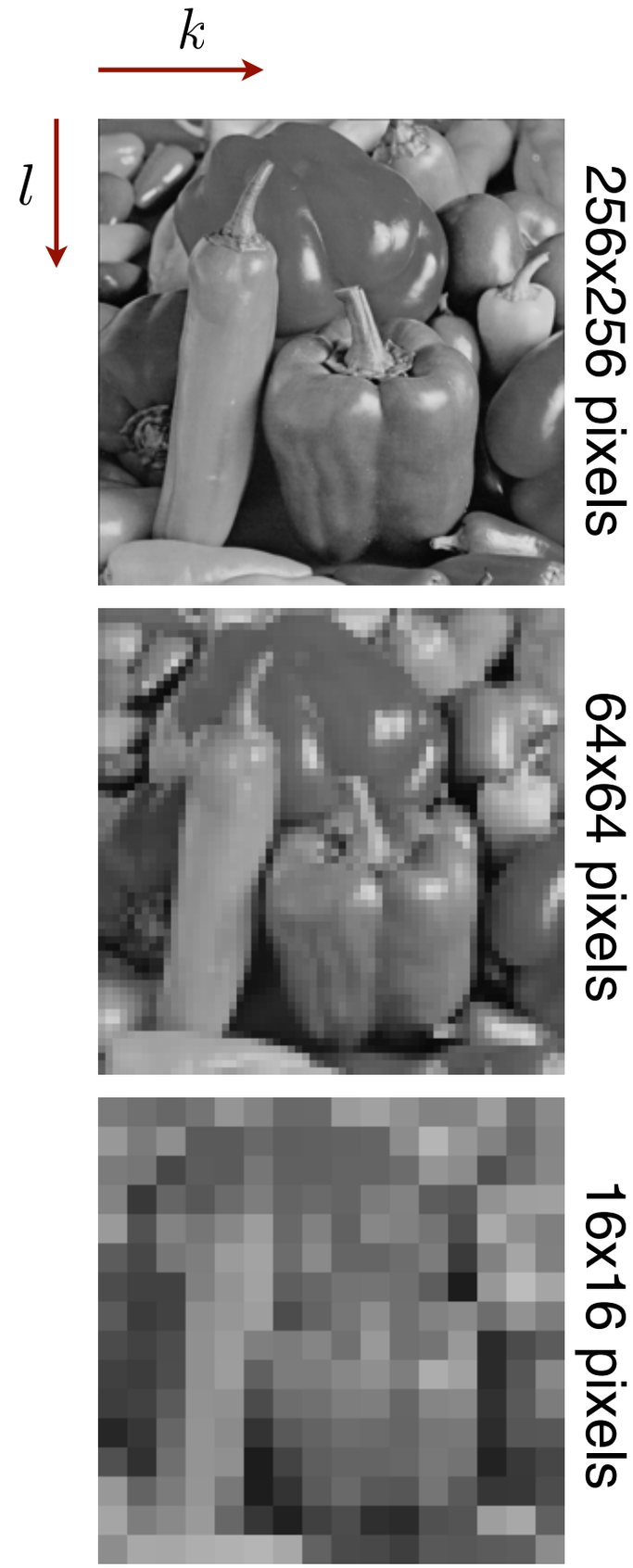


Image representation

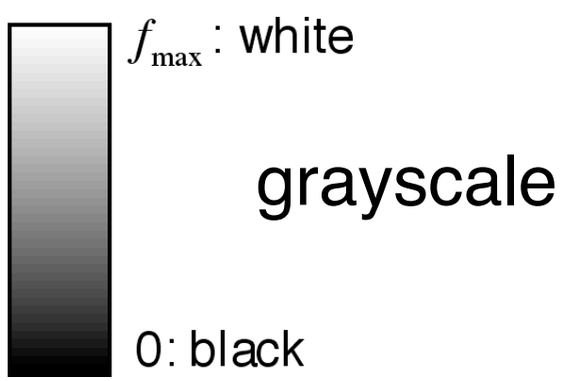
Continuous image (monochrome)

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

- spatial coordinates: (x, y)

- brightness (or gray level):

$f \in [f_{\min}, f_{\max}]$



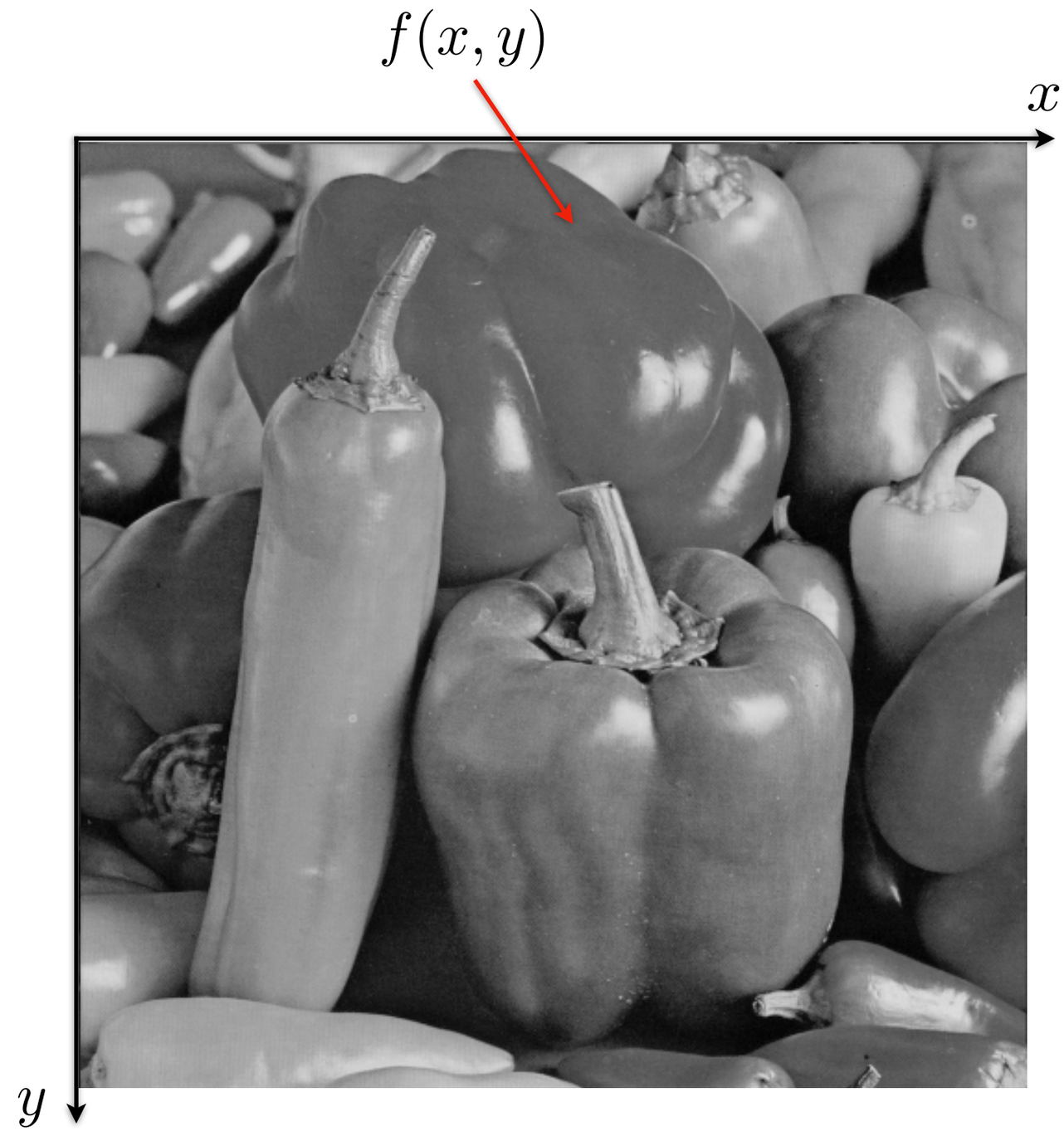
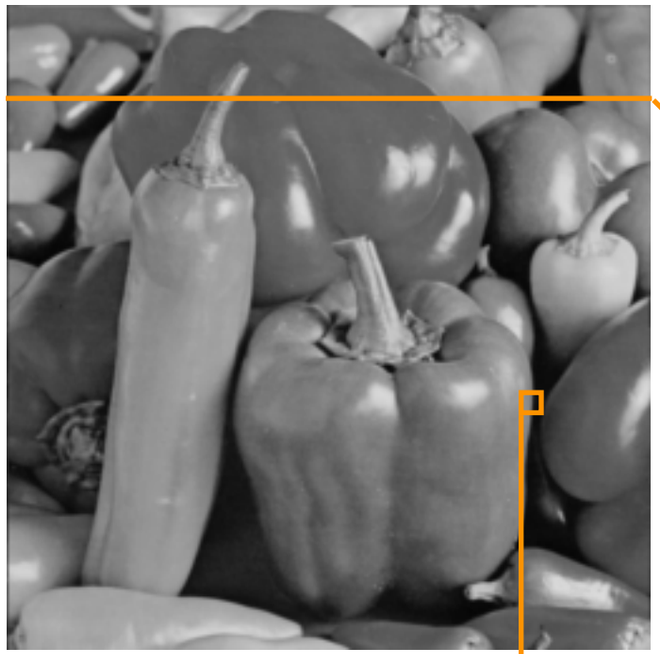
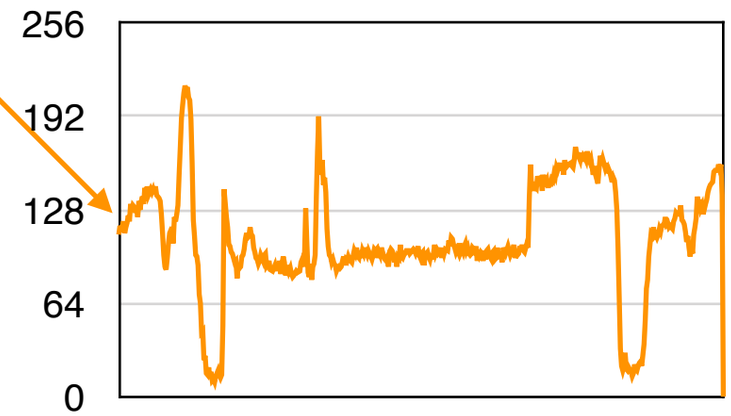


Image representation (cont'd)

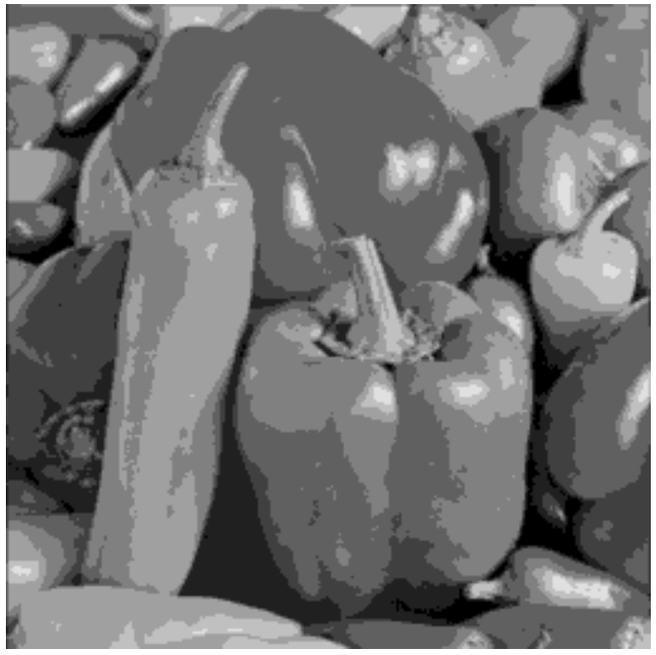
Quantize gray levels





256 gray levels

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

2 gray levels

General-purpose
Grayscale in 8-bit: 0-255

Science
Sensitive camera: 16-bit image

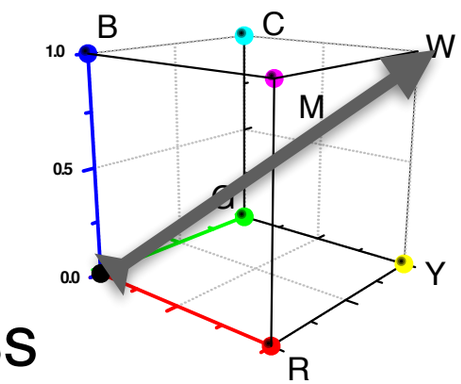
Computation
Floating-point representation
32-bit (float) or 64-bit (double)

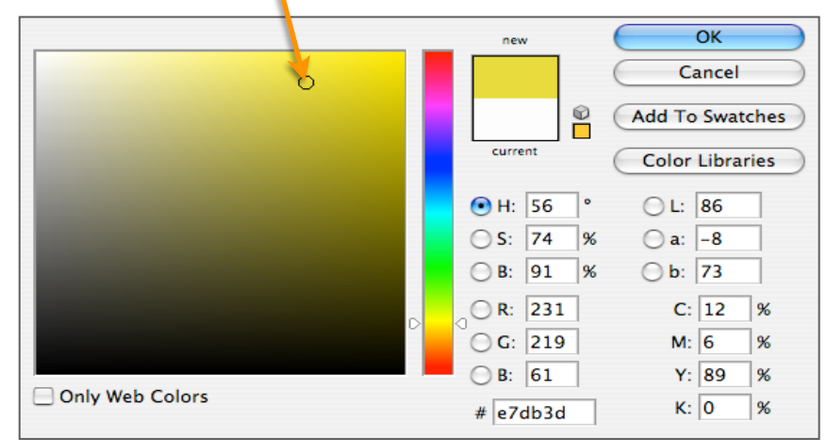
Binary
1-bit: 0 or 1

Color images

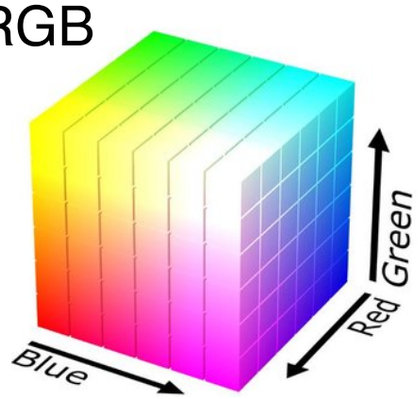
Color-representation systems

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

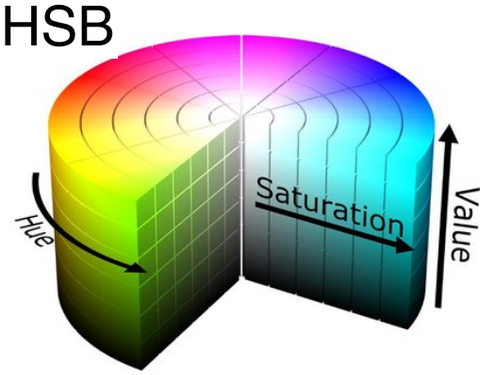


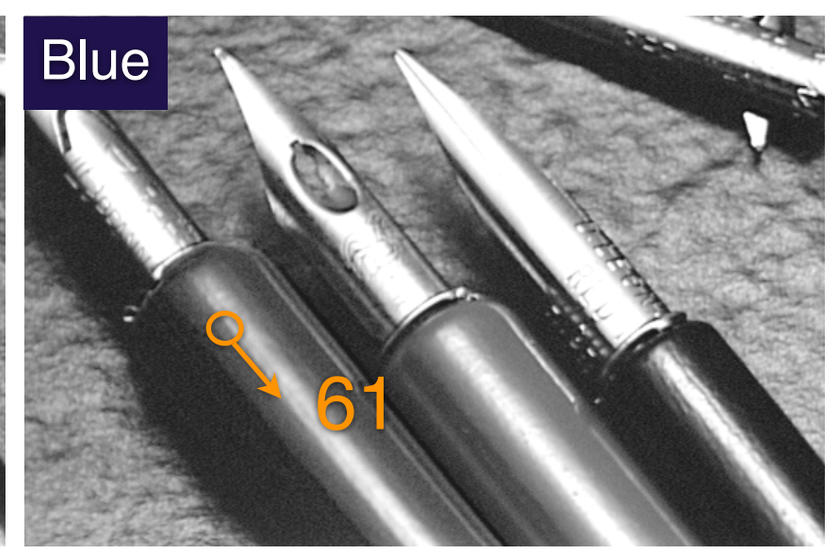


RGB



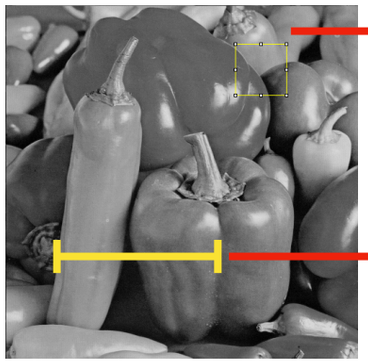
HSB



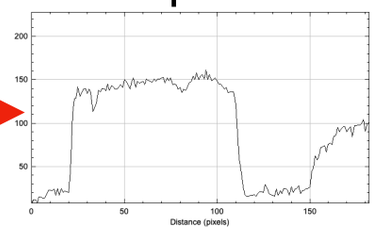


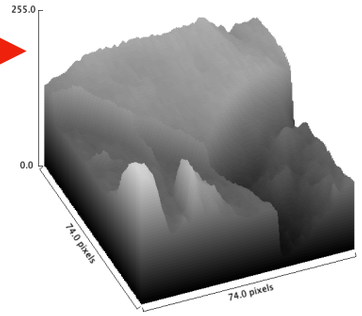
Exploring Scientific Images

Open-source software: ImageJ / FIJI



line profile

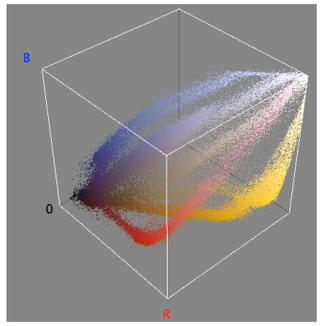




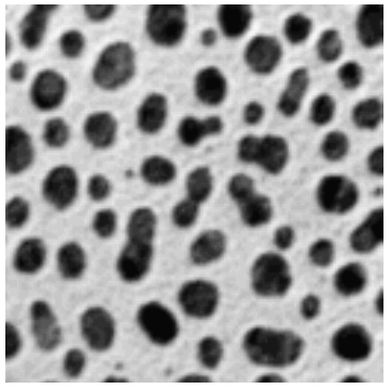
surface plot

Advanced ImageJ plugins

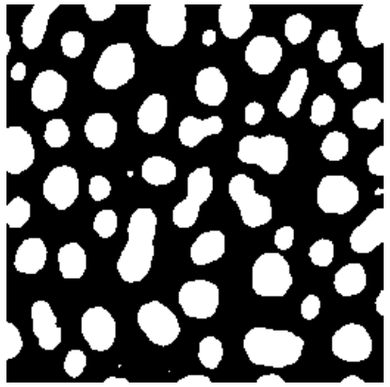
Color image



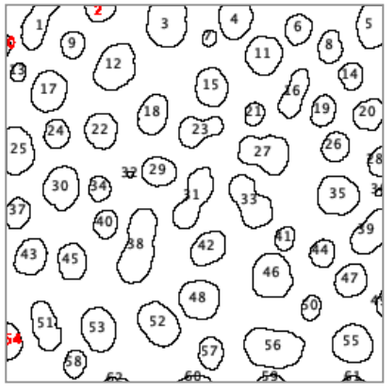
histogram



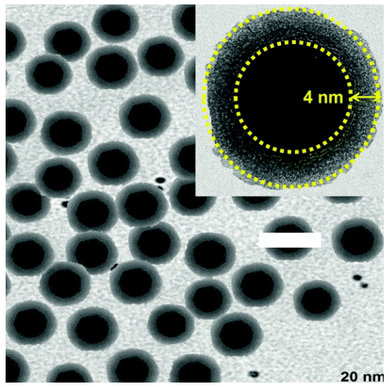
Original



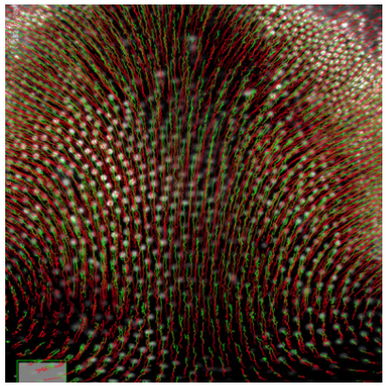
Binary



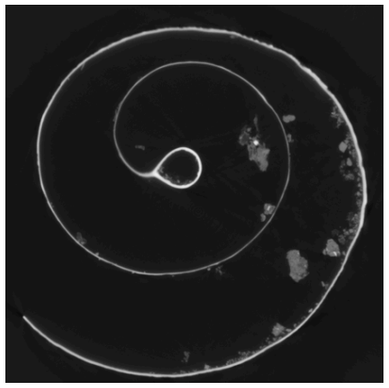
Objects



Measurement

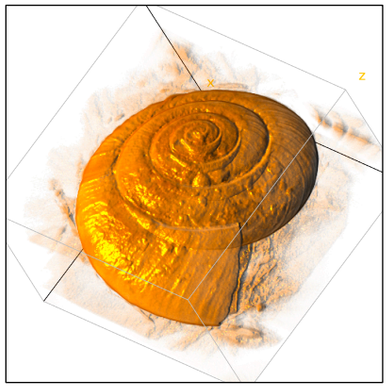


Tracking

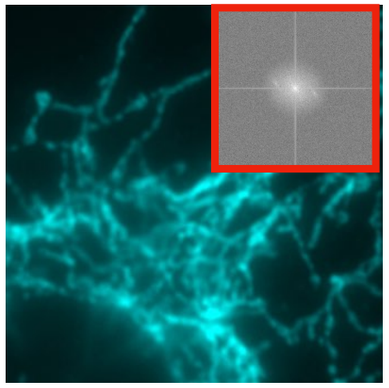


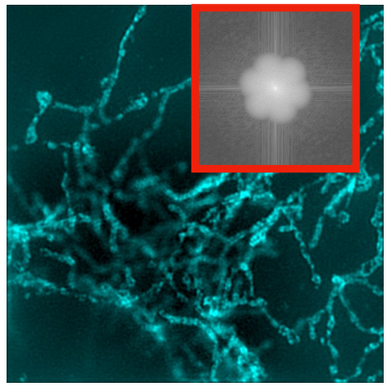
Slice of 3D

MIP of 3D



Volume rendering





Structure Illumination Microscopy

Unser: Image processing

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:

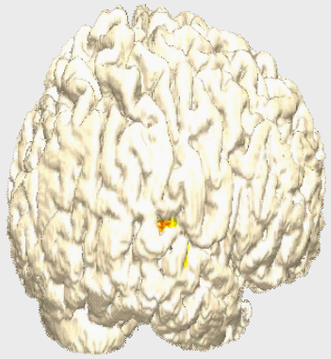
$$\boldsymbol{f}(x, y) = \begin{bmatrix} f_1(x, y) \\ \vdots \\ f_p(x, y) \end{bmatrix}$$

- Image source
  - Device sensitive to EM energy band
    X-ray, ultraviolet, visible,
    infrared, radio-astronomy
  - Non-optical images
    MRI, PET, ultrasound, seismic data

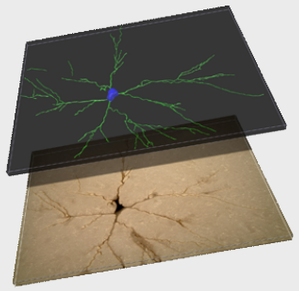
Examples

fMRI Dataset
150 volumes
256×256×110 voxels

$f(x, y, z, t)$

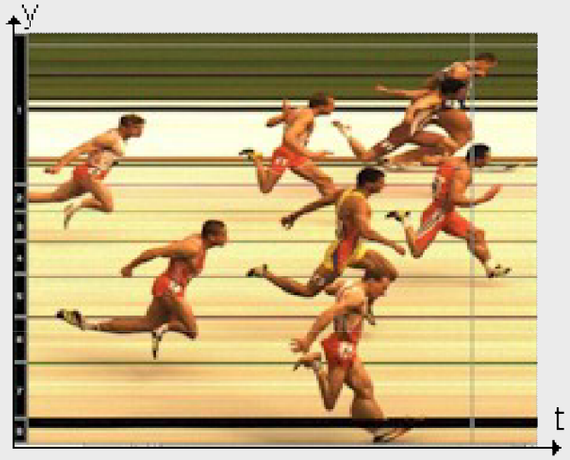


Neuron tracing
mosaic of micrographs 90 planes
of 2048×2048 pixels



Photofinish with a linear camera
2048 pixels
2000 lines/s

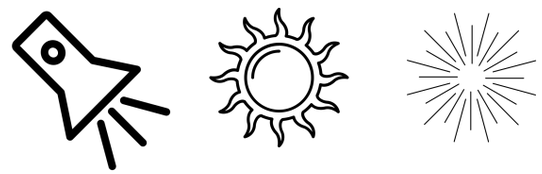
$f(t, y)$



COMPONENTS OF AN IMAGING SYSTEM

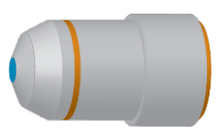
- **Image acquisition**
- **Digital image**
- **Processing tools**
- **Inside a neural network**

Image acquisition

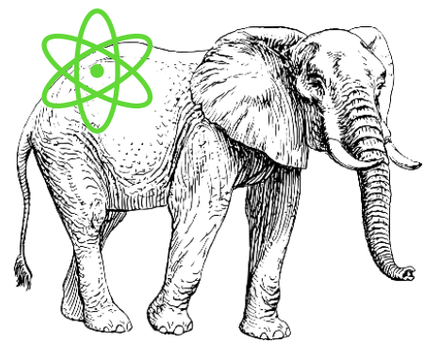


Illumination, radiation, staining

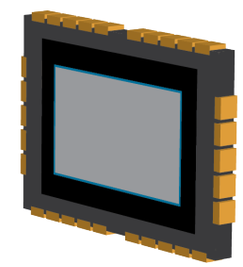
Object



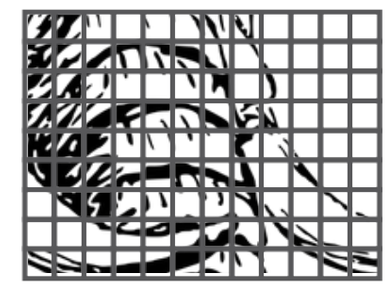
Imaging system, optics



Image



Detection system



Digital Image (Raster)

- **Key elements of an acquisition system**
  - Optics, aperture, depth-of-focus, distorsions
  - Sampling, resolution
  - Sensor: light intensity ⇨ electric signal
  - Quantization and noise
  - Motion control

Mapping pixel values to grayscale level

Digital image

- **Large Image**
  - Graylevel picture: 512 × 512 × 8 bits = 0.25 MB
  - Photography of smartphone (color): ~40 MB
  - Medical imaging CT Scan: 512×512×300×16 bits = 150 MB
  - Whole slide image (pathology): 50'000 × 50'000 x 24 bits
- **Storage**
  - Short-term: RAM (32 Gb) vs. long-term Hard disk (20 TB)
  - Private archive vs. public repository for open science
  - Scientific image : store pixels and metadata
- **Big data**
  - Database of images ⇨ Key for the training of large models
  - Private archive vs. public repository for open science
  - Software of archiving

Processing tools

- **Powerful computers**
  - < 1990: Mainframe or specific hardware
  - 1995-2015: General-purpose personal computer, CPU
  - > 2015: CPU + GPU (for deep learning) + HPC Server

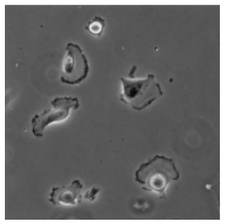
- **System integration**
  - Smart camera

    CCD + Processor + RAM

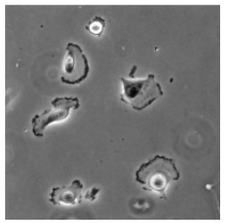
- **Image-processing software**
  - Desktop publishing: Photoshop, GIMP, ...
  - Commercial analysis tool: Matlab, Labview, ...
  - Programming: JAVA, Python (opencv, skimage, ...)
  - Online resources http://bigwww.epfl.ch/demo/

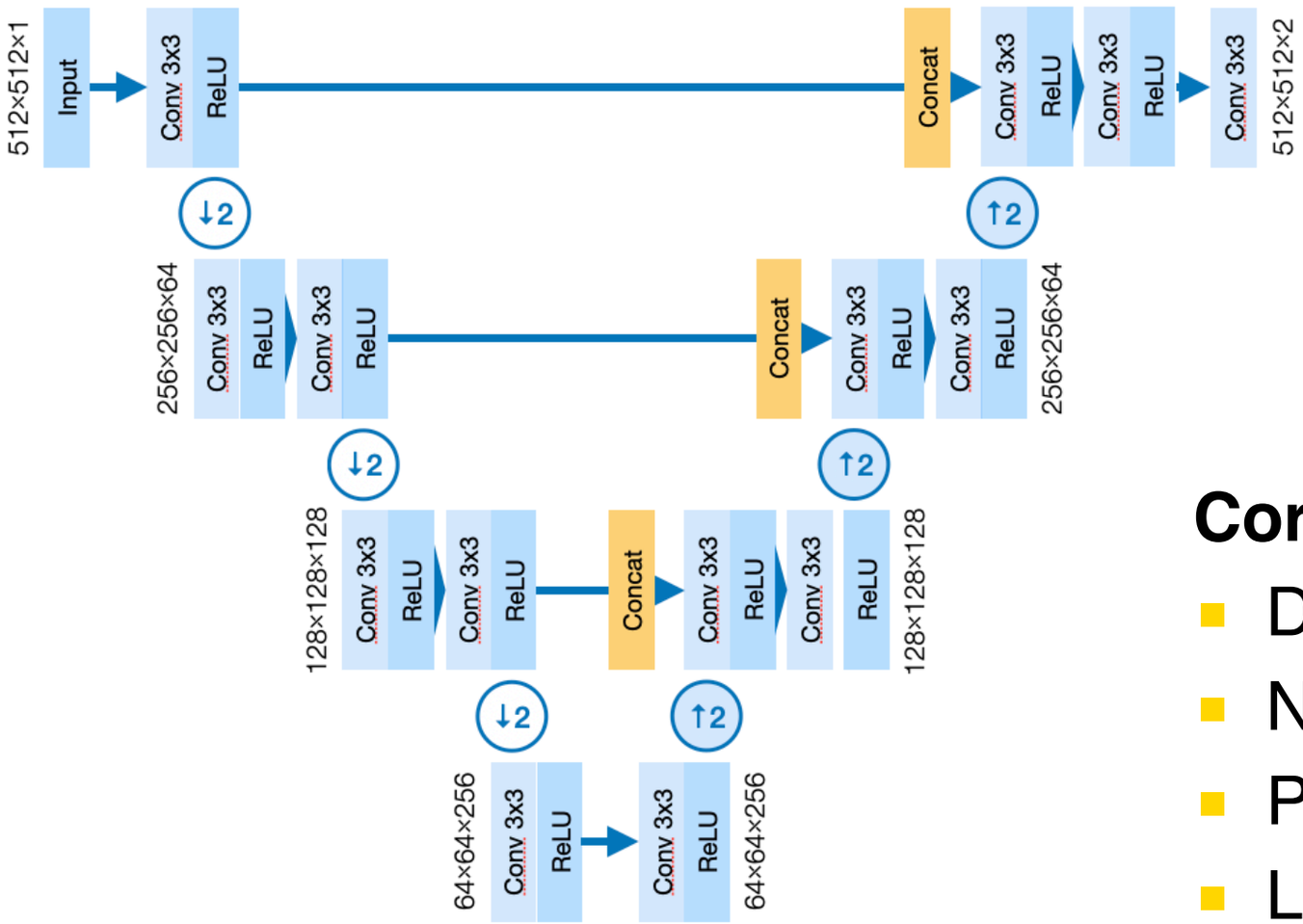
ImageJ
Image Processing and Analysis in Java

Inside a neural network



Convolutional Neural Network
U-Net — Ronneberger et al.,
MICCAI, 2015





U-Net - Ronneberger et al.,
MICCAI, 2015

Training

- 2'000'000 parameters
- > 1'000 images

Core foundations of CNN

- Digital filters: convolution
- Network: layers, channels
- Pixelwise ops: activation
- Linear and non-linear ops
- Multiple scale: pooling
- Image metrics: loss

CONCLUSION

What about the future of the image processing? many indicators of growth

- **Economical factors**
  - Accessibility: declining cost of computers and imaging equipment
  - Technological innovation: (digitizers and displays)
- **New technology trends**
  - Imaging device: CCD, CMOS, ... new sensors -> Computational imaging
  - Processing hardware: CPU - Parallelization - GPU - Large RAM - Large monitor
  - IA: Machine learning, computer vision, emergence of DL in image analysis
  - Image data: images has part of scientific data, model development
- **New applications**
  - Consumer products: digital photography, desktop publishing, HDTV
  - Biomedical: digital radiography, ultrasound, fluorescence microscopy, ...
  - Science: everywhere, from nano-scale to astronomy scale
  - Industry: inspection, and scientific
  - Security: traffic monitoring, biometry

Reference

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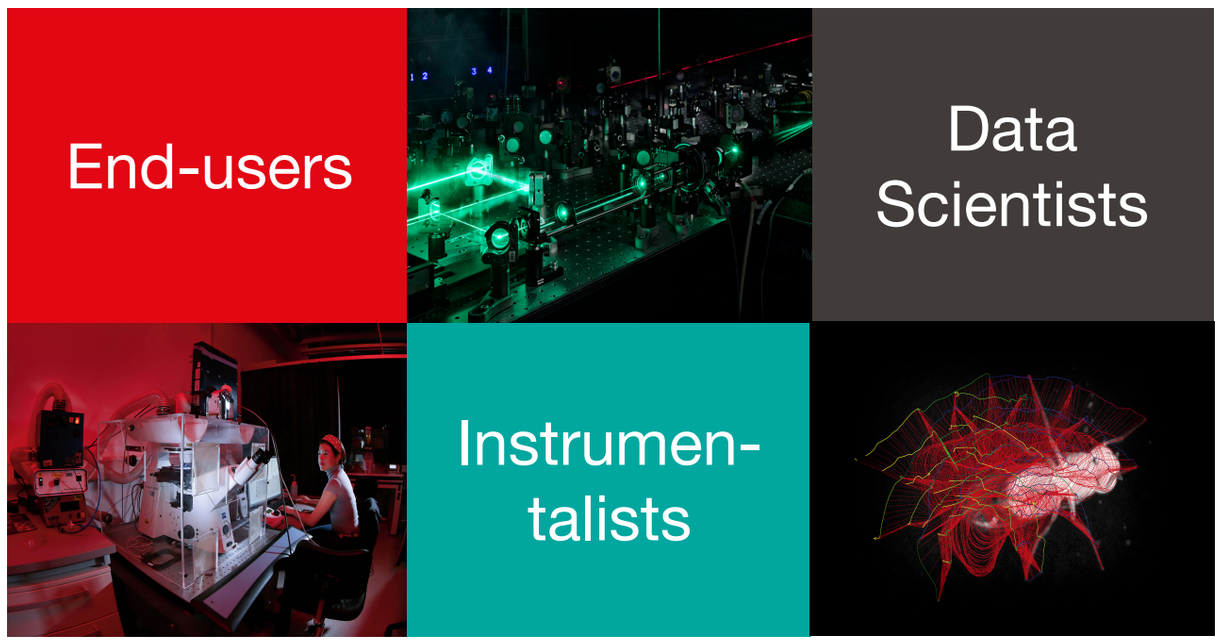
EPFL Center for Imaging

Most of the future progress in imaging will likely result from **interactions and cross-fertilisation** between imaging with **complementary expertise** and from various disciplines.

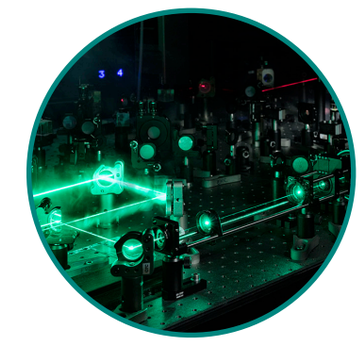
EPFL's exceptional concentration of academic strengths in imaging



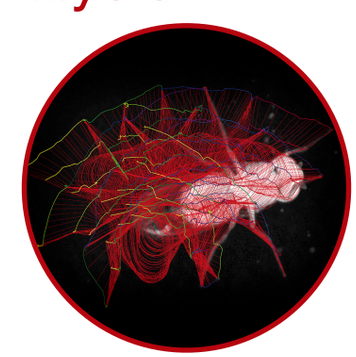
M. Unser Academic Director
L. Donati, Executive Director

A transversal effort across EPFL Schools

Catalyst for interdisciplinary research



Coordinated imaging infrastructure

Top-level training in imaging

Advanced support in image analysis