Image Processing 02
HVS and Image Fundamentals
Part 1

SS 2020

Prof. Dr. Simone Frintrop

Computer Vision Group, Department of Informatics
University of Hamburg, Germany

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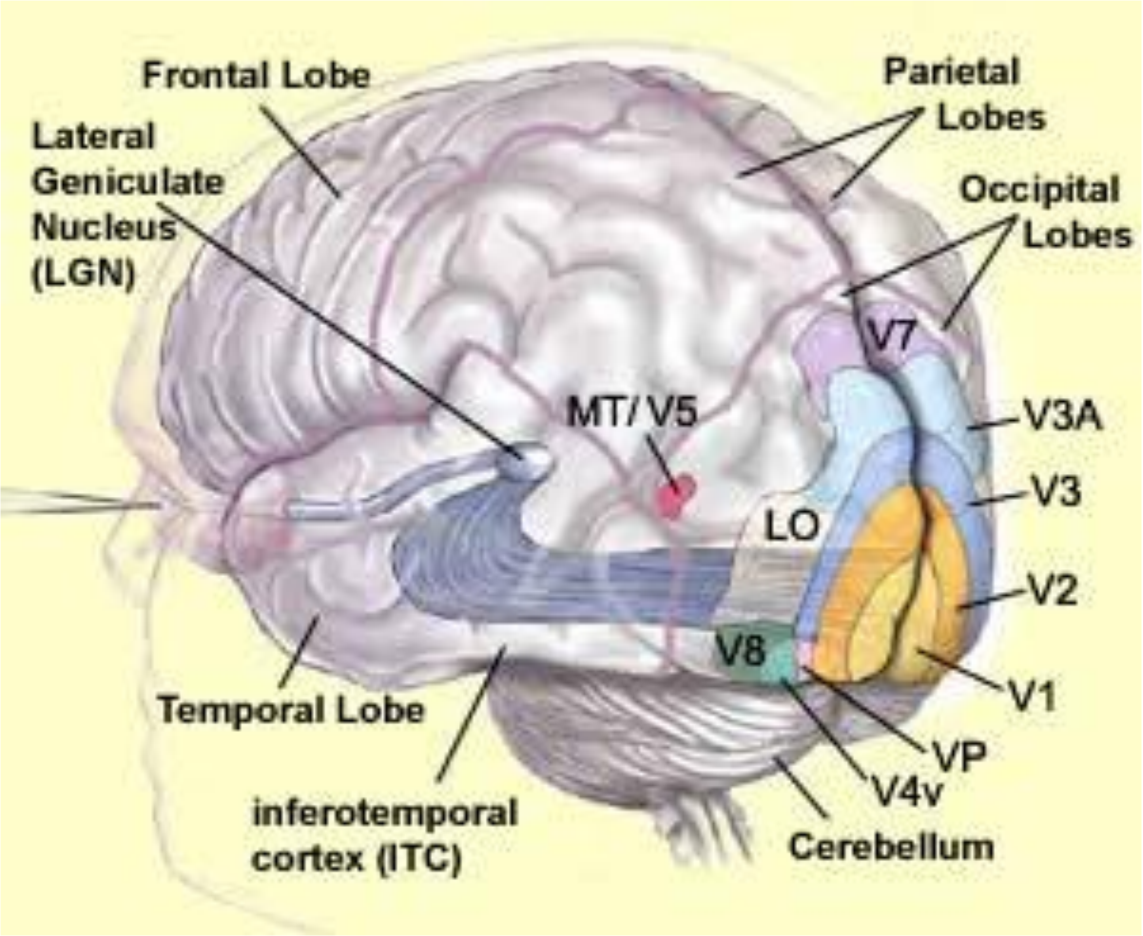
Outline

- Part 1: Human Visual Perception
- Part 2:Image Sources, Light and the Electromagnetic Spectrum
- Part 3: Components of Image Processing Systems, Sensors, Image Sensing and Acquisition
- Part 4: Sampling & Quantization
- Part 5: Image Representations (Matrices and Signals)
- Part 6: Frequencies and Noise

The Human Visual System



[http://thebrain.mcgill.ca/]

The Human Eye

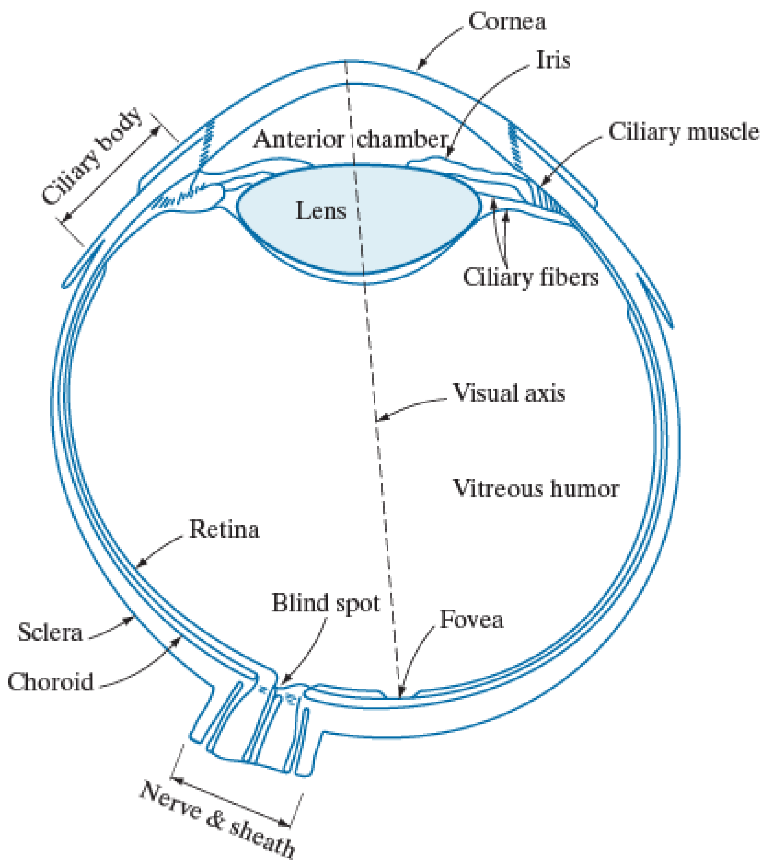
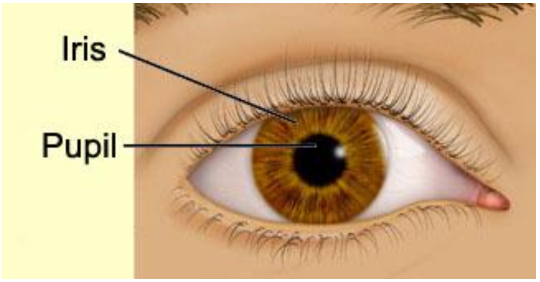


FIGURE 2.1 Simplified diagram of a cross section of the human eye.

anterior chamber: Vorderkammer
ciliary body: Ziliarkörper
ciliary fibers: Ziliarfasern
ciliary muscle: Ziliarmuskel
choroid: Aderhaut
cornea: Hornhaut
iris: Iris
lens: Linse
retina: Netzhaut
sclera: Sklera
vitreous humor: Glaskörper



[Gonzalez/Woods]

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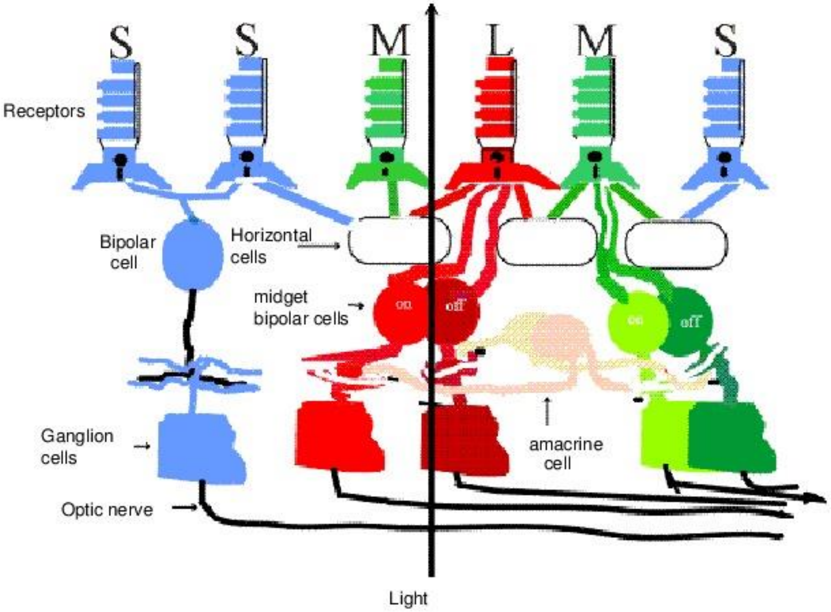
Retina

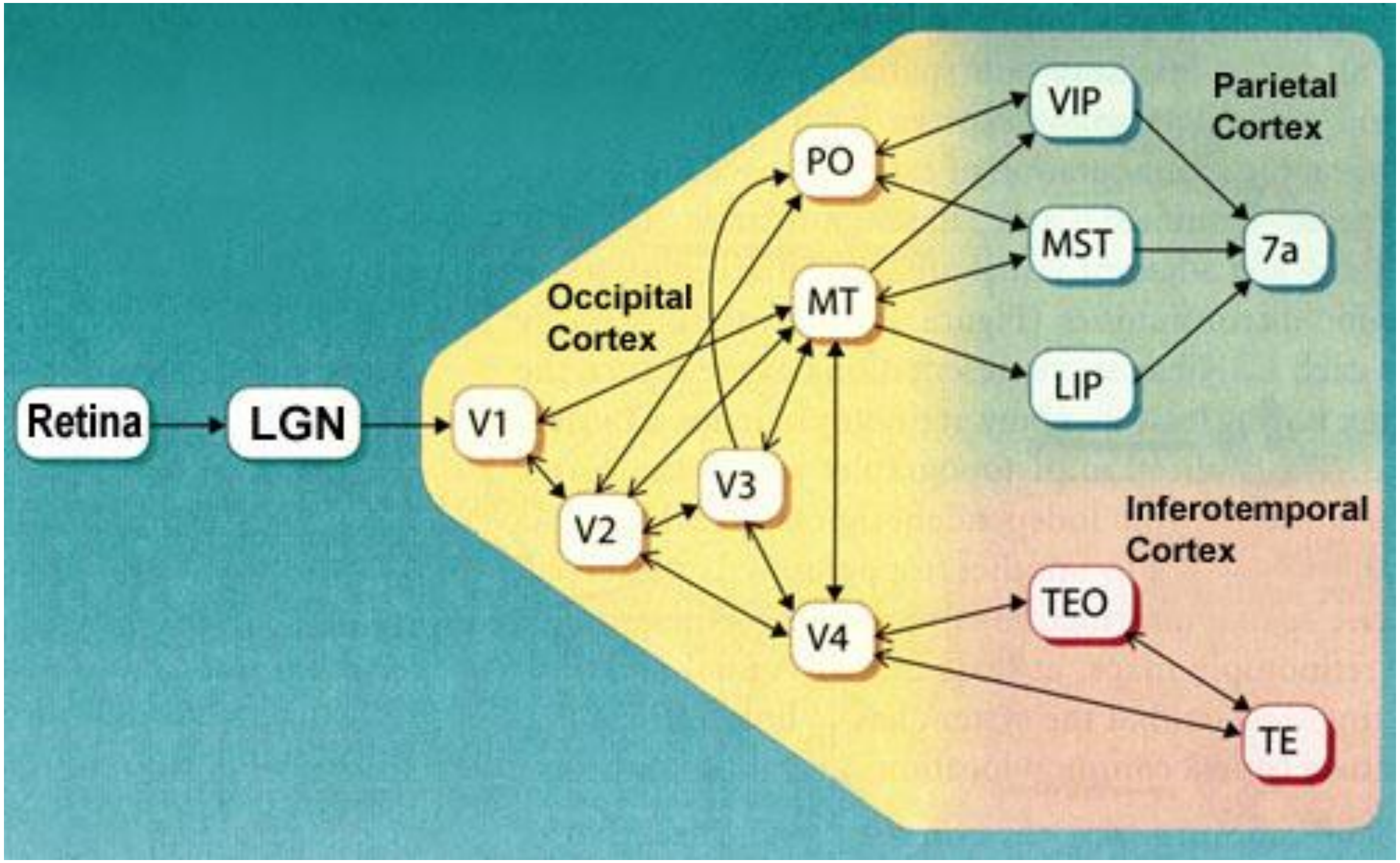
Retina: Netzhaut
Photo receptors: Fotorezeptor/Sehzelle
Rods: Stäbchen
Cones: Zapfen

- **Retina:** A light-sensitive surface at the back of the eye
- Covered with photo-receptors (sensory neurons):
  - **Rods**: ~120 million, light sensitive, not color sensitive
  - **Cones:** only 7 million, color sensitive, concentrated in the **fovea** (but still many cones in periphery)
- 3 types of cones (color receptors):
  - L-cones (long-wavelength) (red)
  - M-cones (middle-wavelength) (green)
  - S-cones (short-wavelength) (blue)
- → Trichromatic theory of color vision: color vision is the result of only 3 types of cells



The retina

The Human Visual System



More in lectures „Computer Vision 1“ and „Computer Vision 2“

[http://thebrain.mcgill.ca/]

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Image Sources

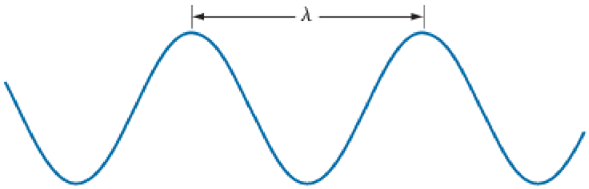
Energy sources for digital images:

- The electromagnetic spectrum
- Acoustic, ultrasonic, electronic sources
- Synthetic images generated by computers

Light and Electromagnetic Spectrum

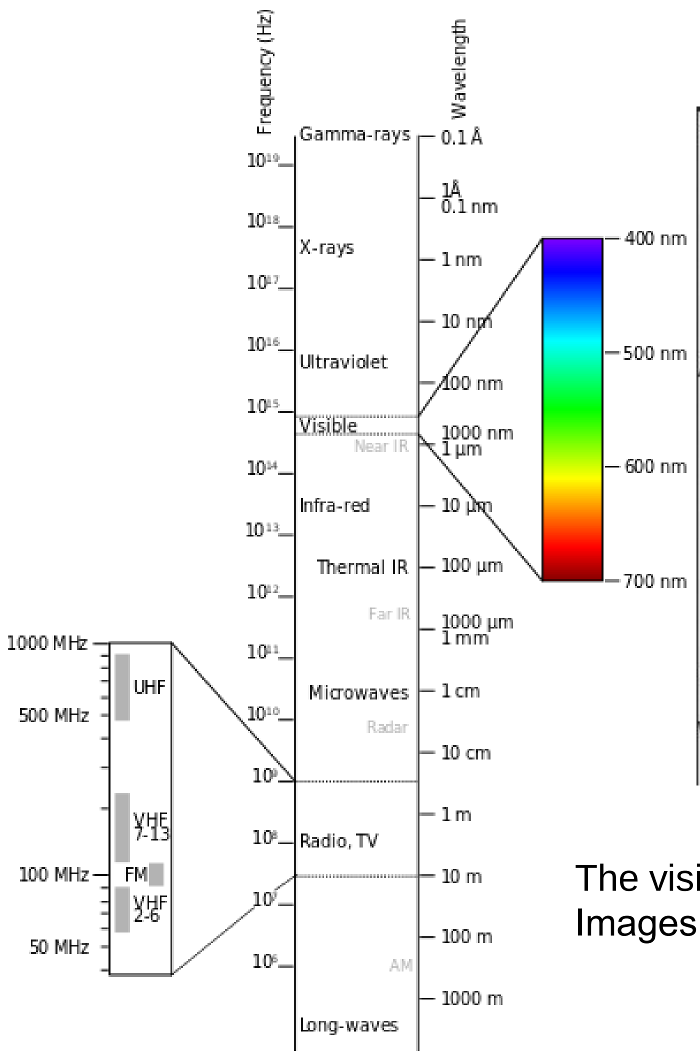
- The **electromagnetic spectrum** is the collective term for all known electromagnetic waves of different wavelength
- Electromagnetic waves are sinusoidal waves of varying wavelength:

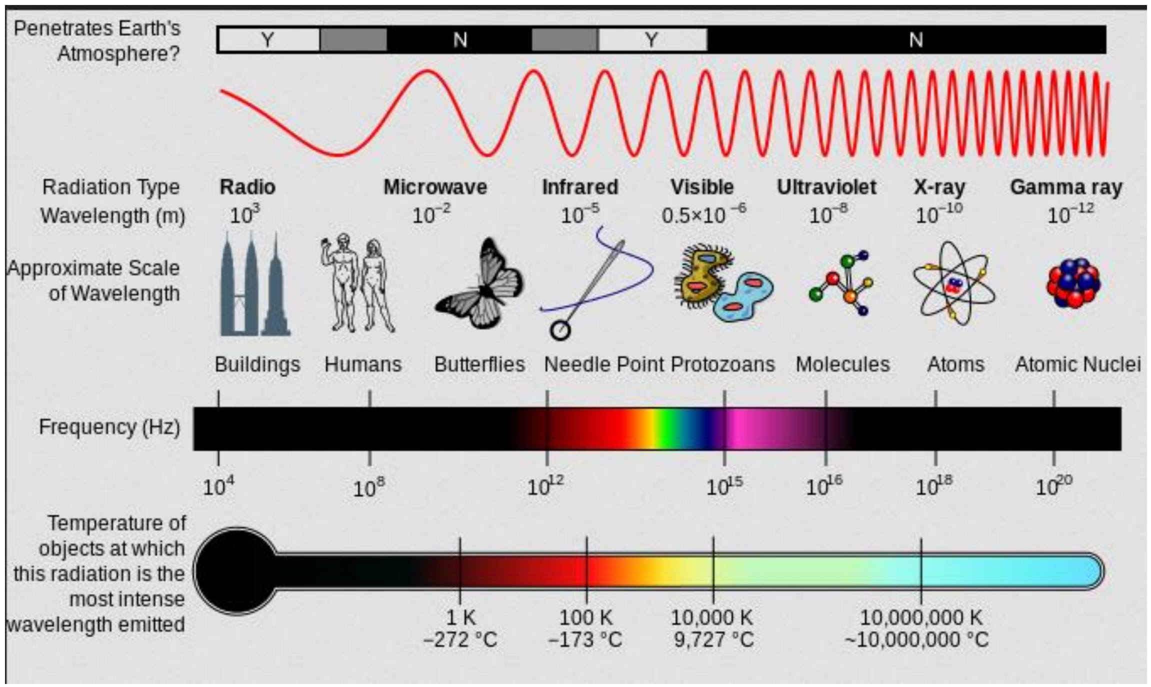
FIGURE 2.11 Graphical representation of one wavelength.



- The waves consist of a stream of particles traveling in waves at the speed of light
- The particles of the stream are called photons and carry energy proportional to frequency

The Electromagnetic Spectrum





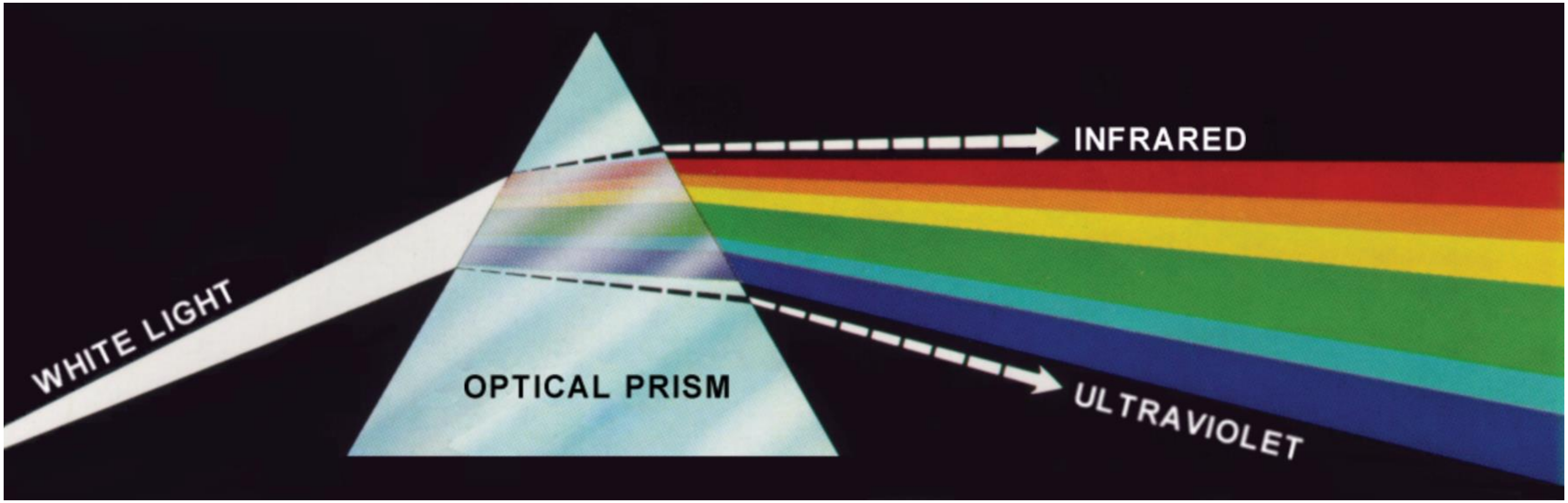
The visible spectrum is a very small portion of the electromagnetic spectrum. Images can also come from other parts than the visible spectrum…

[Wikipedia: Electromagnetic spectrum]

The Visible Spectrum

The visible spectrum consists of light of different wavelengths. These can be visualized by an optical prism.

FIGURE 7.1
Color spectrum seen by passing white light through a prism.
(Courtesy of the General Electric Co., Lighting Division.)



The Visible Spectrum

In the human eye, cones are responsible for color perception, they respond primarily to red, green and blue:

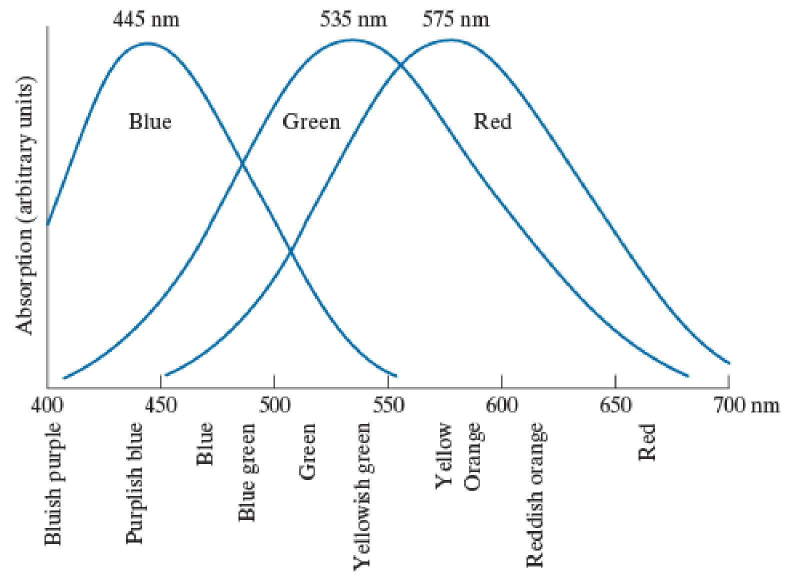


FIGURE 7.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

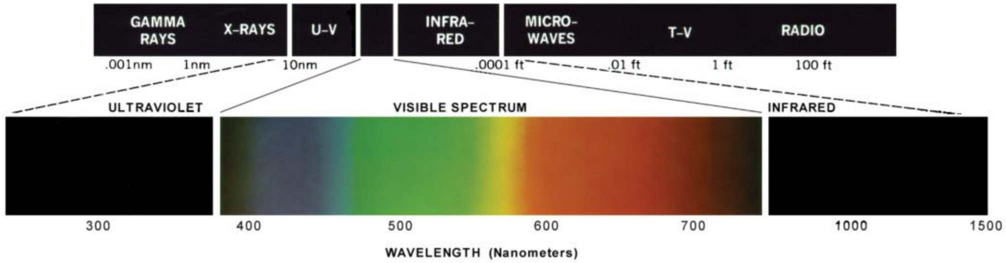


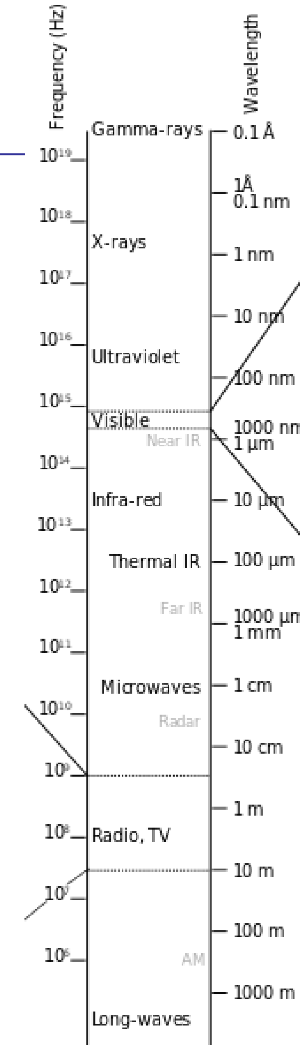
FIGURE 7.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lighting Division.)

The Visible Spectrum

- Most images we are interested in come from the visible spectrum and are captured with ordinary cameras

[Images from ImageNet Dataset]

Gamma-ray imaging

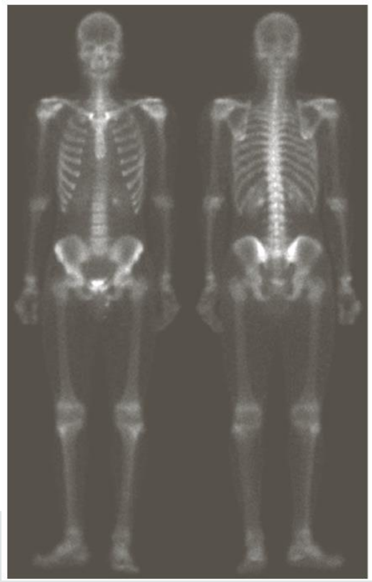


Applications of gamma-ray imaging (Gammastrahlen):

nuclear medicine and astronomy

Nuclear medicine: inject a patient with a radioactive isotope that emits gamma rays

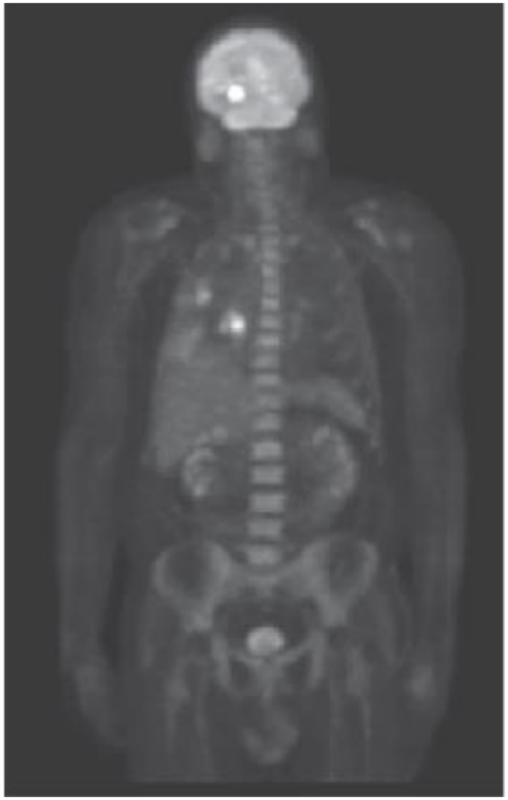
Bone scan from gamma-ray imaging:



[Gonzalez/Woods, Fig. 1.6]

Gamma-ray imaging

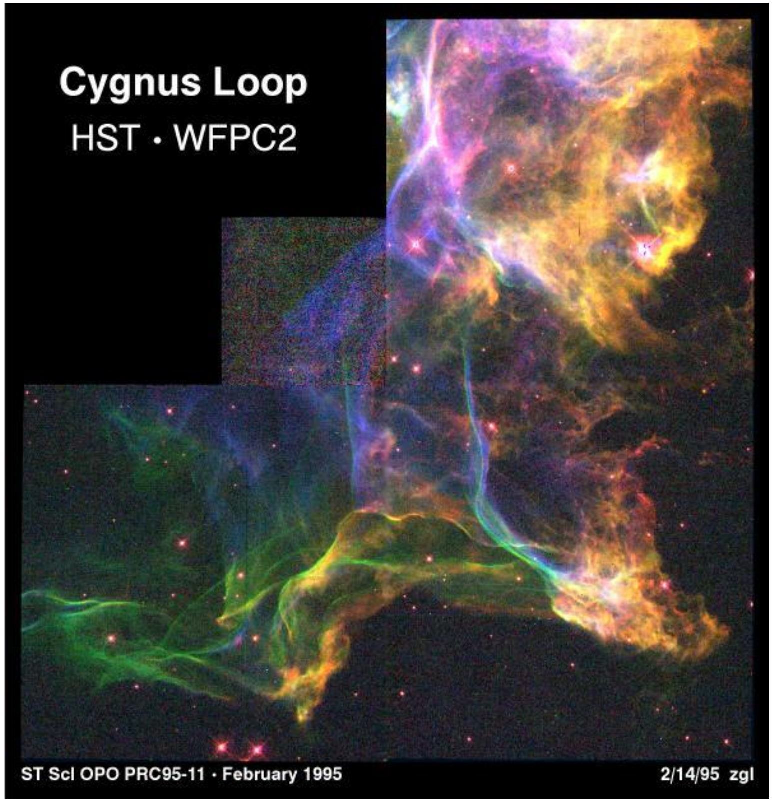
PET (positron emission tomography) imaging:



[Gonzalez/Woods, Fig. 1.6]

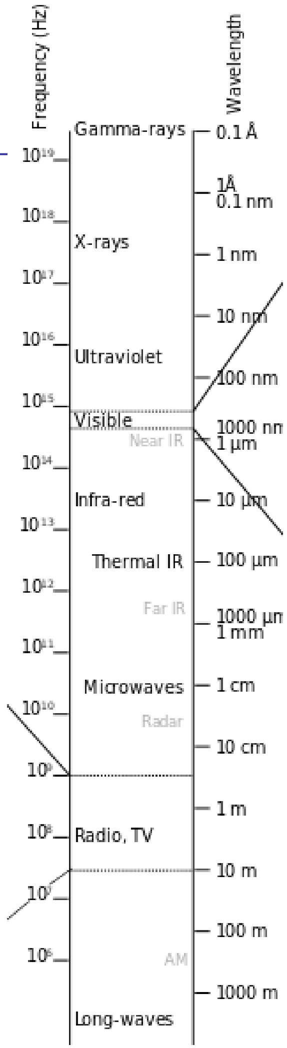
Gamma-ray imaging

Astronomy: an image of the Gygnus Loop (a gas cloud generated by a star which exploded 10000 years ago)



[Gonzalez/Woods, Fig. 1.6; Wikipedia (Cygnusbogen)]

X-ray imaging



X-ray (Röntgenstrahlen) used in medical diagnosis, but also in industry and astronomy

X-ray imaging in medicine:

Chest X-ray

Head CT

[Gonzalez/Woods, Fig. 1.7]

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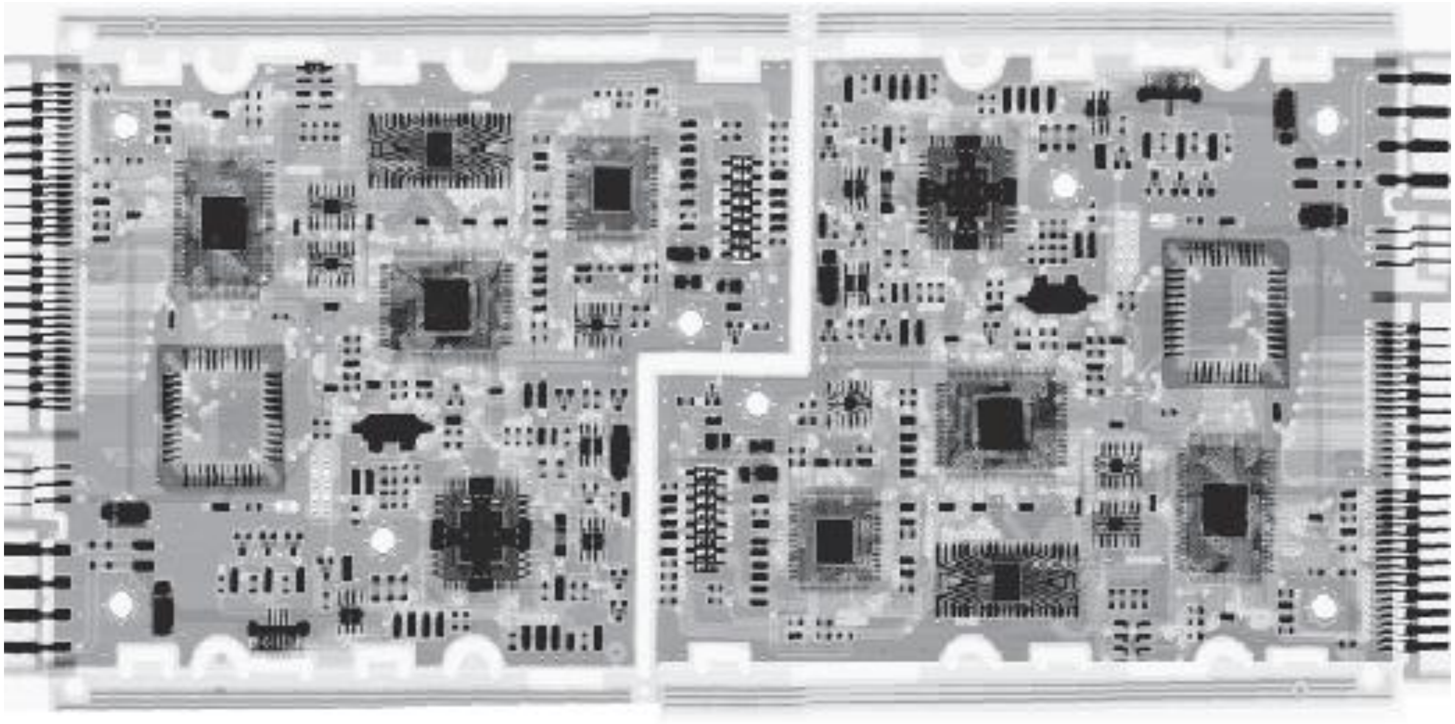
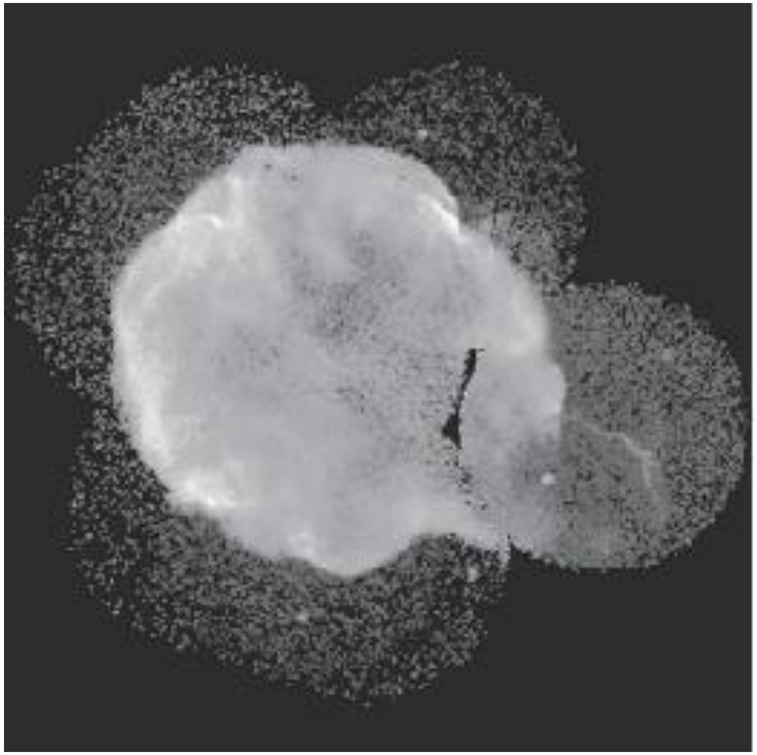
X-ray imaging



Circuit boards

[Gonzalez/Woods, Fig. 1.7]

X-ray imaging

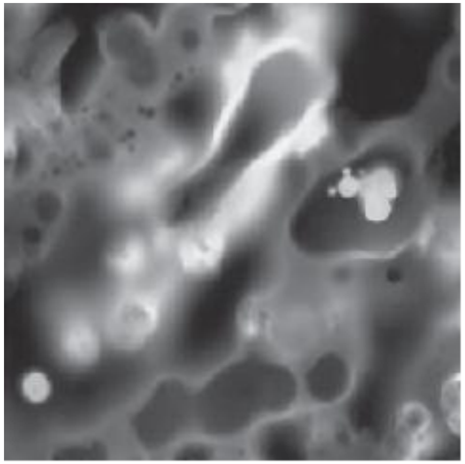


Cygnus Loop

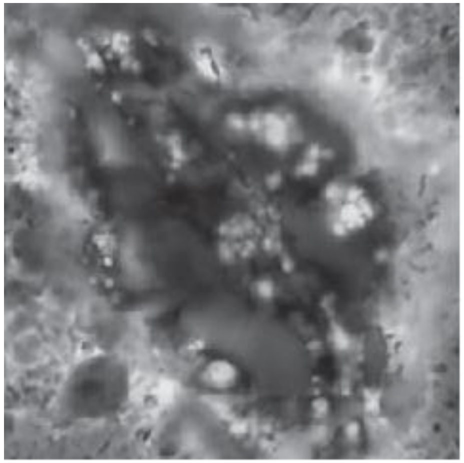
[Gonzalez/Woods, Fig. 1.7]

Ultraviolet band imaging

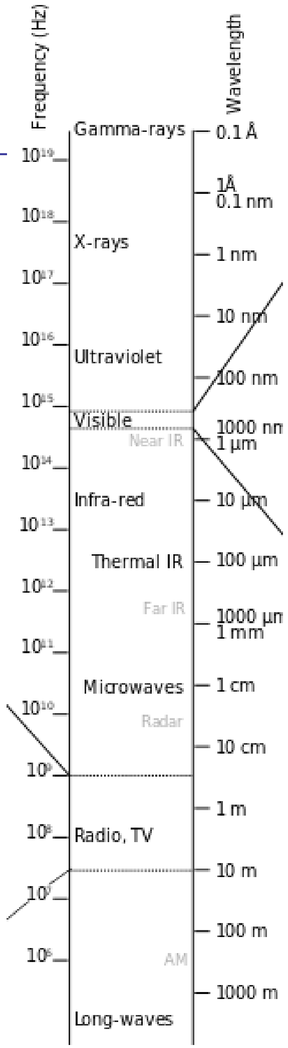
Applications of imaging in the ultraviolet band (UV-Strahlen): lithography, industrial inspection, microscopy, lasers, biological imaging, astronomy



Corn (Maiskorn)

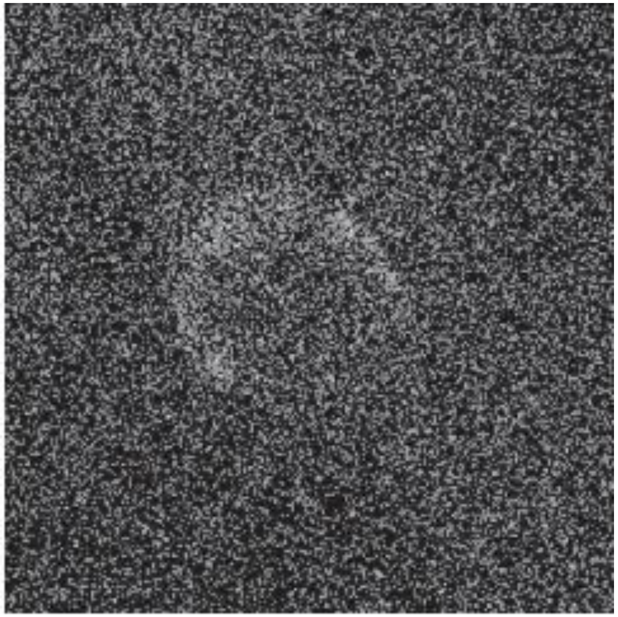


Corn infected by smut (Getreidebrand)



[Gonzalez/Woods, Fig. 1.8]

Ultraviolet band imaging

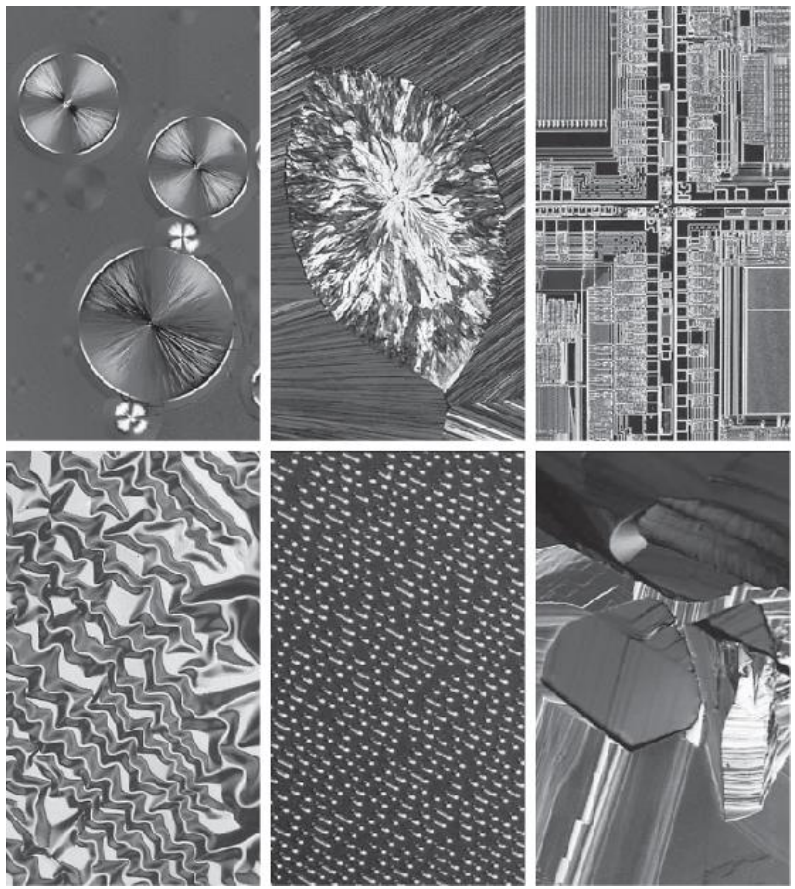


Cygnus Loop

[Gonzalez/Woods, Fig. 1.8]

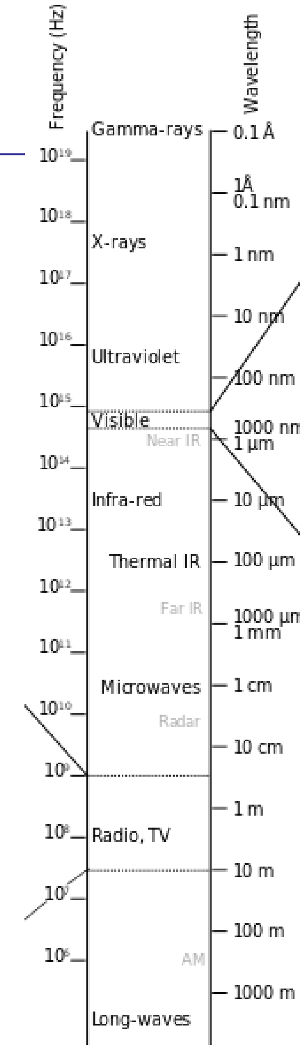
Visible spectrum

Except for normal camera images, light from the visible spectrum is often used in 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.)

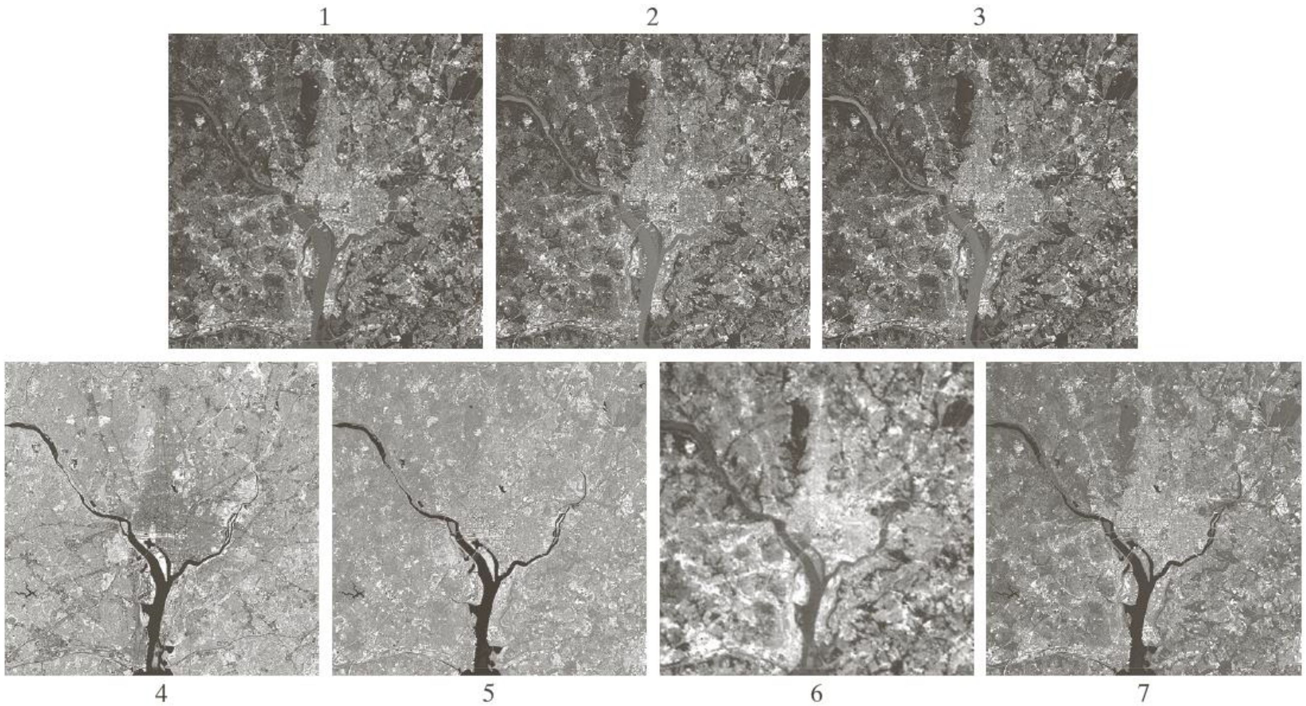


[Gonzalez/Woods]

Visible & infrared spectrum

Satellite images (Washington D.C.):

Recorded with different wavelengths from the visible and infrared spectrum



[Gonzalez/Woods]

Visible & infrared spectrum

TABLE 1.1
Thematic bands of 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	0.53–0.61	Measures plant vigor
3	Visible red	0.63–0.69	Vegetation discrimination
4	Near infrared	0.78–0.90	Biomass and shoreline mapping
5	Middle infrared	1.55–1.75	Moisture content: soil/vegetation
6	Thermal infrared	10.4–12.5	Soil moisture; thermal mapping
7	Short-wave infrared	2.09–2.35	Mineral mapping

Visible & infrared spectrum

FIGURE 1.11
Satellite image of Hurricane Katrina taken on August 29, 2005. (Courtesy of NOAA.)

[Gonzalez/Woods]

Infrared spectrum

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

[Gonzalez/Woods]

Infrared spectrum

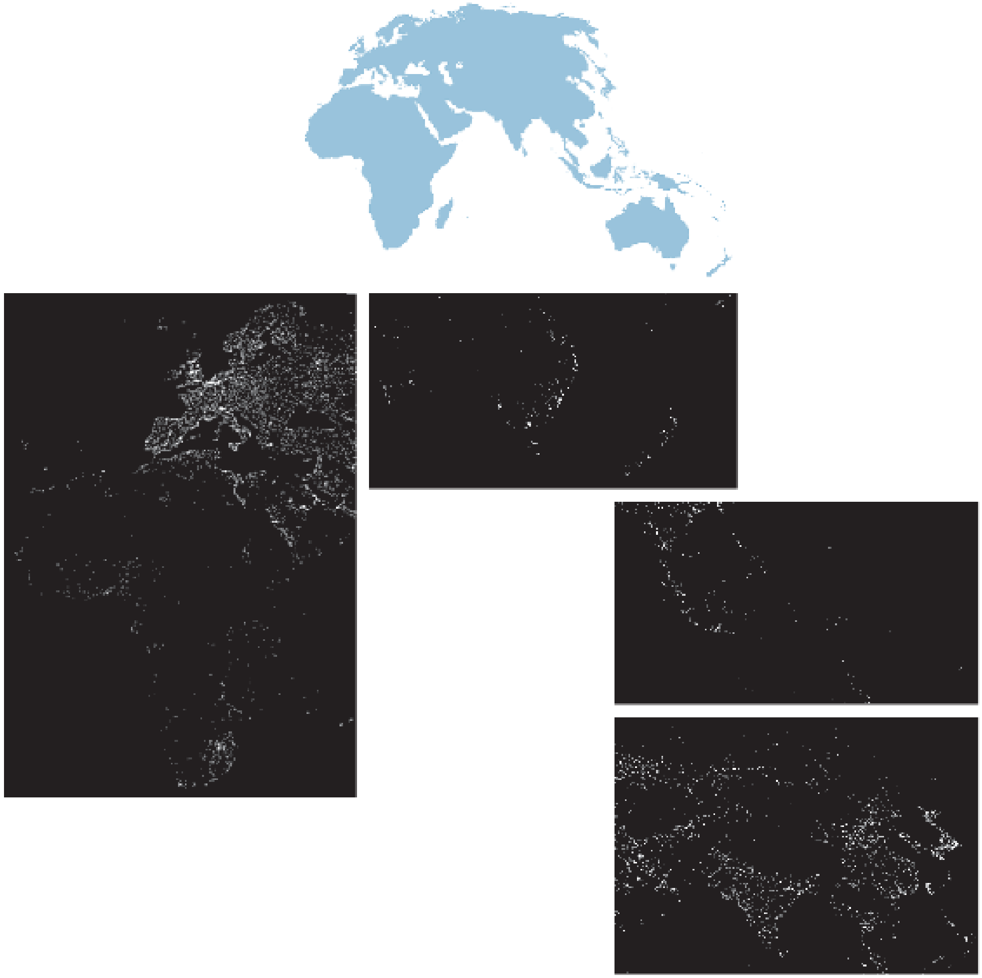


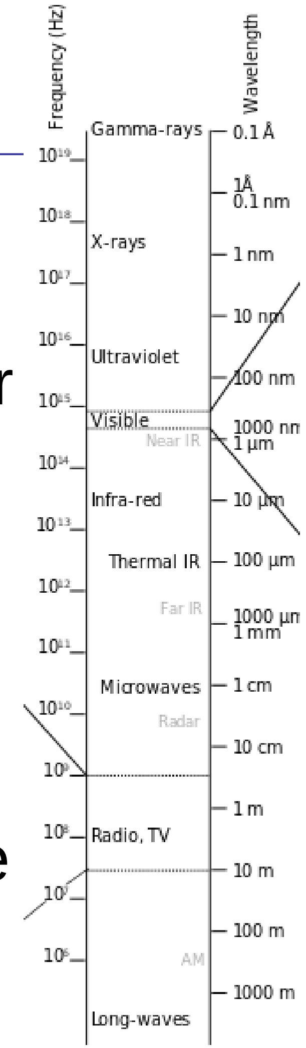
FIGURE 1.13 Infrared satellite images of the remaining populated parts of the world. The small shaded map is provided for reference. (Courtesy of NOAA.)

[Gonzalez/Woods]

Microwave band

Spaceborne radar image of mountainous region in southeast Tibet

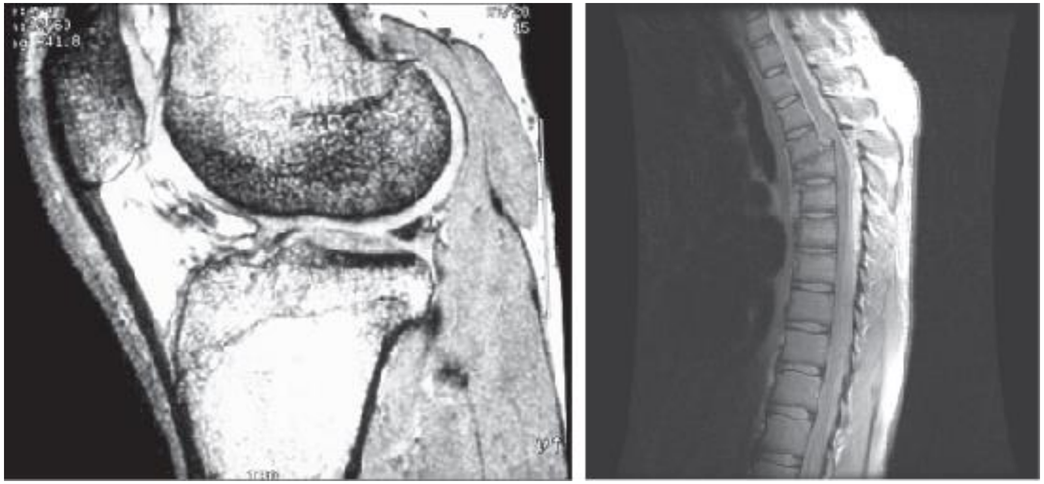
- Main application: radar
- Radar waves are independent of weather or lighting conditions, some radar waves can see through clouds or vegetation, ice or sand
- Provides its own illumination (microwave pulses)



[Gonzalez/Woods, Fig. 1.16]

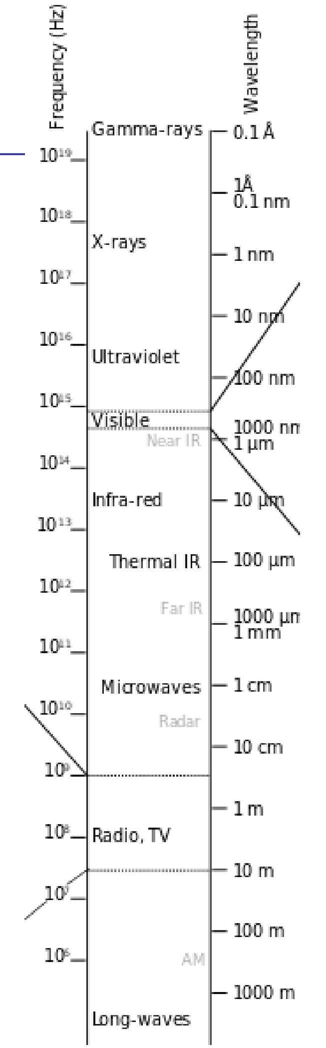
Radio band

- Applications: medicine and astronomy
- Medicine: magnetic resonance imaging (MRI)



a b

FIGURE 1.17 MRI images of a human (a) knee, and (b) spine. (Figure (a) courtesy of Dr. Thomas R. Gest, Division of Anatomical Sciences, University of Michigan Medical School, and (b) courtesy of Dr. David R. Pickens, Department of Radiology and Radiological Sciences, Vanderbilt University Medical Center.)



[Gonzalez/Woods]

Radio band

- Astronomy

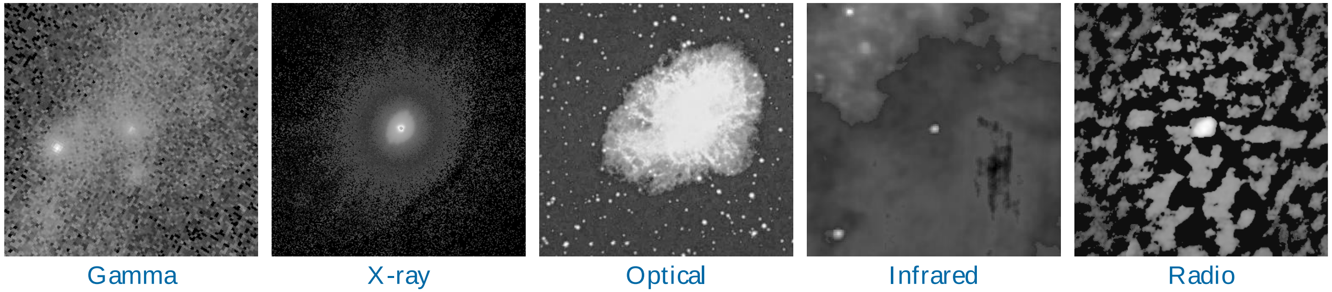
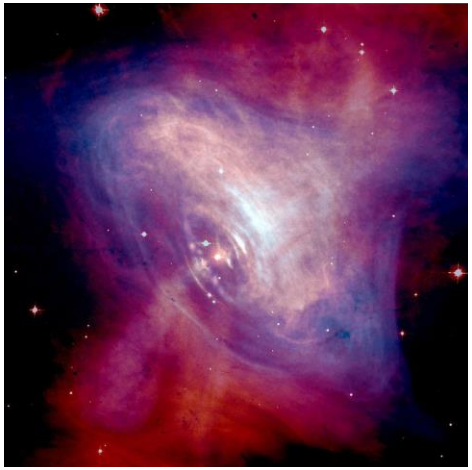
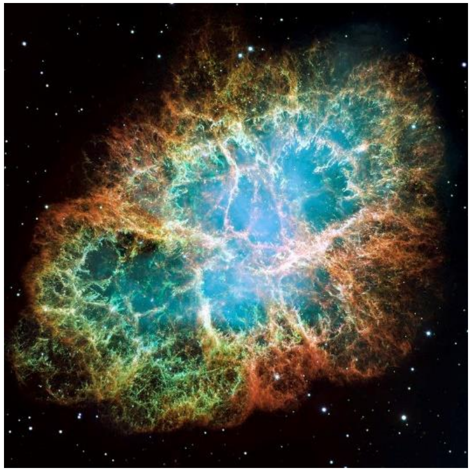


FIGURE 1.18 Images of the Crab Pulsar (in the center of each image) covering the electromagnetic spectrum. (Courtesy of NASA.)



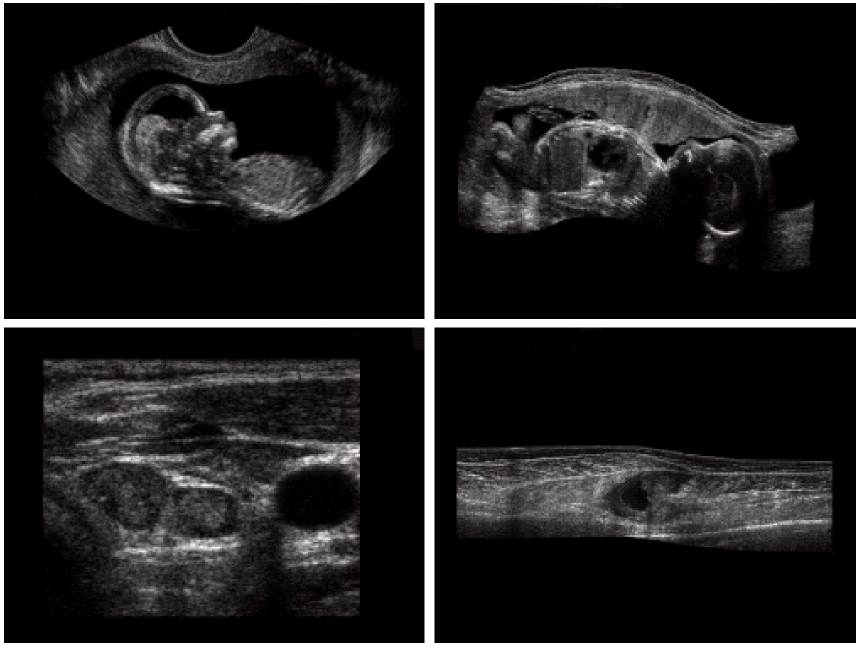


[Gonzalez/Woods; Wikipedia: crab pulsar + Krebsnebel]

Image Sources

There are also other imaging modalities that do not come from the electromagnetic spectrum:

Ultrasound images:



| a | b |
| c | d |

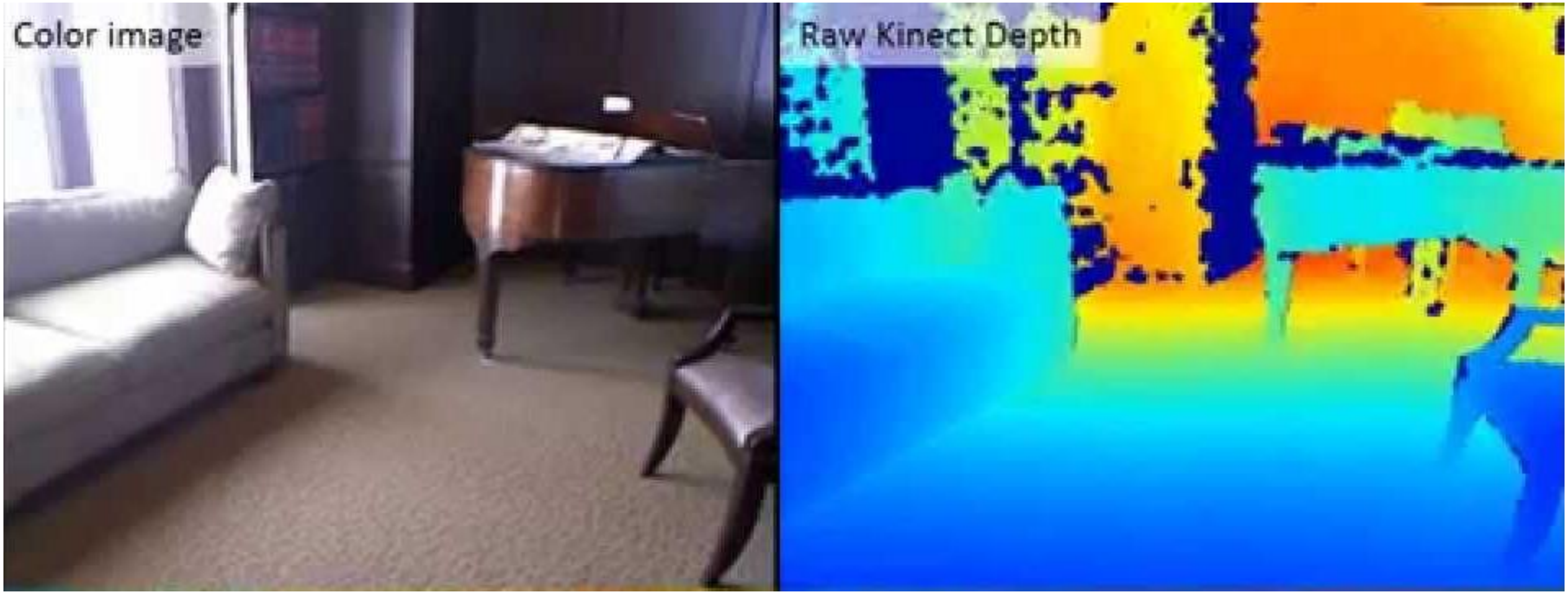
FIGURE 1.20 Examples of ultrasound imaging. (a) Baby. (2) Another view of baby. (c) Thyroids. (d) Muscle layers showing lesion. (Courtesy of Siemens Medical Systems, Inc., Ultrasound Group.)

[Gonzalez/Woods]

Image Sources

Depth images (e.g. from Kinect sensor)

(an infrared laser projector combined with a monochrome CMOS sensor, which captures video data)



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Components of DIP Systems

- Components of image processing systems:

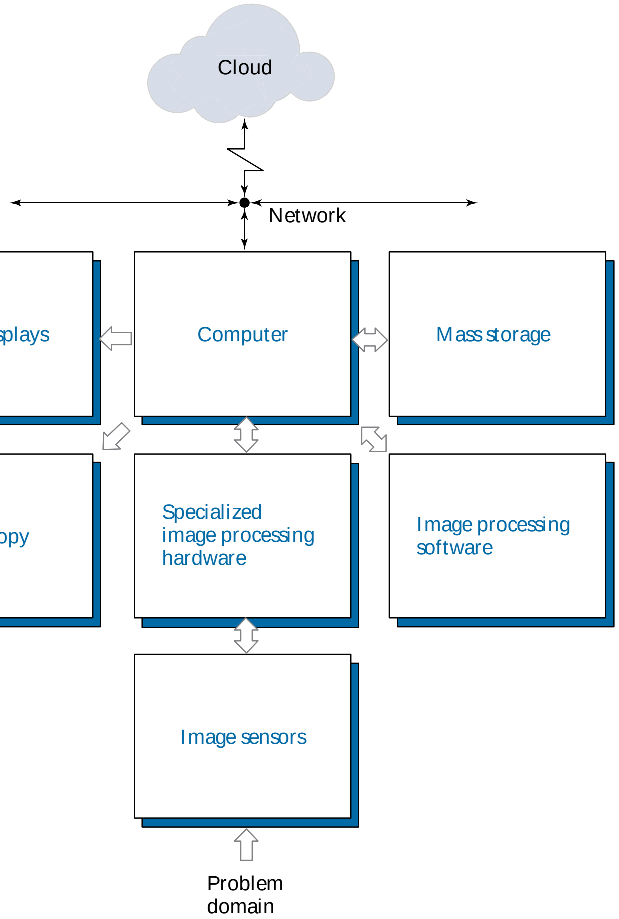


FIGURE 1.24 Components of a general-purpose image processing system.

Computer: from PC to supercomputer
Displays: usually color monitors, but can be also glasses etc
Hardcopy: printer, CDs/DVDs
Mass storage: from computer memory to external storage
Image processing software: in image processing toolboxes/libraries e.g. Matlab Image Processing Toolbox, NumPy/Scikit-image for Python, OpenCV for C++/Python

[Gonzalez/Woods]

Components of DIP Systems

- Components of image processing systems:

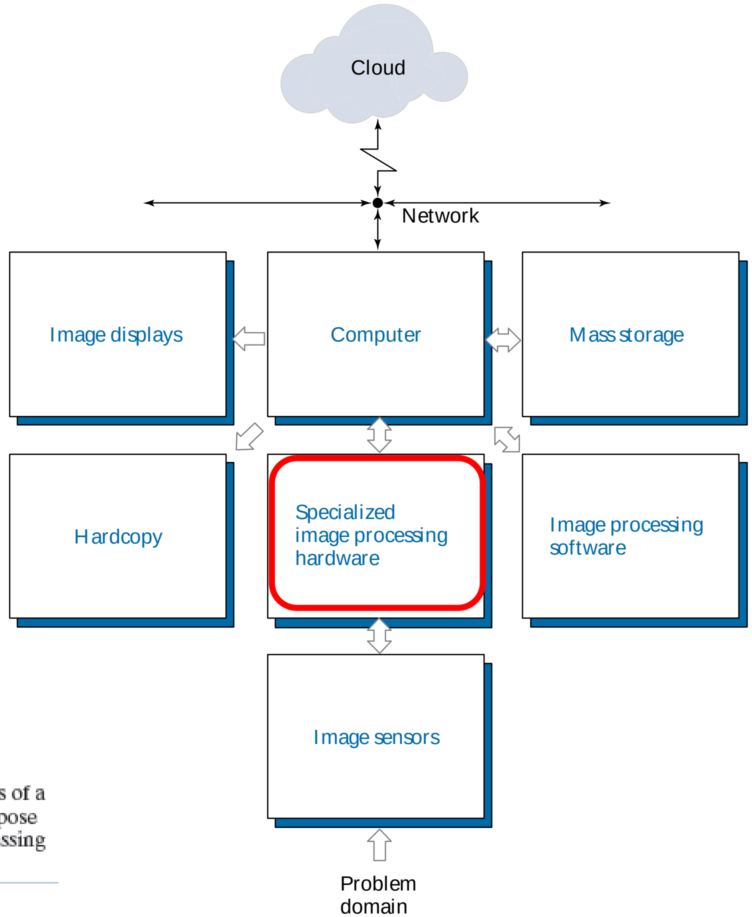


FIGURE 1.24 Components of a general-purpose image processing system.

Specialized image processing hardware:

- Arithmetic logic unit (ALU): performs arithmetic and logical operations in parallel. Central building block of CPUs and GPUs
- Graphical processing units (GPUs)

[Gonzalez/Woods]

Components of DIP Systems

- Components of image processing systems:

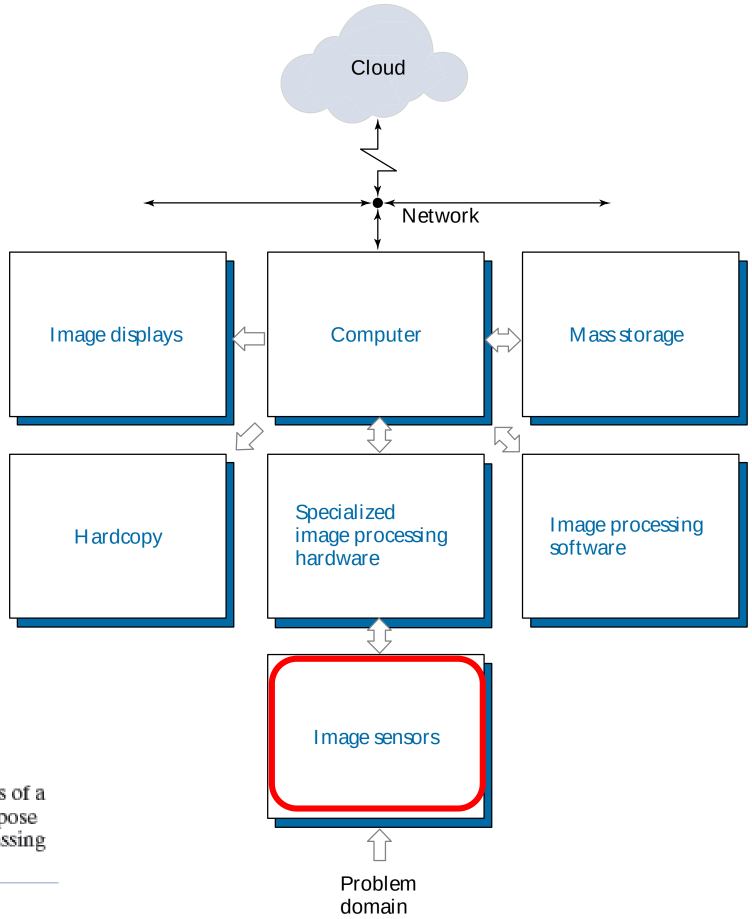


FIGURE 1.24 Components of a general-purpose image processing system.

[Gonzalez/Woods]

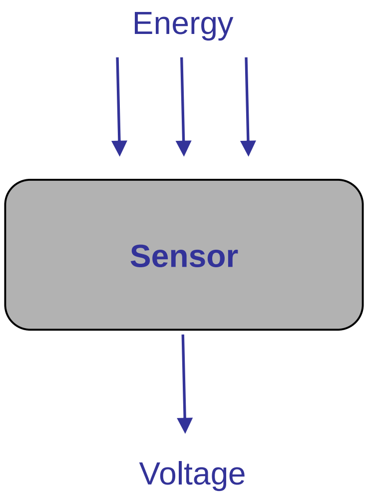
Imaging Sensors

Images obtained from the EM are acquired by sensors that detect energy within a certain frequency band

Principle of sensors:

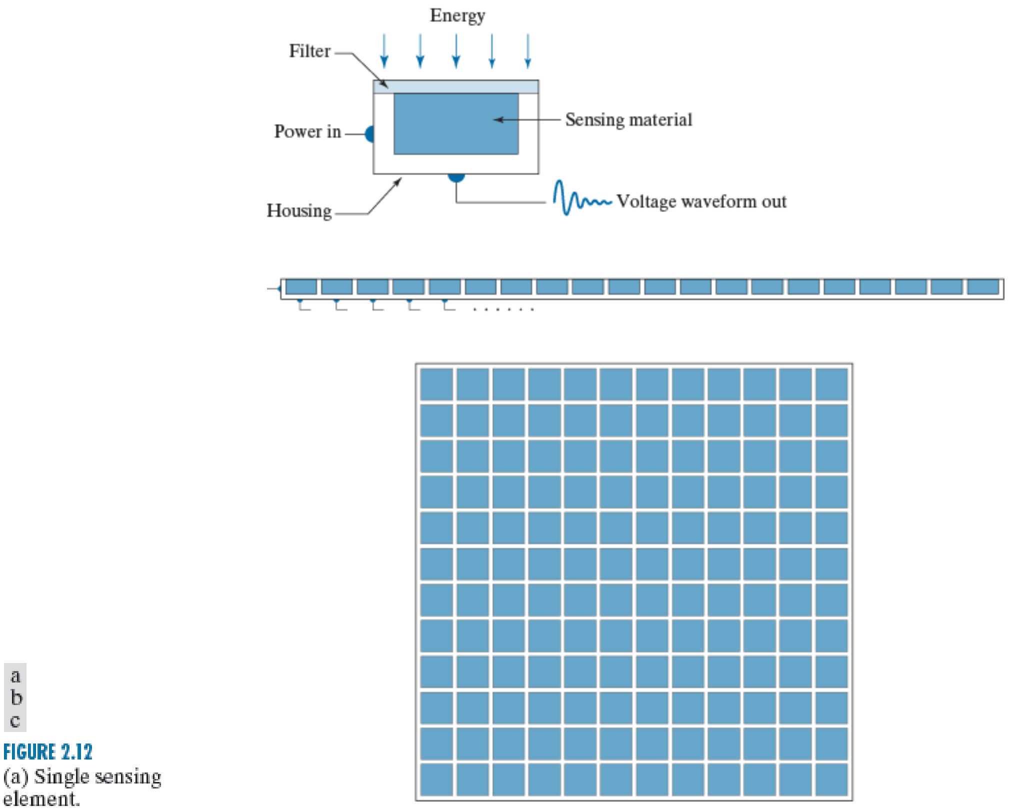
Transform incoming energy into a voltage by a combination of the input electrical power and sensor material which is responsive to the desired type of energy.

The voltage is digitized to obtain a digital image.



Imaging Sensors

Three principal sensor arrangements:



1) Single sensor

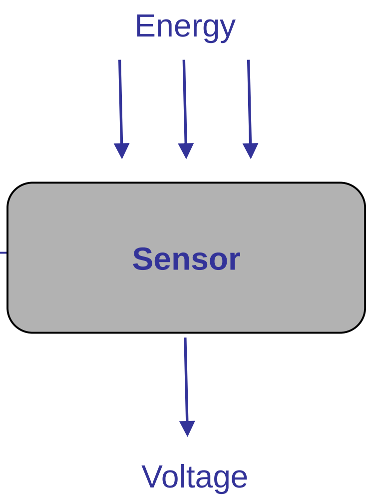
2) Line sensor

3) Array sensor

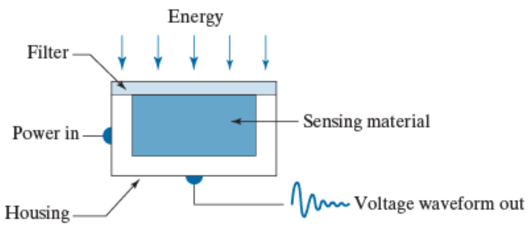
FIGURE 2.12
(a) Single sensing element.
(b) Line sensor.
(c) Array sensor.

[Gonzalez/Woods]

1) Single Sensors



Components of a single sensing element:



Housing: Gehäuse
Silicon: Silizium
Photodiode: Fotodiode

The sensing element transforms the (light) energy with electrical power and the sensor material (e.g. silicon) to a voltage.

A filter improves selectivity (e.g. a green-transmission filter favors green light)

Familiar example for single sensor element: photodiode

[Gonzalez/Woods]

1) Single Sensors

- To obtain an image from a single sensing element, the element must be moved over the scene (“relative displacement in x- and y-directions”)
- Drum arrangement used in high-precision scanning:

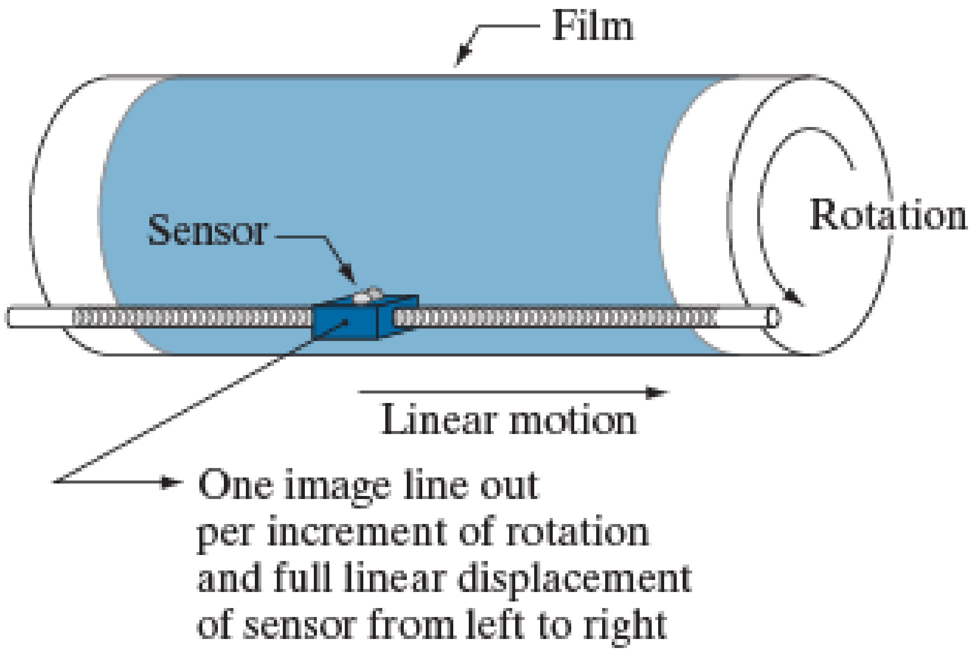


FIGURE 2.13 Combining a single sensing element with mechanical motion to generate a 2-D image.

[Gonzalez/Woods]

1) Single Sensors

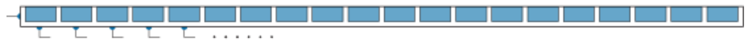
- Alternative arrangement:
- A flat imaging bed with the sensor moving horizontally and vertically

- Advantage of single sensor arrangements:
- Inexpensive way to obtain high-resolution images (mechanical motion can be controlled with high precision)
- Disadvantage: slow, not easily portable

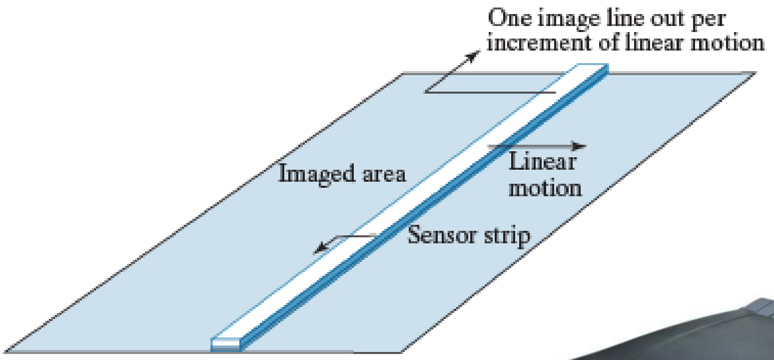
Line sensor: Zeilensensor

2) Line Sensors

Line sensors (or sensor strips) arranges single sensing elements (4000 and more) on a strip in one direction:



Motion perpendicular to this direction obtains the other direction required to obtain 2D images



Applications:

- Scanners
- Imaging geographical areas from aircrafts

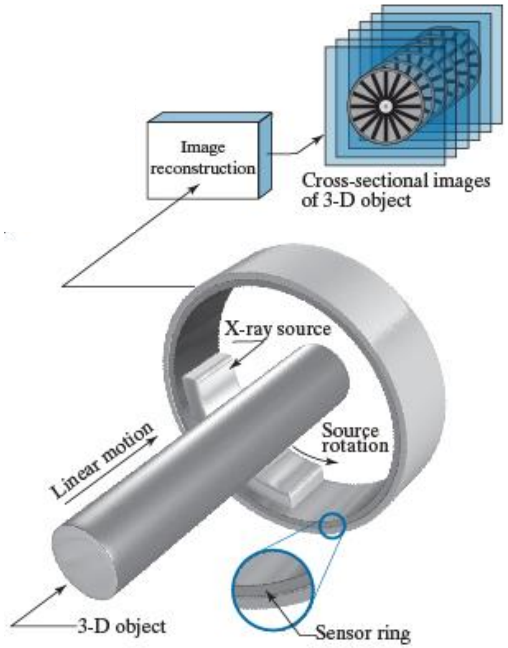
[Gonzalez/Woods]

MRI: MRT

2) Line Sensors

Sensor strips in ring configuration used in medical and industrial imaging to obtain cross-sectional slice images of 3D objects:

Example for circular X-Ray sensor strip:



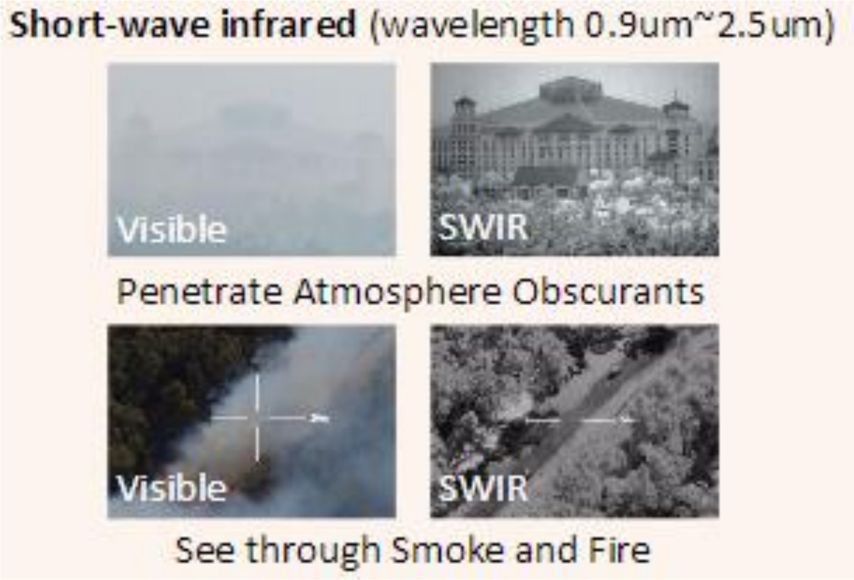
Also used for

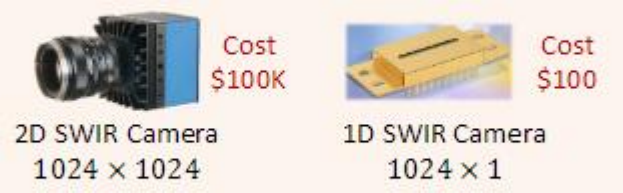
- CT/CAT (computed tomography scan)
- MRI (magnetic resonance imaging)
- PET (positron emission tomography)

[Gonzalez/Woods]

2) Line Sensors

Another example of a line sensor (ECCV 2016): SWIR sensor to measure short-wave infrared light

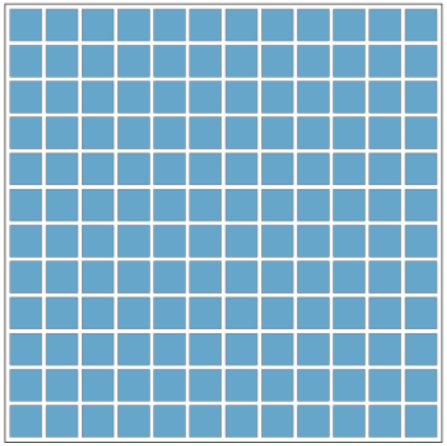




[Wang et al. 2016]

3) Array Sensors

Array Sensors arrange sensing elements in a 2D array:



Typical arrangement in digital cameras, electromagnetic and ultrasonic sensing devices

Digital cameras usually use CCD (charged coupled device) arrays of 4000 x 4000 elements or more

Sensors may integrate light over minutes/hours to reduce noise (see lecture on arithmetic operations on images)

[Gonzalez/Woods]

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Digital image acquisition

Process to acquire digital images with sensor arrays in digital cameras:

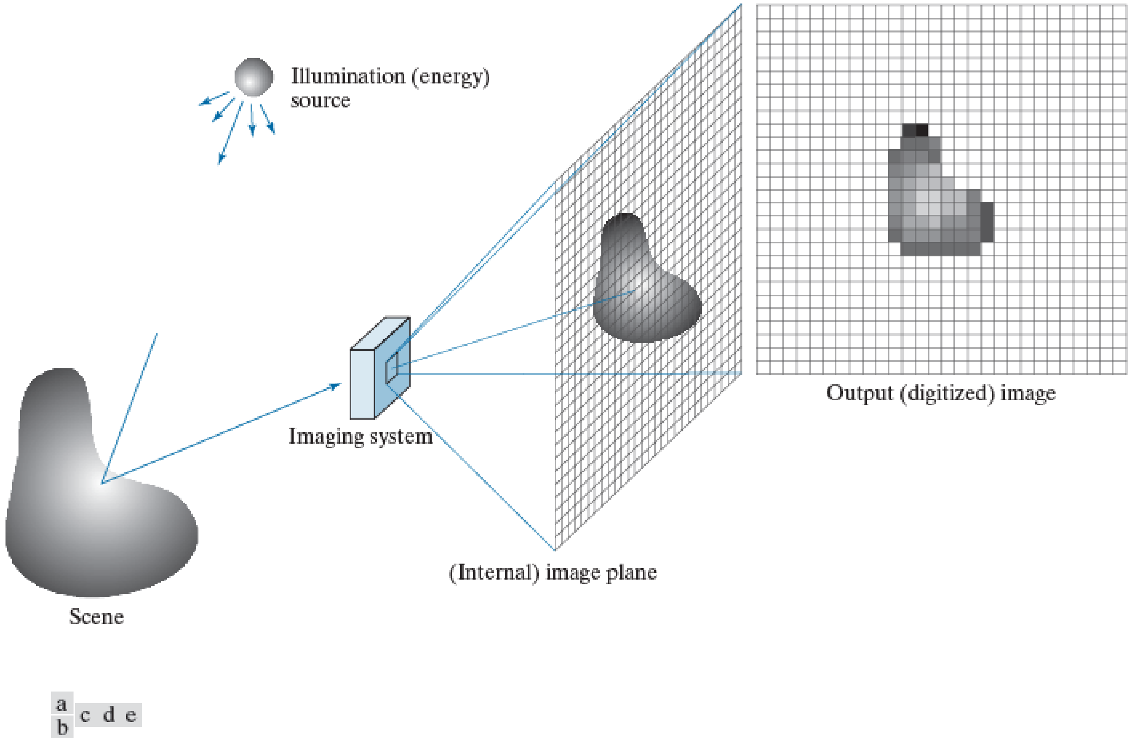

FIGURE 2.15 An example of digital image acquisition. (a) Illumination (energy) source. (b) A scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

[Gonzalez/Woods]

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Image Processing 02
HVS and Image Fundamentals
Part 4

SS 2020

Prof. Dr. Simone Frintrop

Computer Vision Group, Department of Informatics
University of Hamburg, Germany

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Digital image acquisition

Process to acquire digital images with sensor arrays in digital cameras:

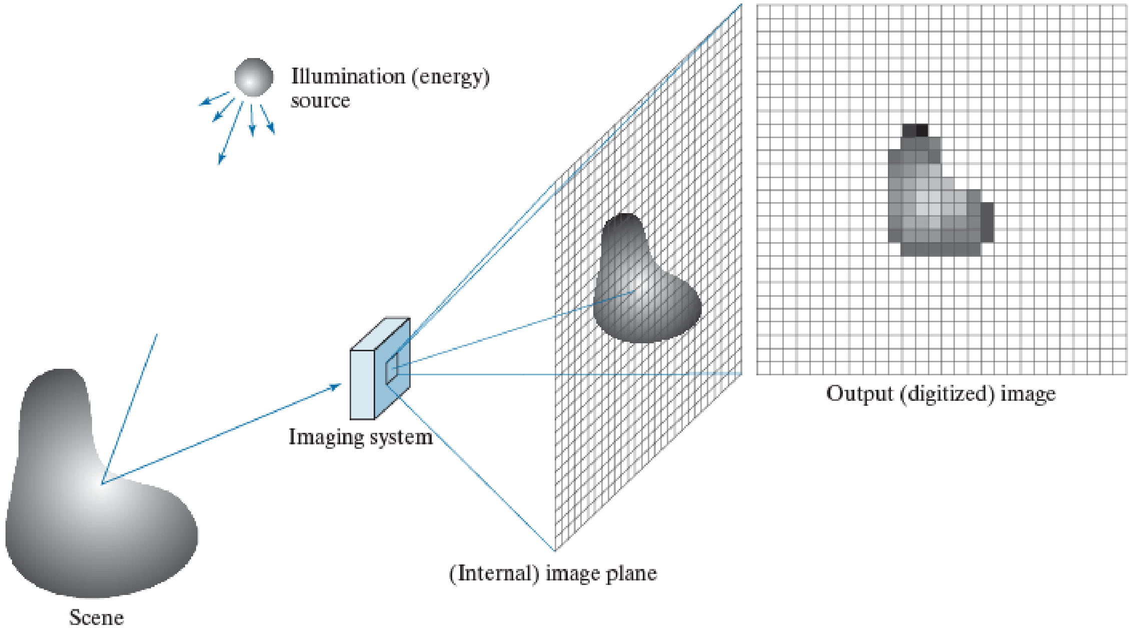


FIGURE 2.15 An example of digital image acquisition. (a) Illumination (energy) source. (b) A scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

[Gonzalez/Woods]

Sampling: Abtastung
Quantization: Quantisierung

Discretization of Images

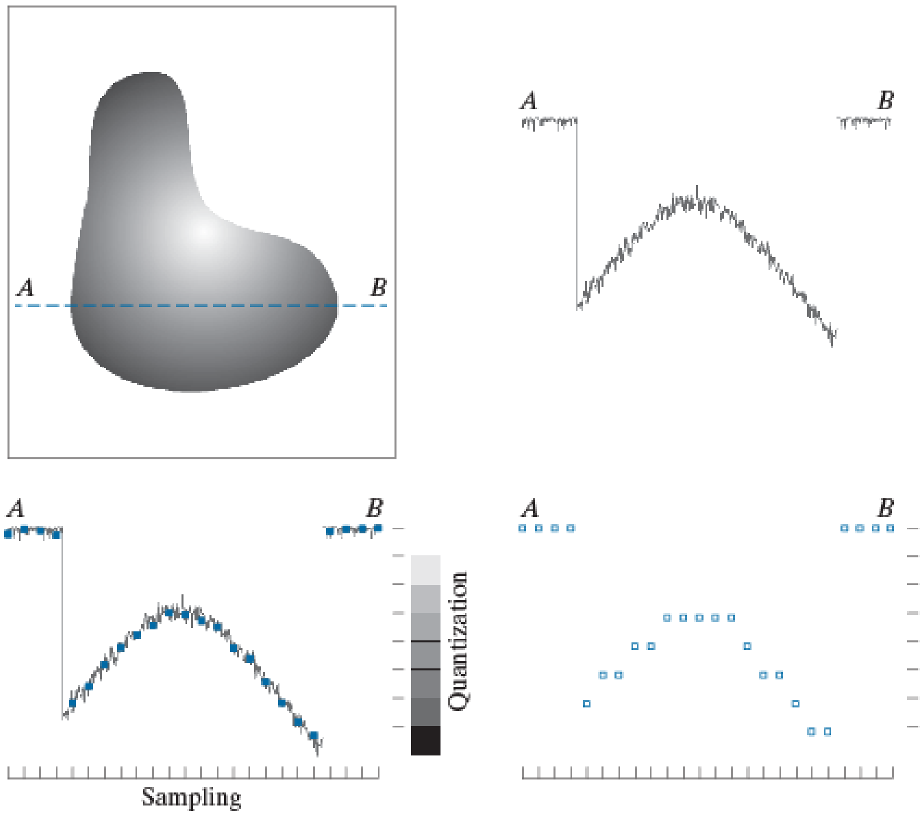
Image functions must be discretized for computer processing:

- spatial discretization: sampling
  the image plane is represented by a 2D array of picture cells
- grey value discretization: quantization
  each grey value is taken from a discrete value range
- temporal discretization of videos into frames
  grey values are taken at discrete time intervals

$$f(x,y,t) \Rightarrow \begin{Bmatrix} f_s(x_1, y_1, t_1), & f_s(x_2, y_2, t_1), & f_s(x_3, y_3, t_1), & \dots \\ f_s(x_1, y_1, t_2), & f_s(x_2, y_2, t_2), & f_s(x_3, y_3, t_2), & \dots \\ f_s(x_1, y_1, t_3), & f_s(x_2, y_2, t_3), & f_s(x_3, y_3, t_3), & \dots \end{Bmatrix}$$

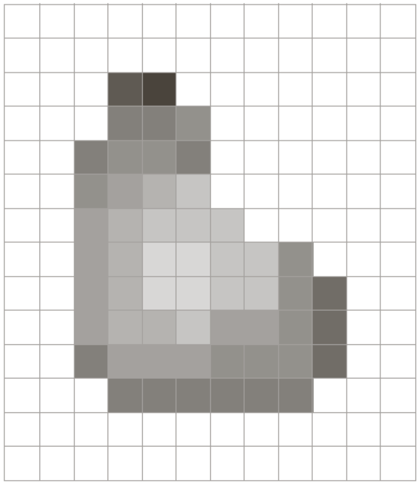
A single value of the discretized image function is called a pixel (picture element).

Sampling and quantization



a b
c d

FIGURE 2.16 (a) Continuous image. (b) A scan line showing intensity variations along line AB in the continuous image. (c) Sampling and quantization. (d) Digital scan line. (The black border in (a) is included for clarity. It is not part of the image).



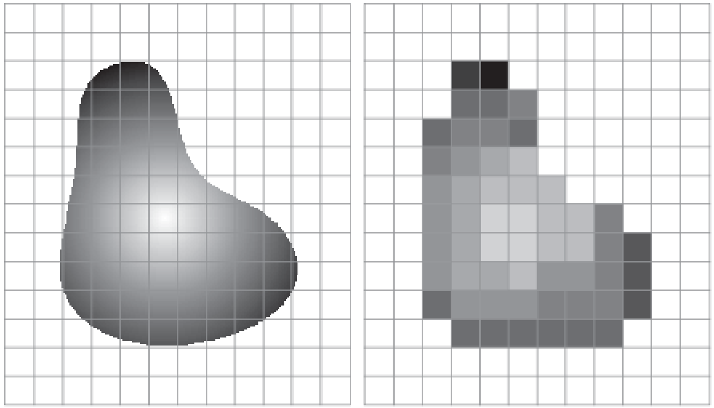
Sampling: Digitizing the coordinate values (how many grid cells)
Quantization: digitizing the amplitude values (how many values per cell)

[Gonzalez/Woods 2017]

Sampling and Quantization

a b

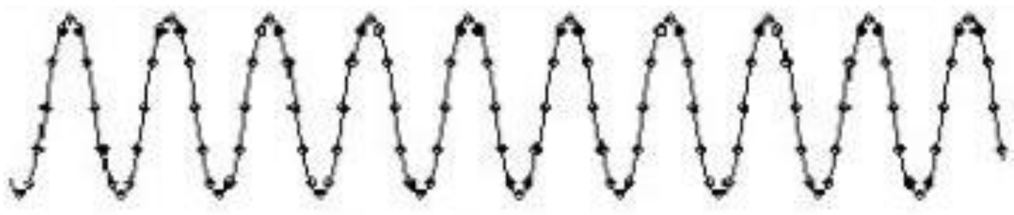
FIGURE 2.17
(a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.



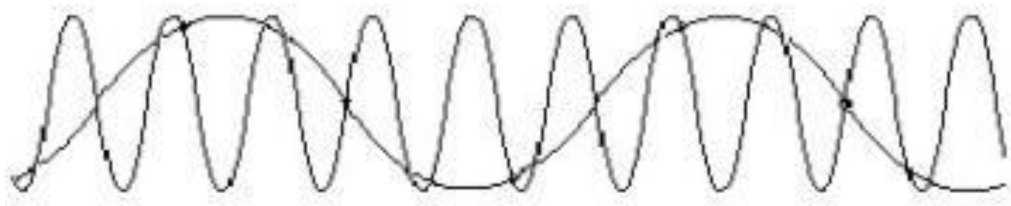
[Gonzalez/Woods]

Sampling

- By discretization, we loose information
- Reconstruction is only possible if the “variability” of a function is captured, that means if the sampling density “fits” to the function:
- Adequately sampled signal:



- Undersampling. Effect: “aliasing”



Sampling Theorem

Sampling Theorem (Nyquist/Shannon):

tells us how high the sampling rate must be to capture all information from a signal

A continuous, band-limited function f can be recovered completely from a set of its samples if the samples are acquired at a rate exceeding twice the highest frequency content of f

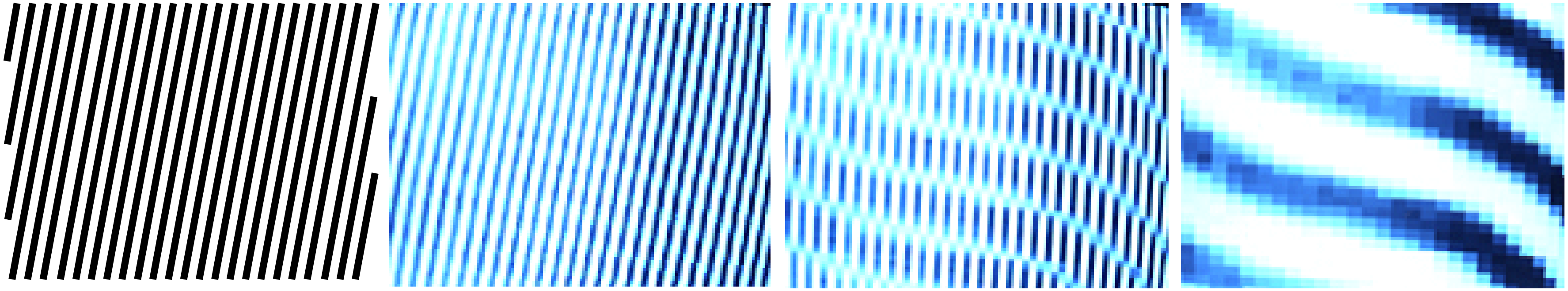
(Band-limited function: all frequencies are in finite interval (band))

Analogous theorem holds for 2D signals

Aliasing

Sampling an image with fewer samples than required by the sampling theorem may cause "aliasing" (artificial structures).

Example:



original 143 x 128 71 x 64 35 x 32

To avoid aliasing, bandwidth of image must by reduced prior to sampling (→ low-pass filtering)

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Image Processing 02
HVS and Image Fundamentals
Part 5

SS 2020

Prof. Dr. Simone Frintrop

Computer Vision Group, Department of Informatics
University of Hamburg, Germany

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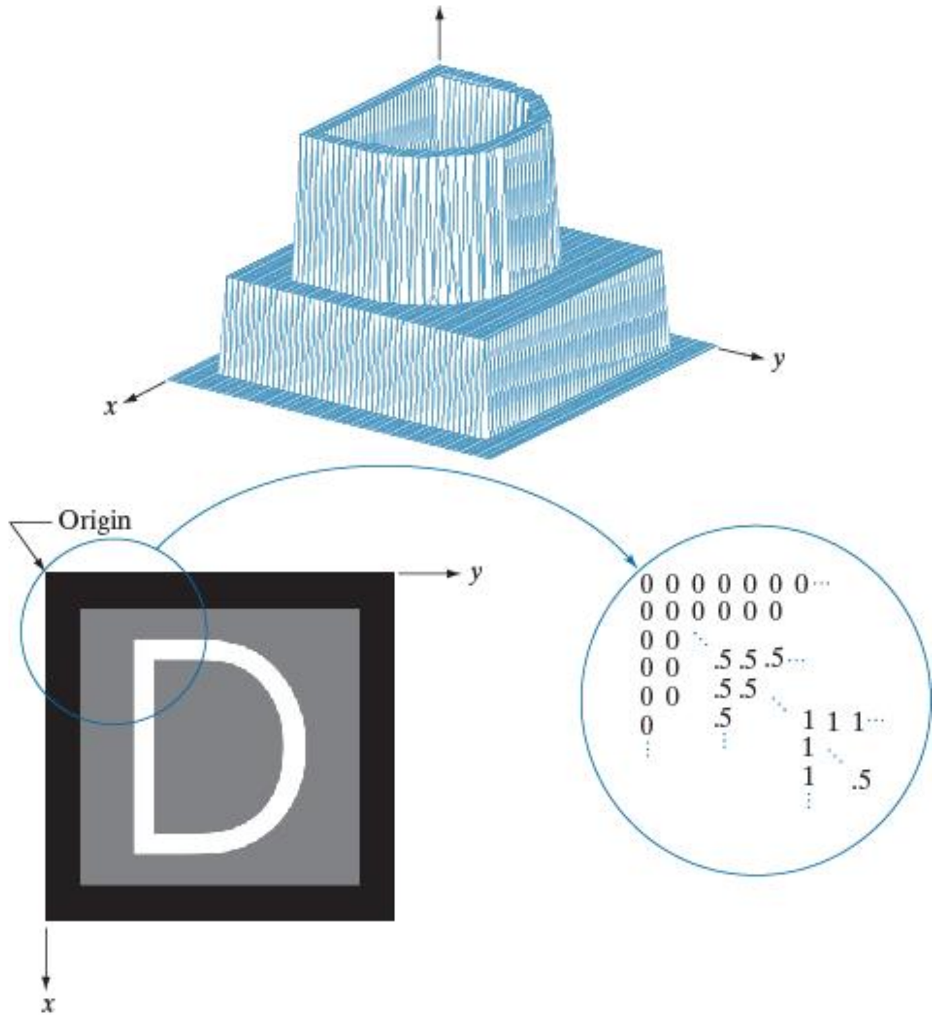
Representation of Images



a
b c

FIGURE 2.18 (a) Image plotted as a surface. (b) Image displayed as a visual intensity array. (c) Image shown as a 2-D numerical array. (The numbers 0, .5, and 1 represent black, gray, and white, respectively.)

[Gonzalez/Woods]

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Representation of Images

- The digital image as a matrix…
- This allows us to apply matrix (and array) operations

39	24	9	15	19	27	36	37	32	27	26	36	36	35	34	36	41	50	57	50	47
51	40	19	12	16	26	36	38	34	31	31	39	34	33	41	53	60	57	51	61	56
48	48	39	13	17	25	33	35	32	31	34	36	33	34	45	59	64	56	46	64	61
35	45	50	18	20	25	31	31	28	29	33	31	34	39	46	51	52	50	48	59	59
19	36	61	35	17	19	35	37	32	31	33	25	41	50	46	46	52	51	43	61	53
24	28	38	79	51	23	26	49	59	42	21	41	53	58	48	40	46	57	64	68	75
42	37	34	71	60	32	27	60	77	56	33	43	52	62	68	70	77	90	101	107	114
34	29	20	22	45	42	35	52	54	42	45	86	80	81	93	103	106	107	110	99	117
52	52	46	39	65	73	76	88	84	86	112	99	87	81	91	103	111	120	130	163	162
86	85	80	88	81	68	69	76	67	65	84	96	100	112	128	140	151	169	185	212	210
88	82	77	81	70	71	91	110	117	126	139	163	175	190	200	203	205	210	216	232	224
106	109	110	132	137	159	179	182	183	192	200	214	215	215	214	216	218	217	214	222	223
169	190	190	201	203	210	215	214	209	207	209	210	217	215	213	215	213	211	218	225	225
210	217	209	208	210	215	219	216	210	207	209	210	217	215	213	216	213	212	218	224	225
208	214	208	208	210	214	218	215	208	206	208	211	217	216	213	216	214	212	219	224	225
198	207	204	206	208	213	216	214	209	208	210	211	218	217	214	217	214	213	219	223	225
201	207	203	210	211	216	219	217	212	211	214	212	219	217	215	217	215	213	220	222	224
197	207	207	212	212	216	218	215	209	208	211	213	219	218	215	218	216	214	221	222	224
200	212	215	208	209	212	215	212	207	206	210	213	220	218	216	219	216	215	221	222	224
204	208	205	207	208	212	216	215	211	212	216	213	220	219	216	219	216	215	221	221	224
212	210	208	205	210	214	215	212	210	211	213	220	220	220	218	215	216	220	224	225	227

Representation of Images

The digital image as a matrix A with dimensions M x N:

$$\mathbf{A} = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & \vdots & & \vdots \\ a_{M-1,0} & a_{M-1,1} & \cdots & a_{M-1,N-1} \end{bmatrix}$$

Image Representations

An image can also be written as one column vector, by appending all columns of an image into the vector

$$\mathbf{A} = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & \vdots & & \vdots \\ a_{M-1,0} & a_{M-1,1} & \cdots & a_{M-1,N-1} \end{bmatrix}$$

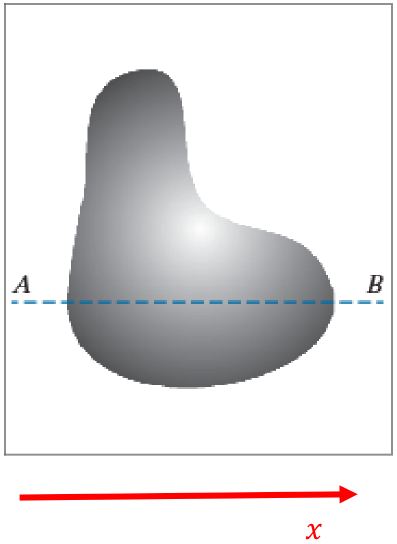
$$V = \begin{matrix} a_{0,0} \\ a_{1,0} \\ \vdots \\ a_{M-1,0} \\ a_{0,1} \\ a_{1,1} \\ \vdots \\ a_{M-1,1} \\ a_{0,N-1} \\ a_{1,N-1} \\ \vdots \\ a_{M-1,N-1} \end{matrix}$$

The Image as Signal

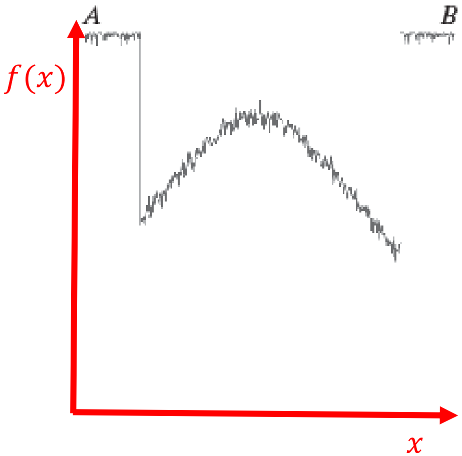
But you can see an image also as a (continuous) signal or function.

Let's look at our previous 1D example:

The intensity profile can be written as f(x)



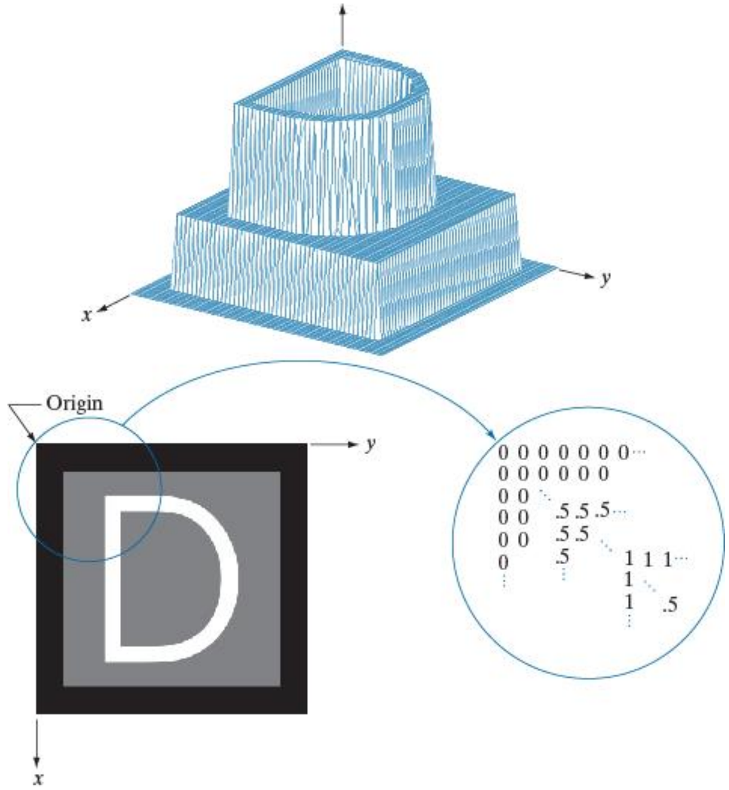
Image



Intensity profile of blue line

The Image as Signal

For 2D, we have 2 spatial axes x and y and the intensity profile is a 2D function $f(x, y)$:



[Images: Steve Seitz]

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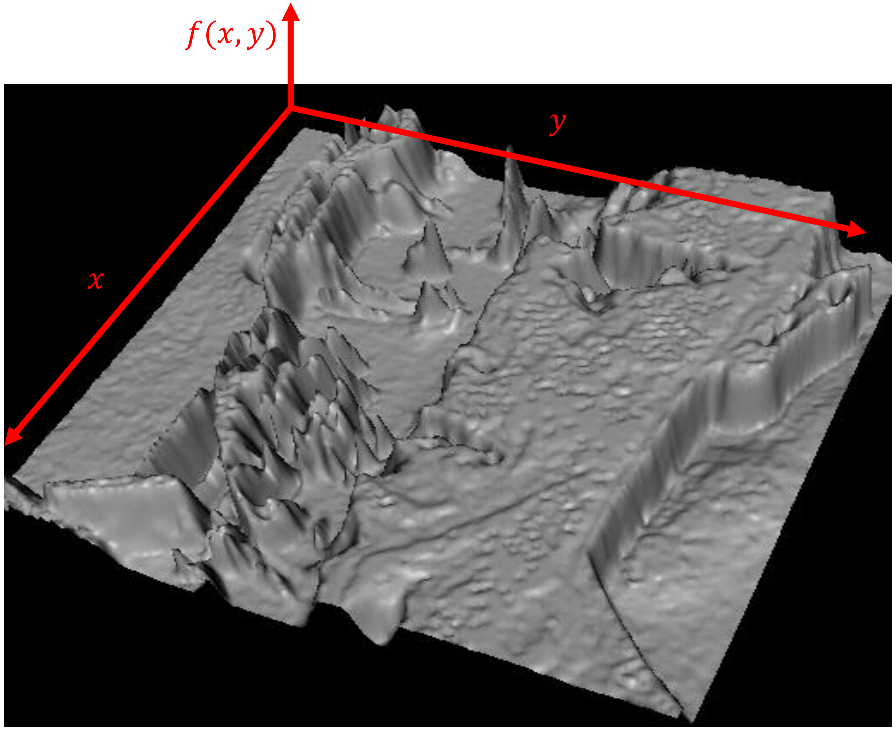
The Image as Signal

For 2D, we have 2 spatial axes x and y and the intensity profile is a 2D function $f(x,y)$:

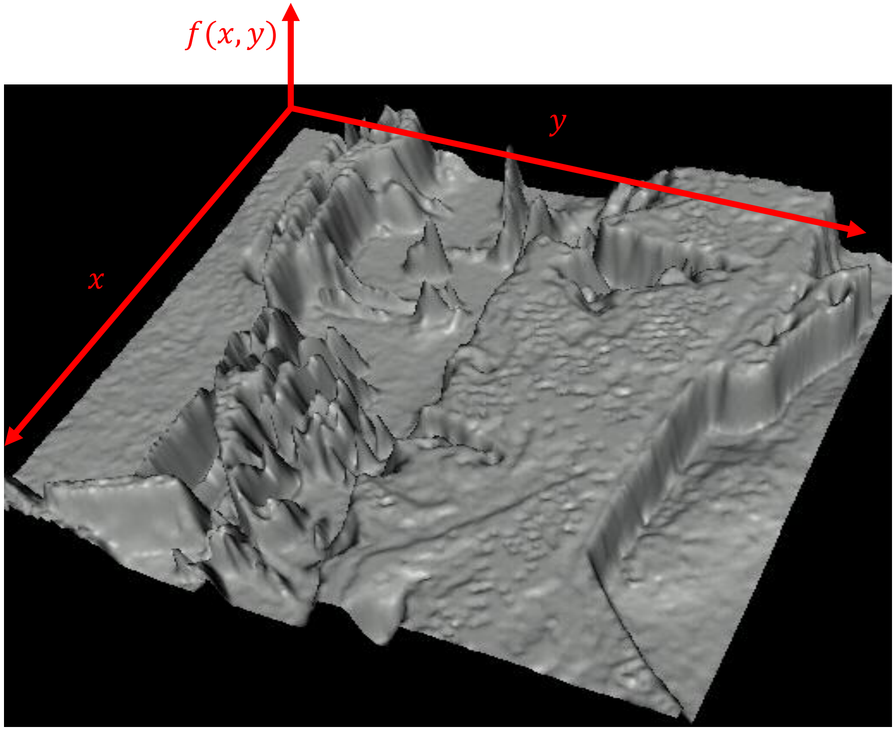


[Images: Steve Seitz]

The Image as Signal

This allows us to use terms and concepts from signal processing such as

- frequencies,
- filters (low-/high-/band-pass),
- (partial) derivatives,
- noise, etc.



Partial derivatives: partielle Ableitungen
Noise: Rauschen, Bildstörungen

[Image: Steve Seitz]

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Representation of Images

- The image A

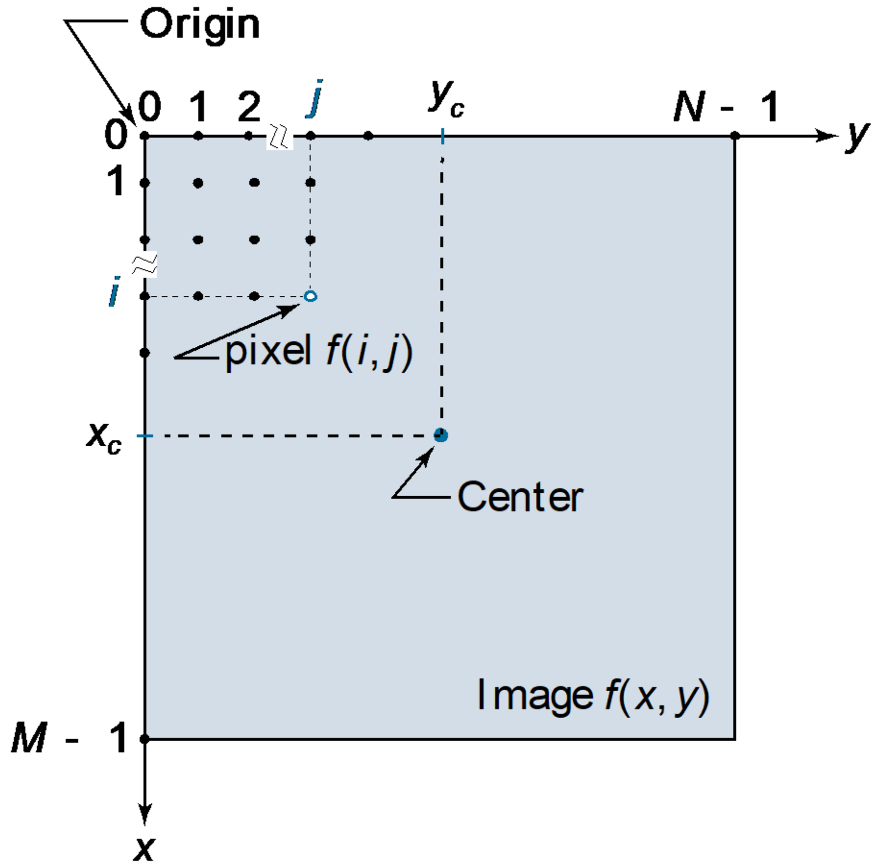
$$\mathbf{A} = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,N-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,N-1} \\ \vdots & \vdots & & \vdots \\ a_{M-1,0} & a_{M-1,1} & \cdots & a_{M-1,N-1} \end{bmatrix}$$

- can also be written as intensity function f(x,y):

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

Image Representations

- Note the unusual arrangement of x and y axis, which is often (but not always) used in image processing:



[Gonzalez/Woods]

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Image Processing 02
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Part 6

SS 2020

Prof. Dr. Simone Frintrop

Computer Vision Group, Department of Informatics
University of Hamburg, Germany

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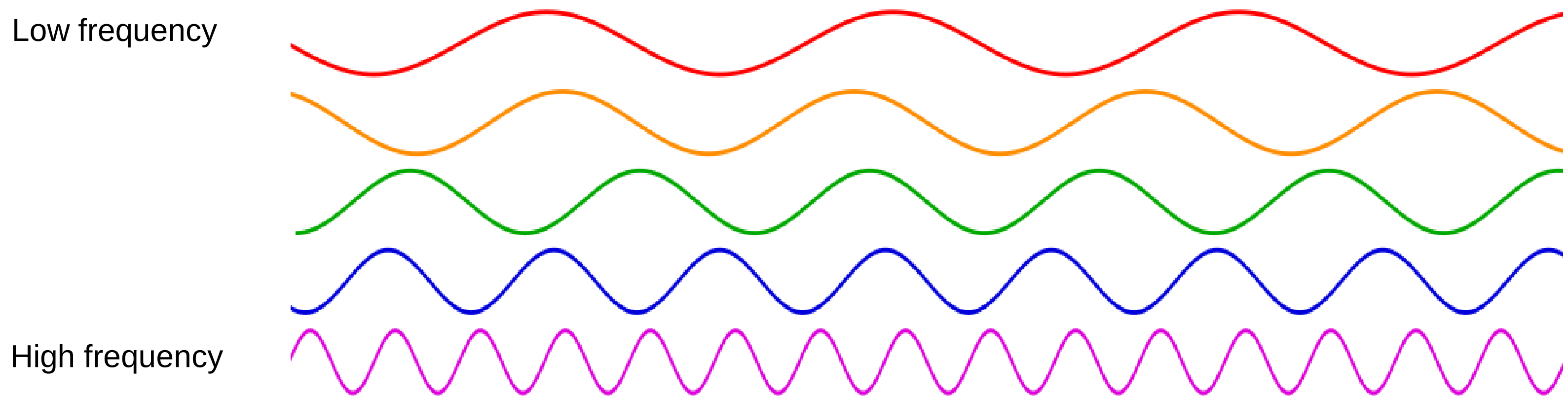
Frequencies

- What are frequencies?
- Frequency: The number of occurrences of a repeating event per unit time (temporal frequency)

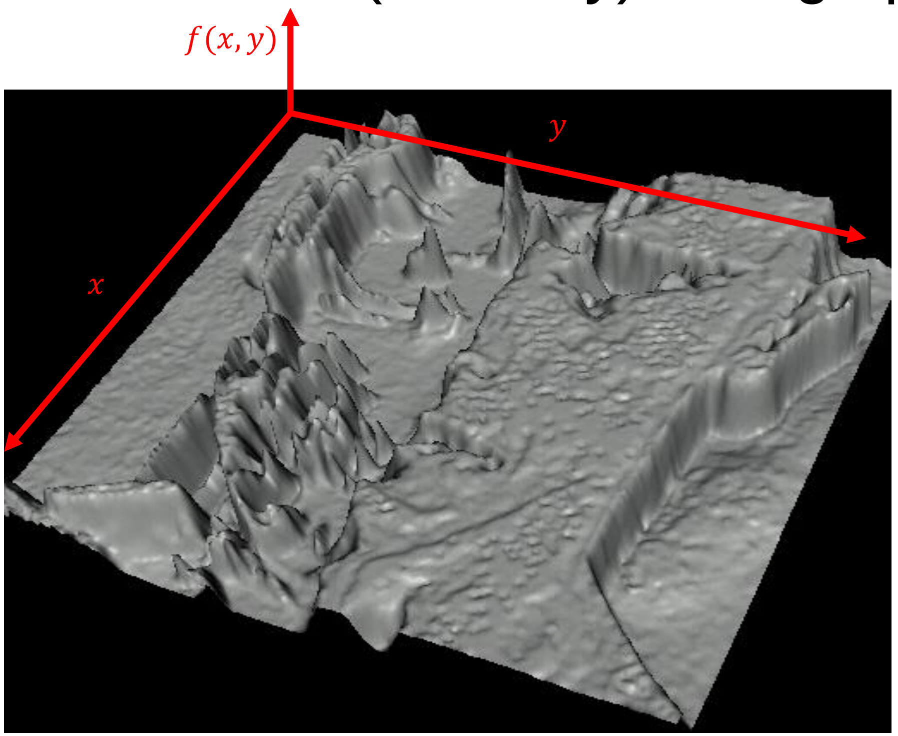


But: there is no time in images! ???

[Wikipedia: Frequency]

Frequencies

- **Spatial frequencies**: replace time axis by spatial displacement axes
- In images: the amount of (intensity) change per unit

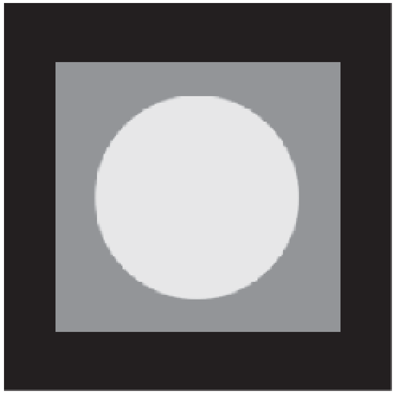


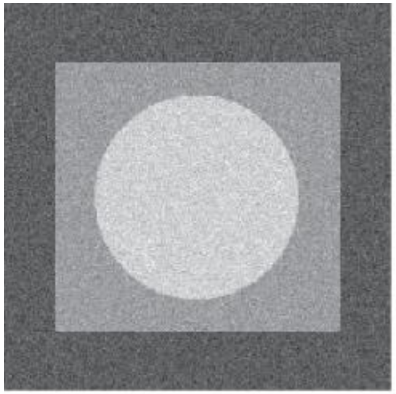
[Image: Steve Seitz]

Noise: „Rauschen“, Bildstörungen

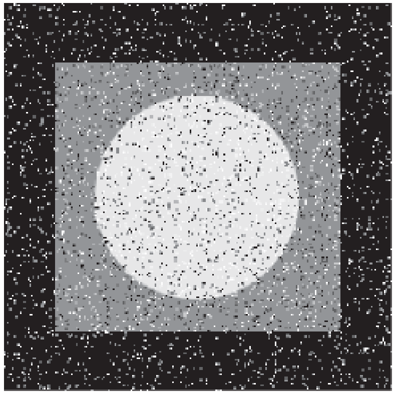
Noise

- What is “noise” in an image?
- Undesired “disturbances” of pixels, pixels that vary from the original signal source
- Noise corresponds to high frequencies in images





Gaussian Noise



Salt & Pepper Noise

[Gonzales/Woods, Chapter 5]

Noise

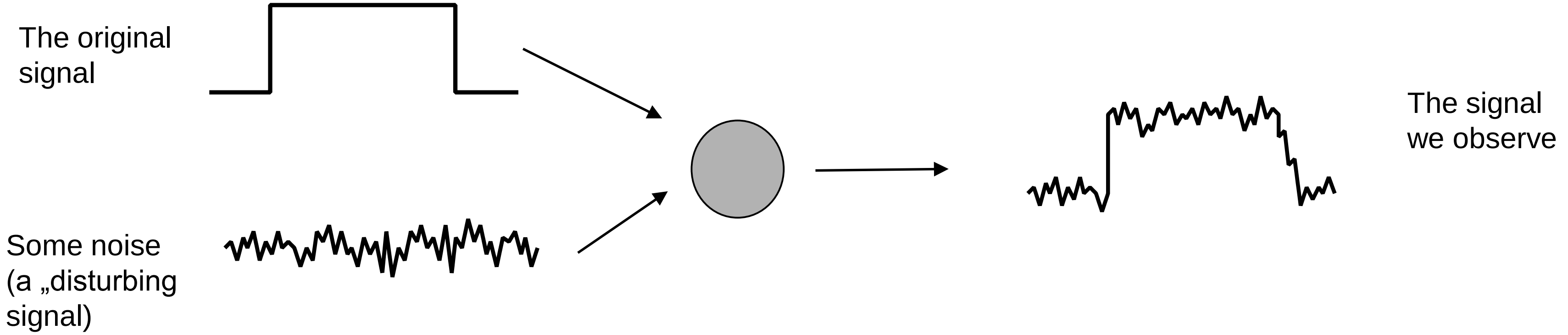
- Noise arises during
  - Image acquisition and/or
  - Image transmission
- Sources of noise during acquisition:
  - (bad) quality of the sensor
  - (low) light levels
  - Temperature
- Sources of noise during transmission:
  - Interference in the transmission channel
  - E.g. wireless network can be affected by lightning or other atmospheric disturbances

[Gonzales/Woods, Chapter 5]

Noise

Noise model:

- We can model noise as an own signal which is combined with the original signal



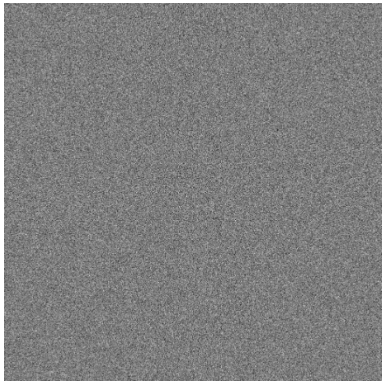
- Usually, this signal is independent of spatial coordinates and uncorrelated to the image content

[Images: Steve Seitz]

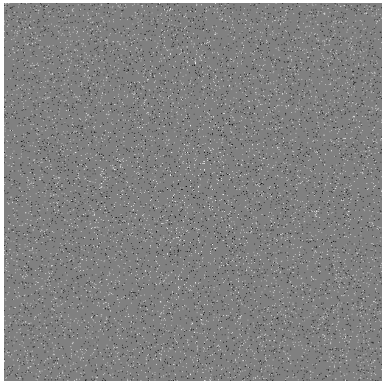
Noise

- Often, we can assume an additive noise model:

- In 2D signals (images), the noise is also a 2D image:



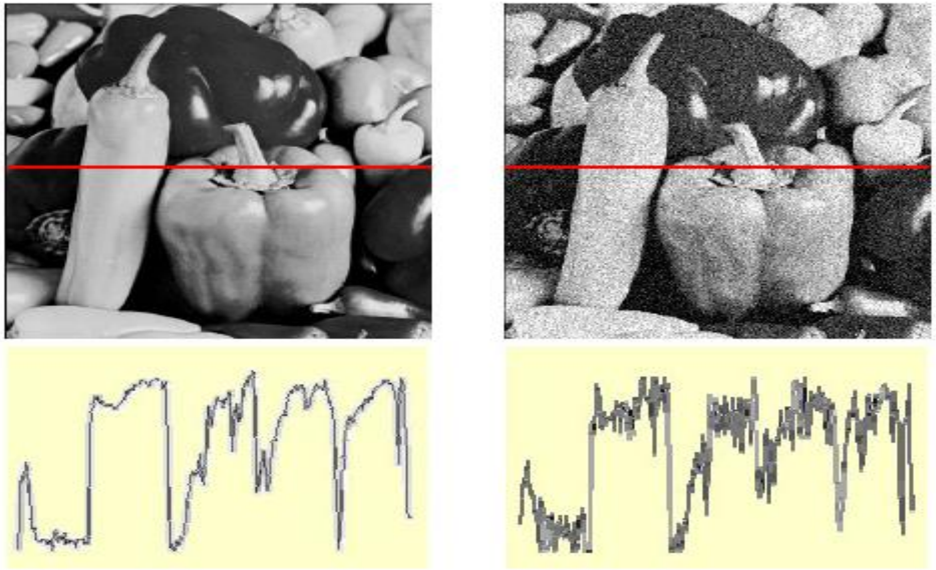
Gaussian noise



Salt and Pepper noise

Gaussian Noise

In Gaussian noise, each pixel deviates from the real signal value by a random value, which is drawn from a Gaussian distribution:

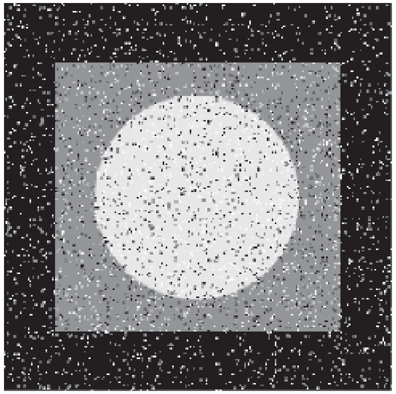


[Image: Martial Hebert]

Salt and Peppar Noise

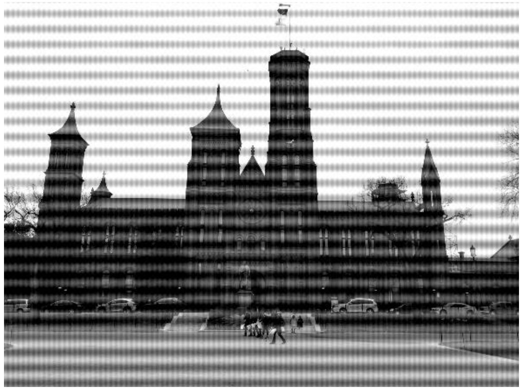
Salt and peppar noise (also *"data drop-out noise"*) is caused by errors in data transmissions.

Corrupted pixels are either set to minimum (peppar) or maximum value (salt)



Other Noise

There are other types of noise, e.g. *periodic noise* which results from electrical or electromechanical interference during the image capturing:



In following parts of the lecture we will see how to remove or reduce noise with digital filters

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Literature

Gonzales/Woods:

- chapter 1 and 2
- Sampling theorem and aliasing: chapter 4.3
- Noise: chapter 5.2