Life Sciences and
Facility Management

Institute of
Computational Life Sciences

Images – the basics

Image and Signal Processing

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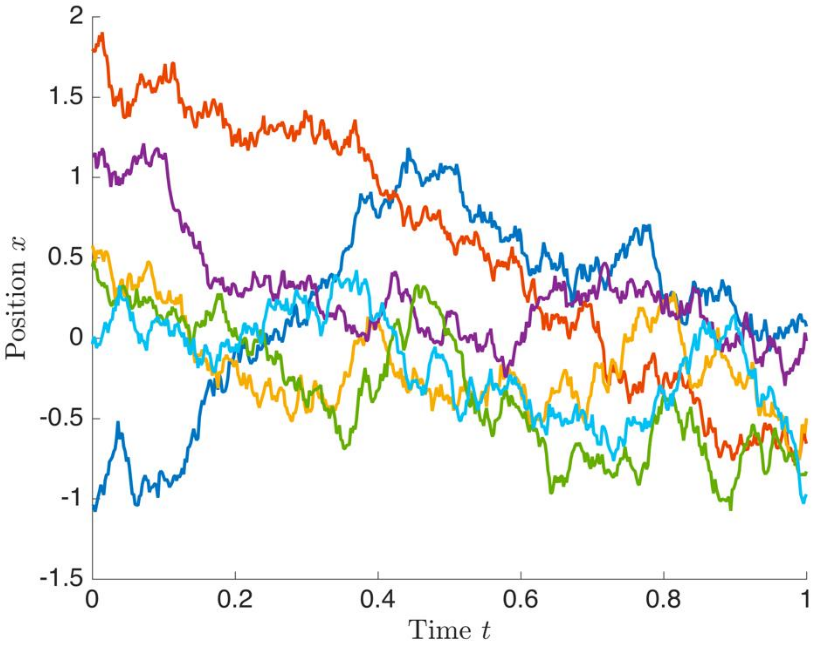
Introduction

From time series analysis
to image processing

From time series to images...

Time series



Image

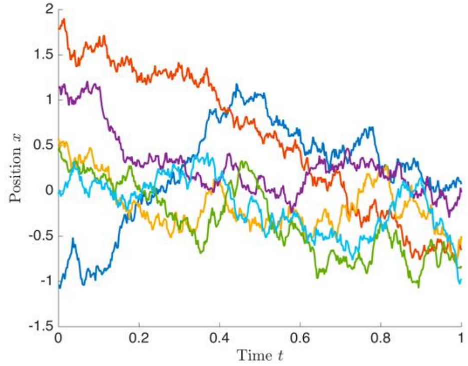
Task: What have these things in common?
What are the differences?

Source: Google Earth Fractals and Chen et al. 2020

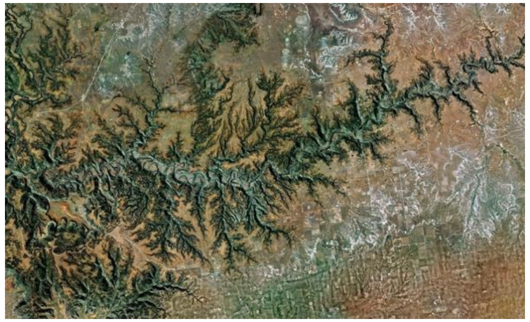
From time series to images...

- What they have **in common**:
  - Both are signals:
    - Measured data that vary over a domain
    - Contain information or patterns
    - May be affected by noise
  - Both can be processed using similar techniques:
    - Filtering
    - Fourier transform
    - Feature extraction

Time series



Image



Source: Google Earth Fractals and Chen et al. 2020

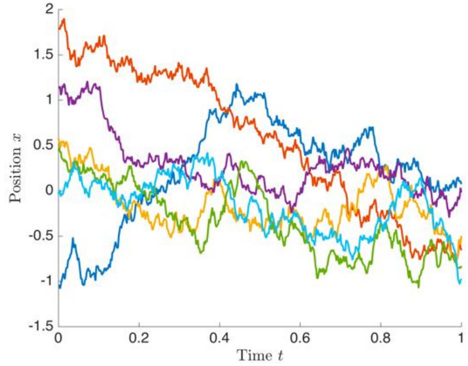
From time series to images...

- What the **differences** are:

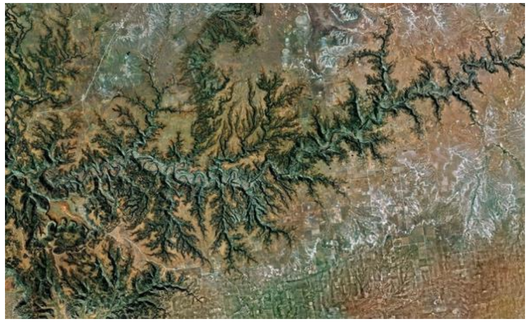
Feature	Time Series	Image
Signal dimension	1D: varies over **time** `x(t)`	2D: varies over **space** `I(x, y)`
Axis meaning	Time	Spatial position (x, y)
Sampling	Uniform in time	Grid over space (pixels)
Processing focus	Trends, frequency, change over time	Edges, textures, shapes
Tools	1D filters, FFT	2D filters, image ops (blur, edge detection)

- Domain shift: **From time domain → spatial domain**
  - We move from analyzing how signals change over time to how they change across space

Time series



Image



Source: Google Earth Fractals and Chen et al. 2020

Topics

- Discretization in 2D
  - Sampling
  - Quantization
- Color spaces
  - Binary / RGB / RGBA / HSL / CMYK ...
  - Conversions
- Basic image operations
  - Cropping
  - Spatial image transformations
- Spatial Fourier analysis
  - (Spectrograms in 2D)
  - FFT for images
- Convolution / filtering / kernels
  - Noise removal / smoothing
  - Gradients and image derivatives
- Features
  - Edge detection
  - Corners / interest points
  - Invariance properties
- Masks / morphological operations
  - Thresholding
  - Contours
  - Erosion / dilation / closure / opening ....

We will continue working with Python...

- OpenCV
- Pillow/PIL
- scikit-image
- Numpy / SciPy / Matplotlib
- Mahotas
- ITK/SimpleITK

Illustration taken from unite.ai. Link

Resources

Books

- *Computer Vision: Algorithms and Applications*. Szeliski, 2021: Link
- *Digital Image Processing*. Gonzalez and Woods, 2009: Link
- *Programming Computer Vision with Python*. Jan Erik Solem, 2012: Link

Online course:

- *First principles of computer vision*. Nayar, 2022. Link

Tutorials

- Image processing (with Pillow): Real Python
- Image processing (with OpenCV): OpenCV.org
- Digital image processing tutorial: tutorialspoint

Objectives

Digital image processing

Objectives of digital image processing

- Build machines that can see
- This involves many aspects:
  - Acquire and represent image data
  - Transform and filter images
  - Enhance image data, or restore missing data
  - Optimize information content (compression)
  - Extract information from image data (sensing)
  - Understand image content (semantics)
  - Decide based on image data
  - Synthesize images

Image acquisition

Image transformation

Image enhancement / restoration

Objectives of digital image processing

- Build machines that can see
- This involves many aspects:
  - Acquire and represent image data
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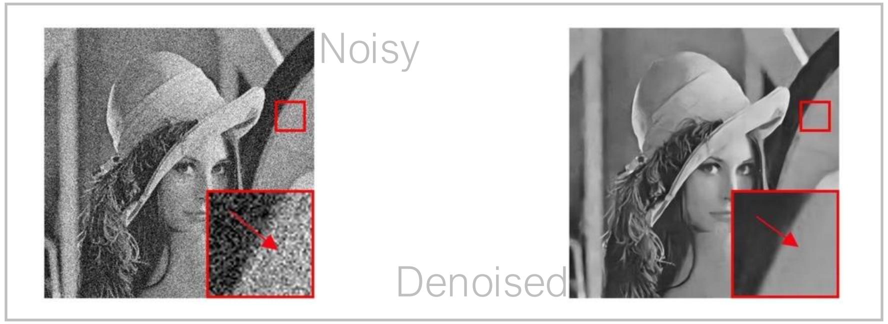
  - Enhance image data, or restore missing data
  - Optimize information content (compression)
  - Extract information from image data (sensing)
  - Understand image content (semantics)
  - Decide based on image data
  - Synthesize images

Image filtering



Extract information / features

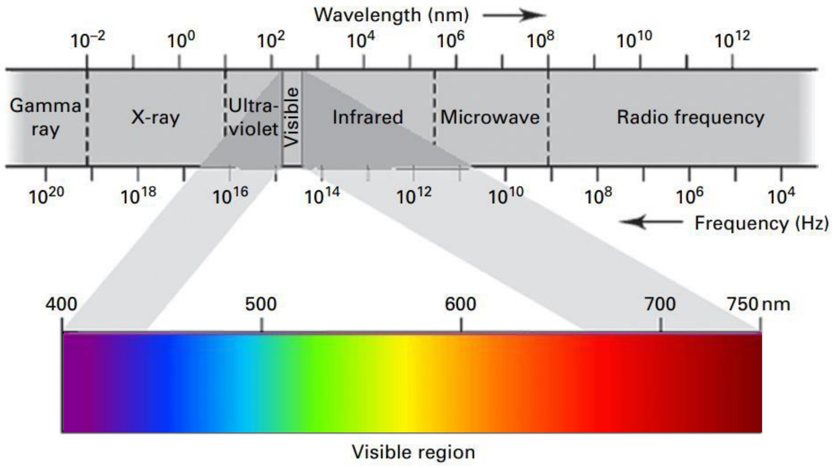
Segmentation

Objectives of digital image processing

- Rule of thumb: The more complex the task, the more machine learning or artificial intelligence is involved
- In this course: Image processing foundations
  - How to represent images?
  - How to process images?
  - Which are the problems to solve?
- Not in this course: Methods of machine learning / AI

Context: Imaging systems by type of radiation (or field) used

- Waves transport the information
- General rules:
  - The shorter the wavelength of a wave, the better it can reveal small details
  - The short the wavelength, the more energy carries a wave
- Type of radiation or field
  - Electromagnetic waves: Radio, microwaves, infrared, visible light, ultraviolet, (soft) x-rays
  - Other waves: Water, sonar, seismic, ultrasound, gravity
  - Particles: Neutrons, protons, electrons, heavy ions, (hard) x-rays, γ-rays



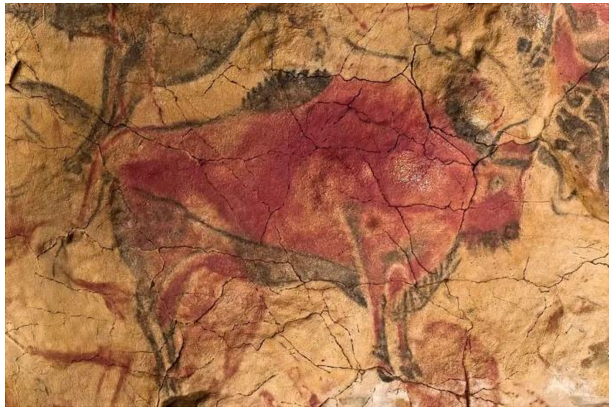
The electromagnetic spectrum arranged according to the energy of the photons, or the frequency of the waves.

A short history of images

...a ridiculously short history

A ridiculously short history of images

- Humans generate, record and transmit images to store and pass on information since the early days

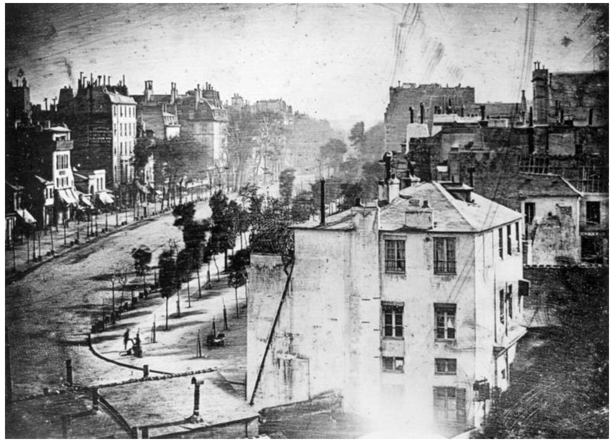


Painting of a bison from the Altamira cave, dating from around 36,000 years ago. (Source: Wikimedia)

A ridiculously short history of images

- Humans generate, record and transmit images to store and pass on information since the early days
- First photograph was pioneered in the 1820s by the Frenchmen Joseph Nicéphore Niépce and Louis Daguerre

1826: View from the Window at Le Gras by Niépce. Possibly the earliest surviving photograph. Source



1838: Boulevard du Temple, Paris. Photography by Louis Daguerre. Source

A ridiculously short history of images

- Humans generate, record and transmit images to store and pass on information since the early days
- First photograph was pioneered in the 1820s by the Frenchmen Joseph Nicéphore Niépce and Louis Daguerre
- First digital image was taken by Russel Kirsch in 1957 using a scanner
- First digital camera using a CCD (charge-coupled device) sensor from Willard S. Boyle and George E. Smith in 1969

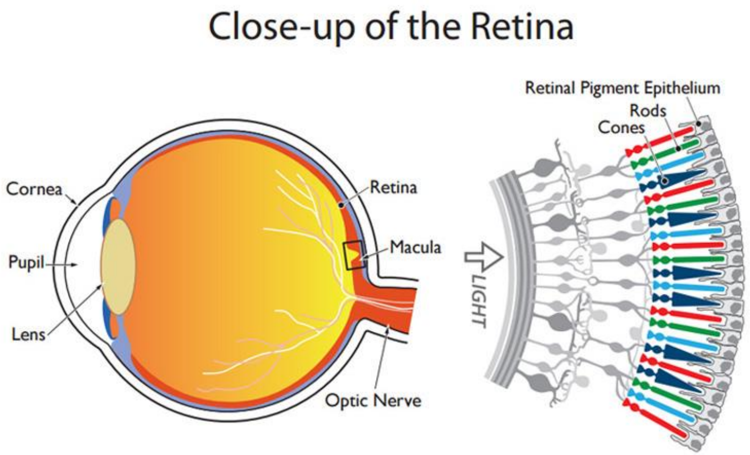
1957: First digital image ever created, by Russel Kirsch. Source

Human visual perception

Take inspiration from nature

Human visual perception

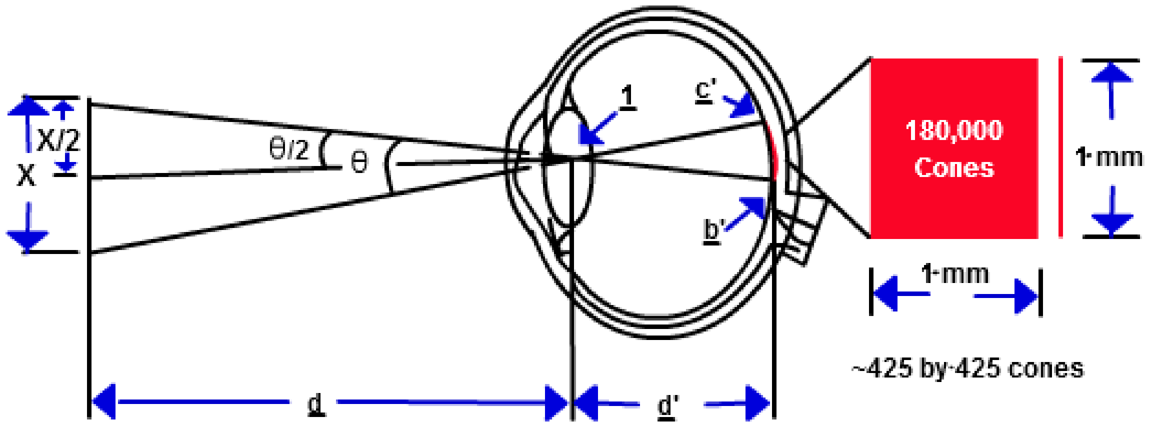
- Up to about 60% of the brain activity are involved in processing visual stimuli
- More surprising facts about the human visual system
  - The image on the retina is upside-down
  - Retina is front-back inverted
  - Peripheral vision is low-res and nearly monochrome
  - The resolution of the eye is only 1 megapixel
  - The eye involves about 100 million photoreceptors
  - The eye has a special night-vision mode



Illustrations: Link, Link

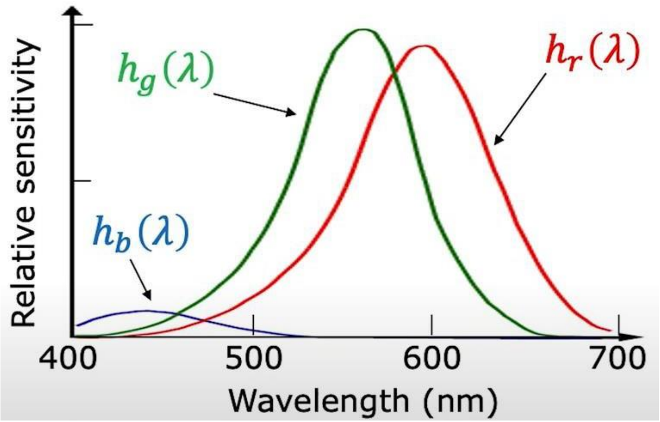
Resolution (human eye)

- The resolution of the human eye varies depending on several factors such as
  - the lighting conditions,
  - the contrast of the objects being observed
  - and the individual's visual acuity (Sehschärfe)
- However, under optimal conditions, the human eye is estimated to have a resolution θ of around 1 arc minute, which is equivalent to θ=1/60°.
- See here for a reasoning:



Human visual perception

- Rods and cones are specialized photoreceptor cells located in the retina of the eye.
  - Rods: very sensitive to light in general, particularly in low-light conditions, provide peripheral vision
  - Cones: Less sensitive to light, but provide the ability to perceive colors, Enable high visual acuity (Sehschärfe)
- Three different cones with different spectral sensitivity



«Quantum efficiency» of red, green and blue cones.

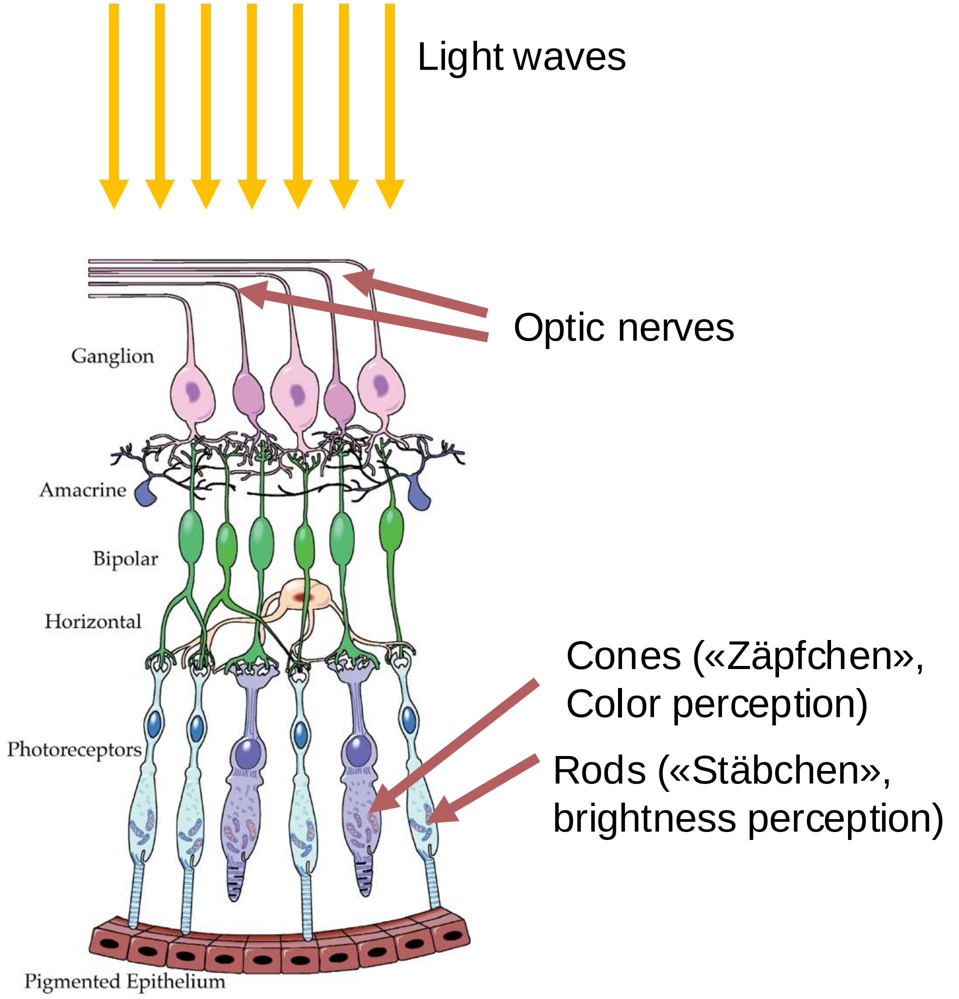
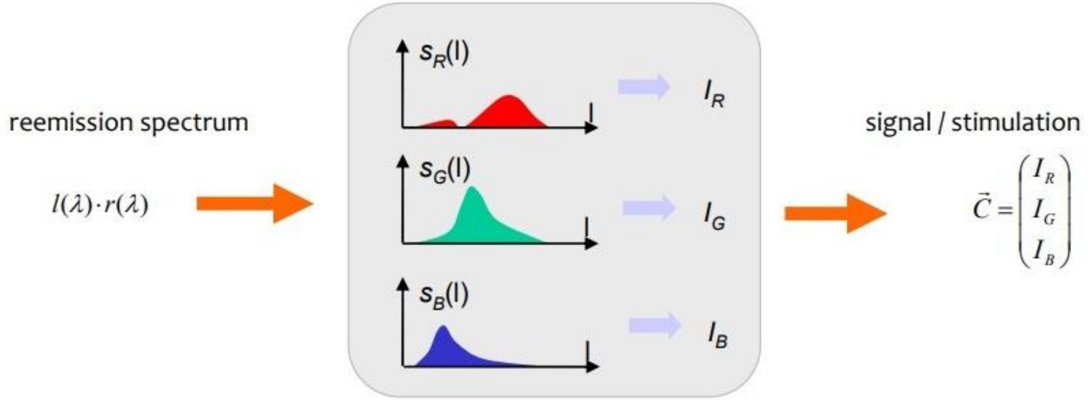


Illustration: Adapted from “Color Appearance”, Fairchild, 2005

Color perception

- Light propagation:
  - Light source spectrum: $l(\lambda)$
  - Reflectance / reemission spectrum: $r(\lambda)$
  - Sensitivity of cone receptors: $s_*(\lambda)$



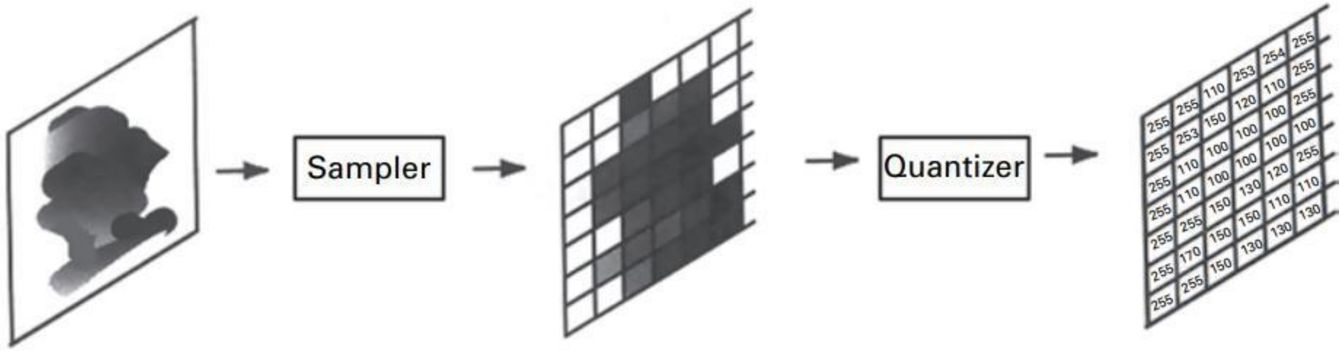
- Result:
  - Signal / stimulation consists of three channels
  - Different stimulation patterns lead to the perception of different colors:

Image representation

Pixels and quantization

Objects and images

- An imaging system captures an **input signal**, e.g., the electromagnetic radiation reflected or transmitted by an object, and generates an **output signal** or **image**.



The relationship between an analog image and a digitized image.

- The advent of computers has opened up enormous new possibilities for the quantitative processing and analysis of images, provided they can be represented by **digital arrays of discrete values**.

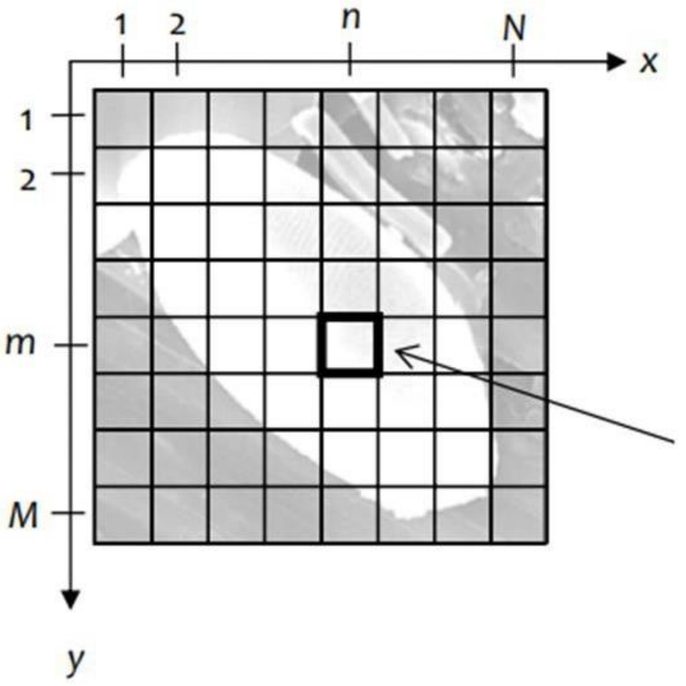
Advantages of digital images?

Task: What are the advantages of digital images compared to physical forms of image data (photographs, paintings, prints, murals, etc.)?

- Data storage takes no physical space
- Data can be copied and shared
- Images can be processed and analyzed
- Data visualization can be adjusted to different needs
- Digital images are much cheaper than physical copies of images

Image data: Matrix representation

- Due to the rasterization, the digital images can be represented naturally by a matrix $f(x, y)$ or by an array.
- A picture element (i, j) is called **pixel** and the value $f(p)$ at the pixel $p = (i, j)$ is called **pixel value**



row-index $1 \leq m \leq M$
column-index $1 \leq n \leq N$

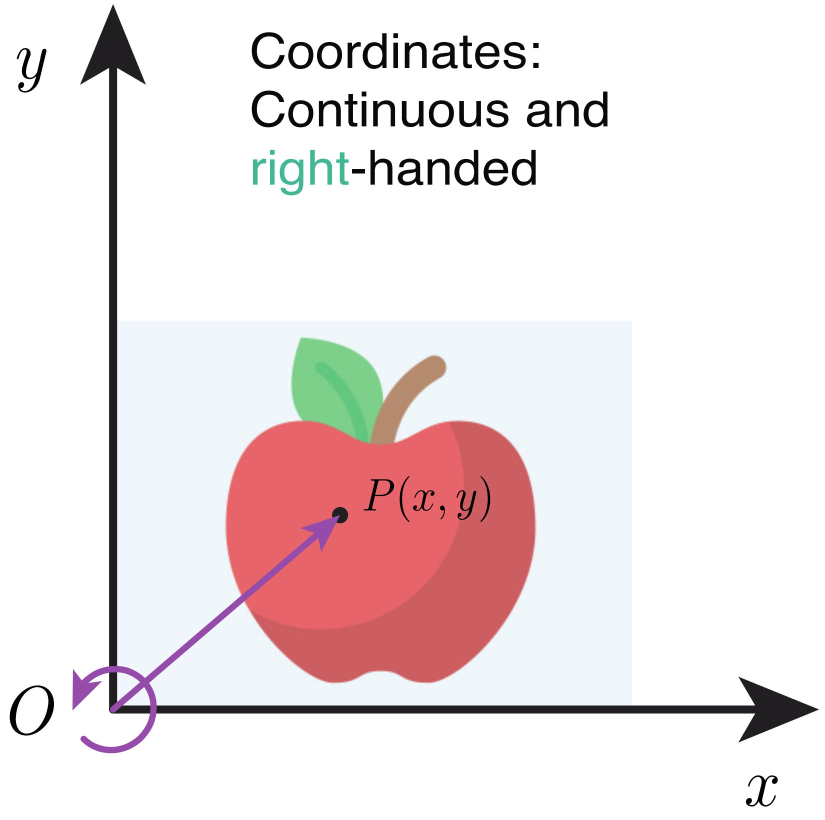
pixel (m, n)
pixel-value f_{mn}

matrix representation

$$\mathbf{B} = (f_{ij}) = \begin{pmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & & \\ f_{m1} & f_{m2} & \cdots & f_{mn} \end{pmatrix}$$

Coordinate systems

- 2D images are organized in 2D grids, having a horizontal and vertical extent
- To locate information in that grid requires two coordinates
- Unfortunately, we need to distinguish between different coordinate systems



Coordinate systems

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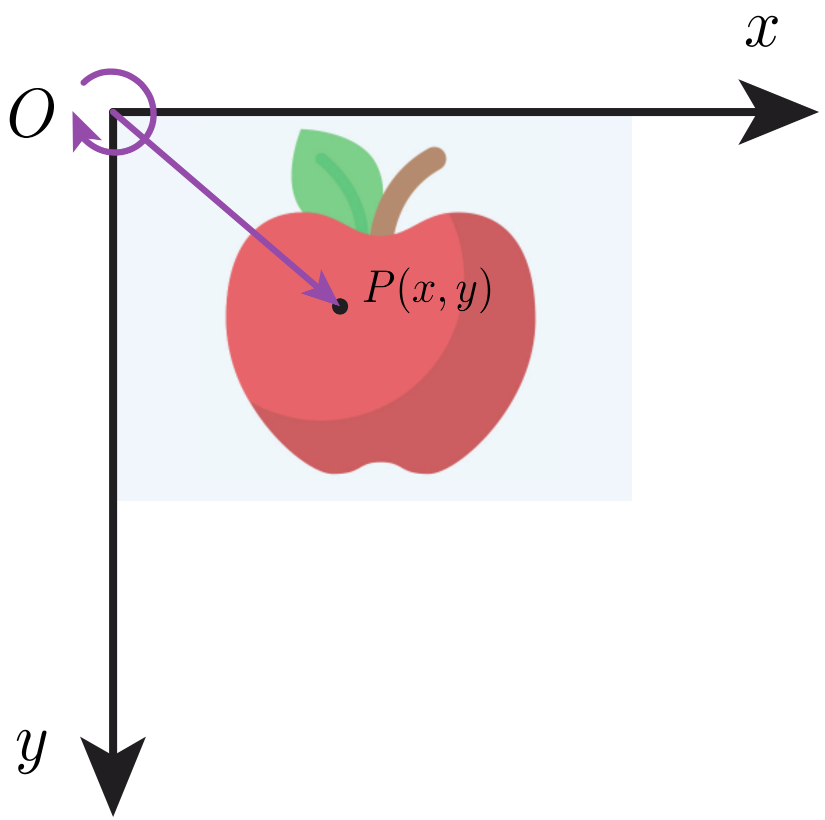
Coordinates:
Continuous and
left-handed



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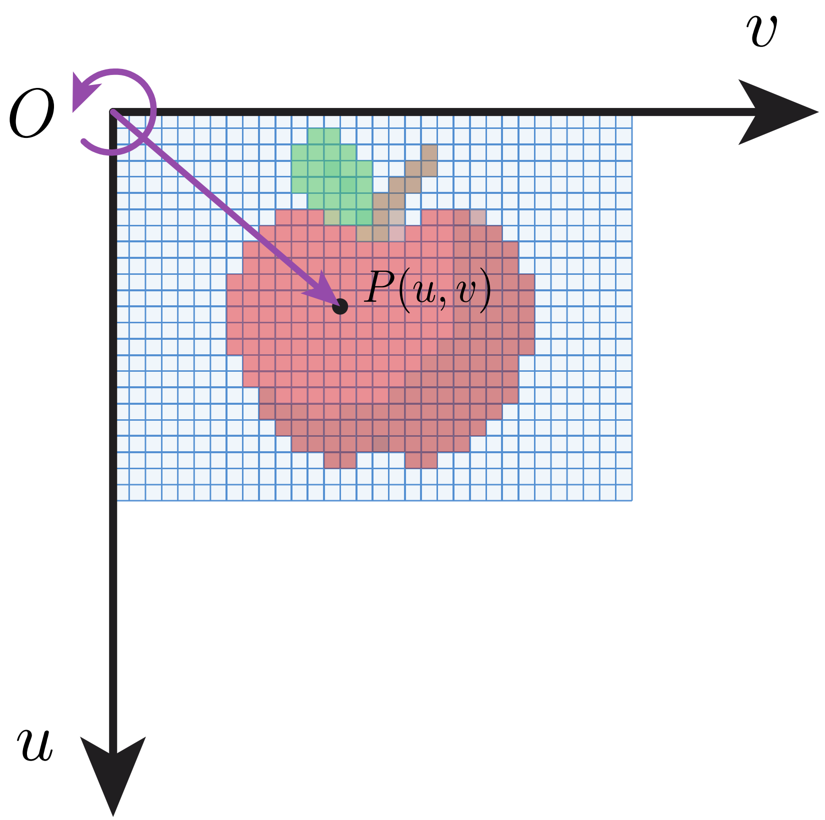
Coordinates:
Discrete and
right-handed



Coordinate systems

Coordinates:
Continuous and
right-handed

Coordinates:
Continuous and
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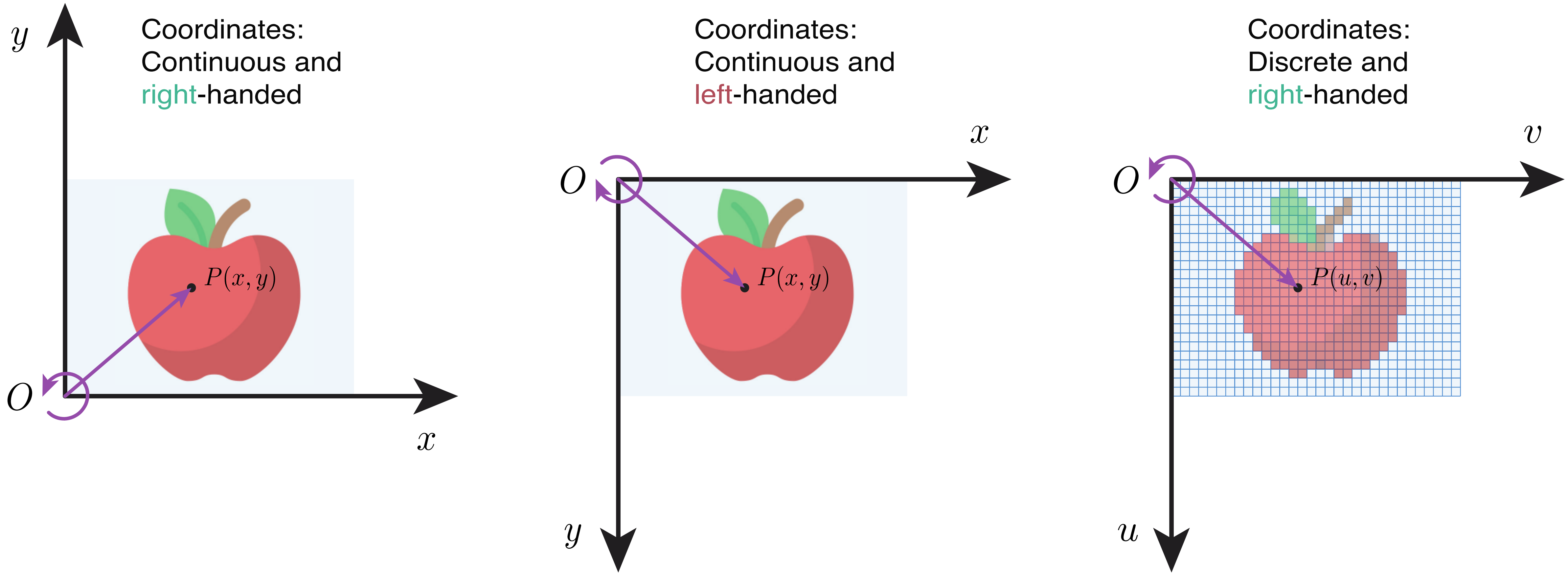
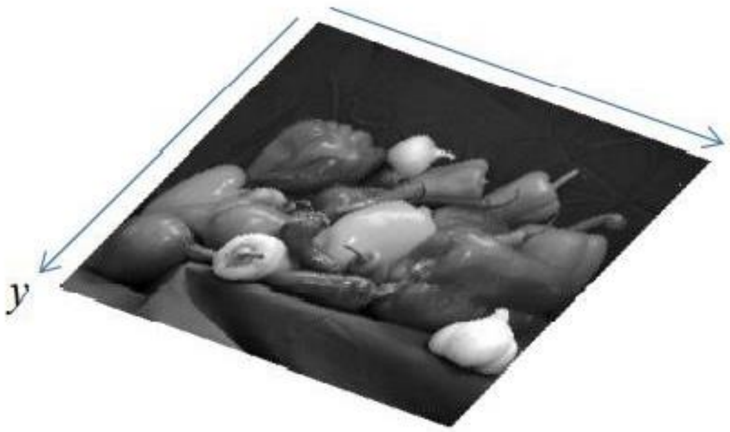
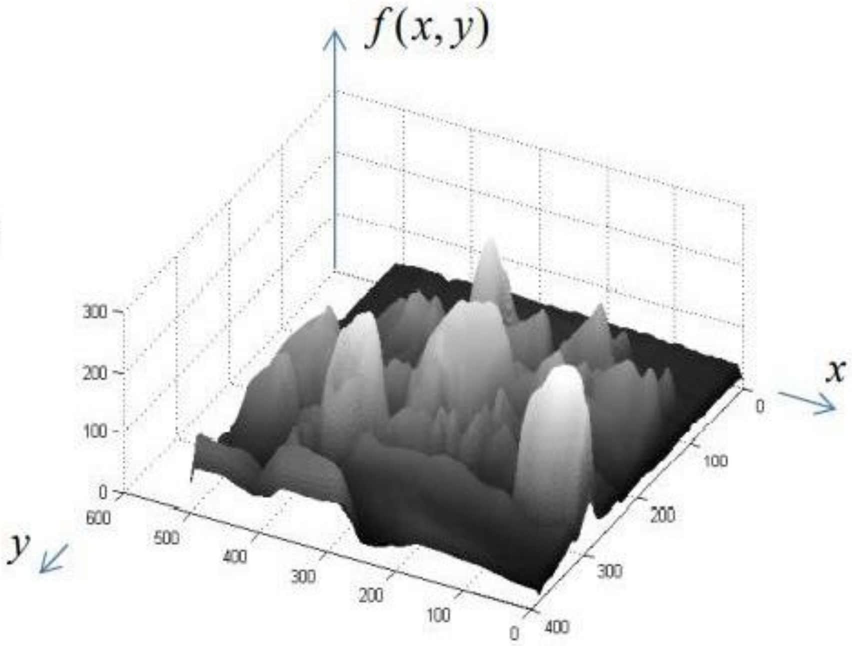


Image as a function

- A painted grayscale image can be considered as a continuous function over a region in $\Omega \in \mathbb{R}^2$, then at each point (x, y) point we get a gray value g which we can describe by a number $g = f(x, y) \in \mathbb{R}$:

$$f : \Omega \in \mathbb{R}^2 \to \mathbb{R}, \quad (x, y) \to f(x, y)$$



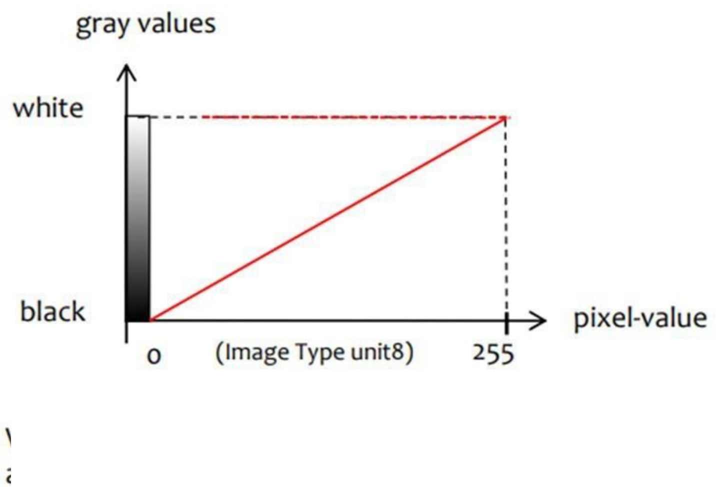


Grayscale values and memory

- Many digital images contain 256 possible gray levels, running from black to white
- This is the number of levels that can be labeled with **8 bits** (i.e., 1 byte) in a binary numbering system.
- It is convenient to allocate a byte of computer memory for storing the brightness level (grayscale) and to reserve the value 0000 0000 (decimal 0) for black and 1111 1111 (decimal 255) for white, resulting in a total of 256 grayscale levels
- The resulting images are said to be 8 bits deep.
- Larger units of storage include:
  - kilobyte (KB) = decimal 1024 (or 2^{10} bytes);
  - megabyte (MB) = 1024KB (or 2^{20} bytes);
  - gigabyte (GB) = 1024MB (or 2^{30}bytes);
  - terabyte (TB) = 1024GB (or 2^{40} bytes).

Pixel value / gray value

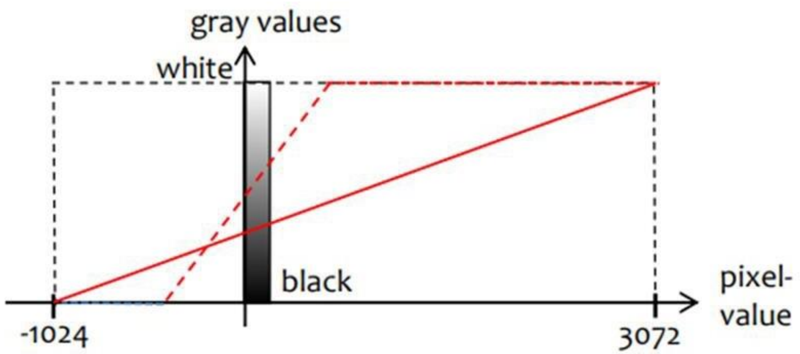
- The human eye can distinguish about 80 shades of gray (this number varies in the literature). Therefore, in **photography**, a grayscale image is sufficiently represented by 8 bits, which allows 256 shades of gray.

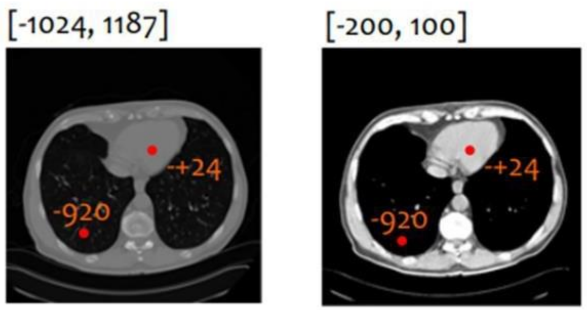


- When processing image data (i.e., when performing calculations with images), integer values no longer make sense and floating-point numbers are used.
- In this case, the gray value range is usually equated with the number range [0, 1].

Pixel value / gray value

- In other domains (like image data processing), the pixel values stand for a different physical measurand than in photography!
  - These measurands record for example the radiation absorption, the magnetization, of the matter, etc.
  - Consequently, the pixel values can lie in a different value range!
- For the visualization of the image data, the computer graphic card expects usually values in the range [0, 255]. So, the pixel value has to be mapped into the gray range of the graphics card:

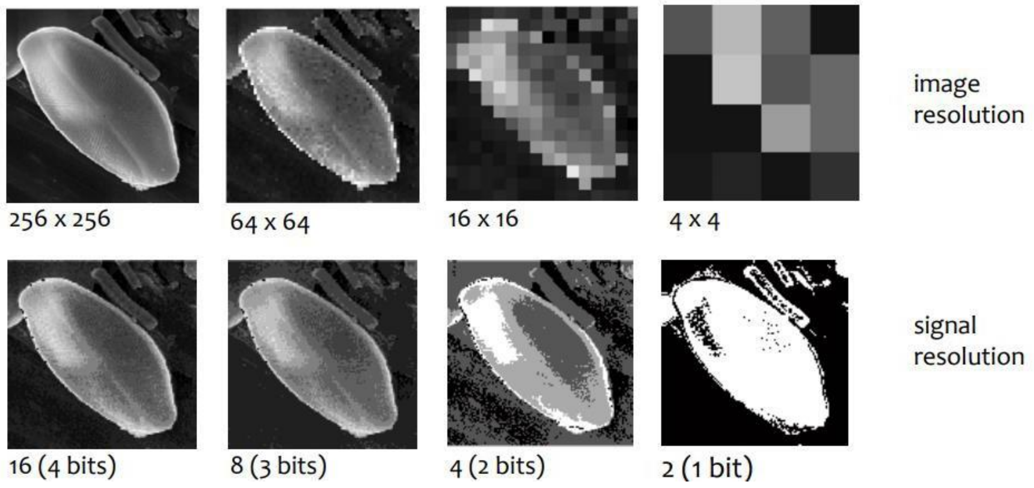


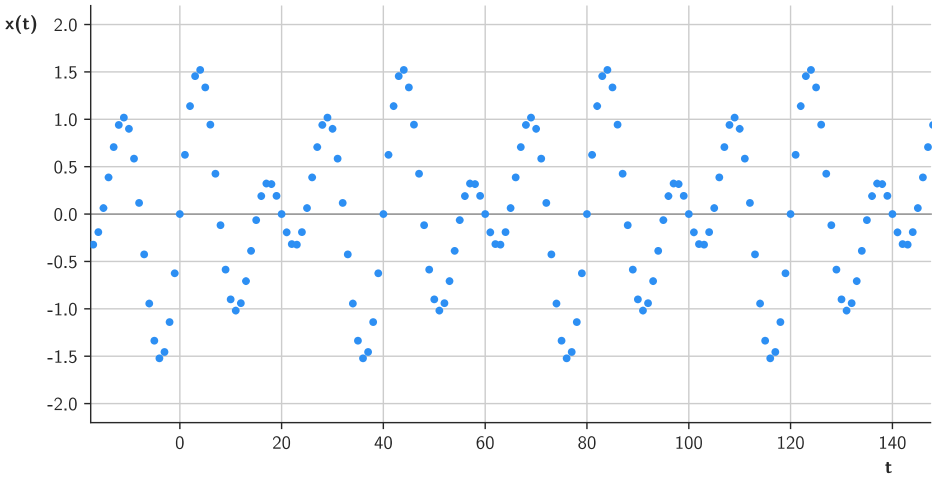


In CT data, the pixel values are between –1024 and 3072. If just a part of the image data range is mapped into the range of the gray values, then we call this windowing.

Digitalization / discretization

- There are two steps involved in digitalization:
  - Spatial quantization (also called sampling)
  - Intensity quantization.
- The term quantization means that a variable cannot take on any value, but only certain permissible (quantized) values, e.g. only integer values, but not the non-integer values in between.





Question: How does the above relate to timeseries data?

Intensity quantization

For gray scale images, each **sampled intensity** value needs to be placed on the nearest available **gray level**. This gives rise to an approximation error known as the **quantization error**, whose effect is minimized by the use of greater numbers of finely spaced gray levels but at the cost of larger image files.

64 shades of gray

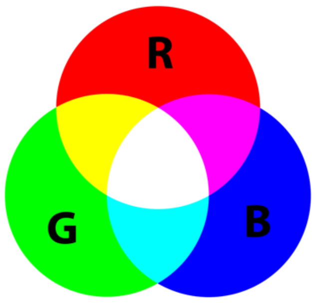
8 shades of gray

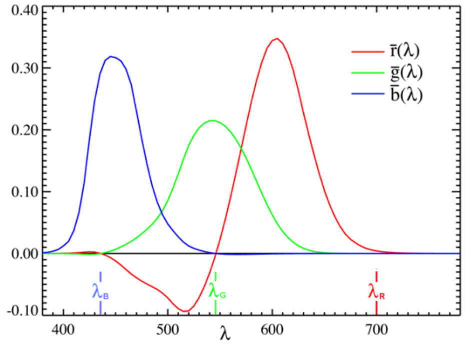
Color representation

Colors and color spaces

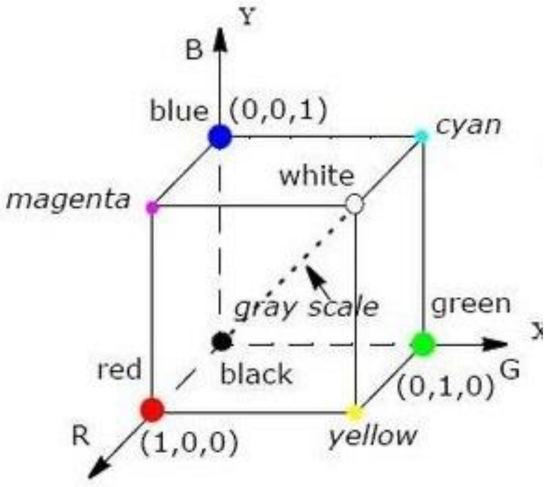
Color representation: RGB

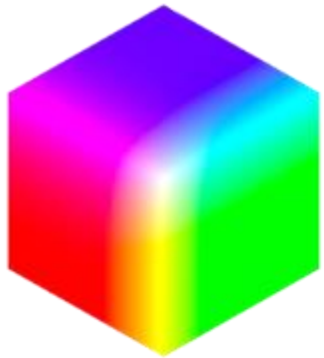
- Trichromatic theory of color vision:
  - The color perception of the human can be imitated by adding three light sources (red, blue, green)
  - By varying the intensity of these three primary colors, a wide range of colors can be represented in the RGB color space
- The CIE 1931 RGB color space
  - Based on a device-independent standard defined by the Commission Internationale de l'éclairage (CIE) in 1931
  - The standard colors R,G,B have wavelengths at 700 nm, 546 nm, 436 nm
- Notes:
  - Many other RGB color spaces exist!
  - Diagonal represents the gray scale axis
  - Values often range between [0, 1], or [0, 255]





These curves do not match the spectral sensitivity curves of humans for various reasons (e.g., color light generation in 1931)



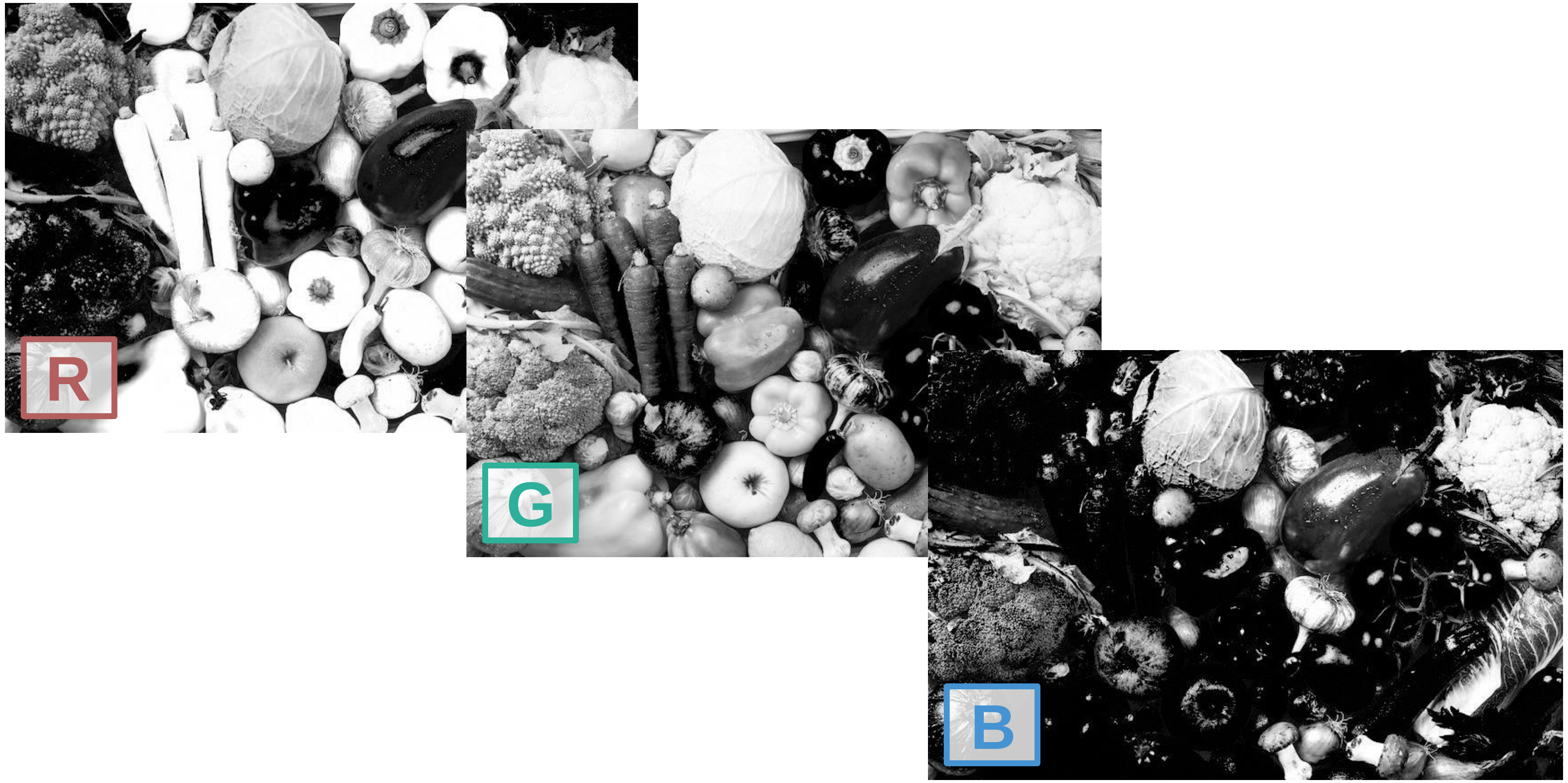


Example: RGB color space

- As a result, the pixel values for an RGB color image contain the RGB values, therefore a color image can be represented by 3 gray scale images.

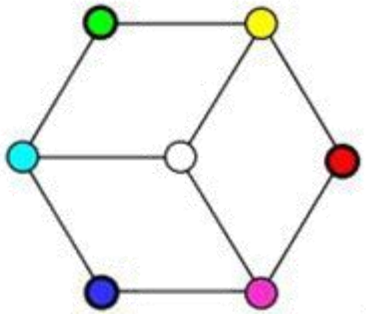
Task: Can you guess which of the below images represent R, G or B?

$$p = \begin{pmatrix} 255 \\ 251 \\ 0 \end{pmatrix}$$



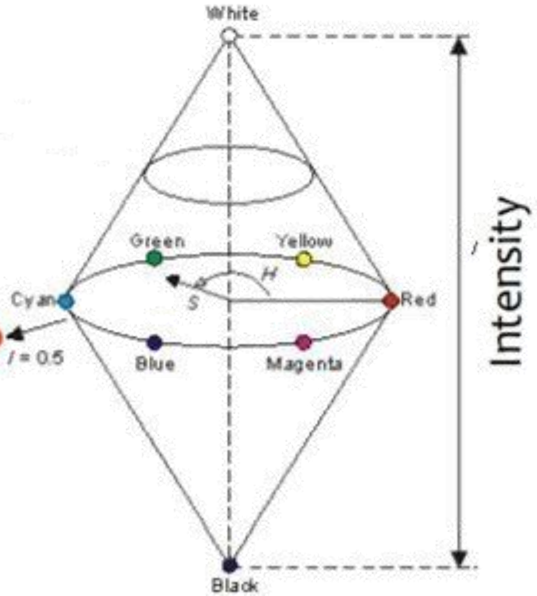
Color representation: HSI

- The RGB space is motivated by human color perception
- It is also the adequate space for cameras and monitors
- However, the color interpretation is rather difficult!
- Solution: The HSI space
  - H: hue
  - S: saturation
  - I: intensity

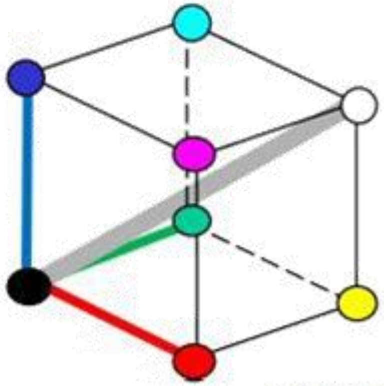


Colors-Wheel

HSI space



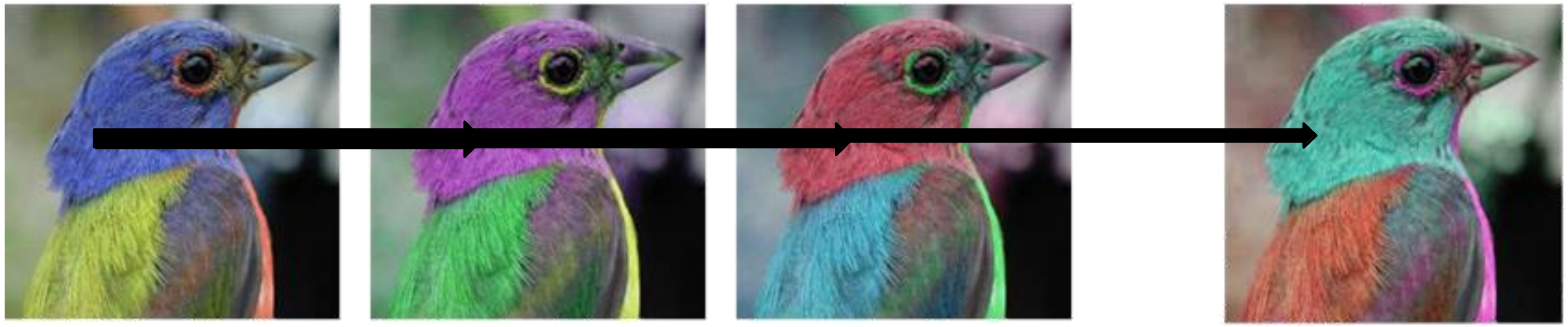
2D Color-Space



RGB space

Color representation: HSI

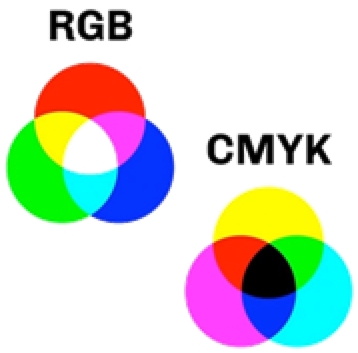
- In the HSI space, the color can be manipulated without affecting the brightness or saturation of color.



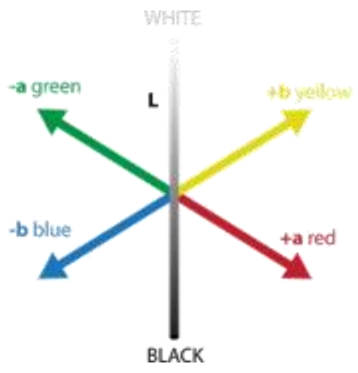
Original   Hue-Shift 1/6   Hue-Shift 2/6   Hue-Shift 5/6

Color representation: Other color spaces

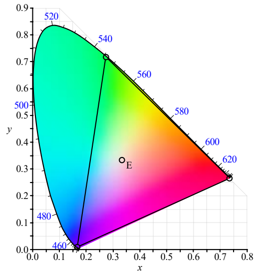
- CMYK (Cyan, Magenta, Yellow, Key / black):
  - Represents colors by subtracting cyan, magenta, and yellow from white light.
  - Hence, it is a subtractive color model (contrary to RGB, or HSI)
  - Includes a black channel (K, key) to improve the reproduction of dark colors
  - Standard color model used in color printing and graphic design.



- L*a*b* (CIELAB):
  - A device-independent color space designed to approximate human vision more accurately than RGB or CMYK.
  - Consists of three components: L* (lightness), a* (green to red), and b* (blue to yellow).
  - Widely used in color science and for color difference calculations



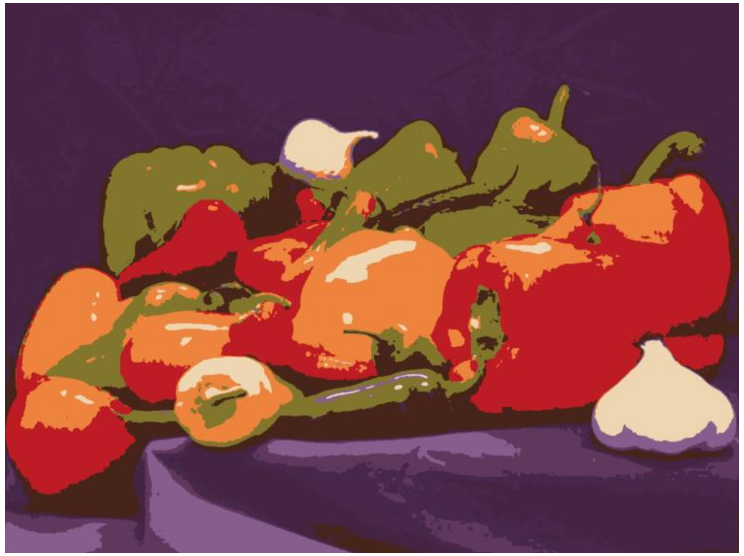
- XYZ (CIE 1931 XYZ):
  - A standard based on human color perception
  - Represents colors using tristimulus values X, Y, and Z, which correspond to the stimulation of the three types of cones in the human eye.



Reduction of color spaces

- Like the gray scale, also the color scale can be reduced
- Simple nearest-neighbor color-mapping yields color bands
- Dither: Method to avoid such pattern by adding noise

Input: $2^{8 \cdot 3} = 2^{24}$ = 16.7 Mio colors
Goal: 10 target colors



Method 1: Nearest neighbor mapping results in color bands and a comic-like appearance.

Demo: Photoshop

Method 2/3: Introduce random noise to avoid bands (second method: use diffusion approach to for better results)

Reduction of color spaces: Color to grayscale conversion

- Goal: convert the three RGB values (per pixel) to one grayscale intensity value.
- There are different models for this conversion

Input image

value

$$V = \max(R,G,B)$$

luminance

$$L = \frac{\max(R,G,B) + \min(R,G,B)}{2}$$

intensity

$$I = \frac{R+G+B}{3}$$

weighted intensity

$$I = 0.3 \cdot R + 0.6 \cdot G + 0.1 \cdot B$$

The digital image processing system

The digital image processing system

A complete digital image processing system/chain is a collection of hardware (equipment) and software (computer programs) that can:

1. Acquire an image and, if applicable, digitalize it via an analog-to-digital converter (ADC),
2. Store the image (either temporarily in a working memory of the computer or permanently on storage devices like solid-state drives)
3. Manipulate / process the image
4. Display the image, using a digital-to-analog converter (DAC).