# Imagery numérique

# Theme 1

# Introduction to Digital Image Processing

# Miscellanea

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**Lectures: Friday 10:00 – 12:00**

**TPs: Friday 13:00 – 15:00**

**Web Site: moodle 13x004 «Imagerie numérique»**

# Organization and evaluation

**Duration:**

- Two semesters
  - Semeter 1: Introduction and foundations (14 lectures)
  - Semester 2: Applications, selected and advanced topics (14 lectures)

**Assestment by the end of each semester:**

- Oral exam – 2/3
- HWs – 1/3

# Content of course

**Semester 1**

Theme 1: Introduction to image processing

Theme 2: The HVS perception and color

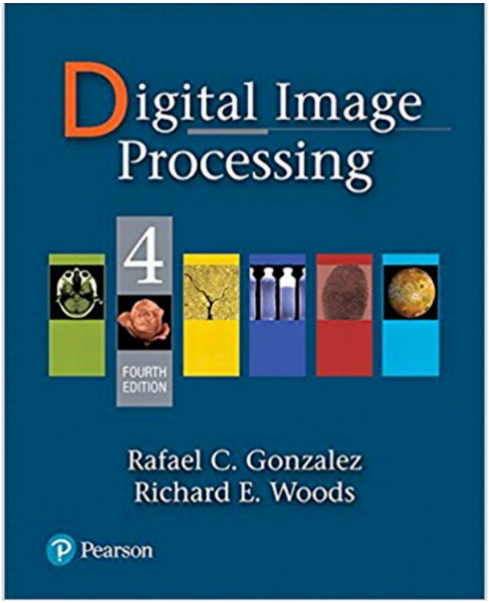
Theme 3: Image acquisition  and sensing

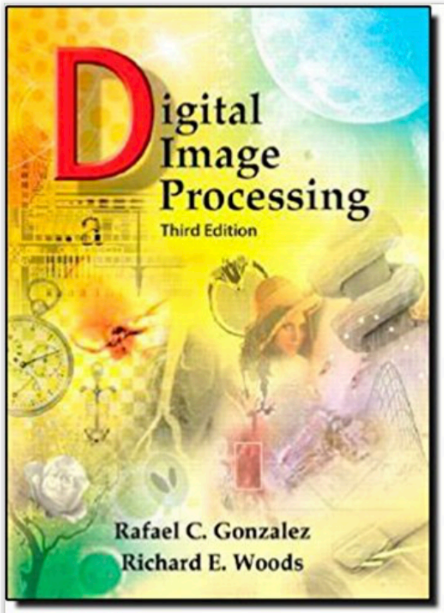
Theme 4: Histograms and point operations

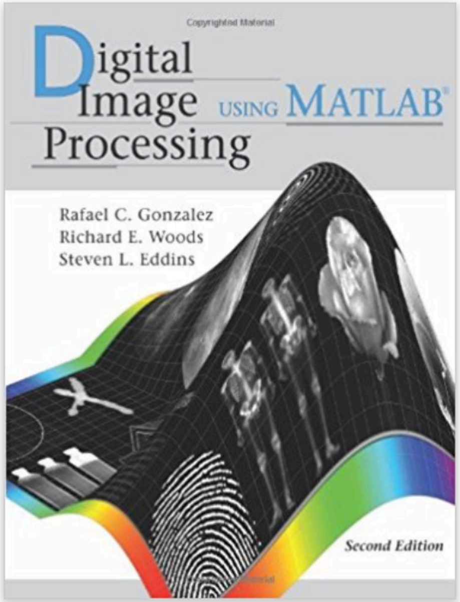
Theme 5: Geometric operations

Theme 6: Spatial filters

# Recommended books




YouTube lectures

Intro to Digital Image Processing (ECSE-4540) Lectures, Spring 2015

by Prof. Rich Radke from Rensselaer Polytechnic Institute

# Copyright notice

This course uses in part some materials from previously mentioned recommended sources.

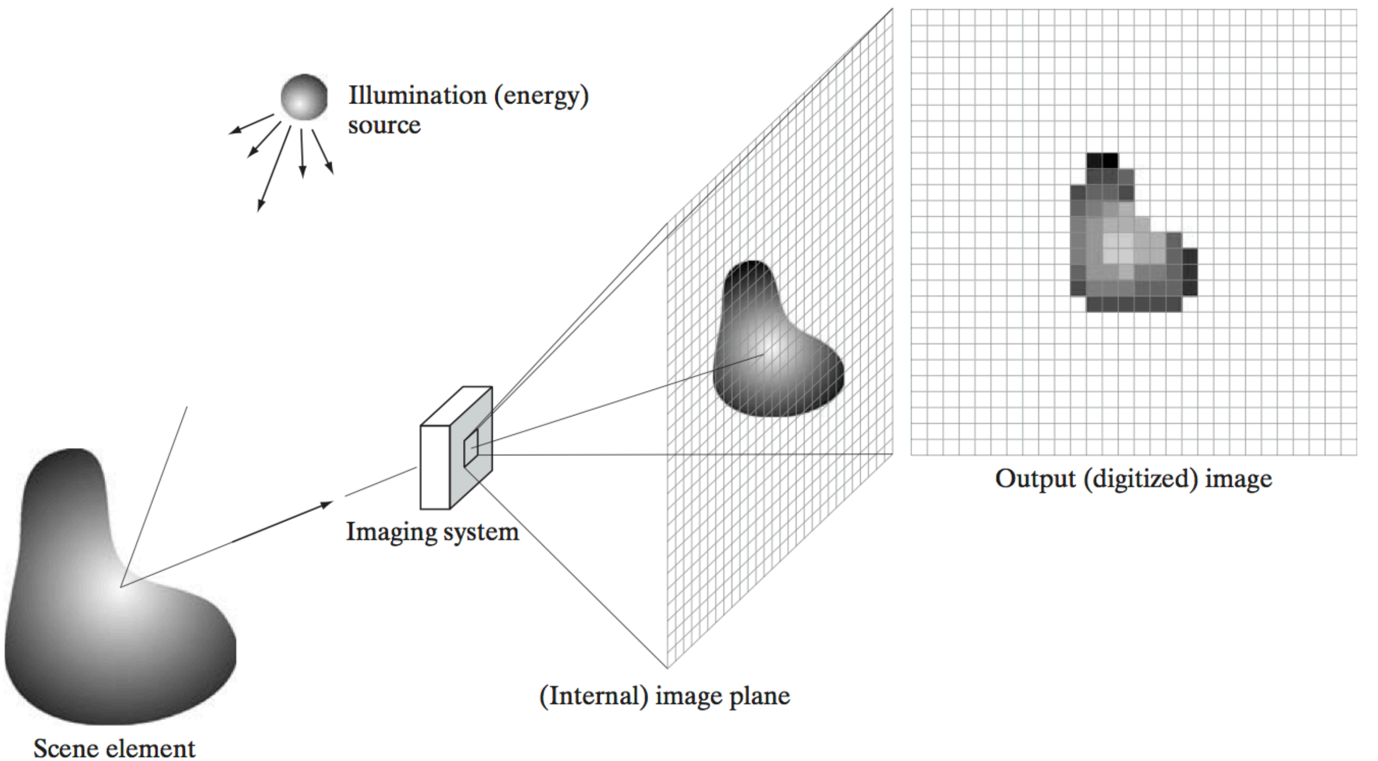
# Content of this lecture

**In this lecture we will consider:**

- What is a digital image?
- What is digital image processing?
- Image processing problems
- Material covered in this course
- Applications of image processing

# Digital images – an introduction

- A **digital image** is a representation of a two-dimensional scene as a finite set of digital values, **called picture elements** or **pixels**

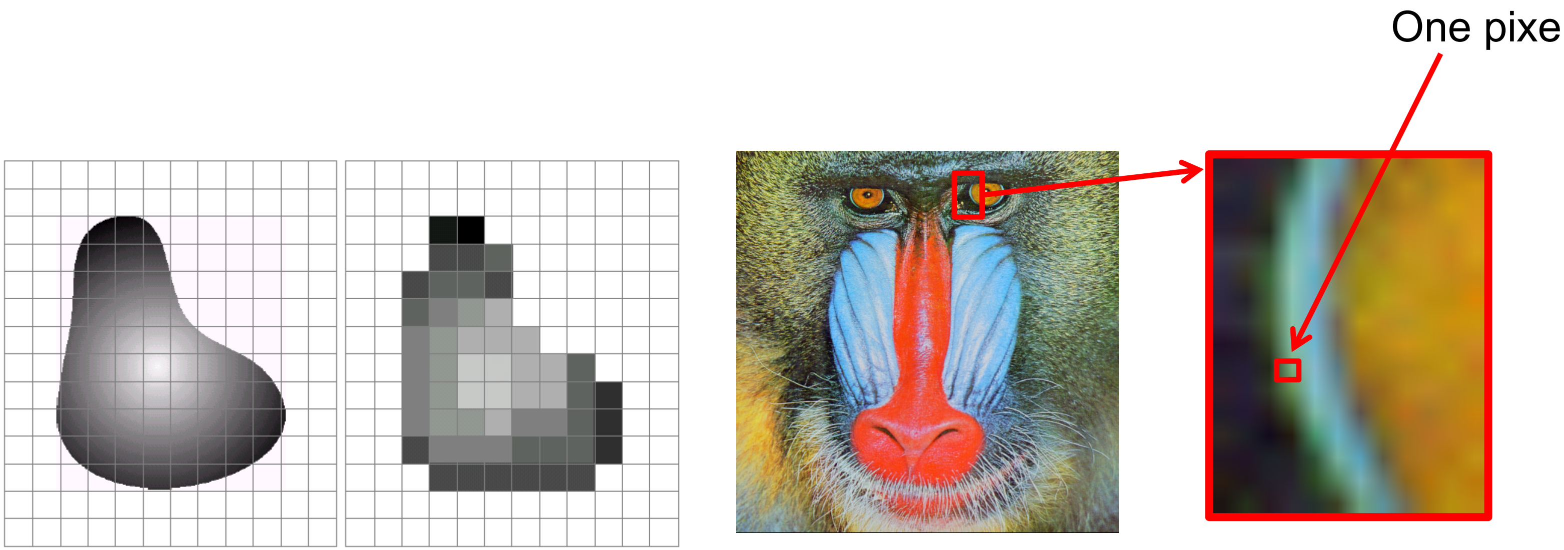



Gonzalez, p. 51

# Digital images – an introduction

- **Pixel values** typically represent gray levels, colors, distance from camera, etc.

- A digital image is just an *approximation* of a real scene




Gonzalez, p. 51

# Digital images – an introduction

- **Common image** formats include:
  - 1 sample per point (grayscale)
  - 3 samples per point (<u>R</u>ed, <u>G</u>reen, and <u>B</u>lue)
  - Video (above information **plus** time)
  - Volumetric data (medical imaging, remote sensing)

**Representation**

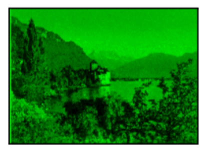
$$f(x,y)$$

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

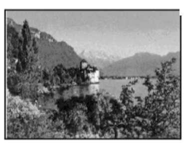
$$f(x,y,z,t)$$

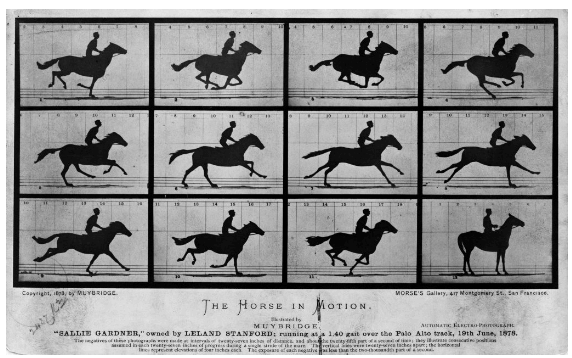
R

G



B









Note: we will focus on grayscale images to demonstrate the main principles

# Modern image processing and interconnections

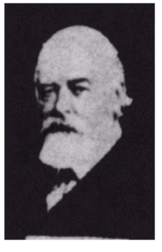
- “**Traditional**“ **digital image (and video) processing** focuses on two major problems:
  - **Improvement** (denoising, restoration, interpolation, decimation, enhancement, inpainting, etc.) of image data for human interpretation
  - **Processing** of image data for storage, transmission and representation for autonomous machine perception (analysis) in applications such as robotics
- Nevertheless, the “**modern**” digital image processing is closely interconnected with:
  - **Computer vision** (mostly all CV problems based on hand crafted descriptors) and **augmented reality**
  - **Multimedia applications** (indexing, similarity search, recommendation systems like Netflix, etc.)
  - **Security** at all levels of physical objects, humans (biometrics) and digital multimedia (watermarking, steganography, digital forensics)
  - **Machine learning** that includes not only traditional recognition/classification, regression and detection but also automatic feature extraction for these tasks in contrast to traditional CV

# Earlier history of DIP

**Early 1920s:** One of the first applications of digital imaging was in the newspaper industry

Newspaper printed image

**Mid to late 1920s:** Improvements resulted in higher quality images: New reproduction processes based on photographic techniques and increased number of tones in reproduced images



15 tone image

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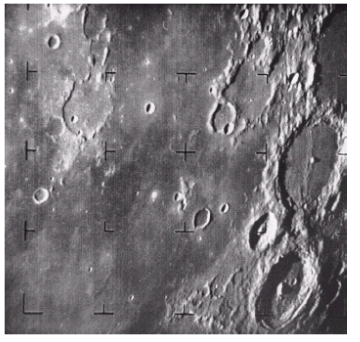
# Earlier hystory of DIP

**1960s:** radar technologies and image processing for moon imaging



**1970s:** Digital image processing begins to be used in medical applications

**1979:** Sir Godfrey N. Hounsfield & Prof. Allan M. Cormack share the Nobel Prize in medicine for the invention of tomography, the technology behind Computerised Axial Tomography (CAT) scans

Computerised Axial Tomography (CAT)

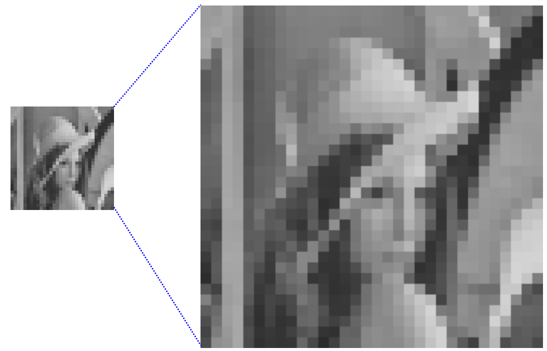
Gonzalez

# Main factors determing image quality

## Number of pixels

256x256

64x64



## Number of grascale levels

256 levels

32 levels

2 levels

# Main factors determing image quality

## Number of grascale levels

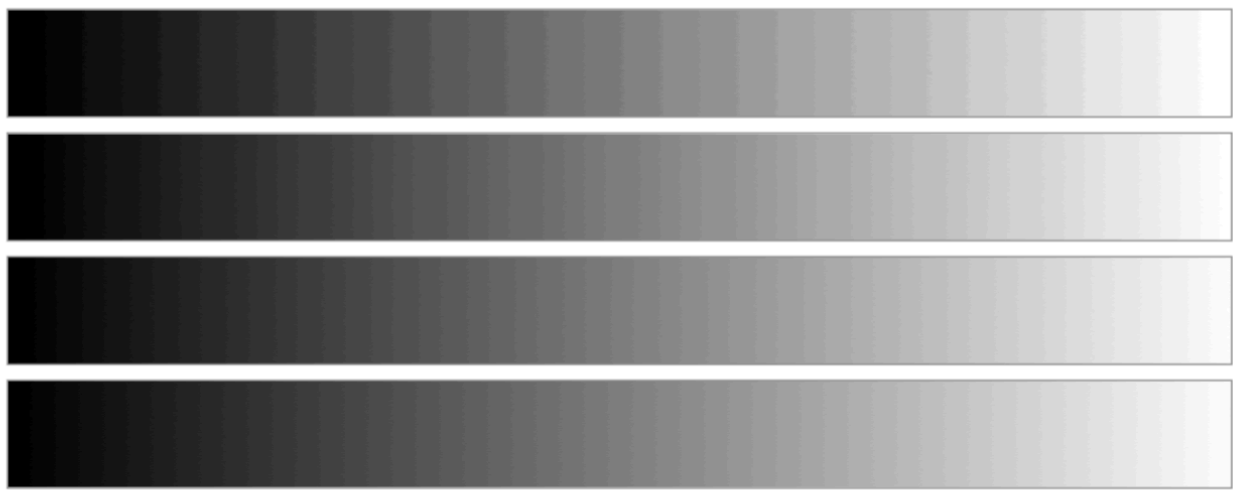
Do we need a lot of grayscale levels? See the difference

32 levels

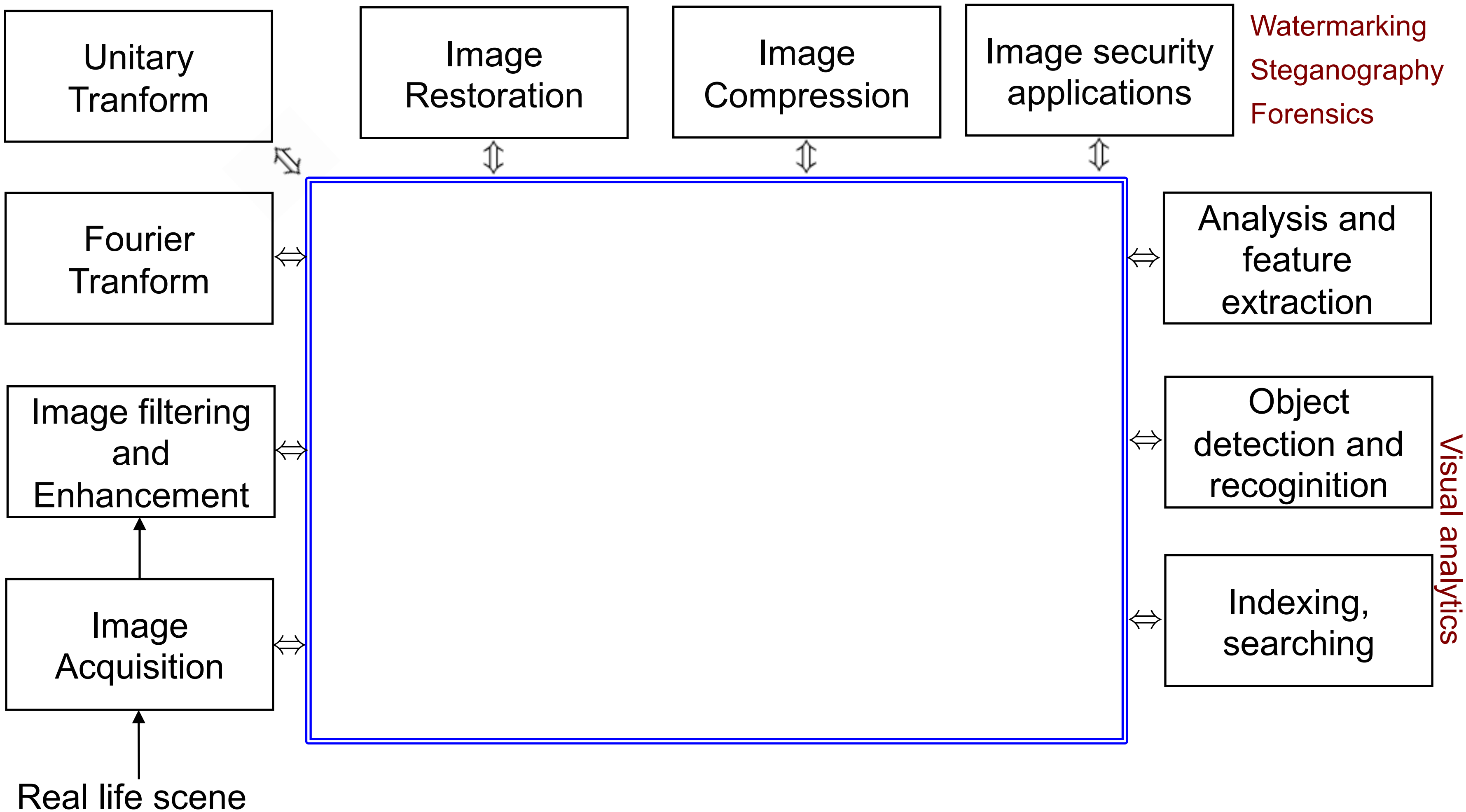
64 levels

128  levels

256  levels



# Main elements of image processing systems



# Main elements of image processing systems

Unitary Tranform

Image Restoration

Image Compression

Image security applications

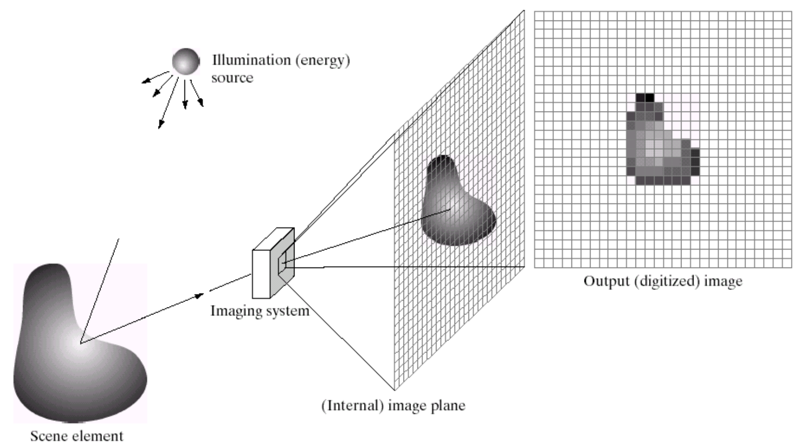
Watermarking
Steganography
Forensics

Fourier Tranform

Image filtering and Enhancement

Image Acquisition

Real life scene




Analysis and feature extraction

Object detection and recoginition

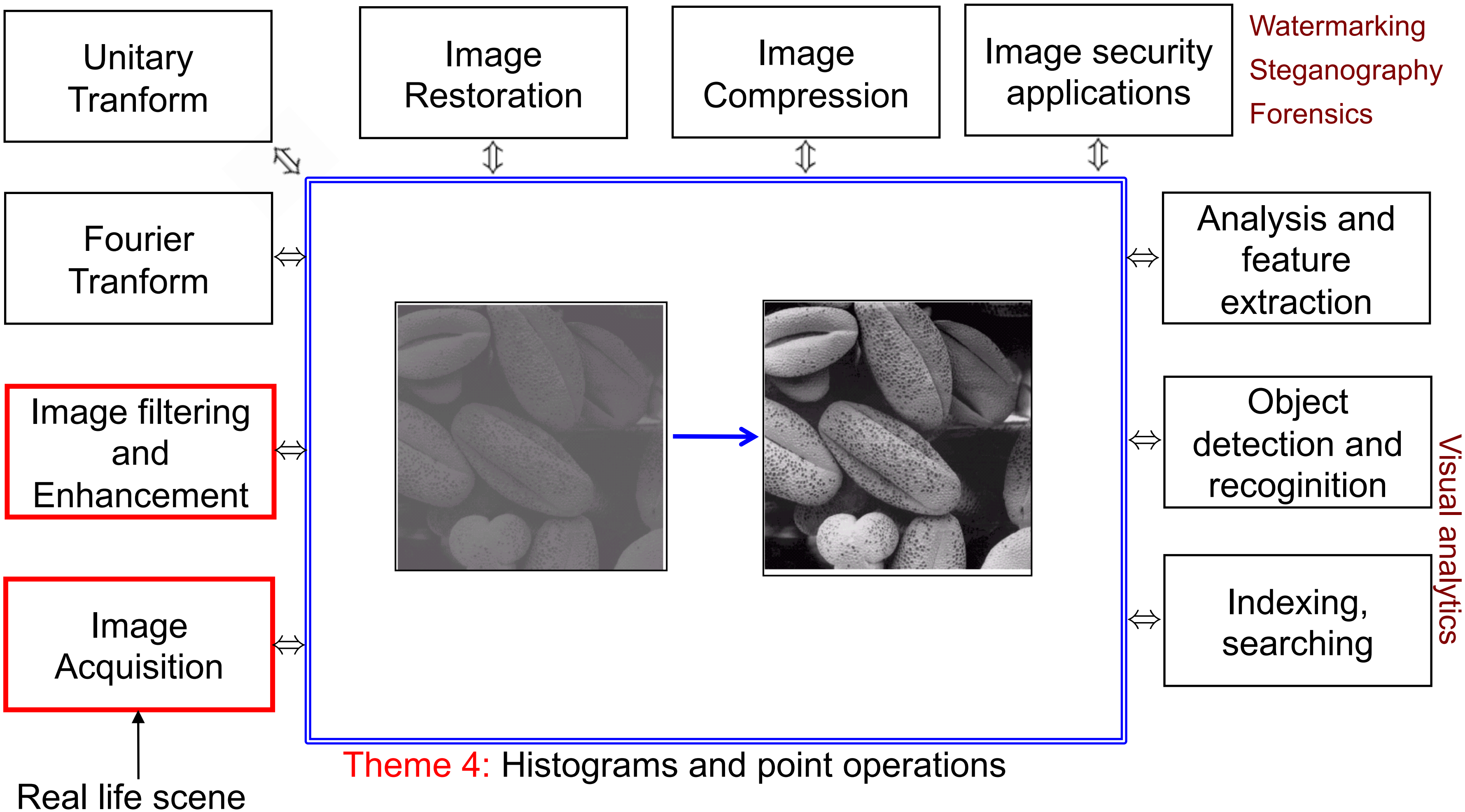
Indexing, searching

Visual analytics

Theme 2: The HVS perception and color

Theme 3: Image acquisition and sensing

# Main elements of image processing systems



# Main elements of image processing systems

Unitary Tranform

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Forensics

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Analysis and feature extraction

Image filtering and Enhancement

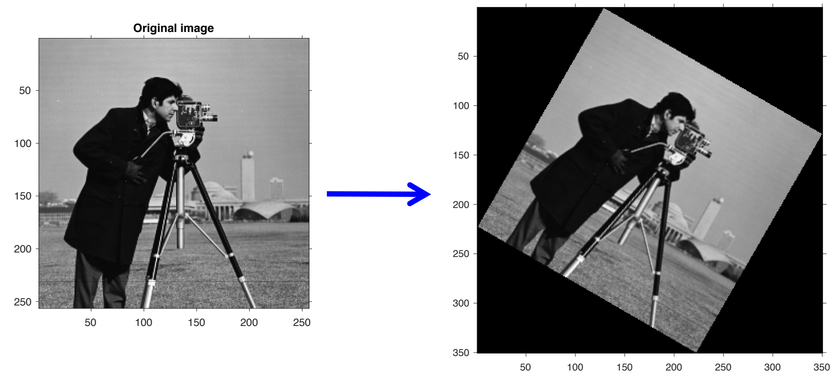
Object detection and recoginition

Image Acquisition

Indexing, searching

Visual analytics

Real life scene




Rotated image

Theme 5: Geometric operations

# Main elements of image processing systems

Unitary Tranform

Image Restoration

Image Compression

Image security applications

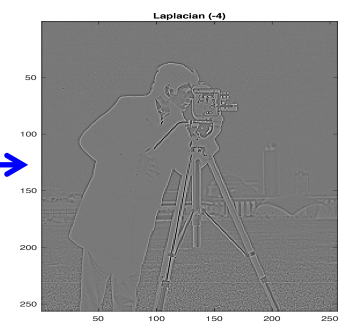
Watermarking
Steganography
Forensics

Fourier Tranform

Image filtering and Enhancement

Image Acquisition

Real life scene


Original image

Laplacian filtering applied to image

Convolving images with different filters

Theme 6: Spatial filters

Analysis and feature extraction

Object detection and recoginition

Indexing, searching

Visual analytics

# Main elements of image processing systems

Unitary Tranform

Image Restoration

Image Compression

Image security applications

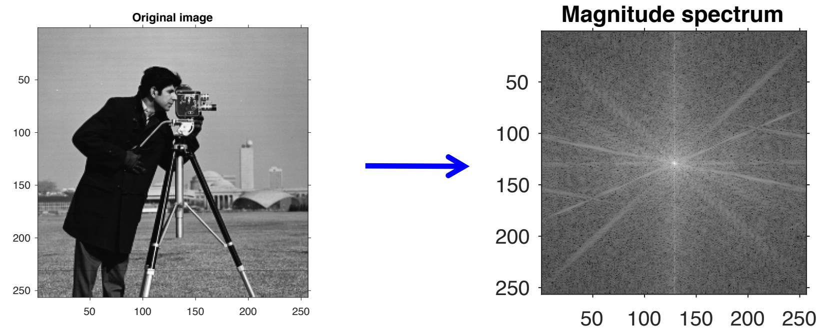
Watermarking
Steganography
Forensics

Fourier Tranform

Image filtering and Enhancement

Image Acquisition

Real life scene




Analysis and feature extraction

Object detection and recoginition

Indexing, searching

Visual analytics

Theme 7: The 2D Discrete Fourier Transform

Theme 8: Frequency domain filtering /sampling and aliasing/

# Main elements of image processing systems

Unitary Tranform

Fourier Tranform

Image filtering and Enhancement

Image Acquisition

Real life scene

Image Restoration

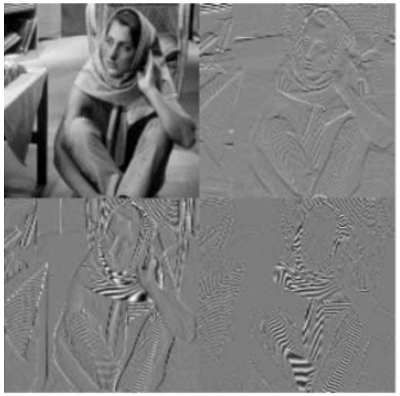
Image Compression

Image security applications

Watermarking
Steganography
Forensics

Other useful transforms such as:

- KLT
- DCT
- Wavelet



Analysis and feature extraction

Object detection and recoginition

Indexing, searching

Visual analytics

Lecture 9: Multiresolution Transforms

# Main elements of image processing systems

Unitary Tranform

Image Restoration

Image Compression

Image security applications

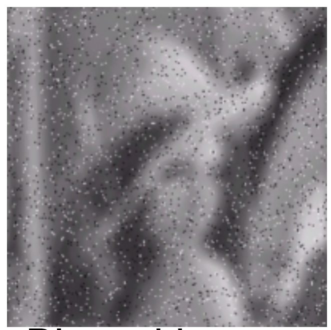
Watermarking
Steganography
Forensics

Fourier Tranform

Image filtering and Enhancement

Image Acquisition

Real life scene



Blurred image

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}$$

Restored image

Inverse problem solution

Deterministic methods

Probabilistic methods

Machine learning methods

Image restoration

Analysis and feature extraction

Object detection and recogінition

Indexing, searching

Visual analytics

# Main elements of image processing systems

Unitary Tranform

Image Restoration

Image Compression

Image security applications

Watermarking
Steganography
Forensics

Fourier Tranform

Image filtering and Enhancement

Image Acquisition

Real life scene

Noisy image

$$\mathbf{y} = \mathbf{x} + \mathbf{z}$$

$$\mathbf{H} = \mathbf{I}$$

Restored/denoised image

Inverse problem solution

Deterministic methods

Probabilistic methods

Machine learning methods

Image denoising

Analysis and feature extraction

Object detection and recoginition

Indexing, searching

Visual analytics

# Main elements of image processing systems

Unitary Tranform

Image Restoration

Image Compression

Image security applications

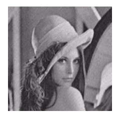
Watermarking
Steganography
Forensics

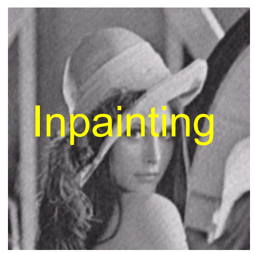
Fourier Tranform

Image filtering and Enhancement

Image Acquisition

Real life scene






Inverse problems

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}$$

difference in the operator $\mathbf{H}$

Restored image

Analysis and feature extraction

Object detection and recoginitition

Indexing, searching

Visual analytics

Other inverse problems: super-resolution, compressive sampling inpainting, demosaicing

# Main elements of image processing systems

Unitary Tranform

Image Restoration

Image Compression

Image security applications

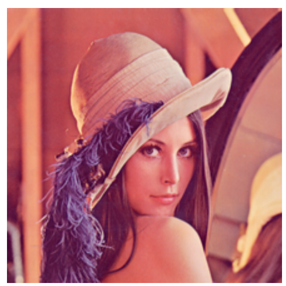
Watermarking
Steganography
Forensics

Fourier Tranform

Image filtering and Enhancement

Image Acquisition

Real life scene



Original image

Compressed image

Analysis and feature extraction

Object detection and recoginition

Indexing, searching

Visual analytics

Theme 10: Lossless image coding

Theme 11: Lossy image compression

# Main elements of image processing systems

Unitary Tranform

Image Restoration

Image Compression

Image security applications

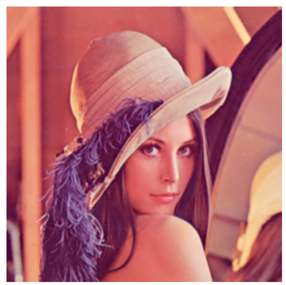
Watermarking
Steganography
Forensics

Fourier Tranform

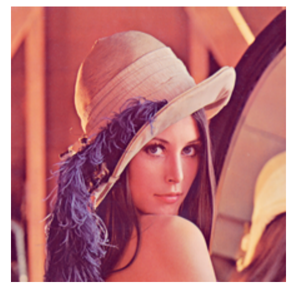
Image filtering and Enhancement

Image Acquisition

Real life scene



Original image



Copyrighted image (secret date inside)


Image security applications

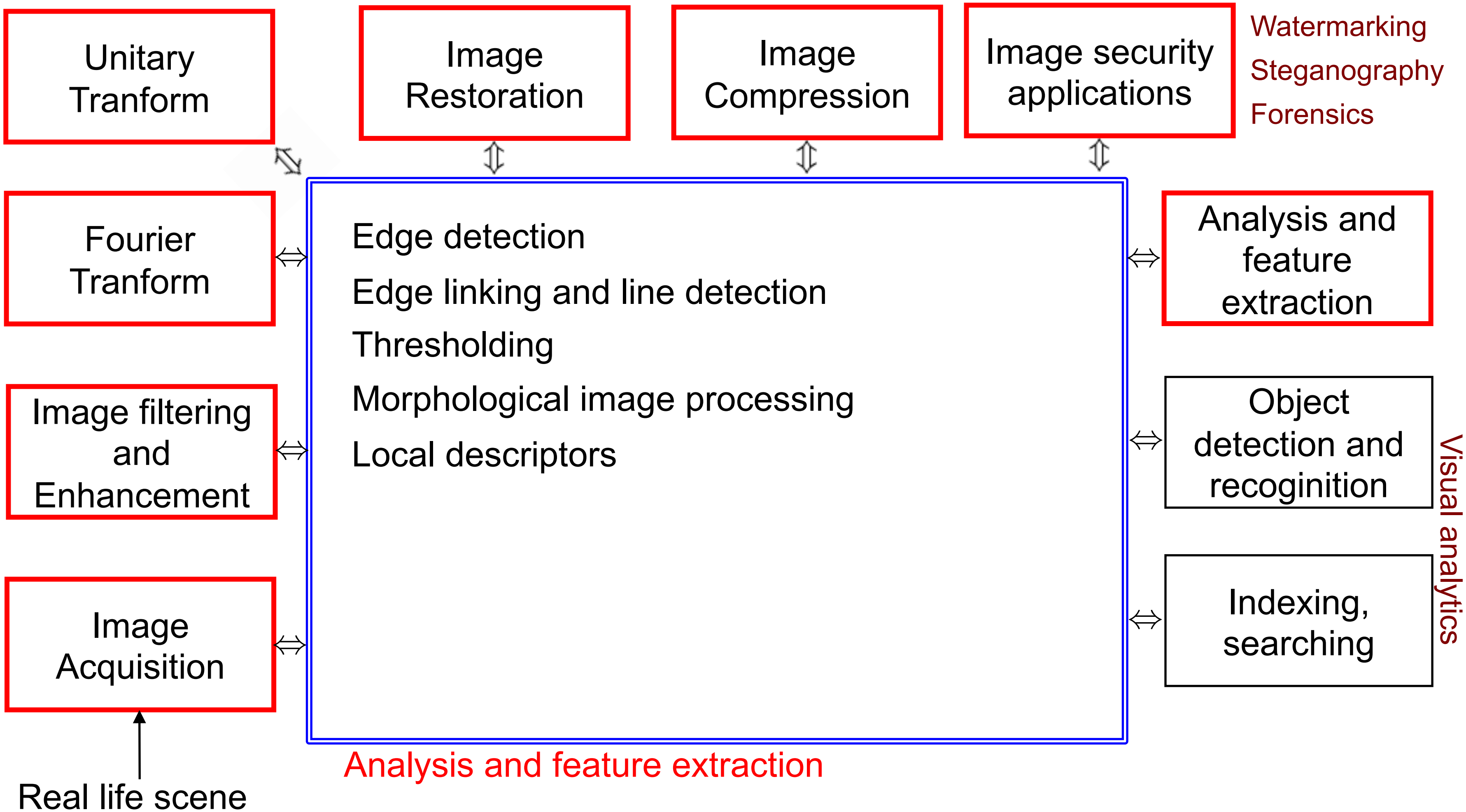
Analysis and feature extraction

Object detection and recogintion

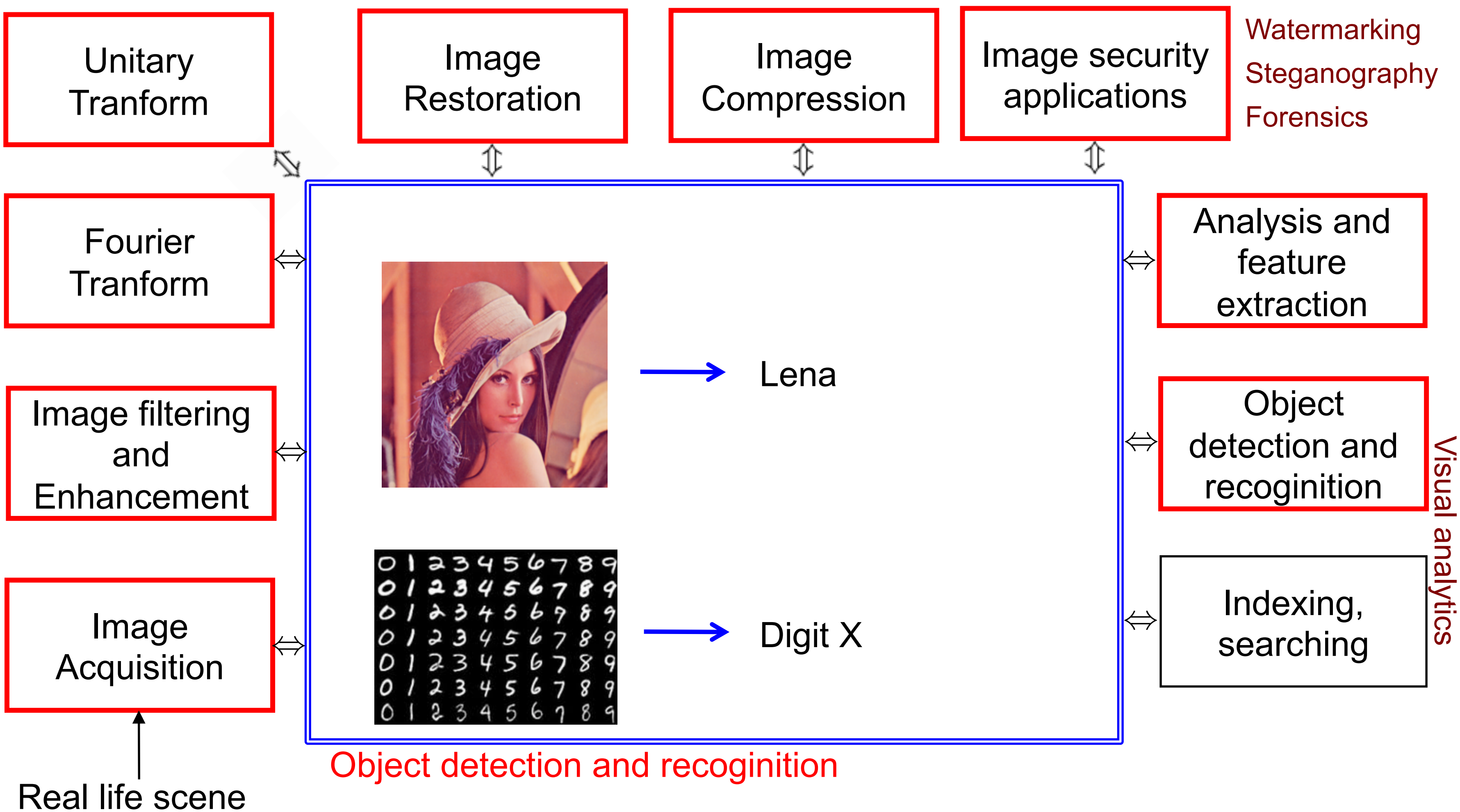
Indexing, searching

Visual analytics

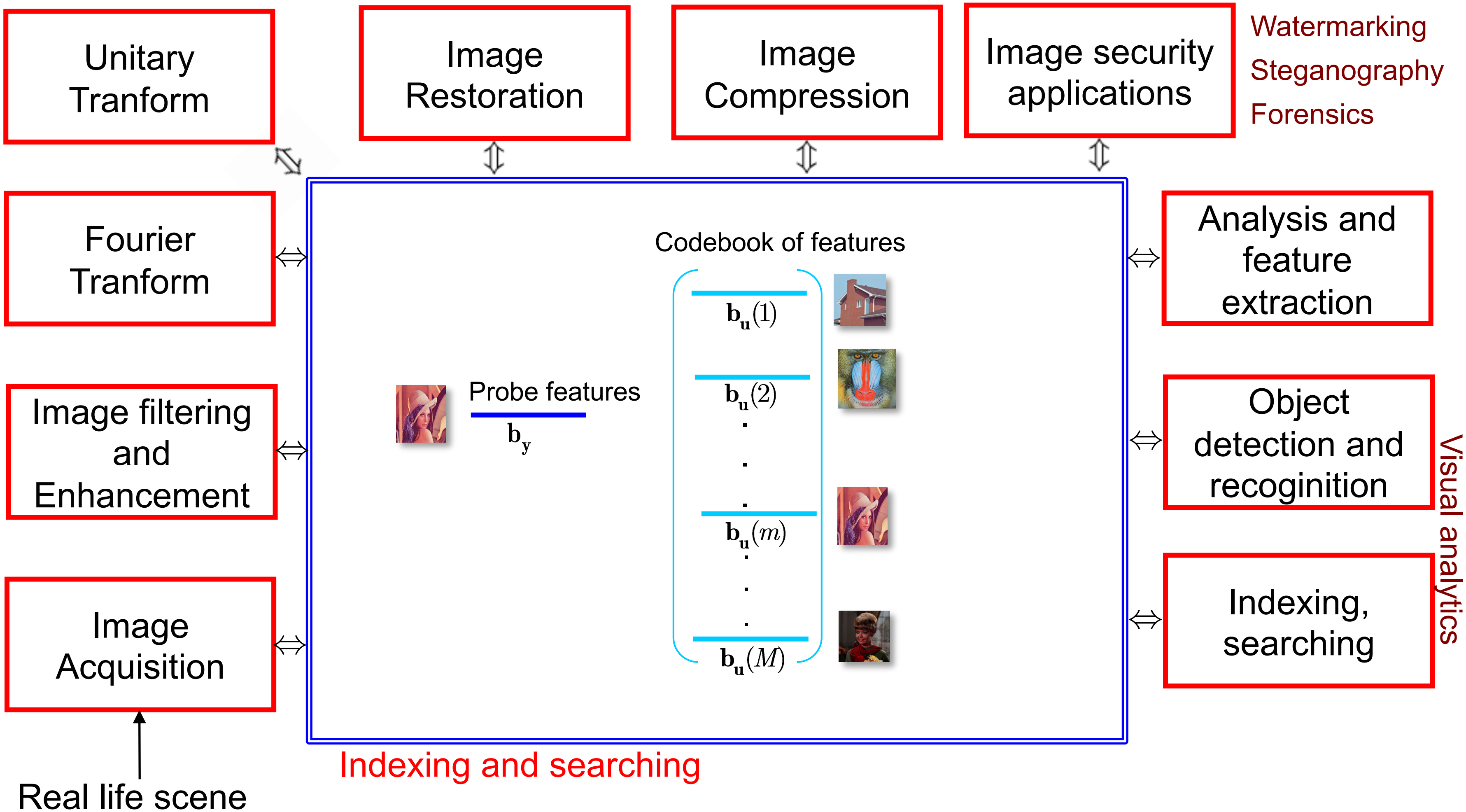
# Main elements of image processing systems



# Main elements of image processing systems



# Main elements of image processing systems



# Goal of course

Despite different applications, existing solutions and used particular methods, there are a few powerful, basic principles that can be used to guide the design of image processing algorithms.

The goal of this course is to introduce these concepts and to investigate their applicability to Image Processing.

# Applications of image processing

- Medical Imaging
- Multimedia security, privacy, trust, digital forensics
- Biometrics
- Astronomy
- Industrial inspections
- Remote sensing and imaging
- Human computer interfaces
- Digital photography and more recently mobile imaging
- Self-driving cars and robots (as part of artificial intelligence systems)

**See Appendix A**

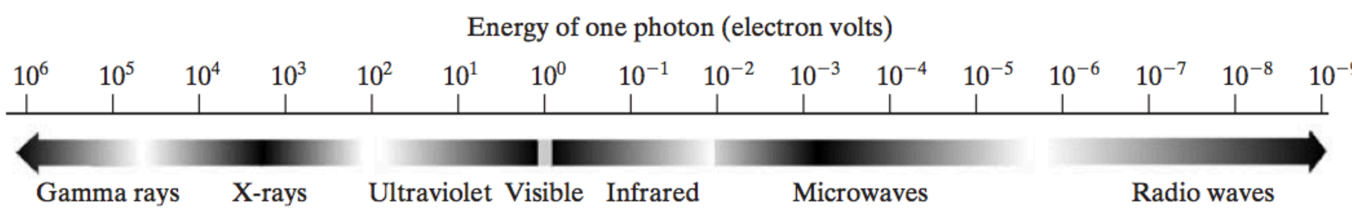



**FIGURE 1.5** The electromagnetic spectrum arranged according to energy per photon.

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# Applications of image processing

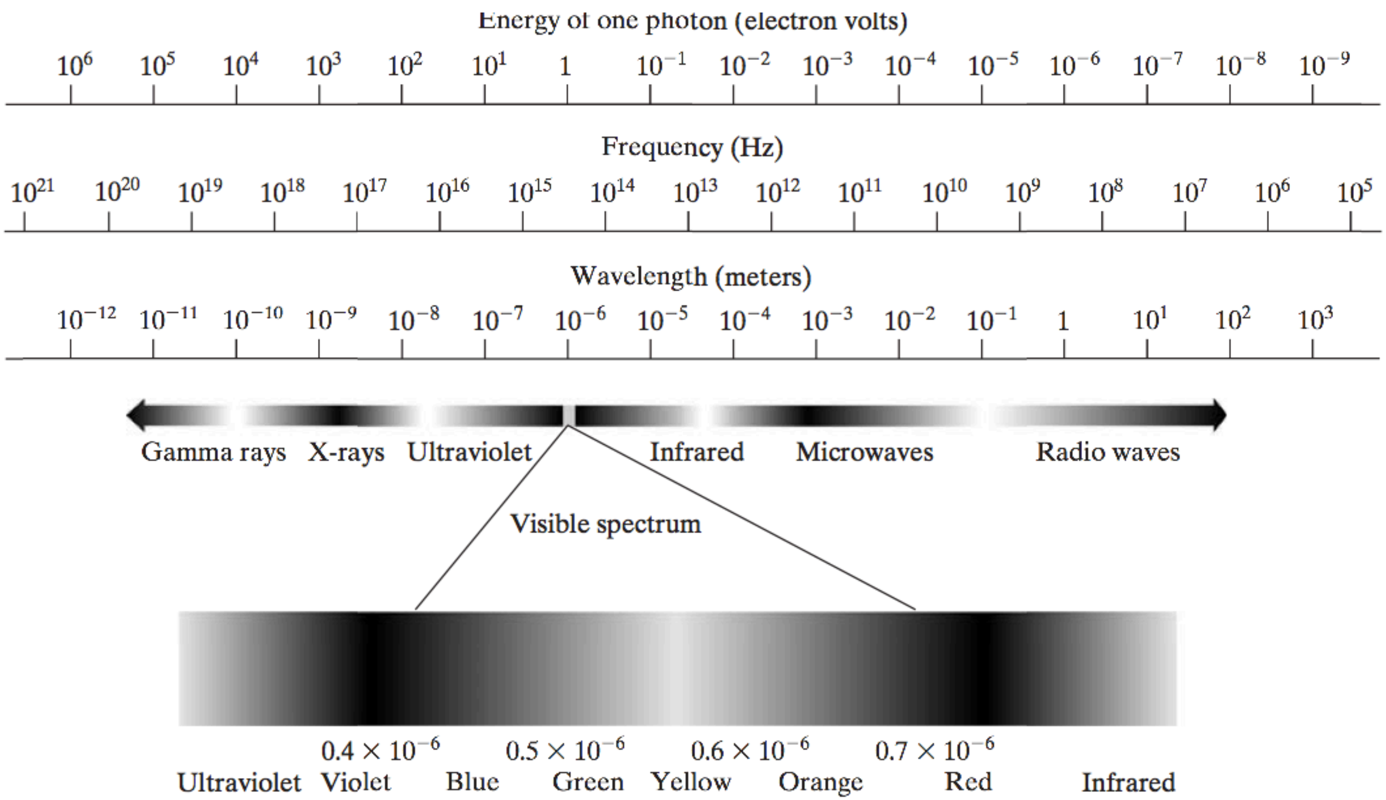


**FIGURE 2.10** The electromagnetic spectrum. The visible spectrum is shown zoomed to facilitate explanation, but note that the visible spectrum is a rather narrow portion of the EM spectrum.

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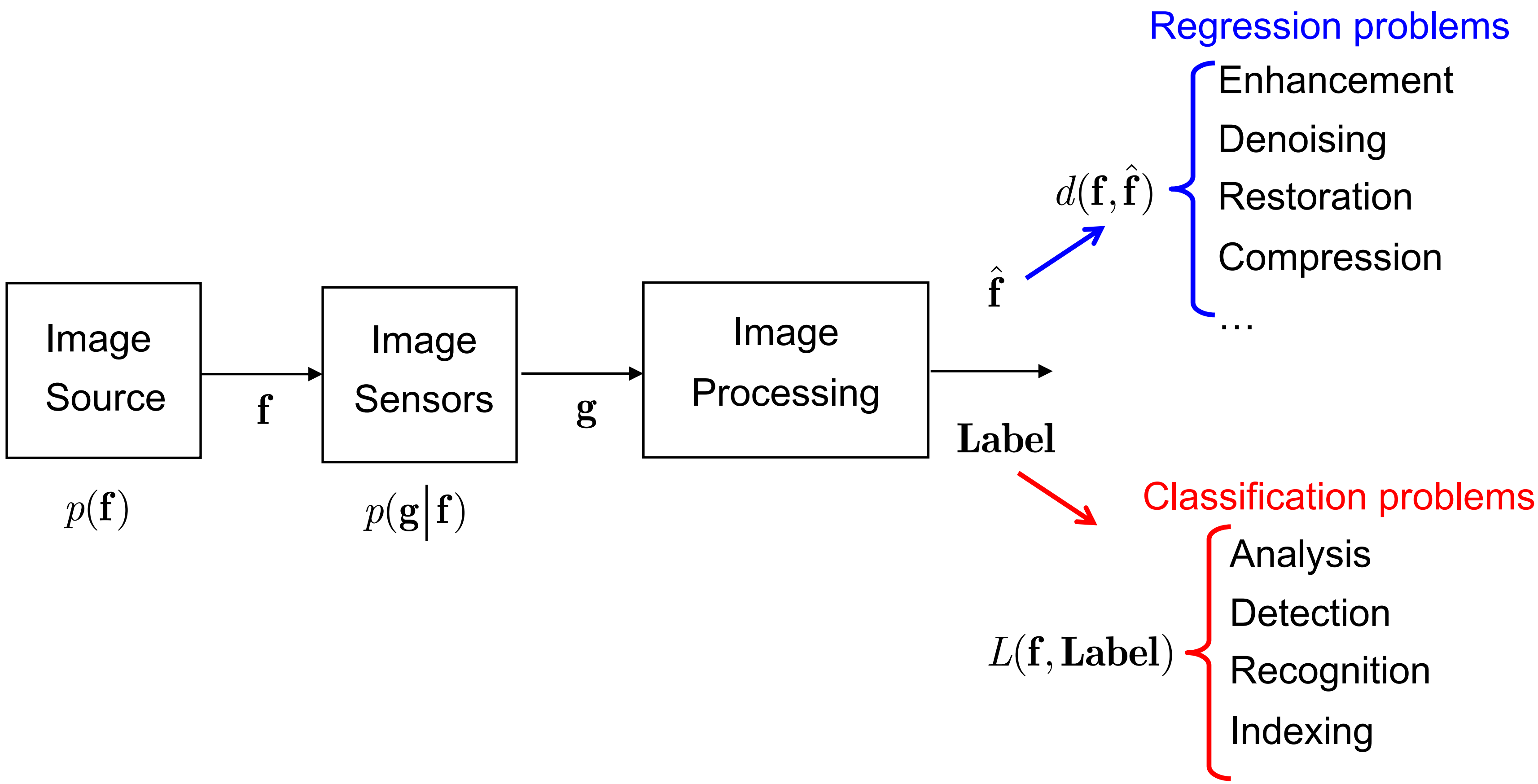
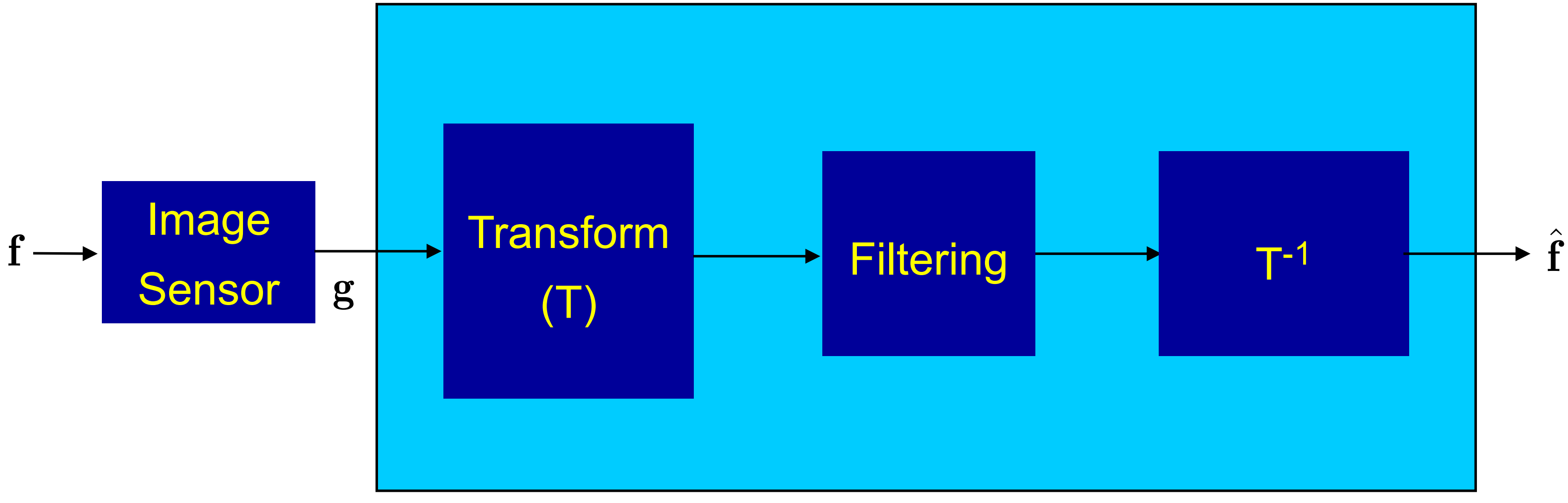
# Analytical framework of this course



# Analytical framework of this course

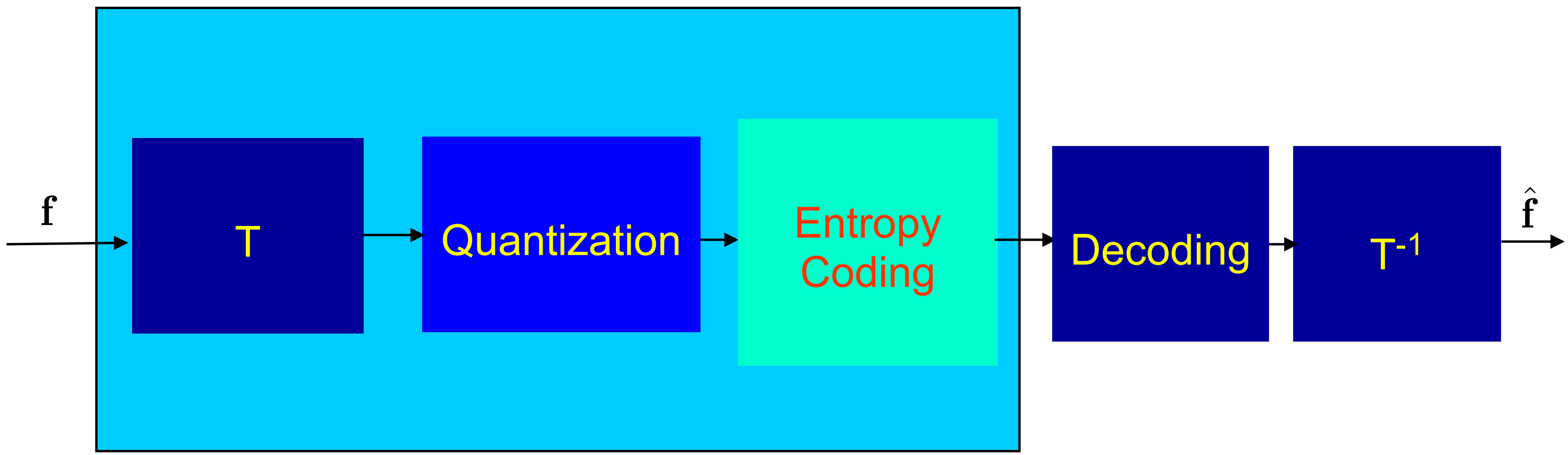
**Regression problems: Restoration, Denoising and Enhancement**




- Define the cost function or similarity measure $d(\mathbf{f}, \hat{\mathbf{f}})$
- Define transform T
  - Analytically (Fourier, Wavelets, etc) or hand-crafted approach
  - Learn from training data – machine learning approach
- Define filtering based on statistics of data and distortion

# Analytical framework of this course

## Regression problems: Image compression

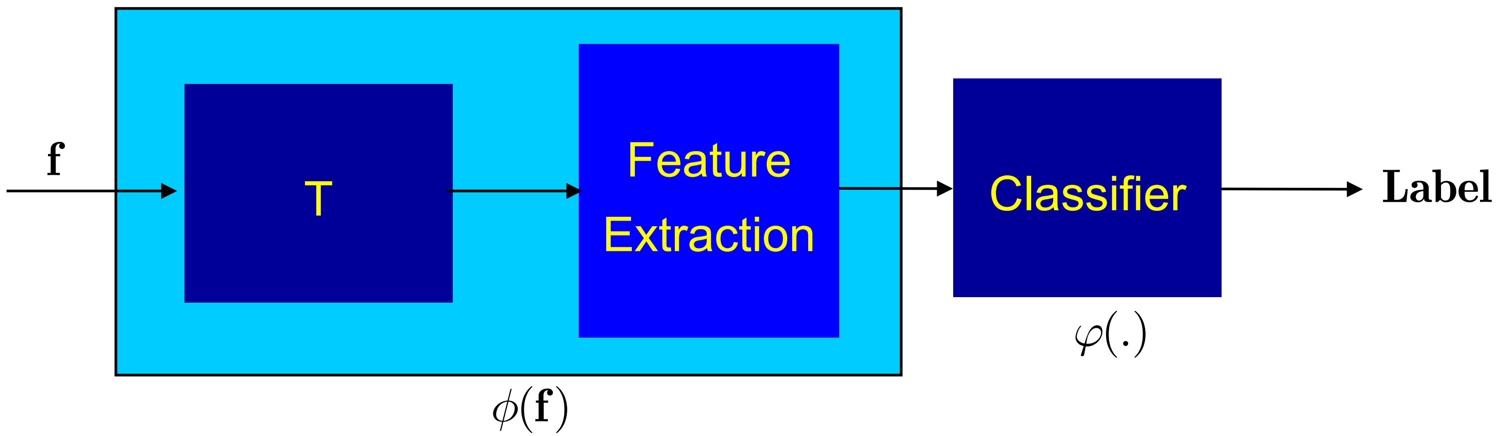



- Define the cost function or similarity measure $d(\mathbf{f}, \hat{\mathbf{f}})$
- Define transform T
  - Analytically (Fourier, Wavelets, etc) or hand-crafted approach
  - Learn from training data – machine learning approach
- Define quantization based on statistics of data

# Analytical framework of this course

**Classification: detection, recognition, indexing**

Hand-crafted feature design (previous systems mostly in Computer Vision)

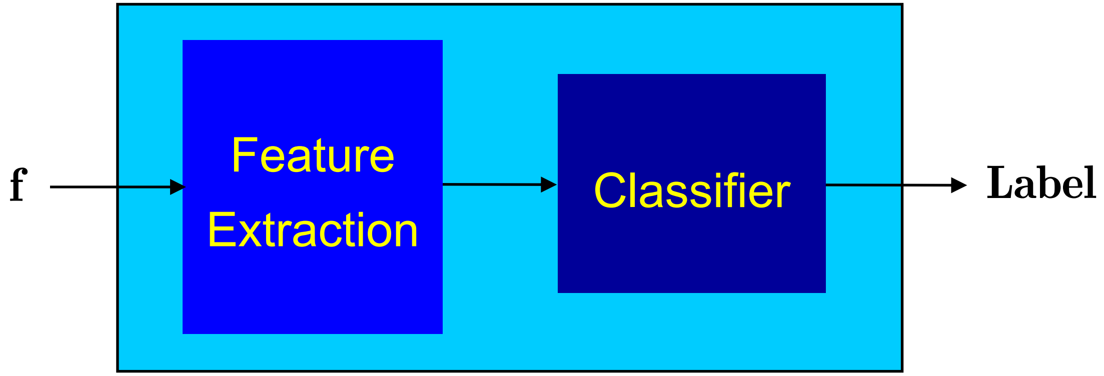



- Define the cost function or similarity measure $L(\varphi\left(\phi(\mathbf{f})\right), \mathbf{Label})$
- Define transform T
- Define features and their aggregation
- Define classifier based on training data $\left\{\mathbf{f}_i, \mathbf{Label}_i\right\}_{i=1}^{N}$

# Analytical framework of this course

## Classification: detection, recognition, indexing

Modern approach: joint feature extraction and classification




- Joint learning of feature extraction and classification $L(\underbrace{\varphi\big(\phi(\mathbf{f})\big)}_{\varphi_\theta(\mathbf{f})}, \mathbf{Label})$
  using training data $\left\{\mathbf{f}_i, \mathbf{Label}_i\right\}_{i=1}^{N}$

There is "no separation" on features, transform as such.

All modules are learned automatically without "human" intervention.

# What we need to know

- Understand the concept of a digital image
- Understand the definition and scope of digital image processing
- Know the fundamentals of the electromagnetic spectrum and its relationship to image generation
- Have a general understanding about the image acquisition and processing
- Know the main fields of image processing applications
- Understand the basic architectures of image processing systems and their main components

# Appendix A

# Gamma-ray imaging

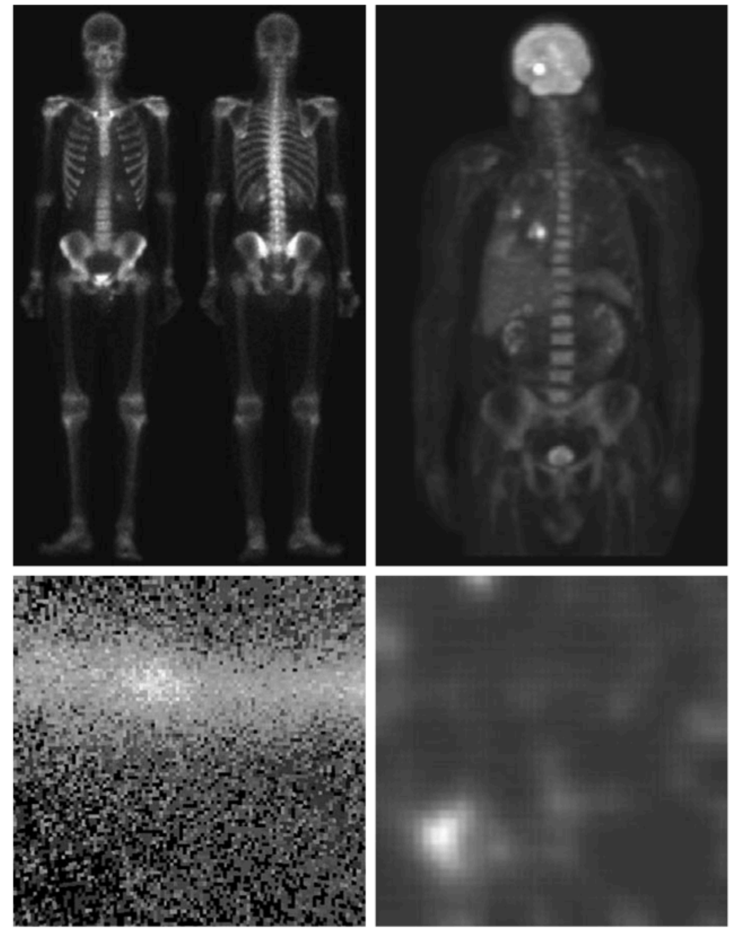
Nuclear medicine imaging:

(positron emission tomography (PET))

- Injecting radioactive isotope emitting gamma ray
- Register gamma rays

Astronomy:

- Images are obtained by a natural radiation (no added isotope)



a b
c d

**FIGURE 1.6** Examples of gamma-ray imaging. (a) Bone scan. (b) PET image. (c) Cygnus Loop. (d) Gamma radiation (bright spot) from a reactor valve. (Images courtesy of (a) G.E. Medical Systems, (b) Dr. Michael E. Casey, CTI PET Systems, (c) NASA, (d) Professors Zhong He and David K. Wehe, University of Michigan.)

Gonzalez, p. 8

# X-ray imaging

Medical diagnostics

Industrial inspections

X-ray imaging in astronomy

Registration on:

- Emission by special X-ray tube (free electrons)
- Registration on special films (old)
- Nowadays, CCD arrays

Extension to computerized axial tomography (CAT) – 3D

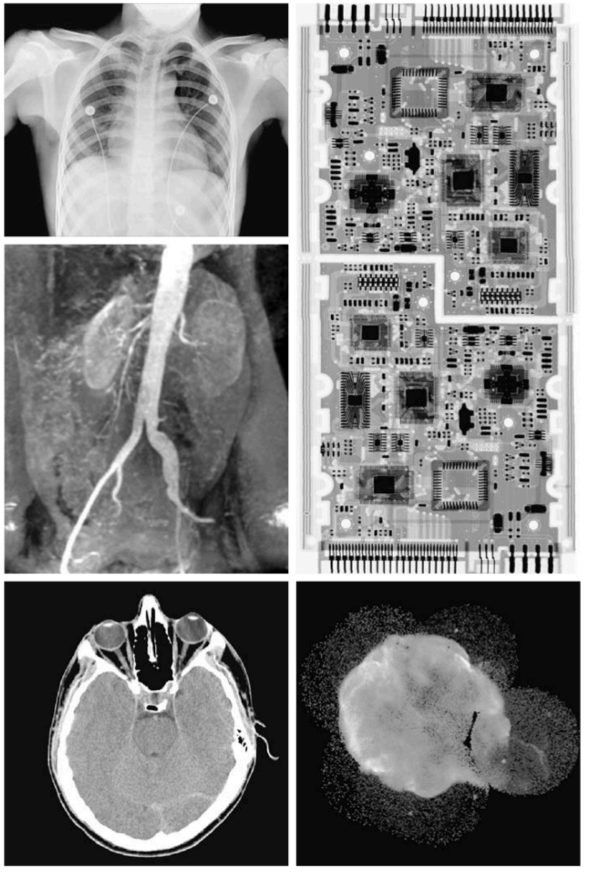



**FIGURE 1.7** Examples of X-ray imaging. (a) Chest X-ray. (b) Aortic angiogram. (c) Head CT. (d) Circuit boards. (e) Cygnus Loop. (Images courtesy of (a) and (c) Dr. David R. Pickens, Dept. of Radiology & Radiological Sciences, Vanderbilt University Medical Center; (b) Dr. Thomas R. Gest, Division of Anatomical Sciences, University of Michigan Medical School; (d) Mr. Joseph E. Pascente, Lixi, Inc.; and (e) NASA.)

Gonzalez, p. 10

# X-ray imaging

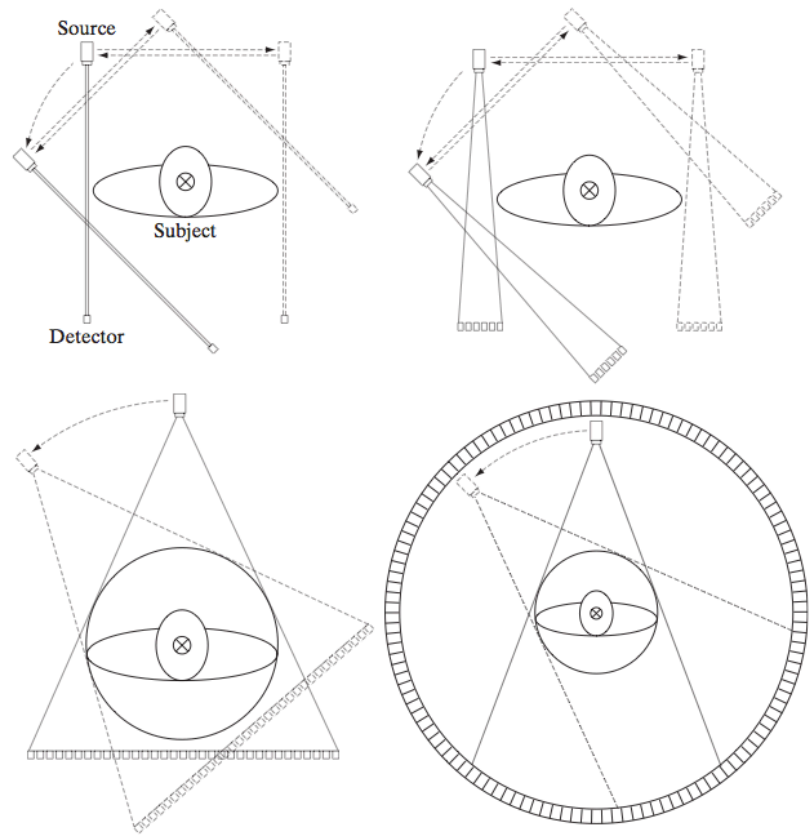
Medical diagnostics

Industrial inspections

Extension to computerized axial tomography (CAT) – 3D

a b
c d

**FIGURE 5.35** Four generations of CT scanners. The dotted arrow lines indicate incremental linear motion. The dotted arrow arcs indicate incremental rotation. The cross-mark on the subject's head indicates linear motion perpendicular to the plane of the paper. The double arrows in (a) and (b) indicate that the source/detector unit is translated and then brought back into its original position.

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# X-ray imaging

Medical diagnostics

Industrial inspections

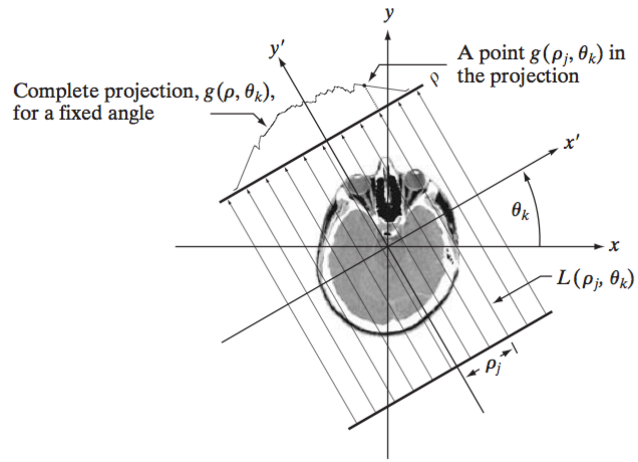
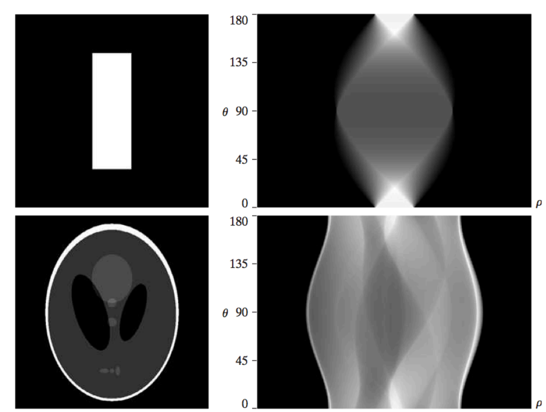


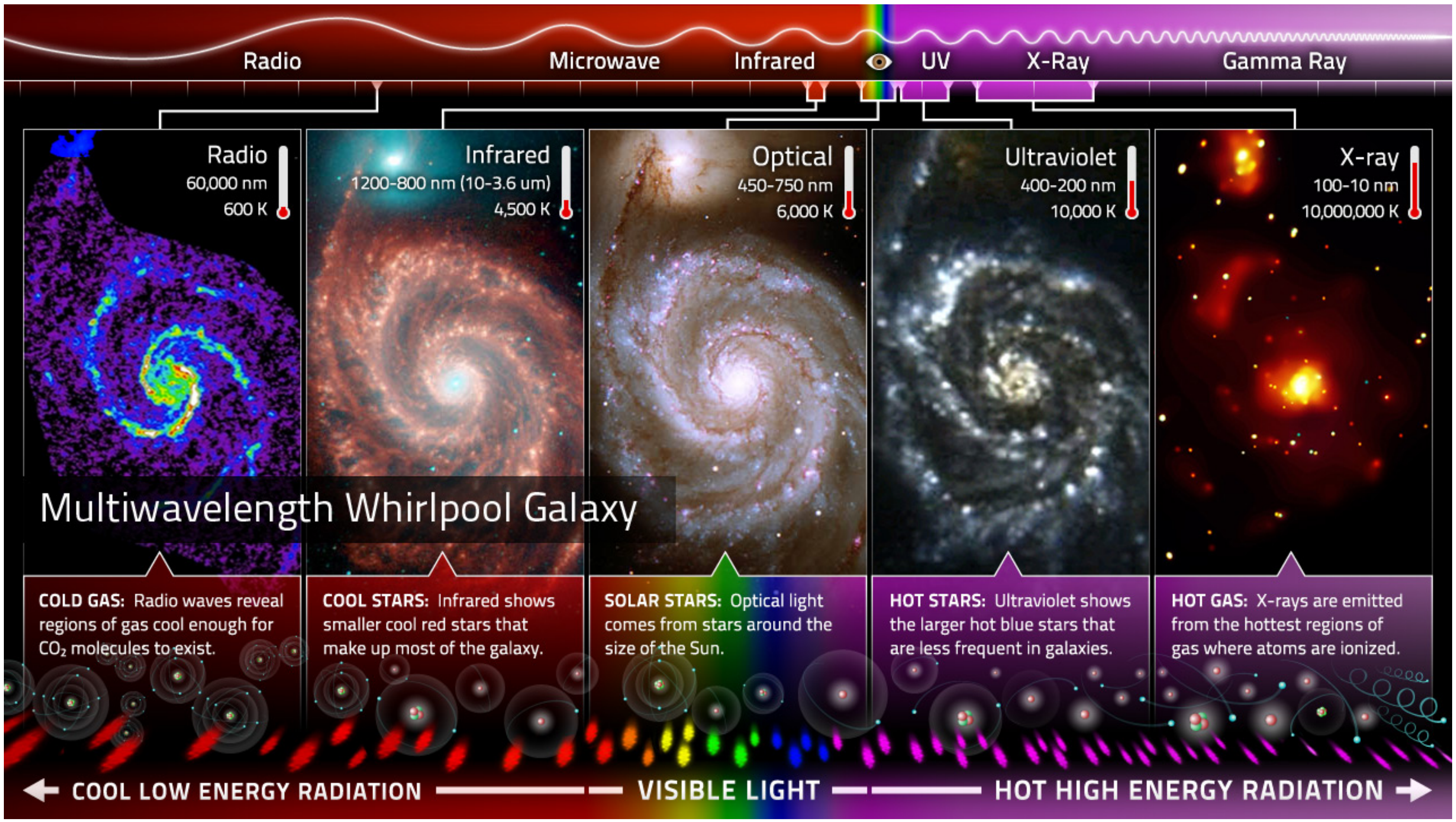

**FIGURE 5.37** Geometry of a parallel-ray beam.




Gonzalez, p. 369 and 372

# A word on astronomical imaging

The same physical phenomena might look completely differently in different bands




http://ecuip.lib.uchicago.edu/multiwavelength-astronomy/images/astrophysics/MWA-whirlpool-galaxy.jpg

# Ultraviolet imaging

Industrial inspections

Microscopy

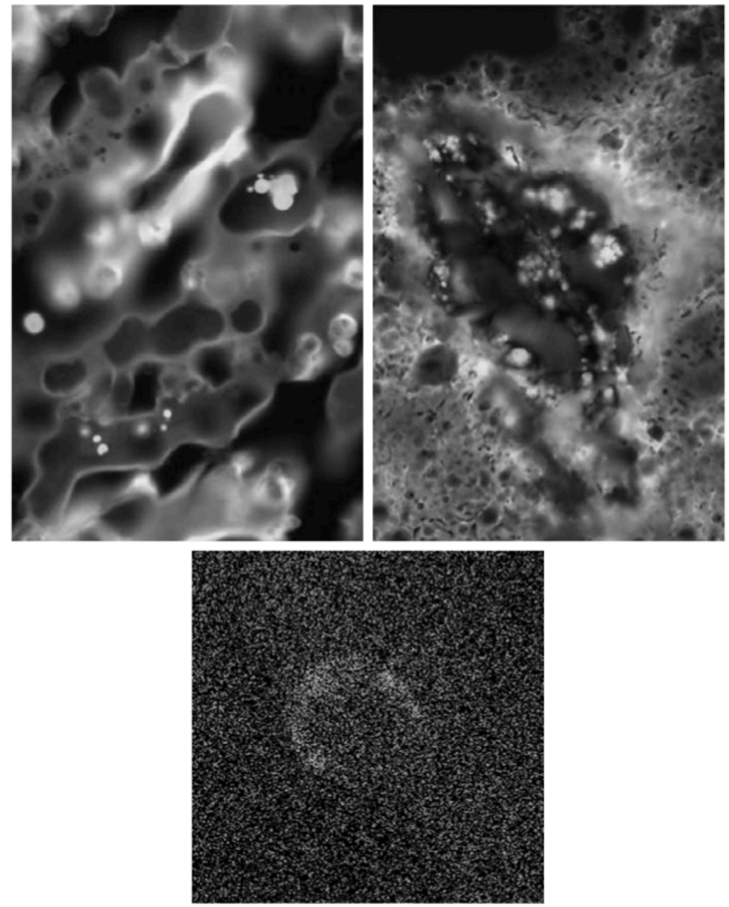
Lasers

Biological imaging

Astronomical observations

a b
c

**FIGURE 1.8** Examples of ultraviolet imaging. (a) Normal corn. (b) Smut corn. (c) Cygnus Loop. (Images courtesy of (a) and (b) Dr. Michael W. Davidson, Florida State University, (c) NASA.)



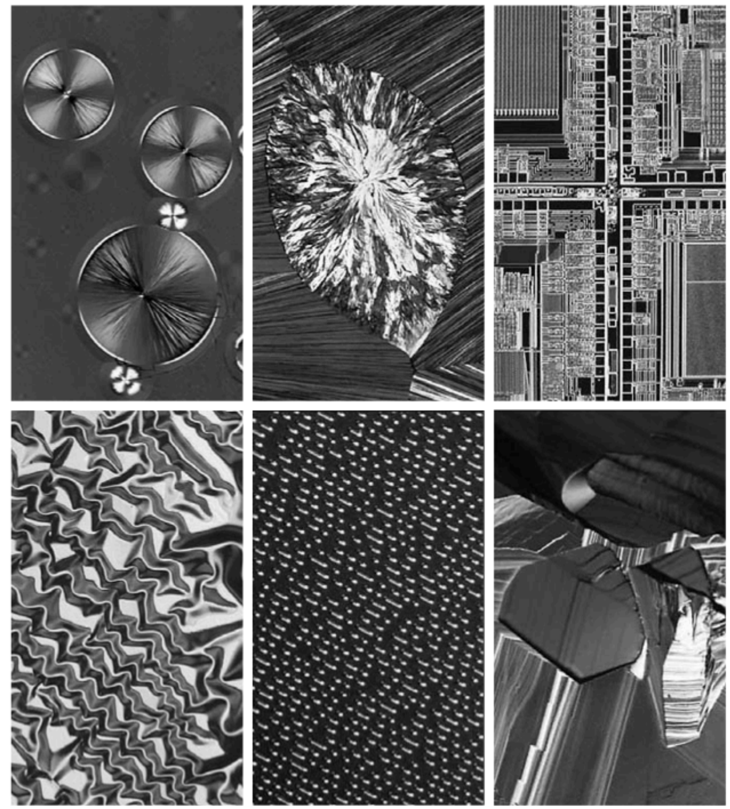
Fluorescence microscopy

uses directed ultraviolet light and observation in the same or different band by separaing a weak reflected light

Gonzalez, p. 12

# Imaging in the visible and infrared bands

Light microscopy



a b c
d e f

**FIGURE 1.9** Examples of light microscopy images. (a) Taxol (anticancer agent), magnified 250×. (b) Cholesterol—40×. (c) Microprocessor—60×. (d) Nickel oxide thin film—600×. (e) Surface of audio CD—1750×. (f) Organic superconductor—450×. (Images courtesy of Dr. Michael W. Davidson, Florida State University.)

Gonzalez, p. 13

# Imaging in the visible and infrared bands

Remote sensing in various subbands

**TABLE 1.1** Thematic bands in NASA's LANDSAT satellite.

| Band No. | Name | Wavelength (μm) | Characteristics and Uses |
|---|---|---|---|
| 1 | Visible blue | 0.45–0.52 | Maximum water penetration |
| 2 | Visible green | 0.52–0.60 | Good for measuring plant vigor |
| 3 | Visible red | 0.63–0.69 | Vegetation discrimination |
| 4 | Near infrared | 0.76–0.90 | Biomass and shoreline mapping |
| 5 | Middle infrared | 1.55–1.75 | Moisture content of soil and vegetation |
| 6 | Thermal infrared | 10.4–12.5 | Soil moisture; thermal mapping |
| 7 | Middle infrared | 2.08–2.35 | Mineral mapping |

Gonzalez, p. 14

# Imaging in the visible and infrared bands

## Remote sensing in various subbands

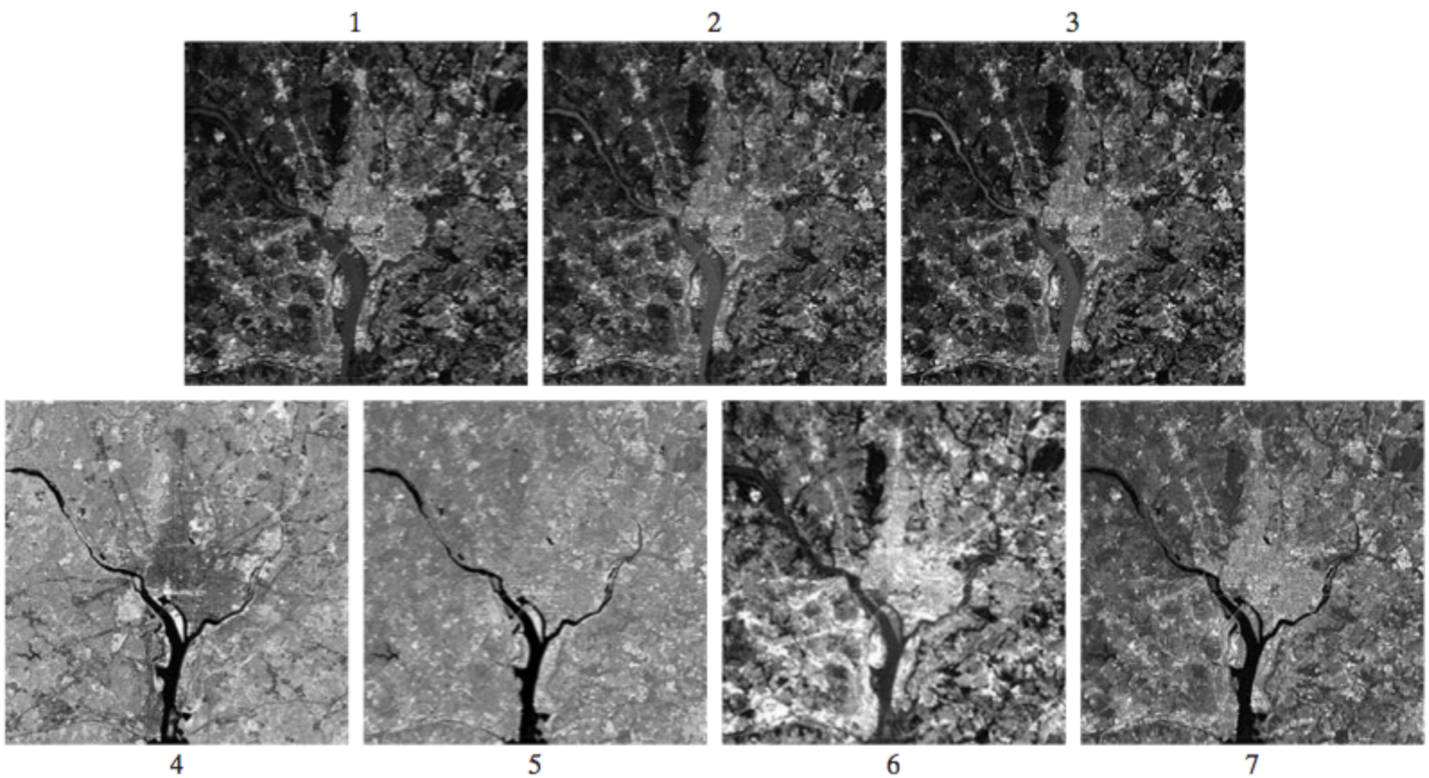


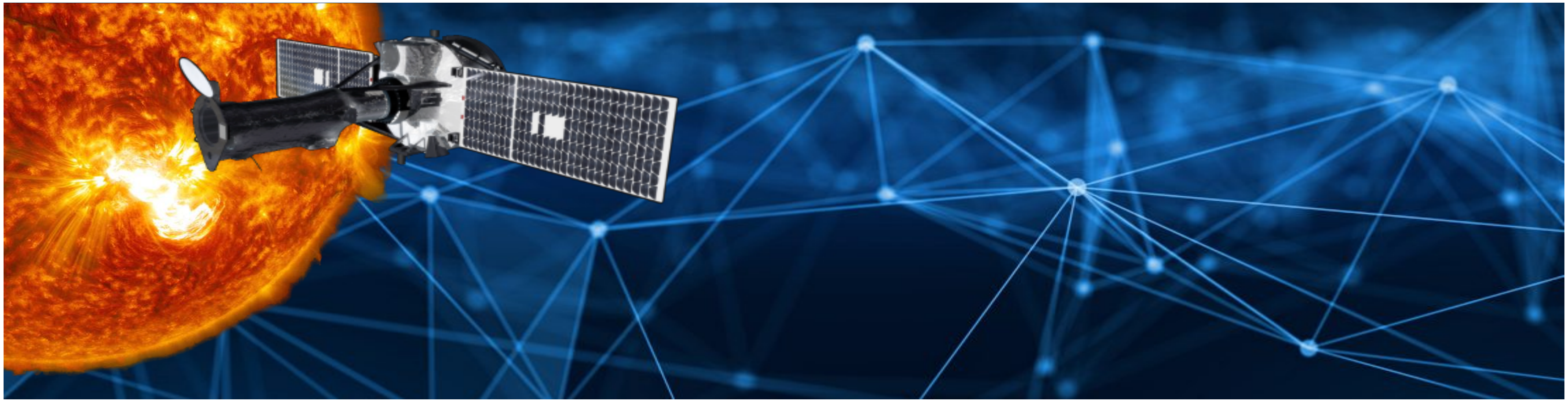

**FIGURE 1.10** LANDSAT satellite images of the Washington, D.C. area. The numbers refer to the thematic bands in Table 1.1. (Images courtesy of NASA.)

Gonzalez, p. 14

# Imaging in the visible and infrared bands

Solar observations

IRIS



UNIGE project:  http://bigastro.unige.ch

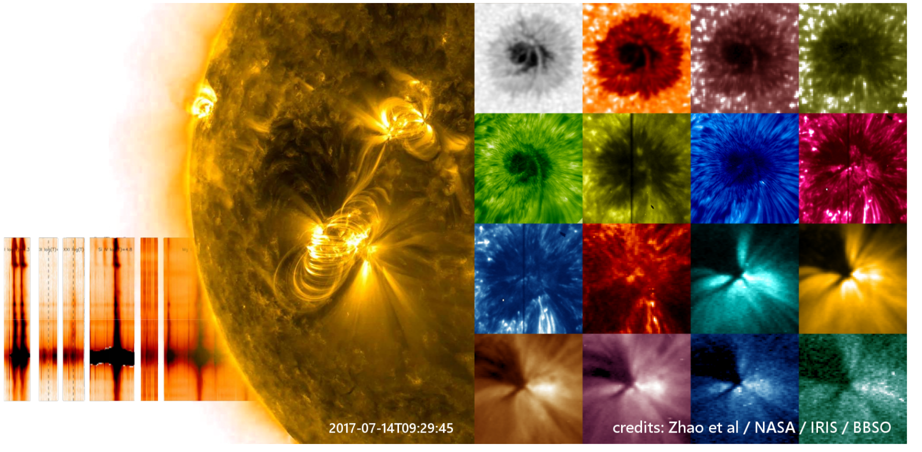
Credit: NASA

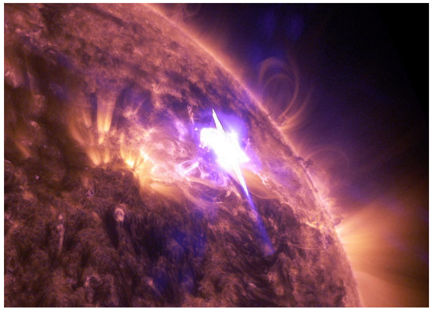
# Imaging in the visible and infrared bands

Solar observations

Information observed from a sun flare

Credit: NASA



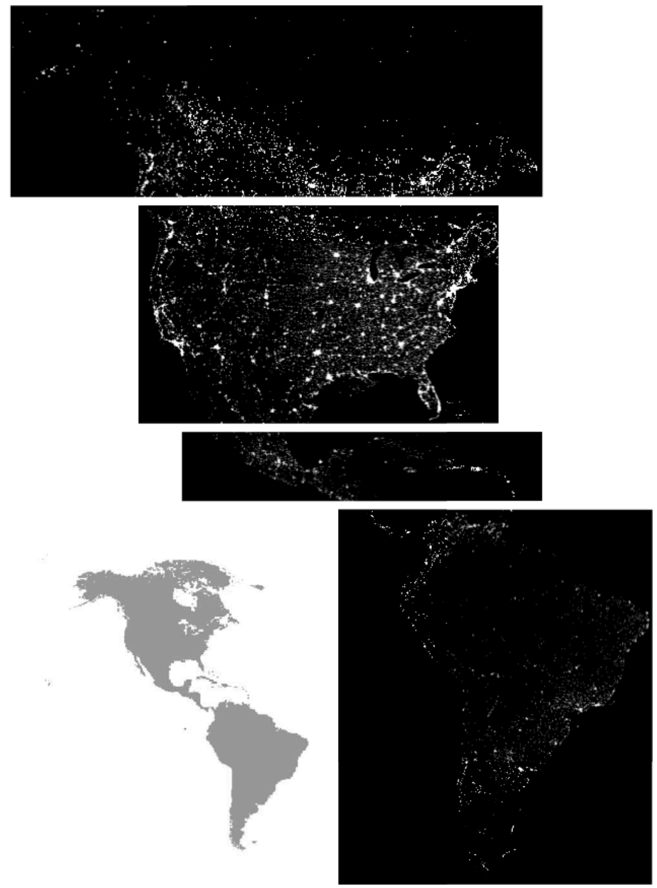
Multi wavelengthes video of a flare observed by SDO

Credits : NASA

# Imaging in the visible and infrared bands

## Infrared remote sensing

**FIGURE 1.12** Infrared satellite images of the Americas. The small gray map is provided for reference. (Courtesy of NOAA.)

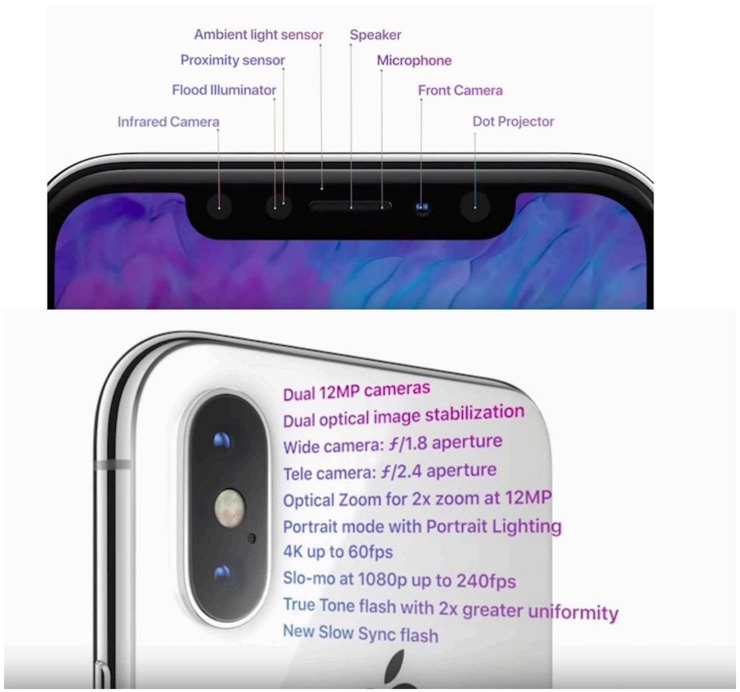


Gonzalez et al, p 16

# Imaging in the visible and infrared bands

Multicamera smart phones

iPhone X




http://www.photographybay.com/2017/09/12/apple-unveils-a-trio-of-iphones-with-impressive-photography-upgrades/

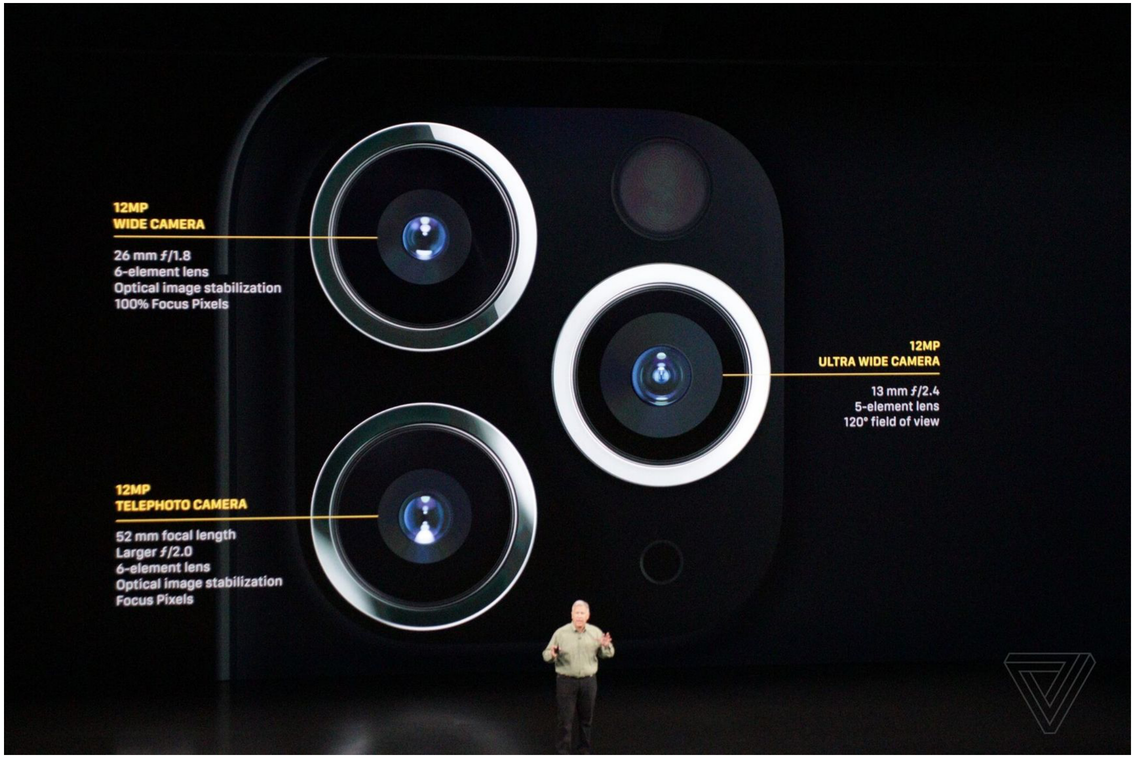
Huawei P20 Pro


https://www.popsci.com/huawei-p20-pro-smartphone-three-cameras

# Imaging in the visible and infrared bands

## Multicamera smart phones

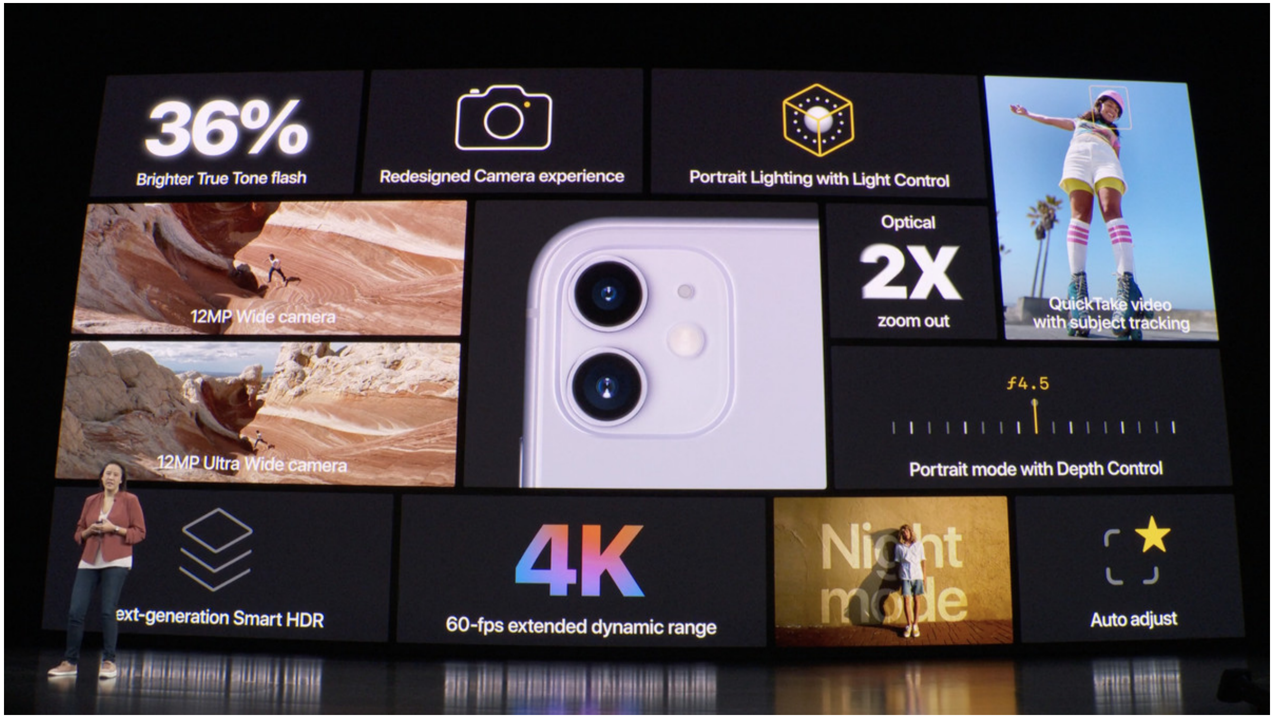
iPhone 11 pro



# Imaging in the visible and infrared bands

## Multicamera smart phones

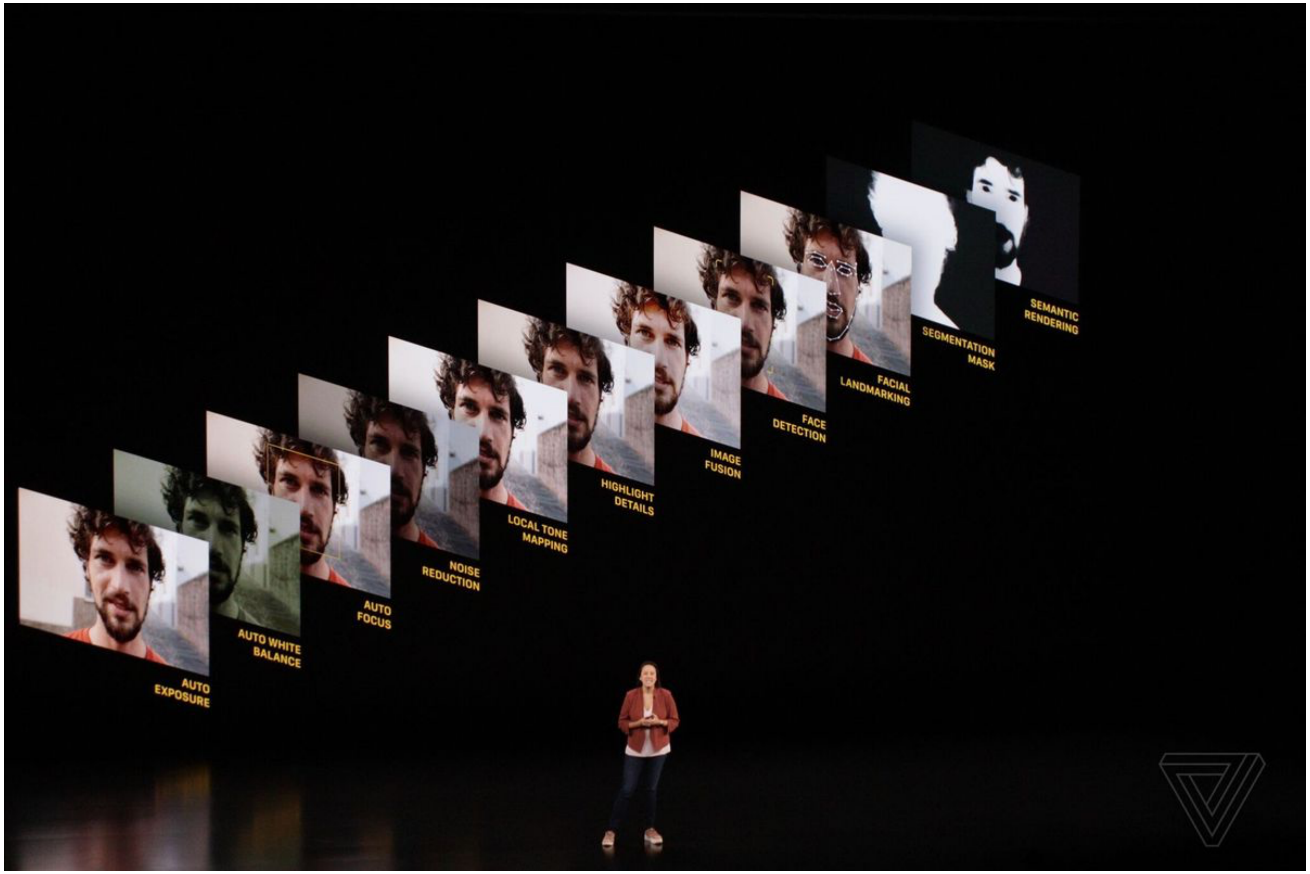
iPhone 11 pro



# Imaging in the visible and infrared bands

Multicamera smart phones

iPhone 11 pro



# Imaging in the visible and infrared bands

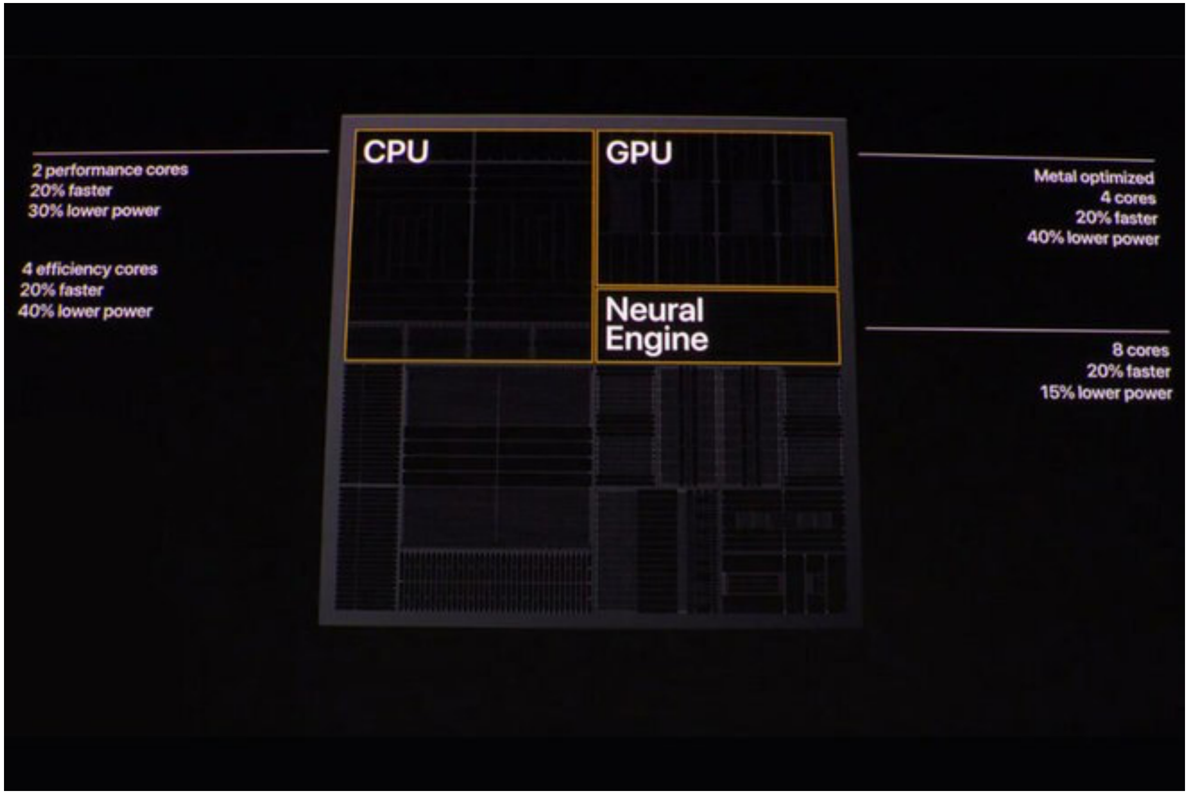
## Multicamera smart phones

iPhone 11 pro

# Imaging in the visible and infrared bands

Multicamera smart phones

iPhone 11 pro



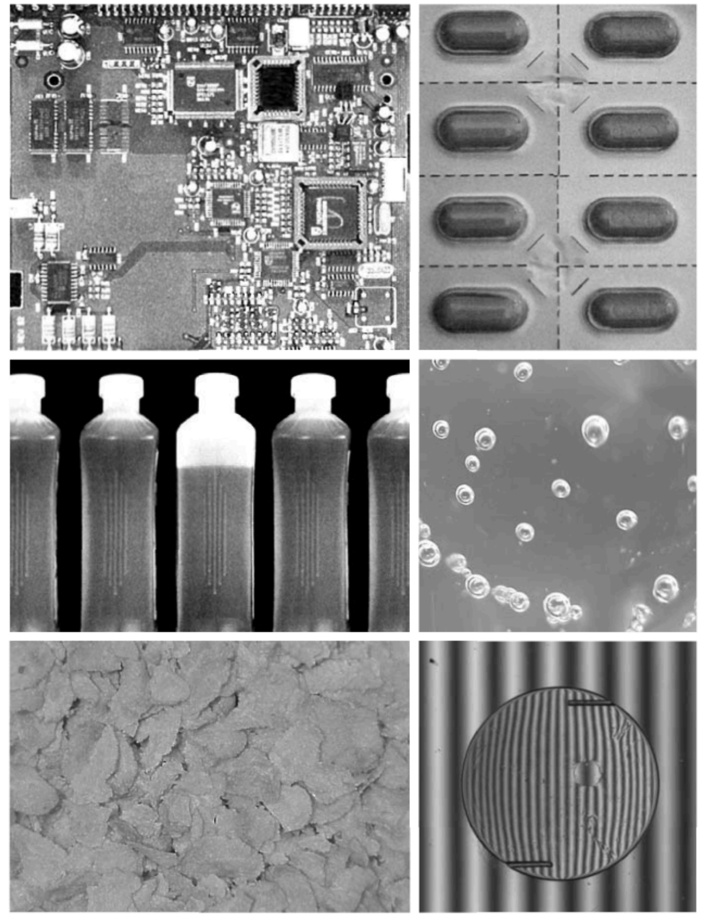
# Imaging in the visible and infrared bands

Multicamera smart phones

iPhone 11 pro

# Imaging in the visible and infrared bands

## Industrial inspection



a b
c d
e f

**FIGURE 1.14** Some examples of manufactured goods often checked using digital image processing. (a) A circuit board controller. (b) Packaged pills. (c) Bottles. (d) Air bubbles in a clear-plastic product. (e) Cereal. (f) Image of intraocular implant. (Fig. (f) courtesy of Mr. Pete Sites, Perceptics Corporation.)

Gonzalez et al, p. 18

# Imaging in the visible and infrared bands

Security applications


a b
c
d

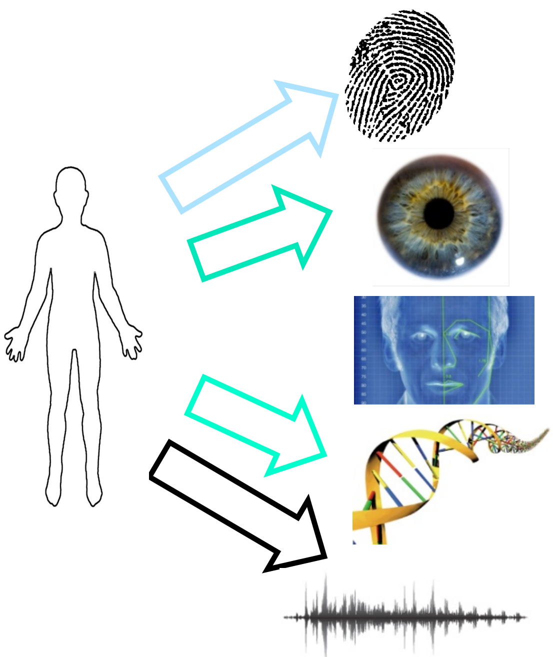
**FIGURE 1.15** Some additional examples of imaging in the visual spectrum. (a) Thumb print. (b) Paper currency. (c) and (d) Automated license plate reading. (Figure (a) courtesy of the National Institute of Standards and Technology. Figures (c) and (d) courtesy of Dr. Juan Herrera, Perceptics Corporation.)

Gonzalez et al, p. 19

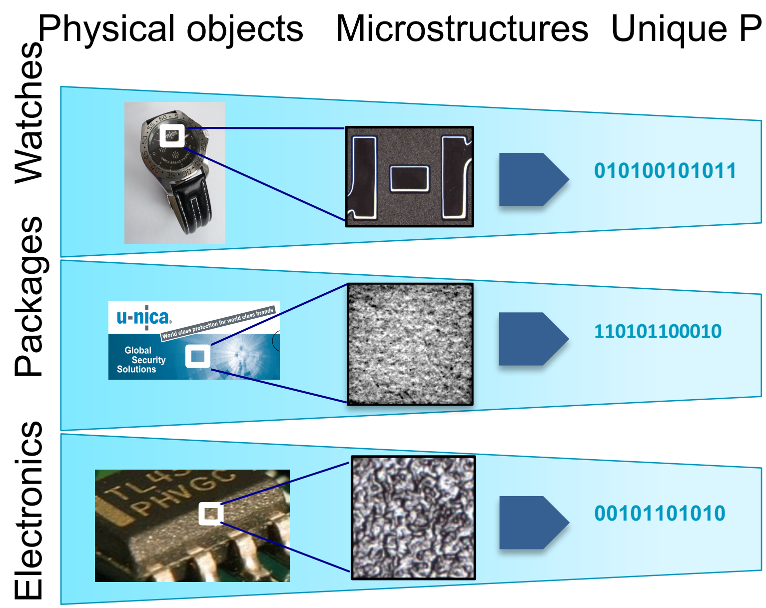
# Imaging in the visible and infrared bands

## Security applications

### Humans = biometrics



### Physical Objects




**All physical objects are unique like humans**

# Imaging in the visible and infrared bands

Security applications –
object identification

Paper microstructures =PUFs

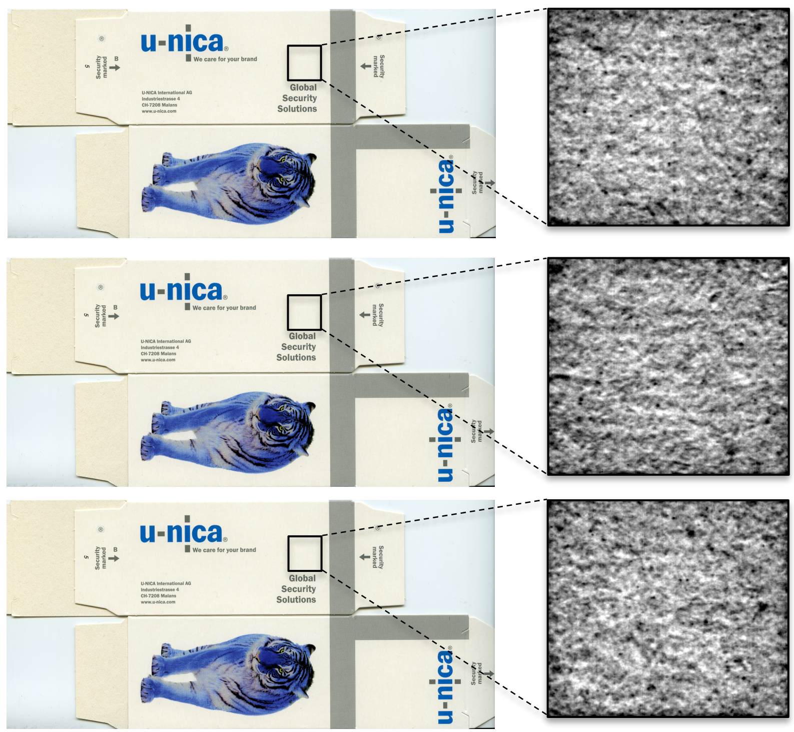
Package 1

Package 2

.

.

Package M




Individually unique PUFs

= unique identifier for Track&Trace

Visibly packages look identical

# Imaging in the visible and infrared bands

Optical sensors for autonomous vehicles and drons


http://www.dailymail.co.uk/sciencetech/article-6127299/Apple-self-driving-car-autonomous-mode-rear-ended-Nissan-reported-crash.html

Apple self driving car 'in autonomous mode' rear ended by a Nissan in first reported crash of the iPhone maker's secret vehicle

One of Apple's self-driving cars was involved in a minor crash for the first time

A self-driving Lexus RX 450h attempted to merge onto the highway when it was rear-ended by a 2016 Nissan Leaf, according to a filing with California's DMV

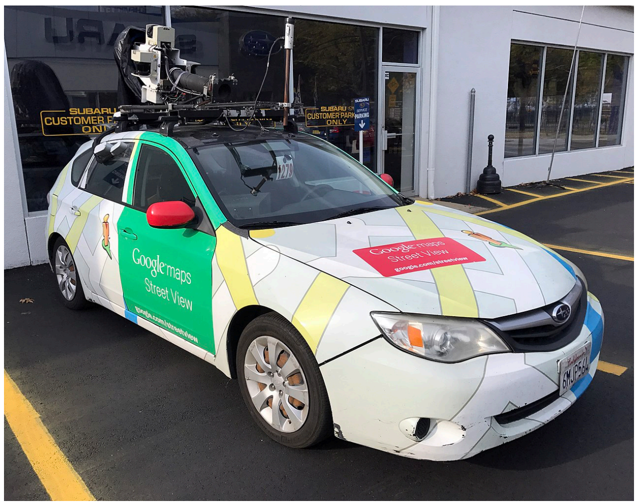
No humans were injured as a result, but both of the vehicles were damaged

The incident shows that Apple is still in the race to test autonomous vehicles

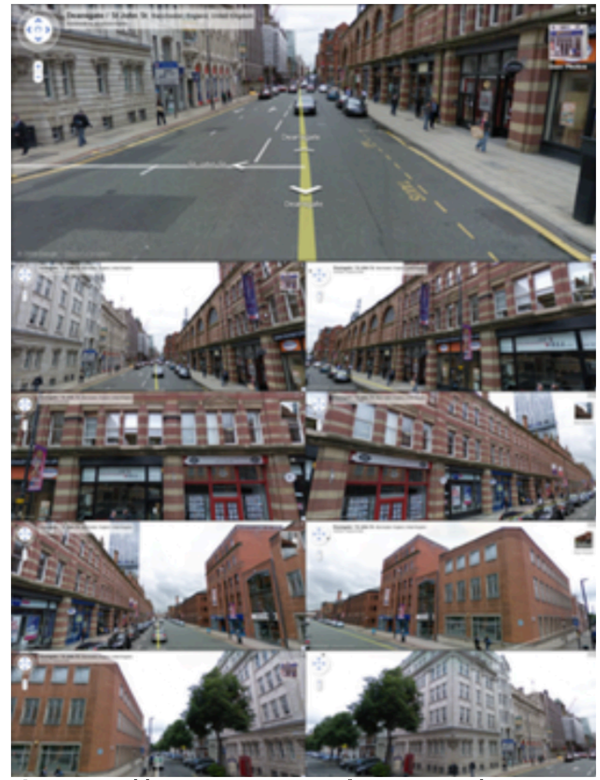
# Imaging in the visible and infrared bands

Navigation systems

- Google street view
- Google maps




A Street View car parked at a Subaru Service Center in Jersey City, New Jersey



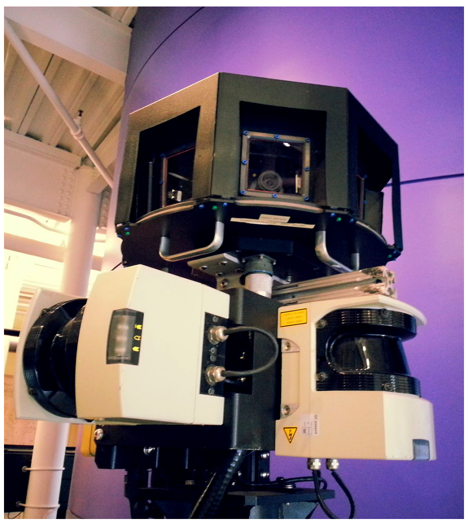
https://www.google.com/streetview/

https://en.wikipedia.org/wiki/Google_Street_View

# Imaging in the visible and infrared bands

Navigation systems

- Google street view
- Google maps



Google Street View camera mounted on a "trike", on display at the Computer History Museum in Mountain View, California

Google Trike in Cambridge Bay, Nunavut, August 2012

https://en.wikipedia.org/wiki/Google_Street_View

# Imaging in the visible and infrared bands

## New imaging principles

512 Vol. 10, No. 3 / September 2018 / Advances in Optics and Photonics Tutorial

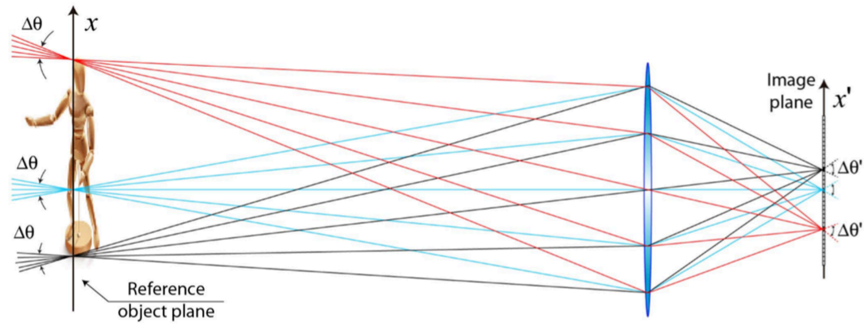
Advances in Optics and Photonics

### Fundamentals of 3D imaging and displays: a tutorial on integral imaging, light-field, and plenoptic systems

MANUEL MARTÍNEZ-CORRAL[1,*] AND BAHRAM JAVIDI[2,3]

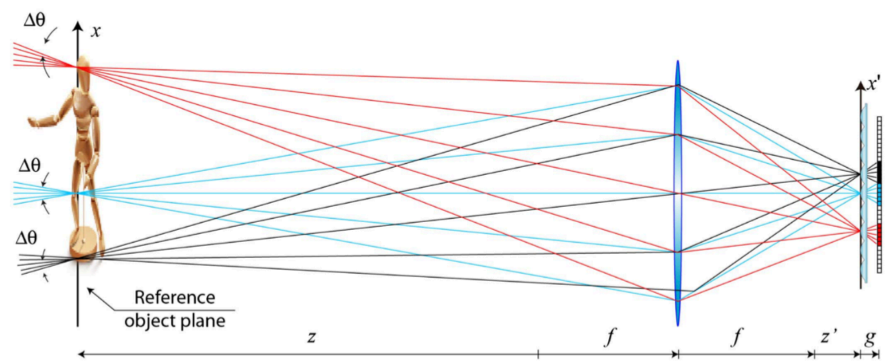
[1]3D Imaging and Display Laboratory, Department of Optics, University of Valencia, E46100 Burjassot, Spain
[2]University of Connecticut, Electrical & Computer Engineering Department, 371 Fairfield Way, Storrs, Connecticut 06269, USA
[3]e-mail: Bahram.Javidi@UConn.edu
*Corresponding author: manuel.martinez@uv.es

Figure 11




Scheme of a conventional photographic camera. Every pixel collects a cone of rays with the same spatial coordinate but with variable angular content.

Figure 21




Single scheme of a plenoptic camera.

# Imaging in the visible and infrared bands

## New imaging principles

512 Vol. 10, No. 3 / September 2018 / *Advances in Optics and Photonics* **Tutorial**

Advances in Optics and Photonics

### Fundamentals of 3D imaging and displays: a tutorial on integral imaging, light-field, and plenoptic systems

Manuel Martínez-Corral[1,*] and Bahram Javidi[2,3]

[1]3D Imaging and Display Laboratory, Department of Optics, University of Valencia, E46100 Burjassot, Spain
[2]University of Connecticut, Electrical & Computer Engineering Department, 371 Fairfield Way, Storrs, Connecticut 06269, USA
[3]e-mail: Bahram.Javidi@UConn.edu
*Corresponding author: manuel.martinez@uv.es

**Figure 14**

(a) (b) (c)

(a) Subset of 7 × 7 EIs (300 × 300 pixels each) of the 3D scenes. A movie obtained after composing the EIs of the central row of the integral image is shown in Visualization 1; (b) central EI; and (c) grid of 300 × 300 microimages (11 × 11 pixels each) of the 3D scene. The zoomed area is scaled by a factor of 5.

# Imaging in the visible and infrared bands

## New imaging principles

Multi-Shot Single Sensor Light Field Camera Using a Color Coded Mask

Ehsan Miandji
*dept. of Science and Technology*
*Linköping University, Sweden*

Jonas Unger
*dept. of Science and Technology*
*Linköping University, Sweden*

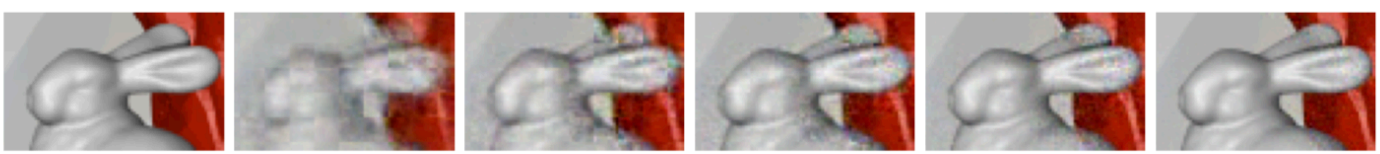
Christine Guillemot
*INRIA, Campus de Beaulieu*
*Rennes, France*

***Abstract*—We present a compressed sensing framework for reconstructing the full light field of a scene captured using a single-sensor consumer camera. To achieve this, we use a color coded mask in front of the camera sensor. To further enhance the reconstruction quality, we propose to utilize multiple shots by moving the mask or the sensor randomly. The compressed sensing framework relies on a training based dictionary over a light field data set. Numerical simulations show significant improvements in reconstruction quality over a similar coded aperture system for light field capture.**

***Index Terms*—light field camera, coded aperture**

$$\underbrace{\begin{bmatrix} \mathbf{y}^{R,1} \\ \mathbf{y}^{G,1} \\ \mathbf{y}^{B,1} \\ \mathbf{y}^{R,2} \\ \mathbf{y}^{G,2} \\ \mathbf{y}^{B,2} \\ \vdots \\ \mathbf{y}^{R,s} \\ \mathbf{y}^{G,s} \\ \mathbf{y}^{B,s} \end{bmatrix}}_{\triangleq \mathbf{y} \in \mathbb{R}^{\omega\lambda s}} = \underbrace{\begin{bmatrix} \mathbf{\Phi}^{1,R,1} & \dots & \mathbf{\Phi}^{\nu,R,1} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \dots & \mathbf{0} & \mathbf{\Phi}^{1,G,1} & \dots & \mathbf{\Phi}^{\nu,G,1} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{\Phi}^{1,B,1} & \dots & \mathbf{\Phi}^{\nu,B,1} \\ \mathbf{\Phi}^{1,R,2} & \dots & \mathbf{\Phi}^{\nu,R,2} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \dots & \mathbf{0} & \mathbf{\Phi}^{1,G,2} & \dots & \mathbf{\Phi}^{\nu,G,2} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{\Phi}^{1,B,2} & \dots & \mathbf{\Phi}^{\nu,B,2} \\ \vdots & \vdots & \ddots & \vdots & & & & & \\ \mathbf{\Phi}^{1,R,s} & \dots & \mathbf{\Phi}^{\nu,R,s} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \dots & \mathbf{0} & \mathbf{\Phi}^{1,G,s} & \dots & \mathbf{\Phi}^{\nu,G,s} & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{\Phi}^{1,B,s} & \dots & \mathbf{\Phi}^{\nu,B,s} \end{bmatrix}} \underbrace{\begin{bmatrix} \mathbf{x}^{1,R} \\ \vdots \\ \mathbf{x}^{\nu,R} \\ \mathbf{x}^{1,G} \\ \vdots \\ \mathbf{x}^{\nu,G} \\ \mathbf{x}^{1,B} \\ \vdots \\ \mathbf{x}^{\nu,B} \end{bmatrix}}_{\triangleq \mathbf{x} \in \mathbb{R}^{\omega\nu\lambda}},$$

$$\mathbf{y} = \mathbf{P\Phi x},$$



(a) *reference* (b) *1 shot* (c) *3 shots* (d) *5 shots* (e) *9 shots* (f) *15 shots*

Fig. 3: Visual quality comparison for the number of shots ($s$). See Fig. 4 for the corresponding PSNR values.

# Imaging in the microwave band

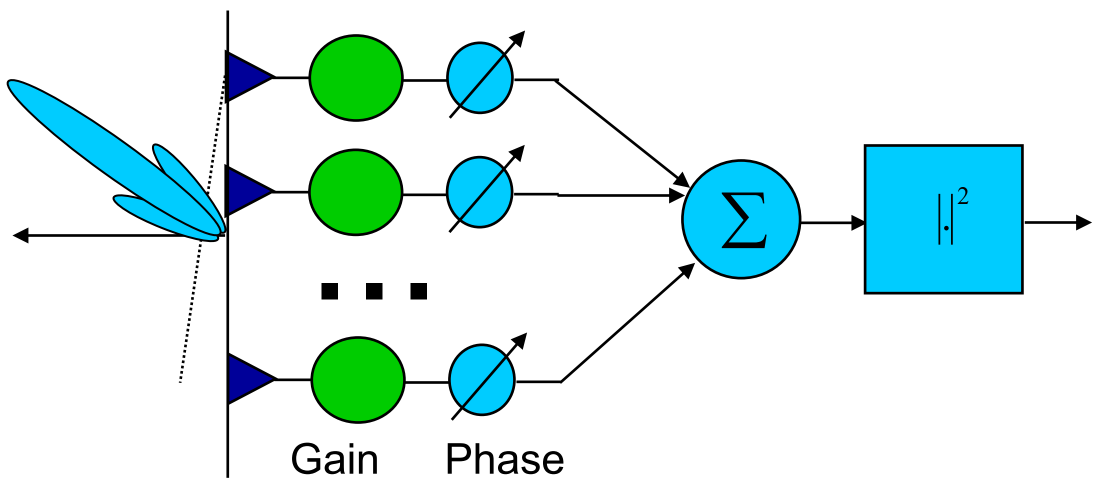
Radar imaging

- all weather (clouds)
- all time
- any ambient light conditions
- many surfaces and penetrate via clouds, ice, vegetation, sand

Radars use antennas and antenna arrays for imaging instead of lenses

Radar and Radiometry

Imaging Systems



# Imaging in the microwave band

Radar imaging

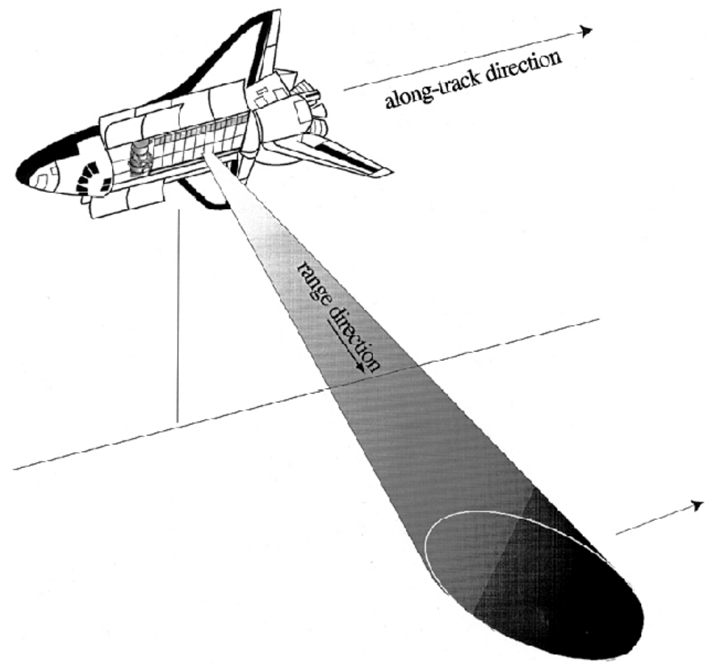
- all weather (clouds, fog)
- all time
- any ambient light conditions
- many surfaces and penetrate via clouds, ice, vegetation, sand

Radars use antennas and antenna arrays for imaging instead of lenses

Radars for:

Imaging

Navigation (self-driving cars, drones)



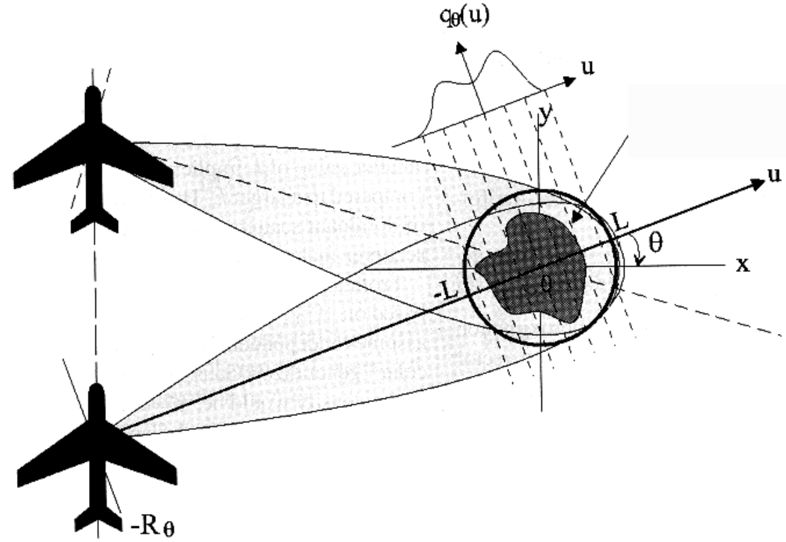

Proc. IEEE, March, 2000

# Imaging in the microwave band

Radar imaging

- all weather (clouds, fog)
- all time
- any ambient light conditions
- many surfaces and penetrate via clouds, ice, vegetation, sand

Spotlight-mode synthetic aperture radar (SAR)

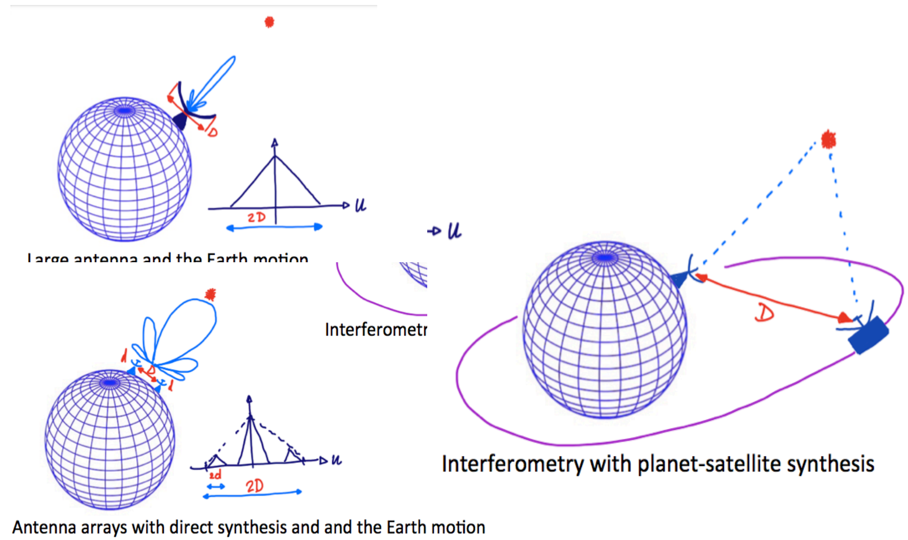


# Imaging in the microwave band

## Radar imaging

Radars use antennas and antenna arrays for imaging instead of lenses

Various imaging configurations

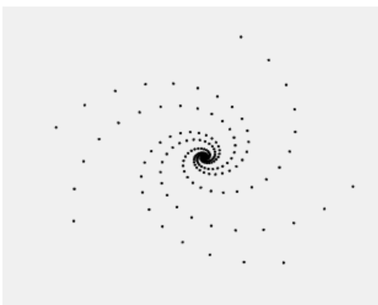
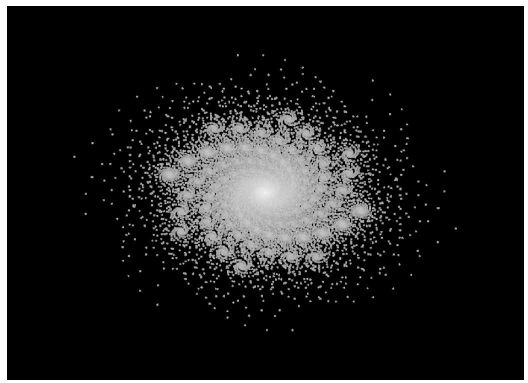
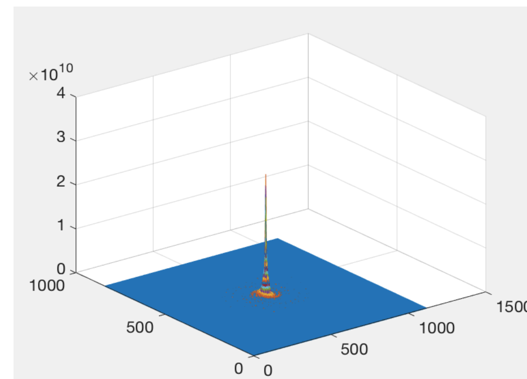


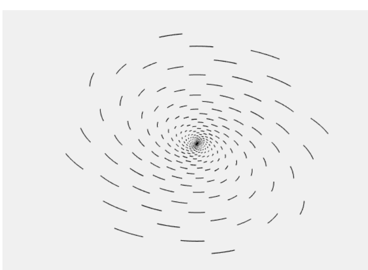
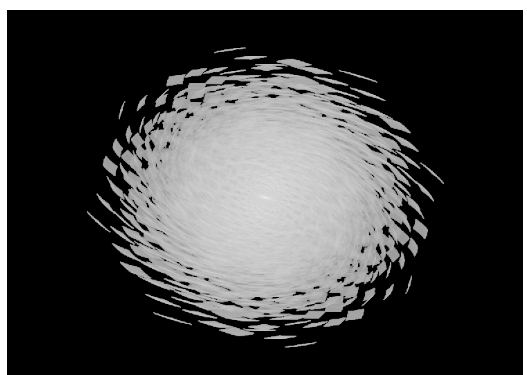
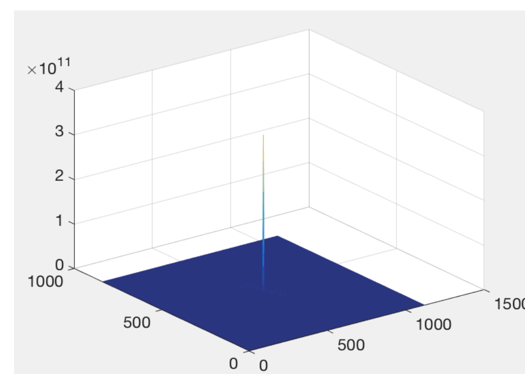

**ALMA, EVLA, LOFAR, VLBI,…, SKA**

# Imaging in the microwave band

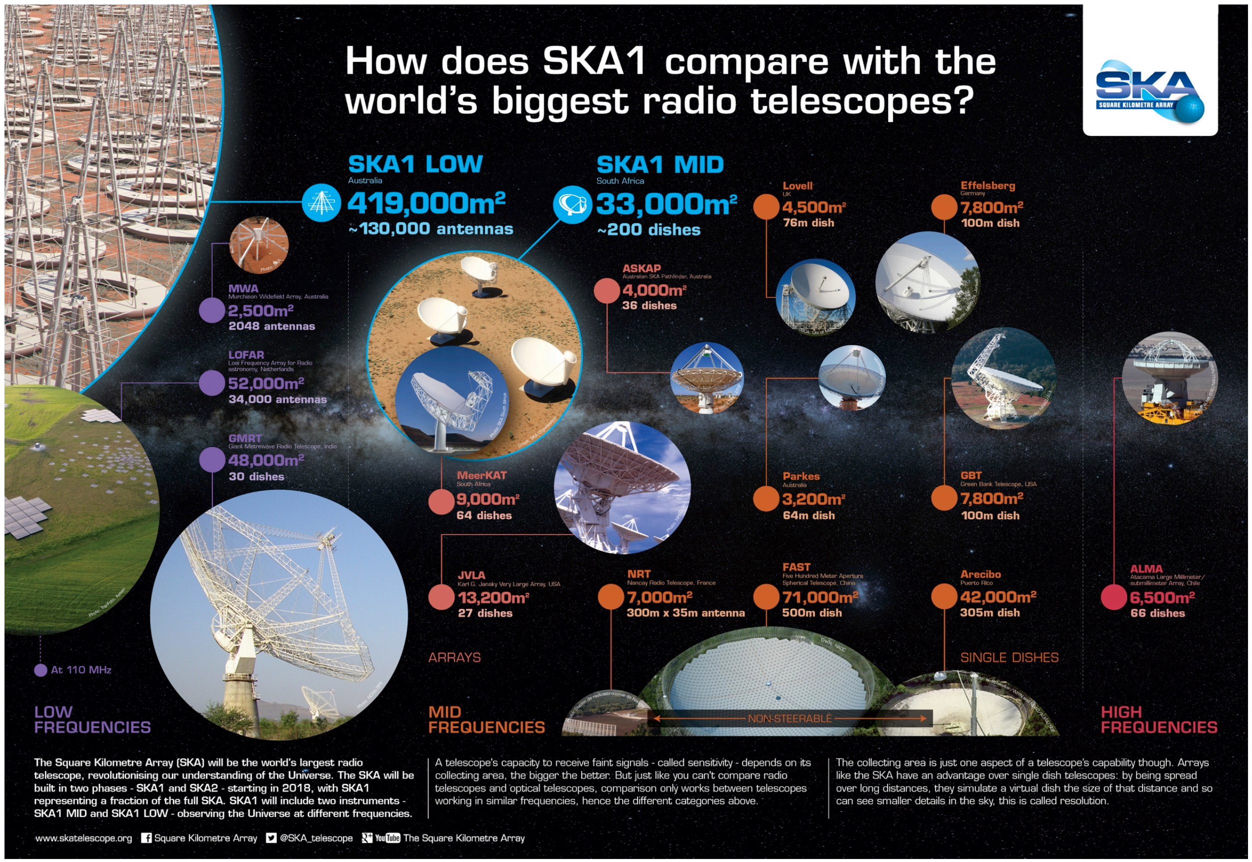
SKA geometry for radioastronomy

Geometry | Spatial spectrum (uv-plane) | PSF (directional antenna pattern)

# Imaging in the microwave band



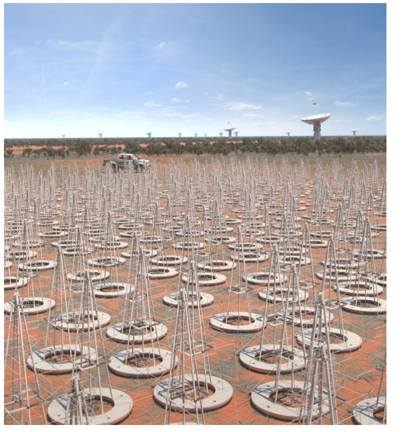

Credits: SKA

**The international radio telescope of the 21$^{st}$ century**

# Imaging in the microwave band

SKA geometry for radioastronomy

The SKA will use around 3000 High Frequency dishes, each 15 m in diameter



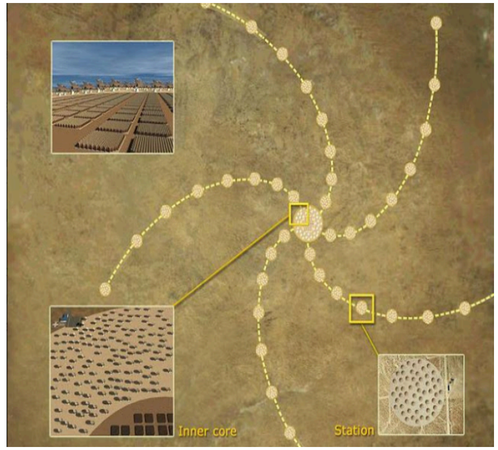
Low Frequency Aperture Array in Australia

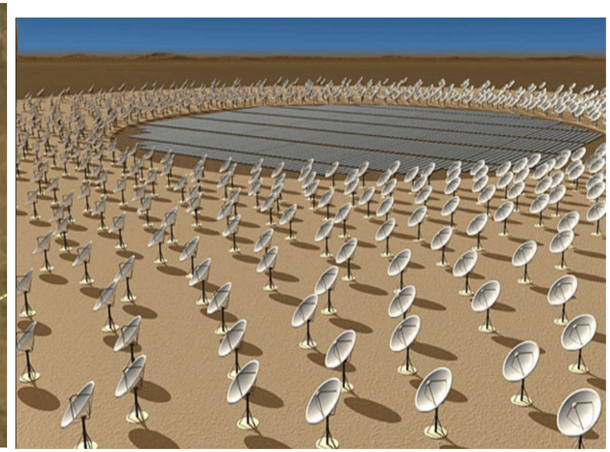
Mid Frequency Aperture Array in South Africa

Credits: SKA

# Imaging in the microwave band

SKA geometry for radio-astronomy



- Huge amount of data (expected data are about 1 PB per day)
- Problems with Big Data:
  - Reconstruction (where? and how?)
  - Intercontinental data exchange
  - Storage
  - Analytics and Science

Credits: SKA

# Other imaging modalities

"Sound" imaging

- Geological applications (around 100 Hz)
- Marine applications
- Medical applications (1 to 5 MHz sound pulses)

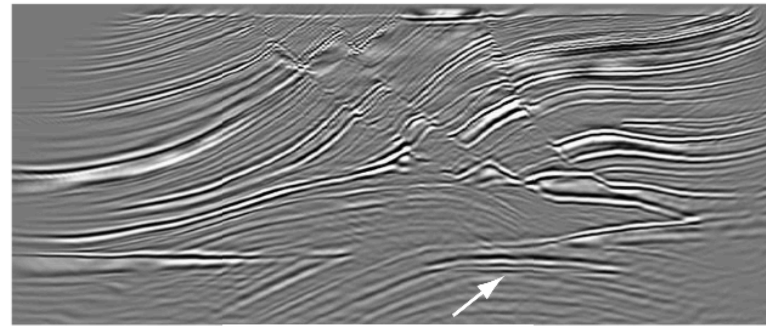
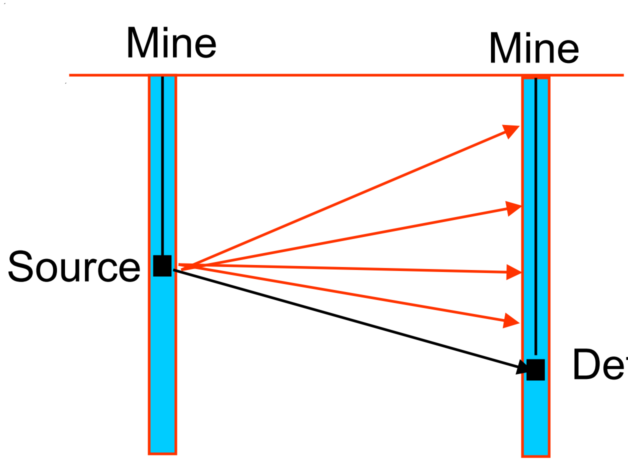
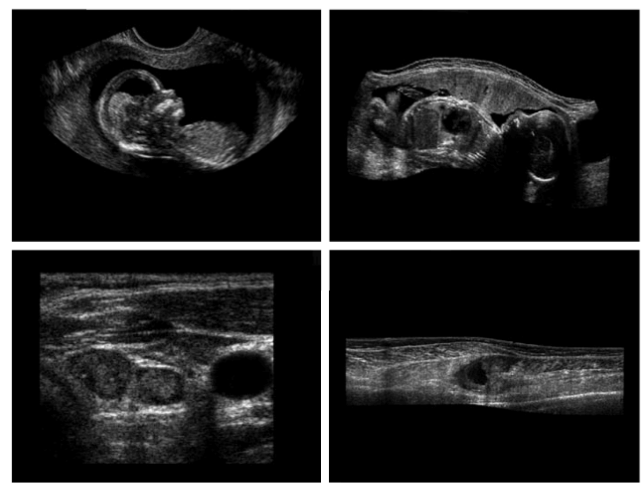


**FIGURE 1.19** Cross-sectional image of a seismic model. The arrow points to a hydrocarbon (oil and/or gas) trap. (Courtesy of Dr. Curtis Ober, Sandia National Laboratories.)



a b
c d

**FIGURE 1.20** Examples of ultrasound imaging. (a) Baby. (b) Another view of baby. (c) Thyroids. (d) Muscle layers showing lesion. (Courtesy of Siemens Medical Systems, Inc., Ultrasound Group.)

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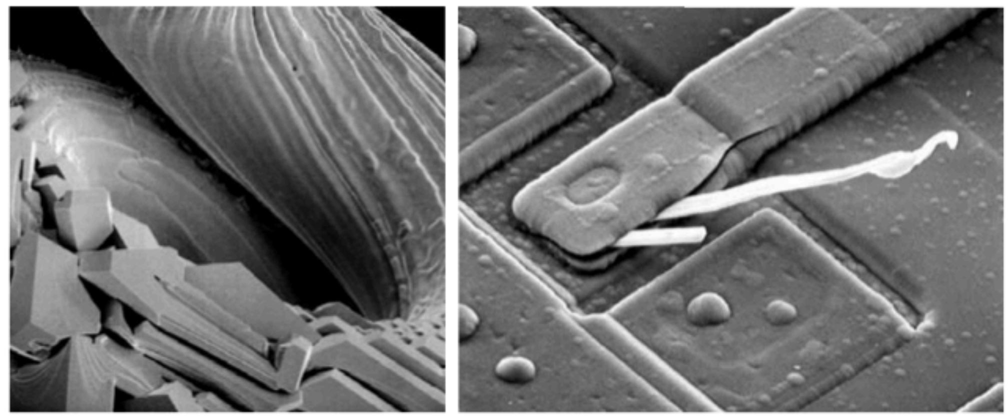
# Other imaging modalities

Transition electron microscope (TEM) imaging

- “project” a beam of electrons through a specimen
- Project to the phosphor and obtain a viewable image

Scanning electron microscopy (SEM)

- Scan with the electron beam in a raster way and register the viewed image on the phosphor screen (about 10,000x)



a b

**FIGURE 1.21** (a) 250× SEM image of a tungsten filament following thermal failure (note the shattered pieces on the lower left). (b) 2500× SEM image of damaged integrated circuit. The white fibers are oxides resulting from thermal destruction. (Figure (a) courtesy of Mr. Michael Shaffer, Department of Geological Sciences, University of Oregon, Eugene; (b) courtesy of Dr. J. M. Hudak, McMaster University, Hamilton, Ontario, Canada.)

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