Digital Image Processing

II. Digital Image Fundamentals

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Digital image processing

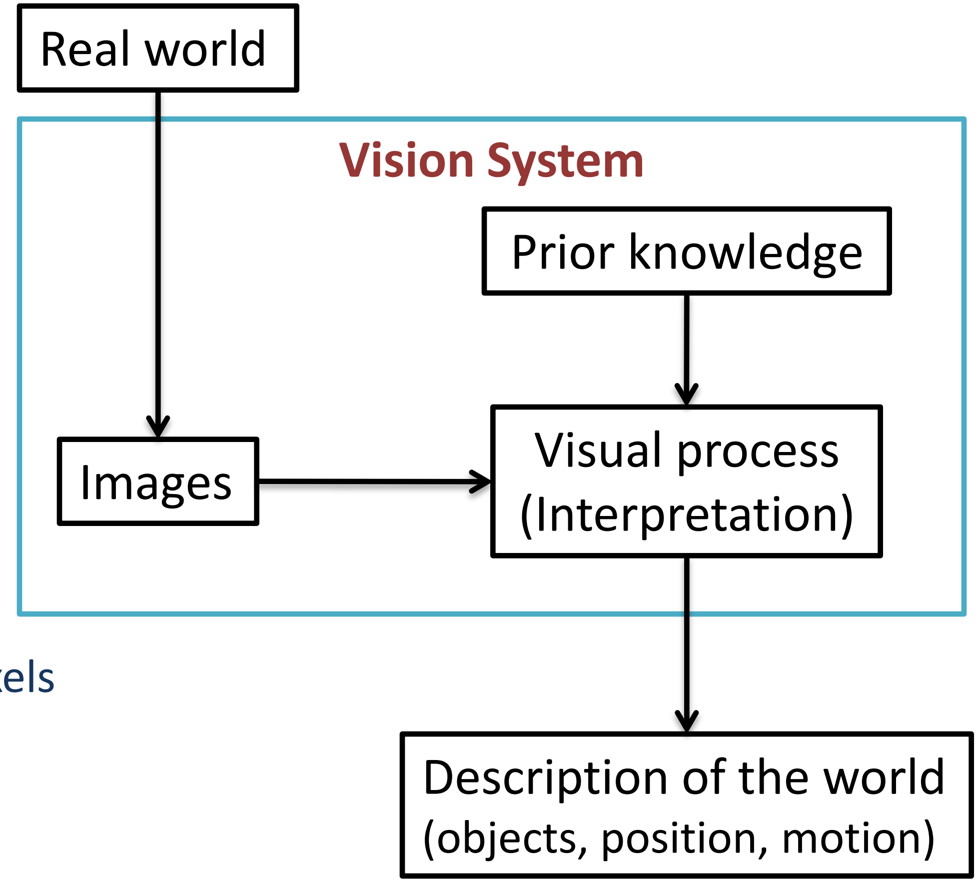
- Outline
  - Elements of the human visual system
    (structure of the human eye / image formation in the eye)
  - Digital image sensing and acquisition
    (review of existing imaging sensors, camera models, a simple image formation model)
  - Representing digital images
    (continuous representation, discrete representation, color models, transformations between color models)
  - Summary

What is digital image processing (DIP)

- Processing digital images by the mean of a digital computer
  - Mathematical and probabilistic formulations
  - Originally inspired by biological systems
    - Human / animals eyes,
  - In practice however it is very hard to reproduce all the human visual system despite decades of research.

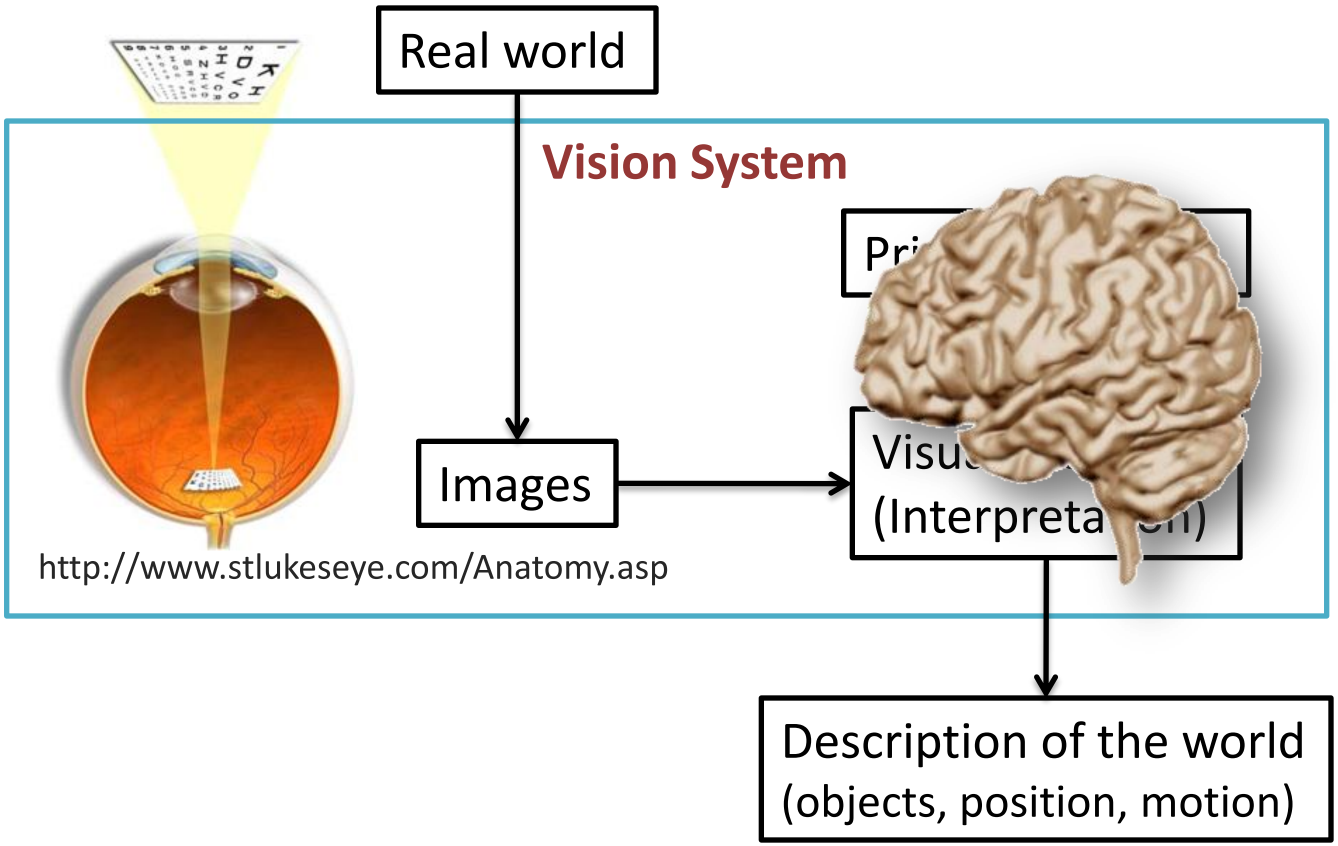
What is does it mean seeing ?

- Real world
  - 3D structure made of objects
- Images
  - 2D structure
  - Colors are Information about the incoming light
- Vision system
  - Maps real world objects into pixels on the retina.
  - Describe the world from the pixels available on the retina.



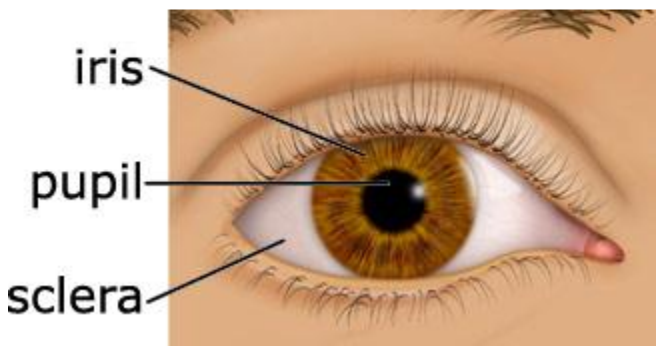
Biological vision

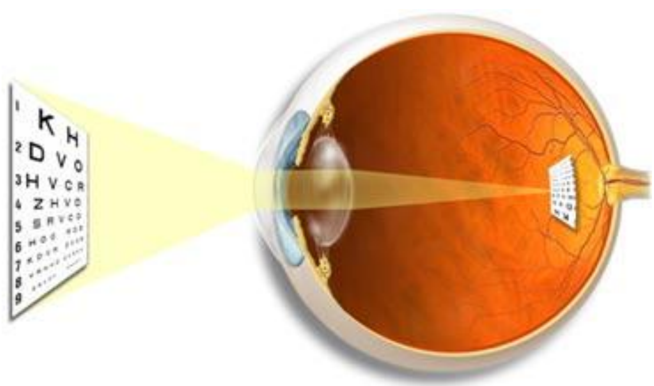
- Human (biological) vision is extremely complex !!

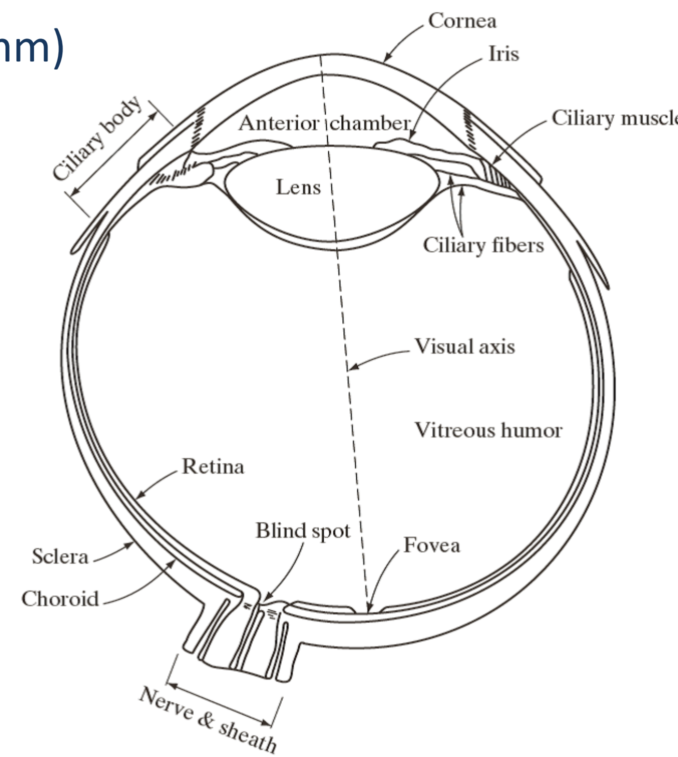


Elements of human visual system

- The human eye
  - Sophisticated, complex, but inspiring
  - Nearly a sphere (avg diameter of approx. 20mm)

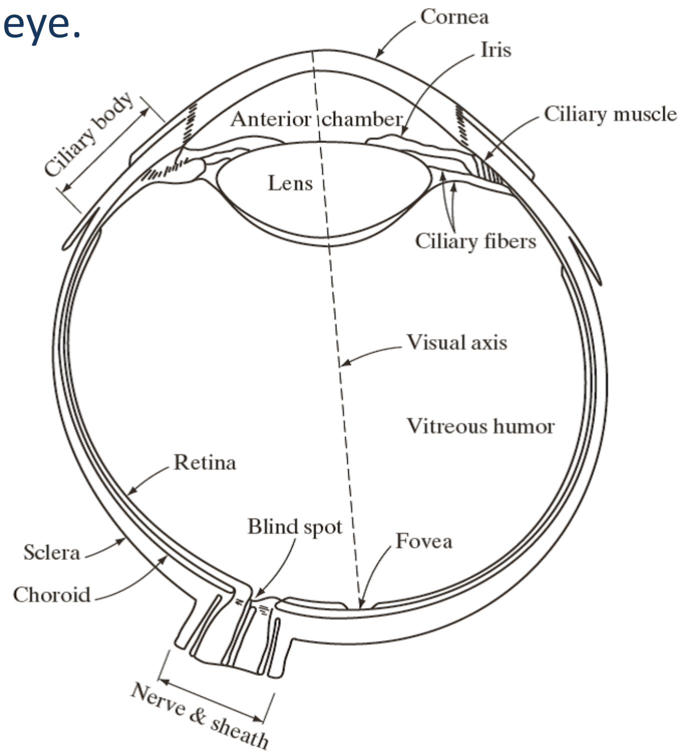






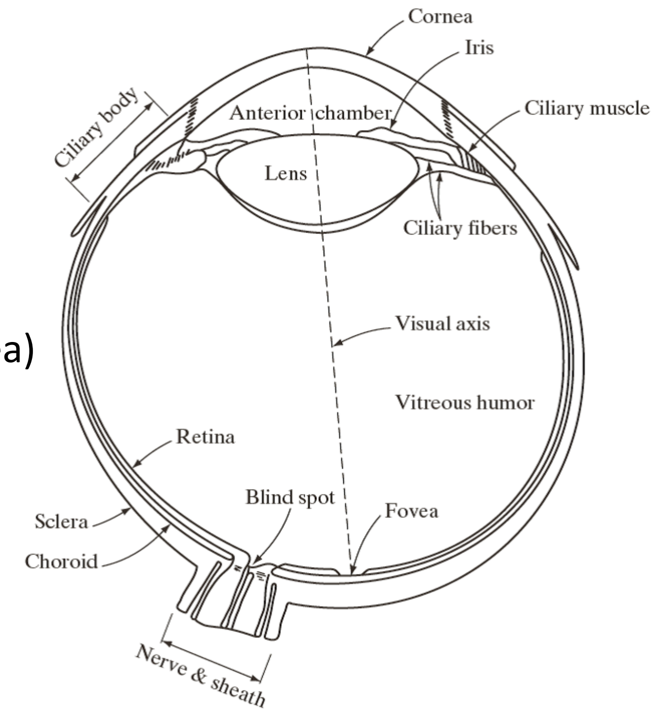
Elements of the human visual system

- The human eye
  - The Ciliary muscle contracts or expands
    to control the amount of light that enters the eye.
  - The lens :
    - contains 60 – 70% water, 6% fat and more proteins.
    - It absorbs approximately 8% of the visible light spectrum.
    - Infrared and ultraviolet light are absorbed appropriately by proteins (in excessive amounts they can damage the eye)



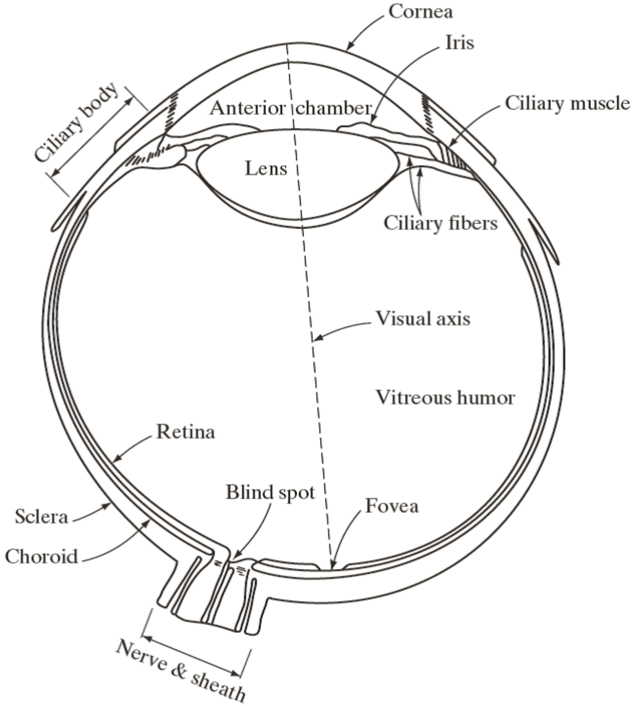
Elements of the human visual system

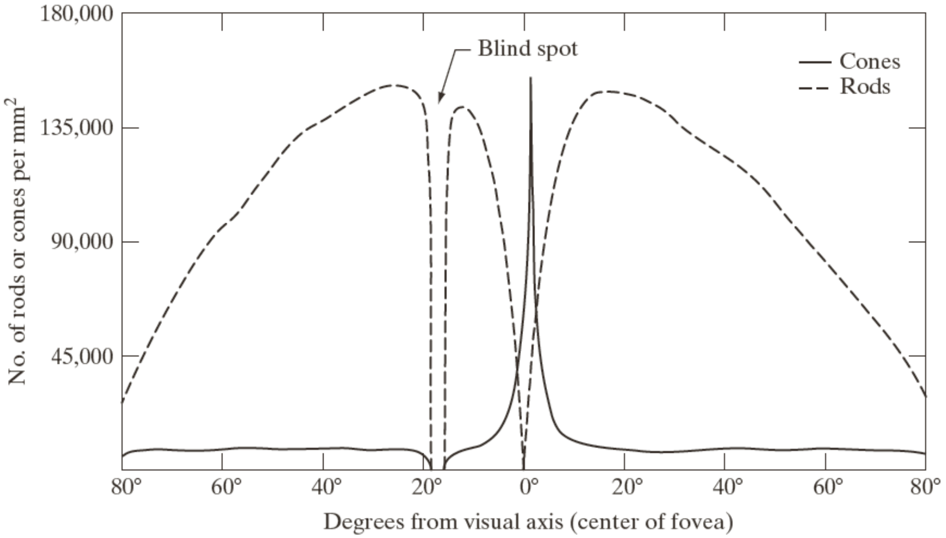
- The human eye – The retina
  - Light from an object outside the eye is imaged on the retina
  - Light receptors are distributed over its surface
    - Cones receptors
      - 6 to 7 million,
        mainly located near the fovea (central area)
      - Highly sensitive to color
    - Rods
      - 75 to 150 million distributed over the retina surface
      - Serve to give a general overall picture of the field of view
      - Sensitive to low level of illumination



Elements of human visual system

- The human eye – The retina





Distribution of cones and rods in the retina
(A cross section of the retina)

• Absence of sensors near the optic nerve results in a blind spot.

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Elements of the human visual system

- The human eye – The fovea
  - Cone receptors are concentrated in the fovea
  - Can be seen as a square sensor of 1.5x1.5mm.
  - Density of cones in this area ~ 150.000 elements per mm2
  - Each receptor is connected to its own nerve end
    - Humans can resolve fine details with these cones

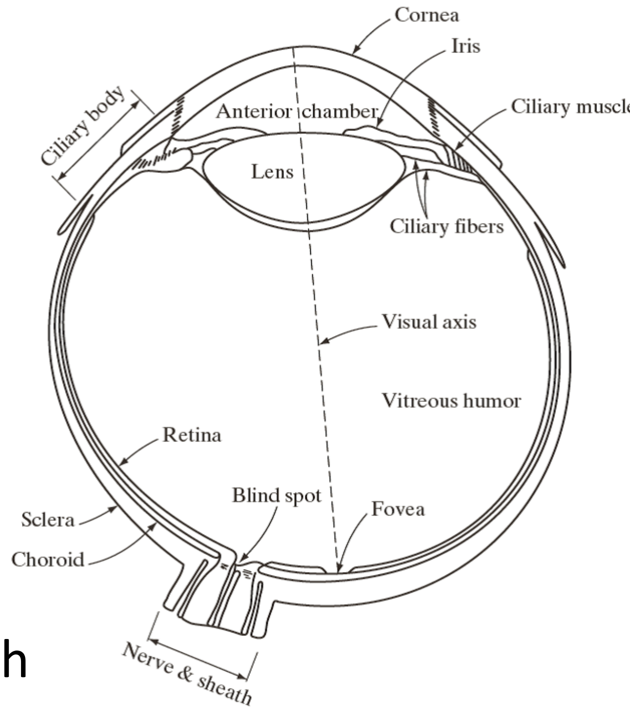


Image formation in the eye

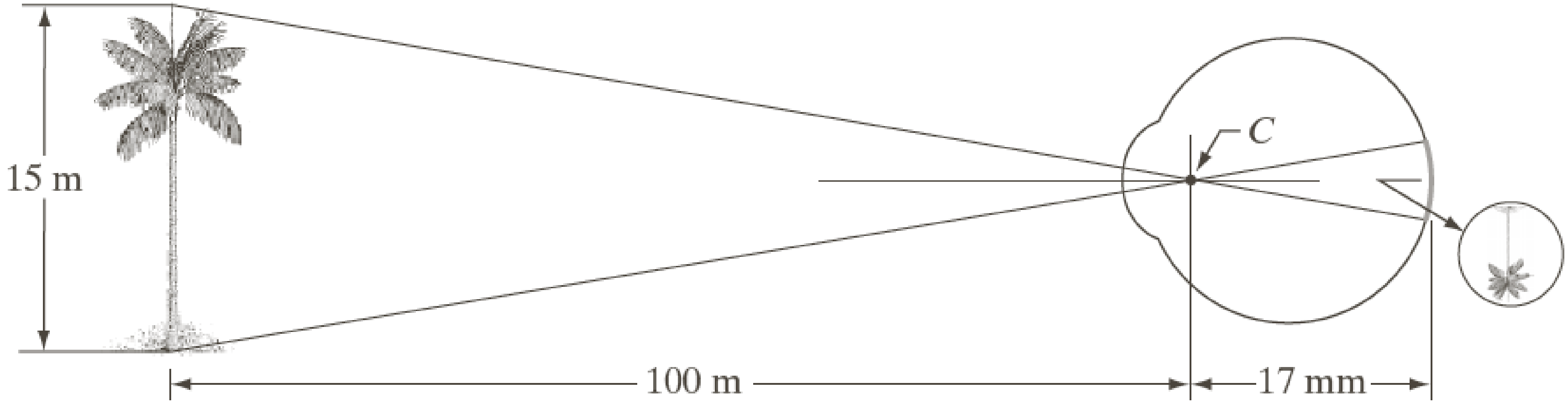
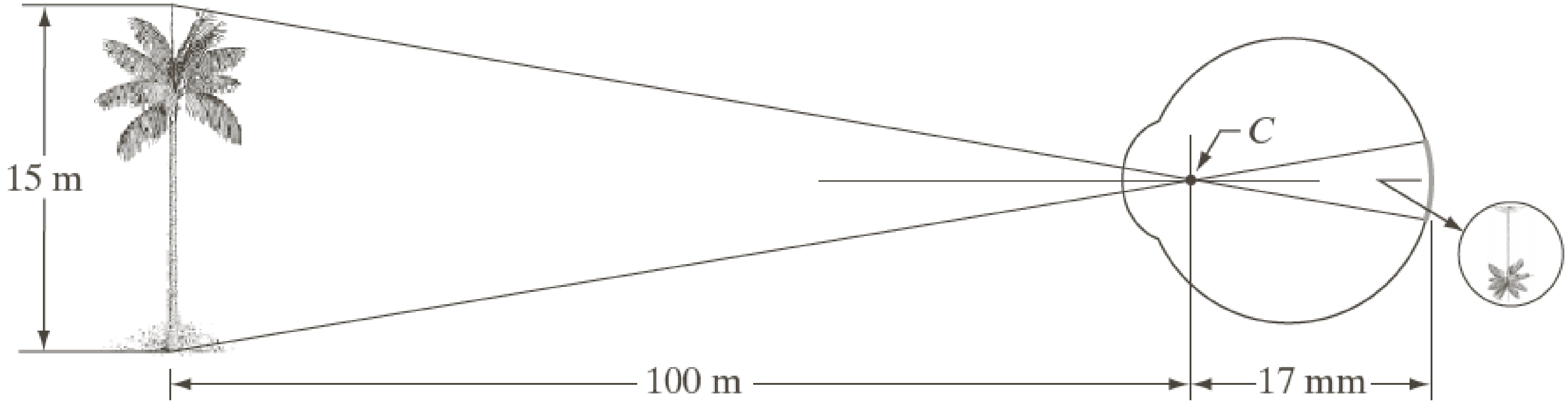


Image formation in the eye

- Short quiz
  - What is the height of the tree in the image (on the retina)?



  - The retinal image is focused primarily on the region of the fovea
  - Perception then takes place (the brain then will be in charge of the other tasks)

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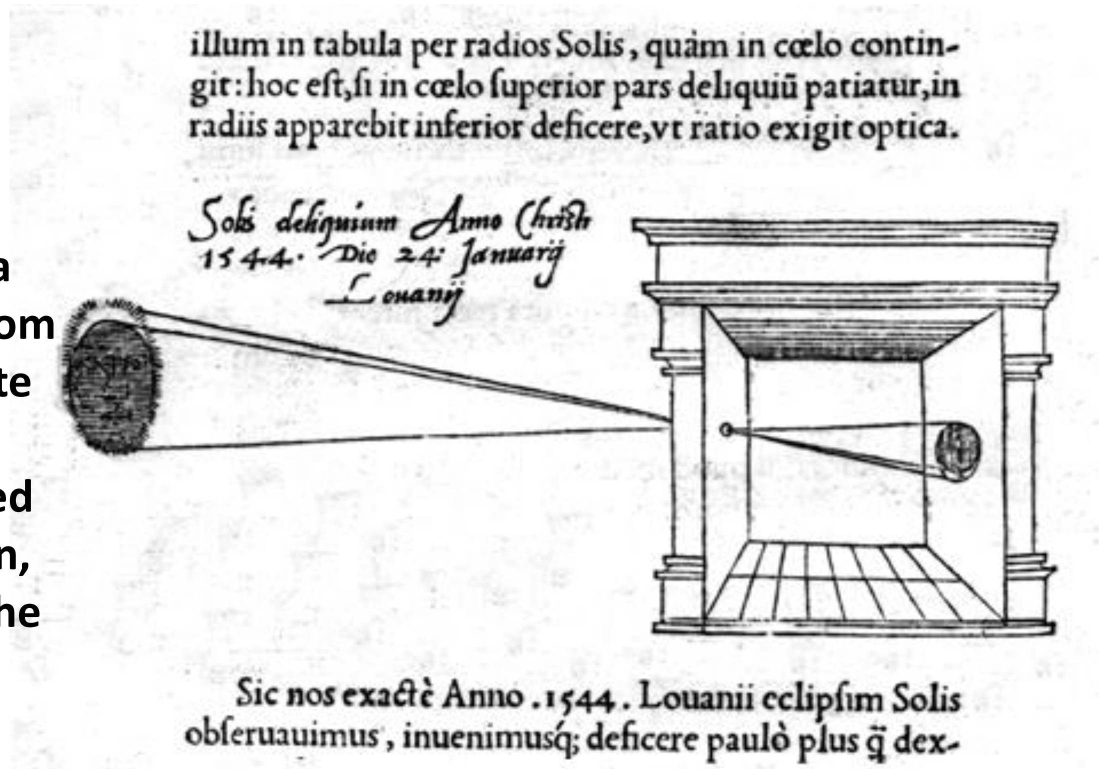
Digital imaging

Example: camera obscura

- The old days

“When images of illuminated objects … penetrate through a small hole into a very dark room … you will see [on the opposite wall] these objects in their proper form and color, reduced in size … in a reversed position, owing to the intersection of the rays”



http://www.acmi.net.au/AIC/CAMERA_OBSCURA.html
(Russell Naughton)

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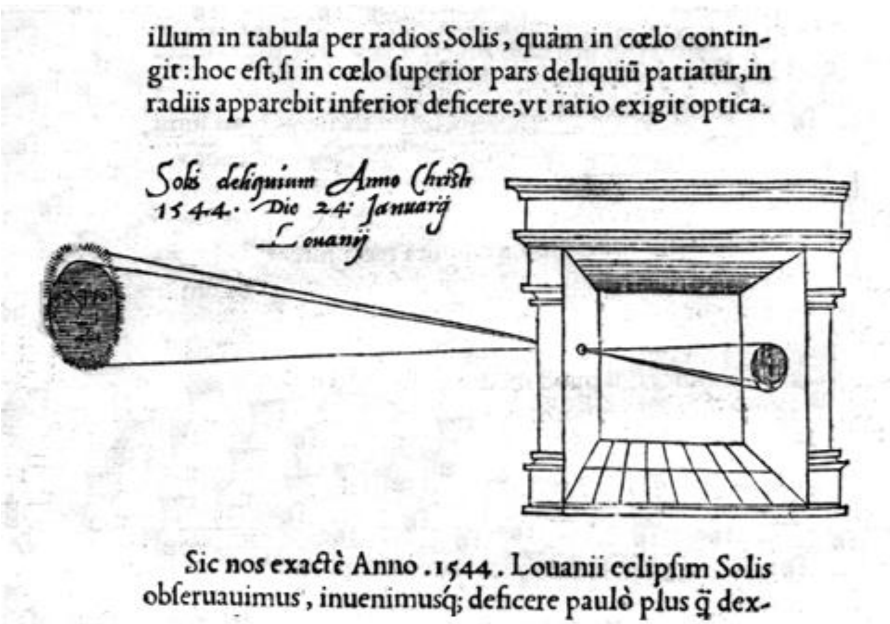
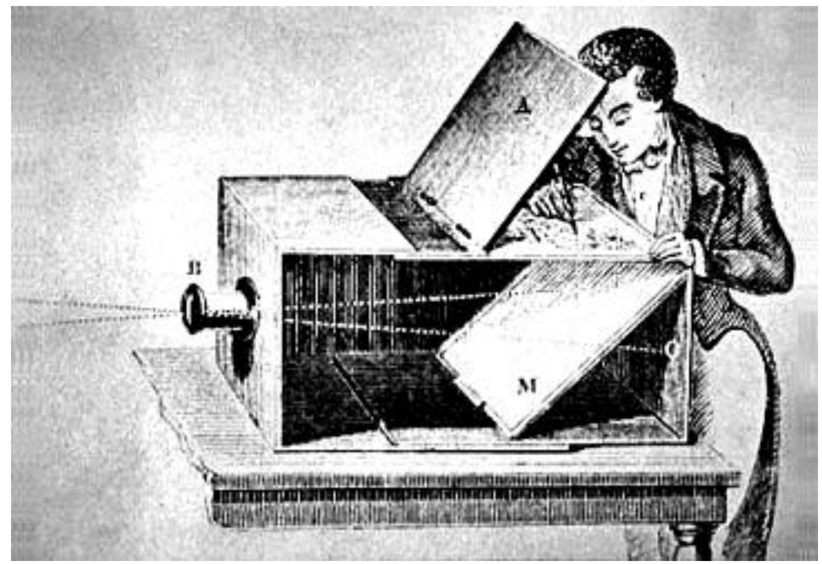
Camera obscura

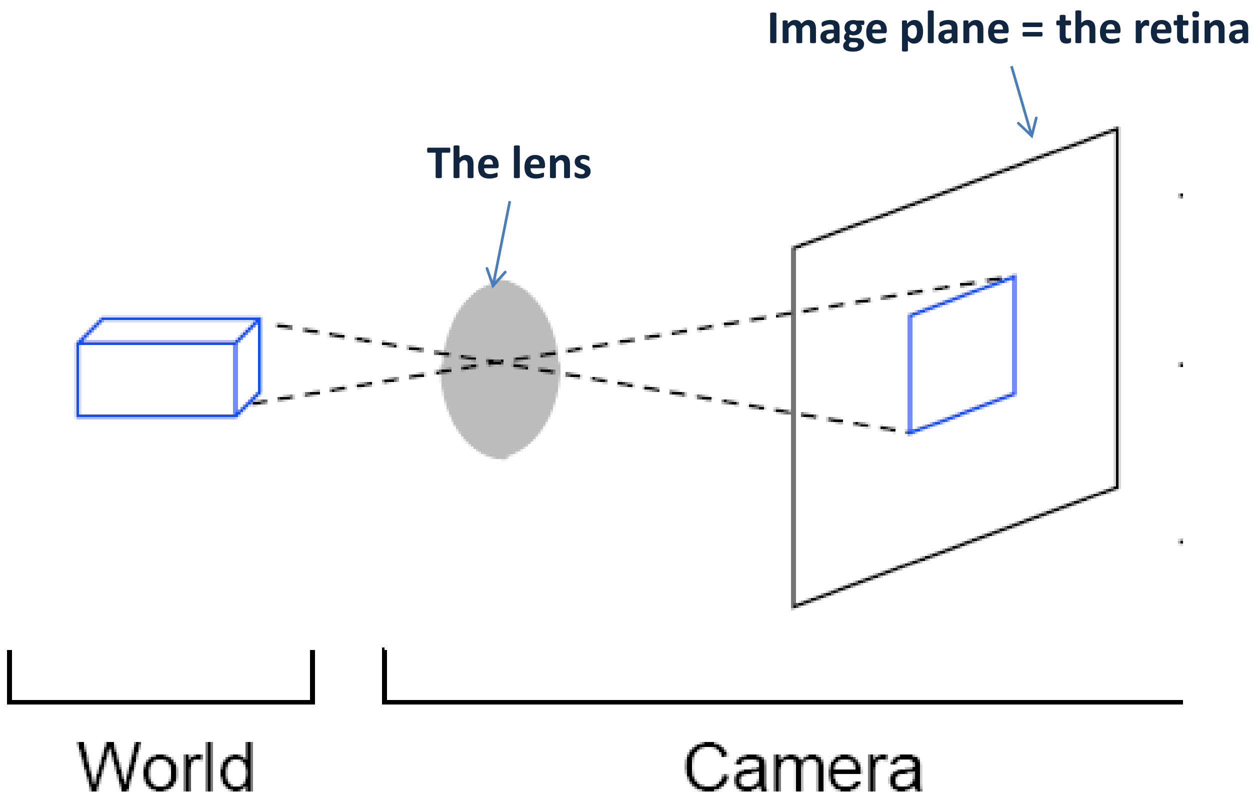
- The old days



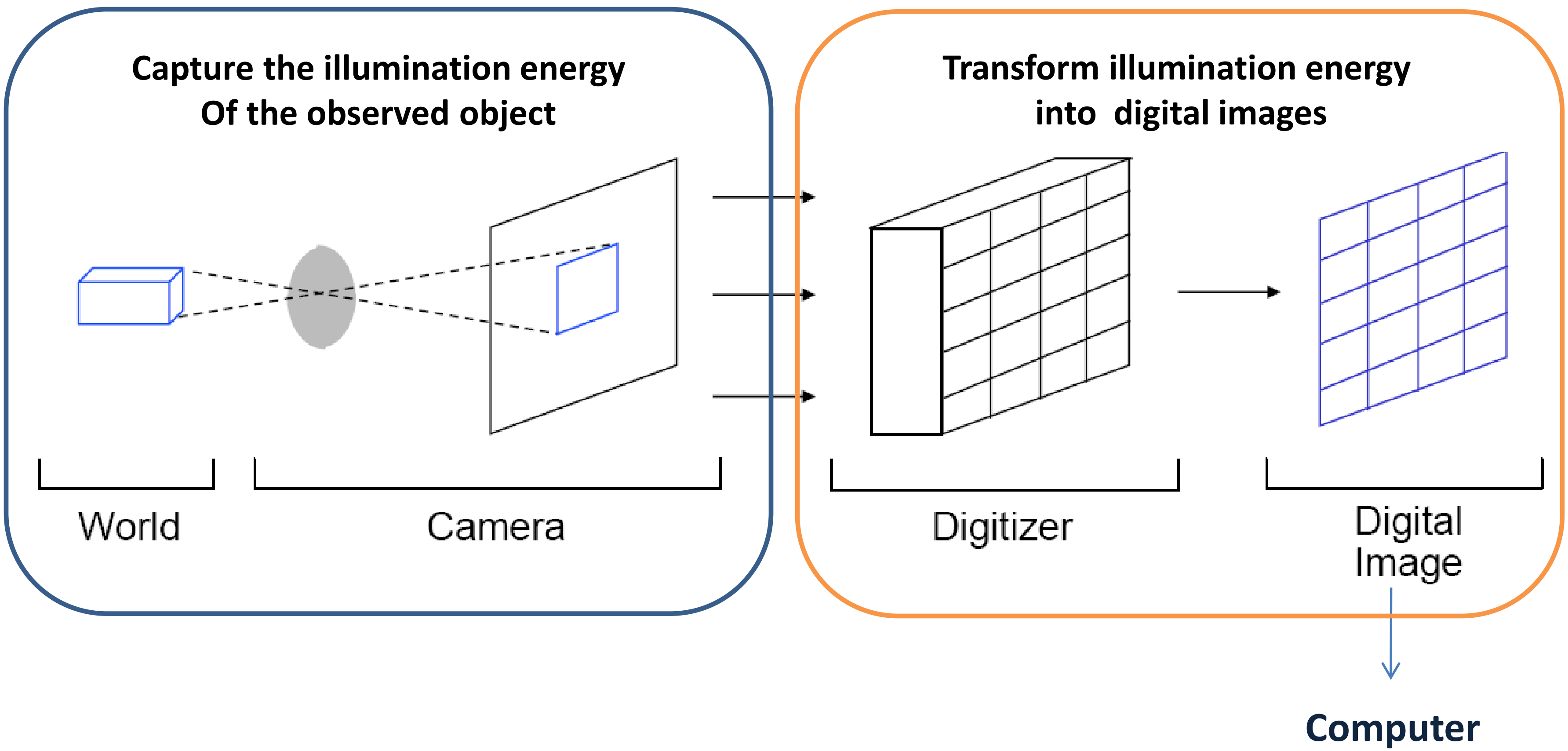


http://www.acmi.net.au/AIC/CAMERA_OBSCURA.html (Russell Naughton)
- used to observe eclipses (eg., Bacon, 1214 – 1294).

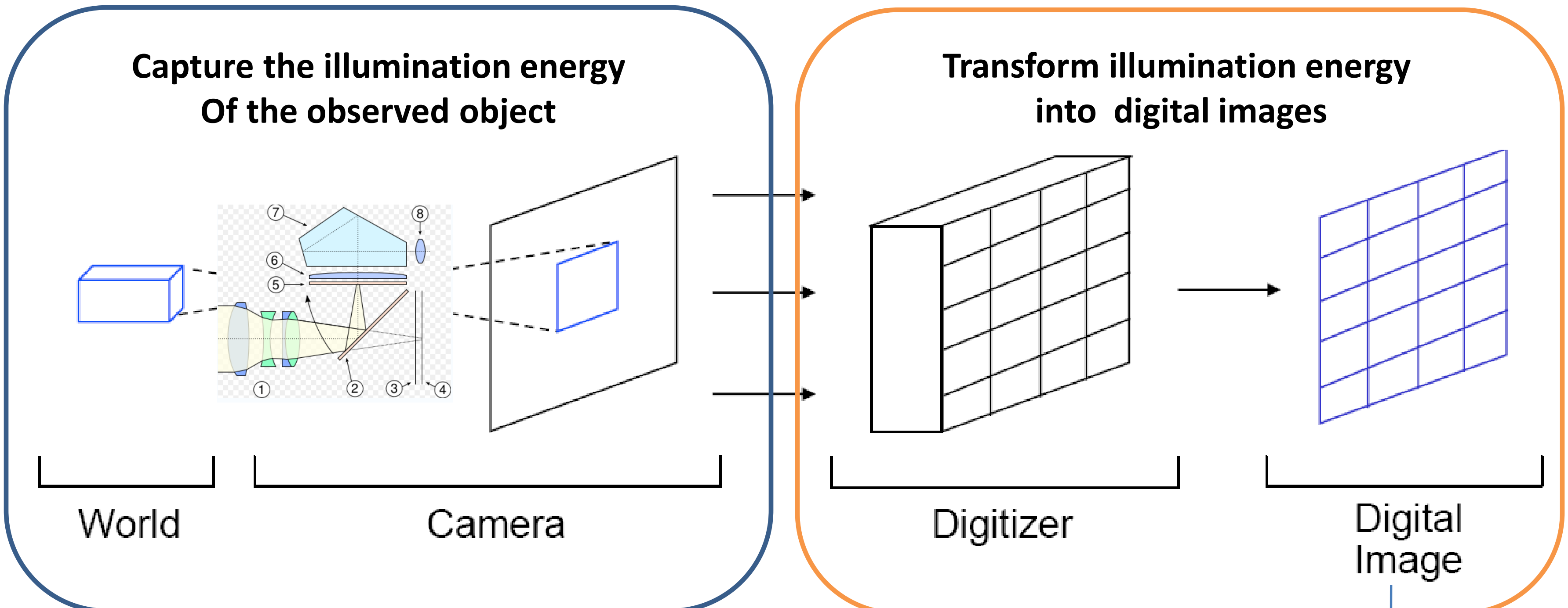
Digital imaging



Digital imaging



Digital imaging



Complex optical components

Several types of sensors

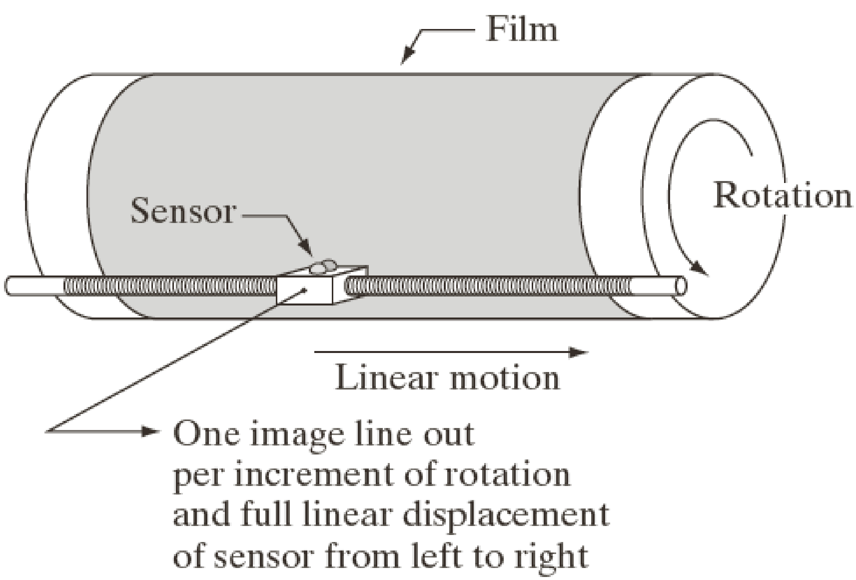
Computer

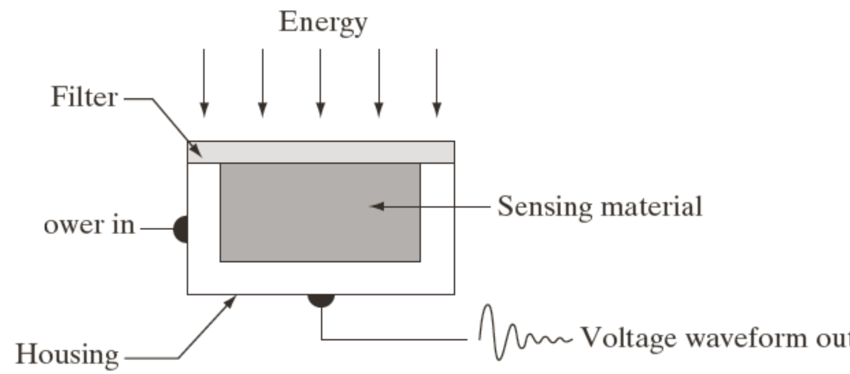
Digital imaging

- Transforming incoming illumination energy into digital images
  - Incoming illumination energy is transformed into voltage by sensors that are responsive to particular type of energy being detected
  - The digital quantity is obtained by digitizing the voltage.
- Existing sensors
  - Using a single sensor
  - Sensor strips (vector of sensors)
  - Sensor arrays

Example of imaging sensors

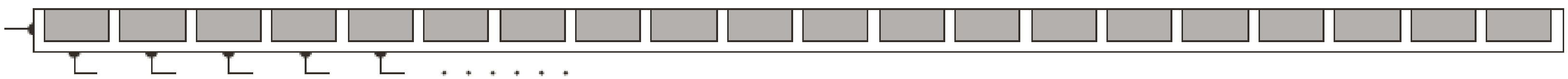
- Image acquisition using a single sensor





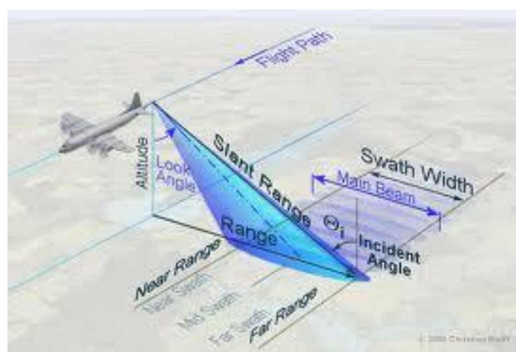
Examples of imaging sensors

- Image acquisition using sensor strips (vector of sensors)
  - An in-line arrangement of sensors in the form of a sensor strip
    - Eliminates the horizontal motion of the sensor



  - Generates one line of the image per time step.

flat-bed scanners



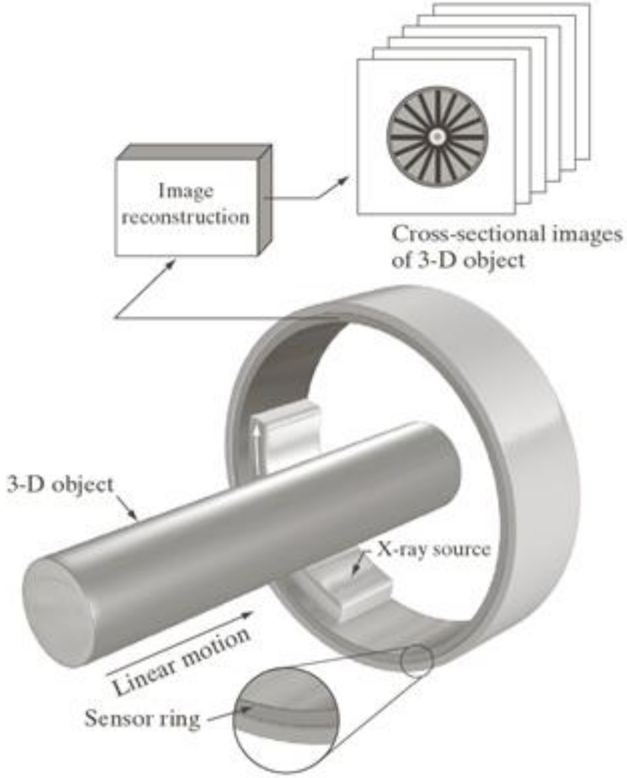
Airborne imaging

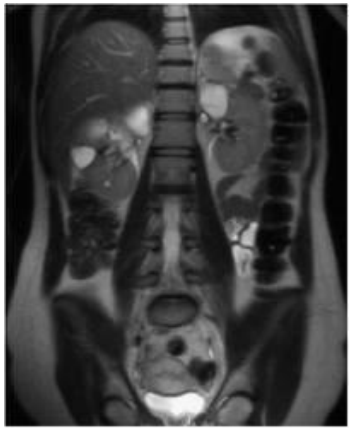
CT imaging

Examples of imaging sensors

- Image acquisition using sensor strips (vector of sensors)
  - CT, MRI, PER imaging
    - Sensor strips are mounted in a ring configuration

CT imaging





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Examples of imaging sensors

- Image acquisition using sensor arrays
  - The predominant arrangement found in digital cameras
  - CCD arrays can be packaged in rugged arrays of > 4000x4000 elements
  - Sensor response proportional to the integral of the light energy (similar approach is used in astronomical and other applications requiring low noise images
  - Operation
    - Collect the incoming energy and focus it onto an image plane
    - Image plan produces outputs proportional to the integral of the received light
    - These outputs are converted into analog signal (voltage)
    - The analog signal is then digitized to produce and image

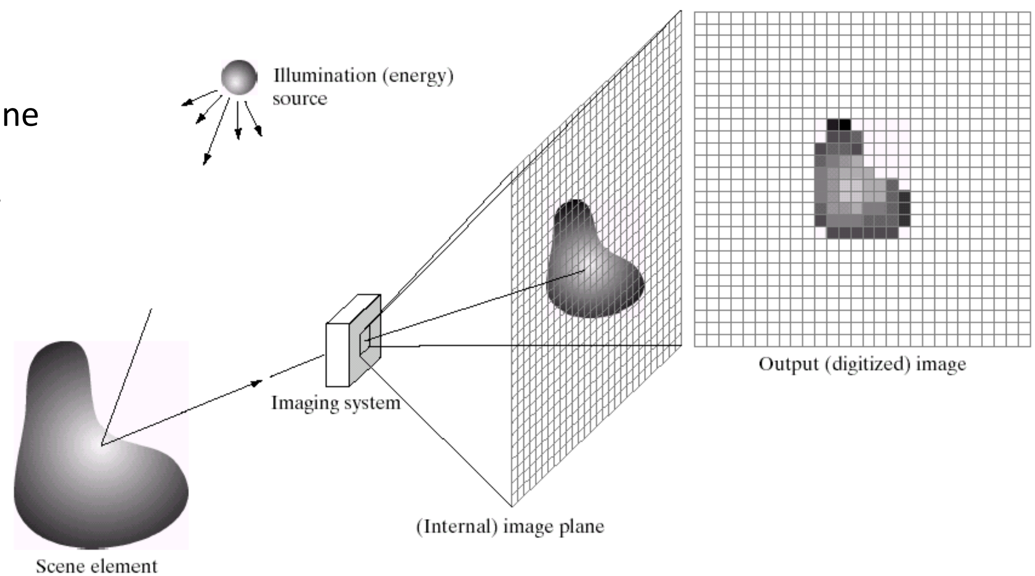

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Image formation model

- Purpose: a mathematical model of the acquisition process
  - How to get good images
  - Inverse problems
    - From the image, we want to compute the 3D structure of the world, recognize objects, make the robots navigate freely, etc …

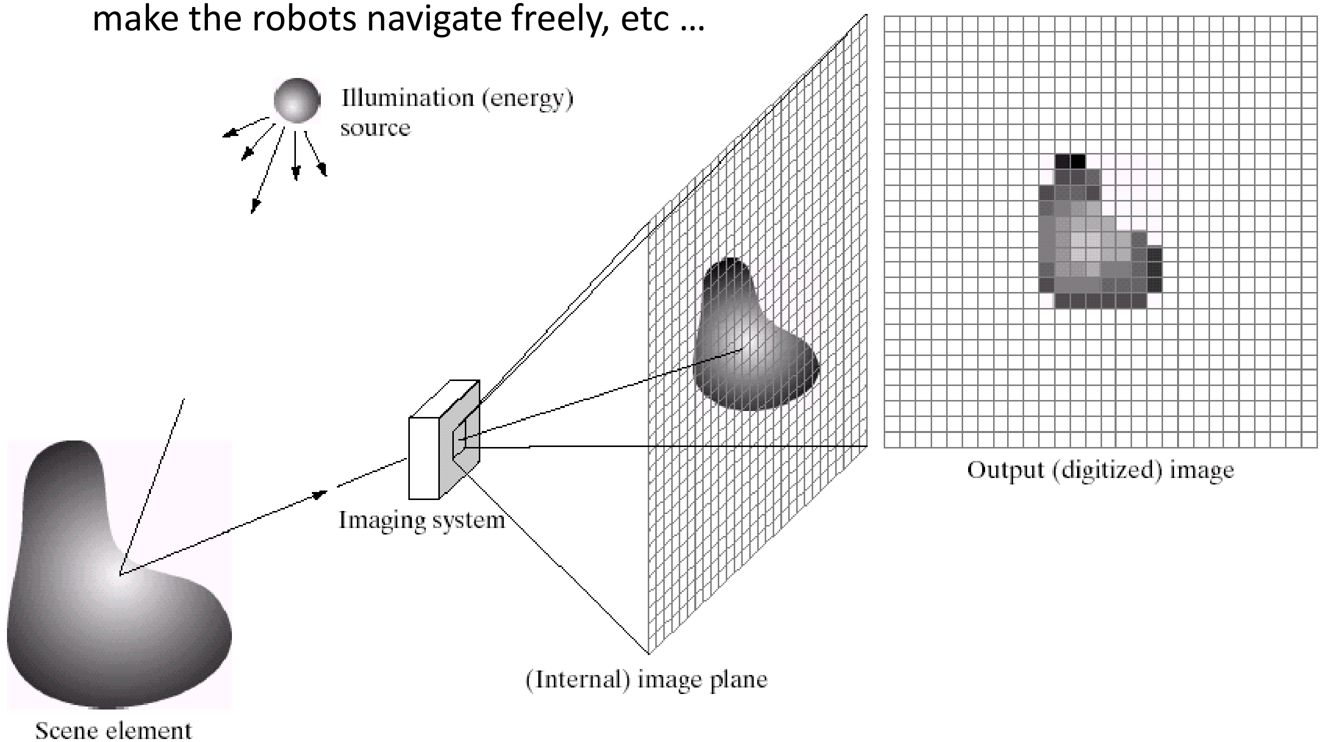

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Image formation model

- Geometry
  - Given an object and a camera, how is the geometry of the object going to be in the 2D image ? (geometry = shape, size, dimensions, etc.)
  - Parameters involved
    - Geometry of the imaged object
    - Type of lenses
- Color formation
  - Given an object and a camera, how is the appearance of the object going to be in the 2D image ? (appearance = color)
  - Parameters involved
    - Lighting conditions
    - Material properties of the images object (or scene)
    - Type of sensors

Image formation model

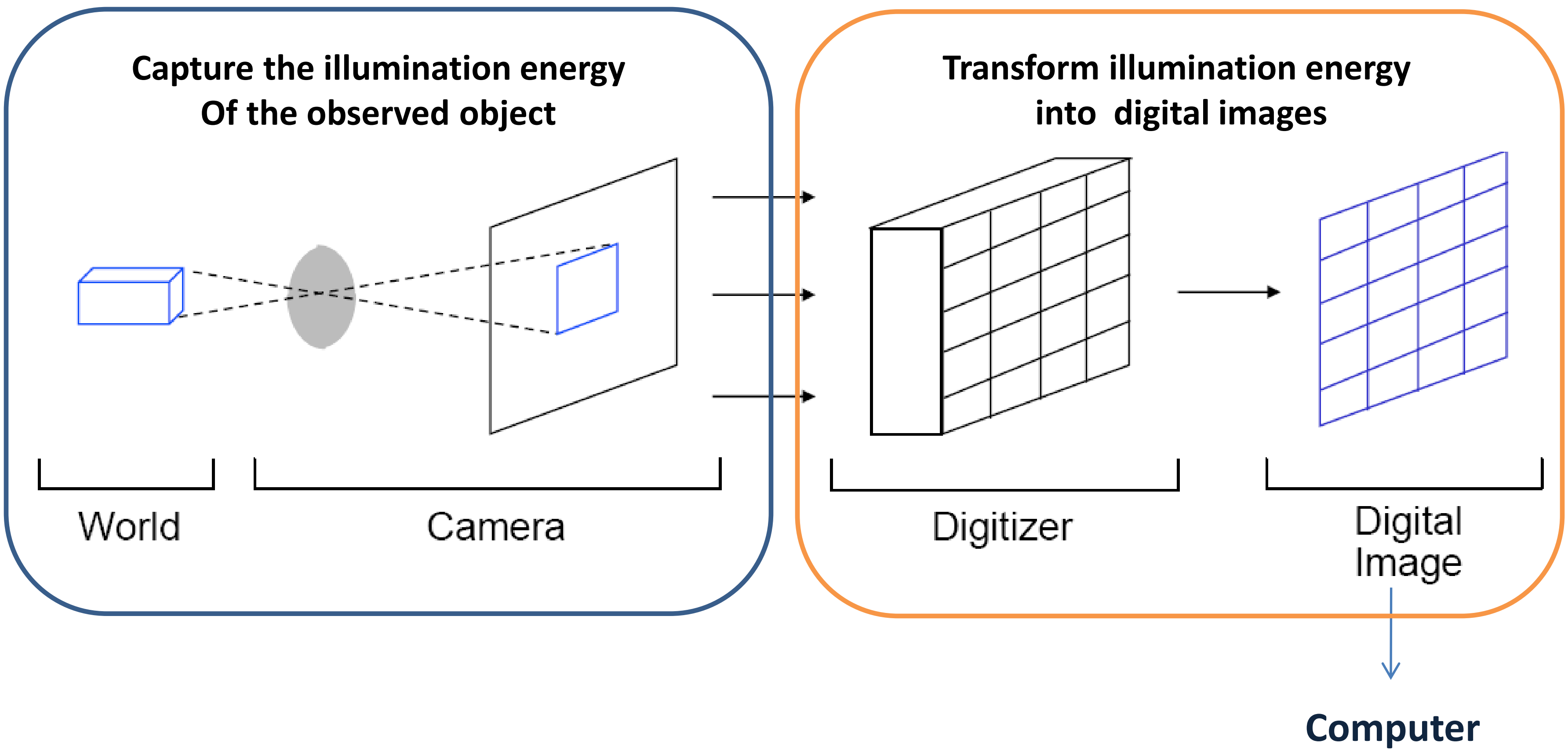

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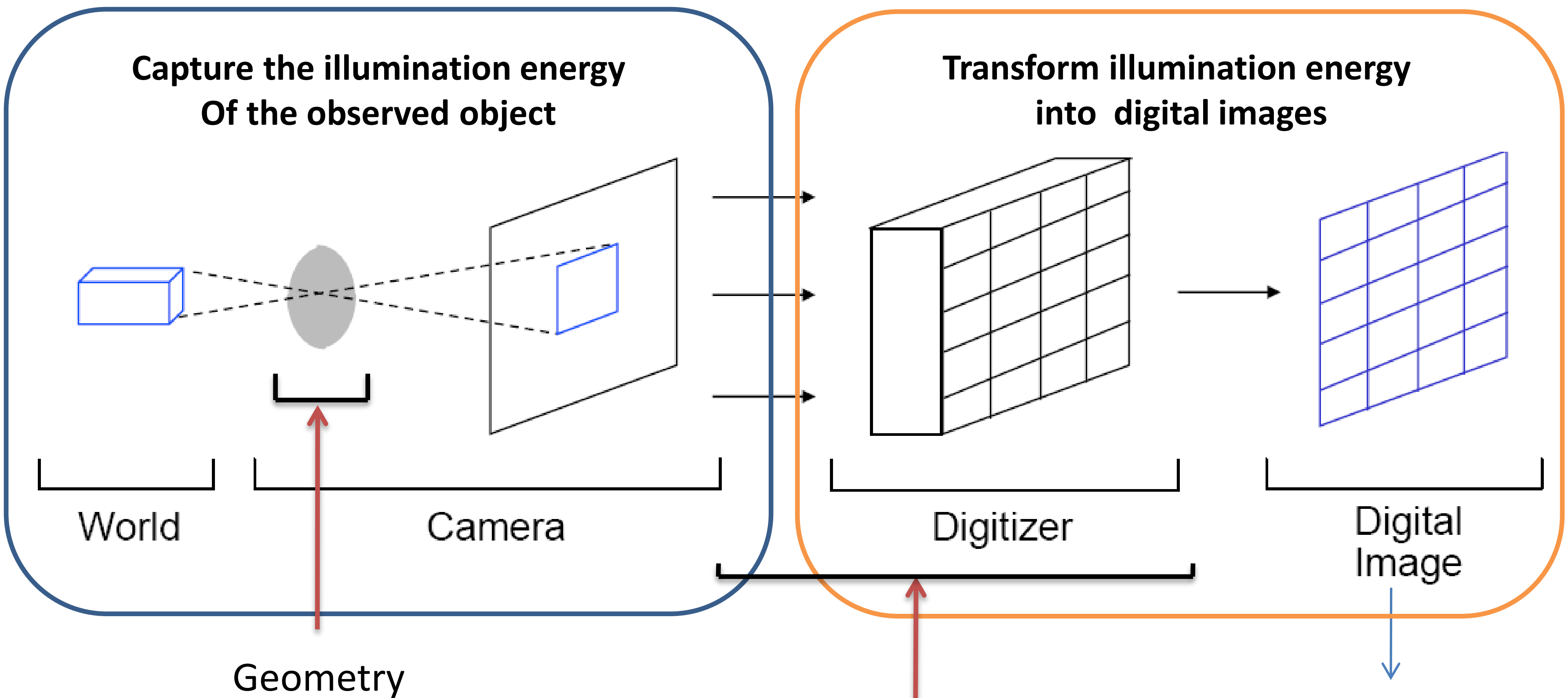
Image formation model



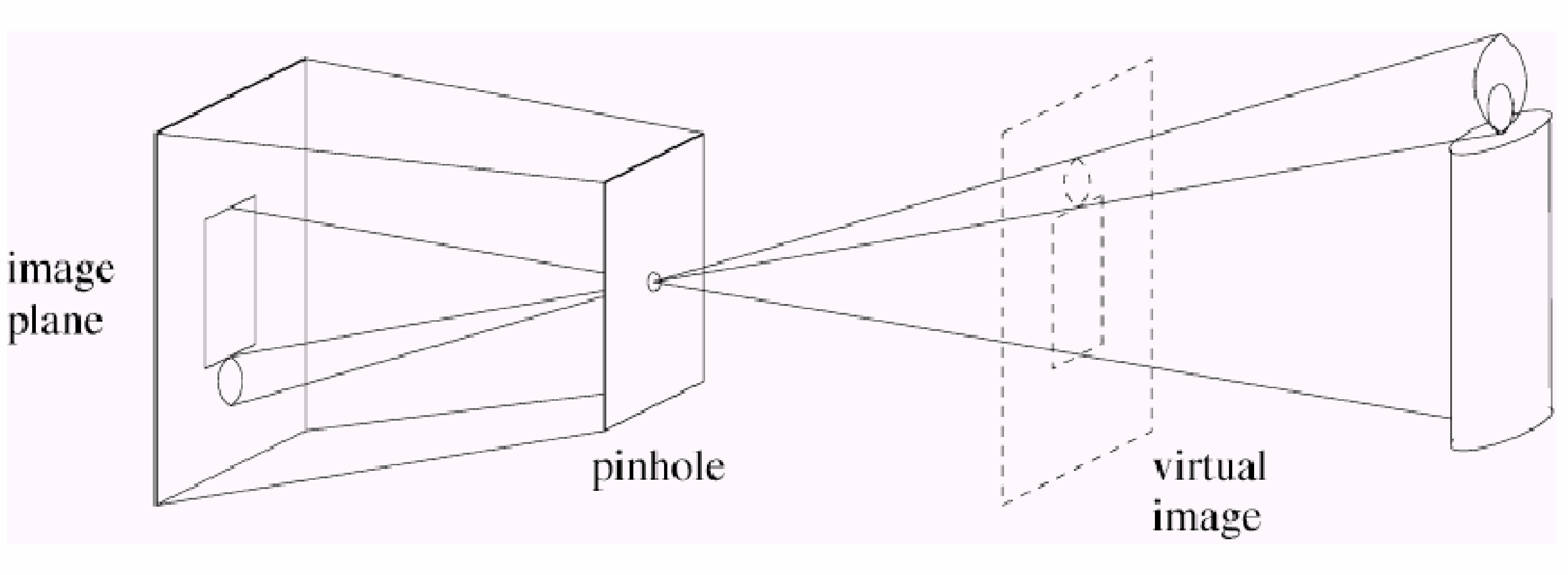
Geometry
(referred as *camera geometry*,
Studied in detail in
Computer vision lecture)

Colors
(referred as *image
formation model)*

Computer

Camera geometry model

- The pinhole (central imaging) camera model



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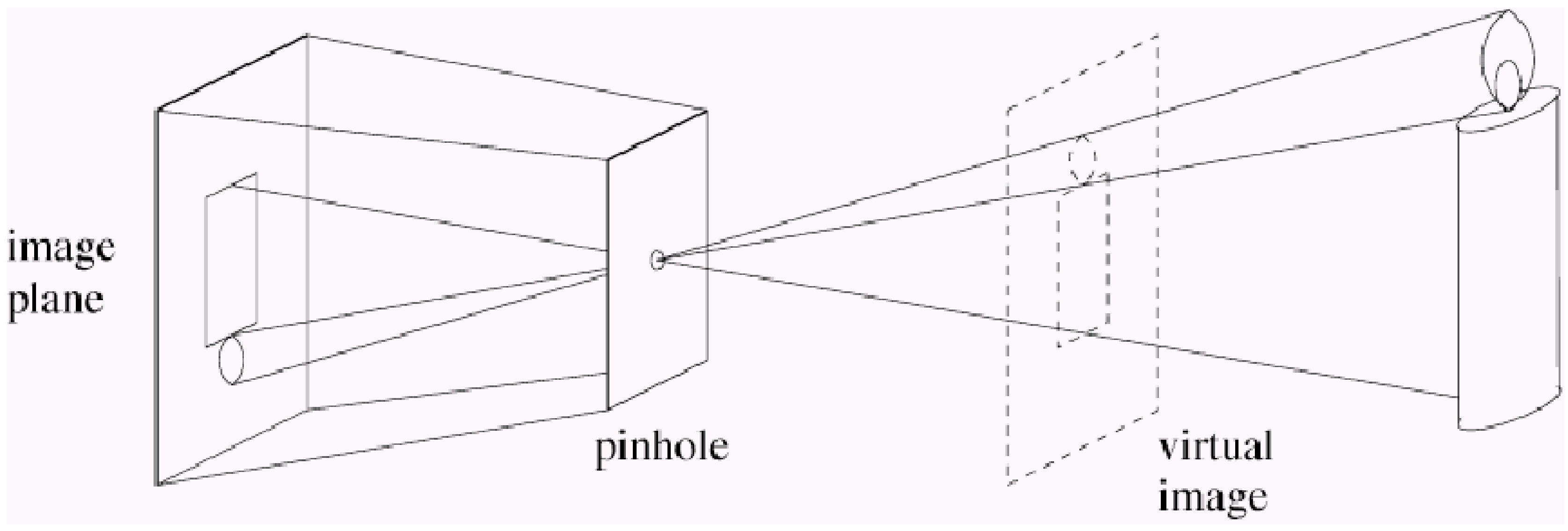
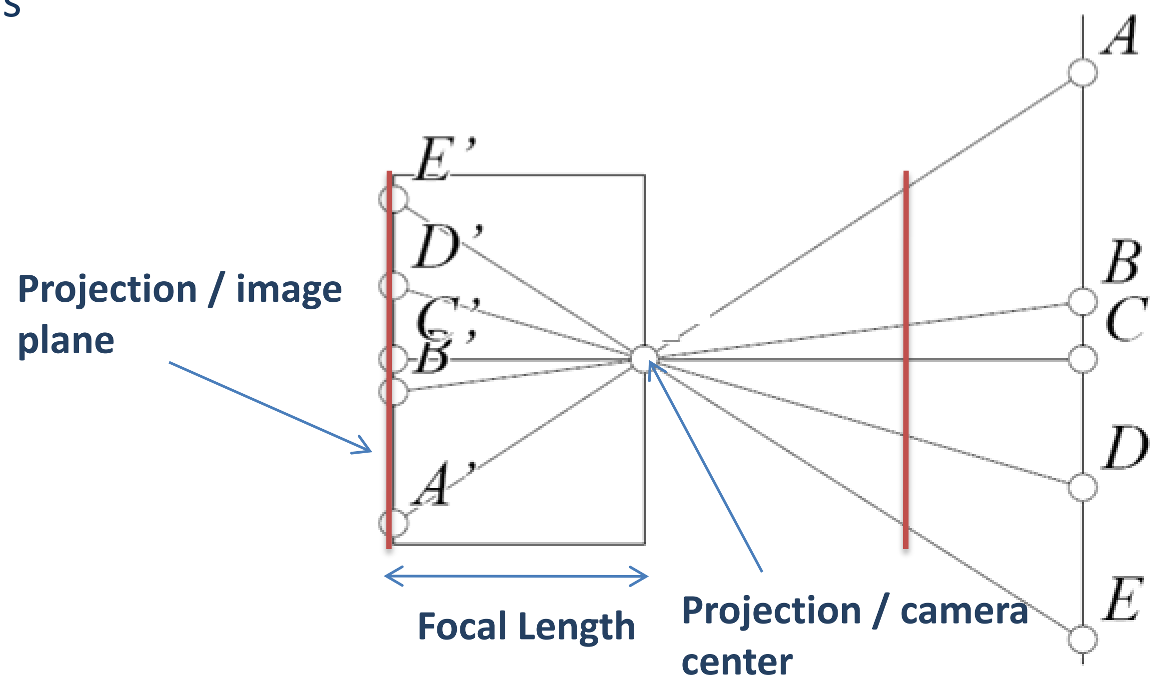
Camera geometry model

- The pinhole (central imaging) camera model
  - Perspective projection of 3D points (the scene) onto a 2D plane (image plane / retina)



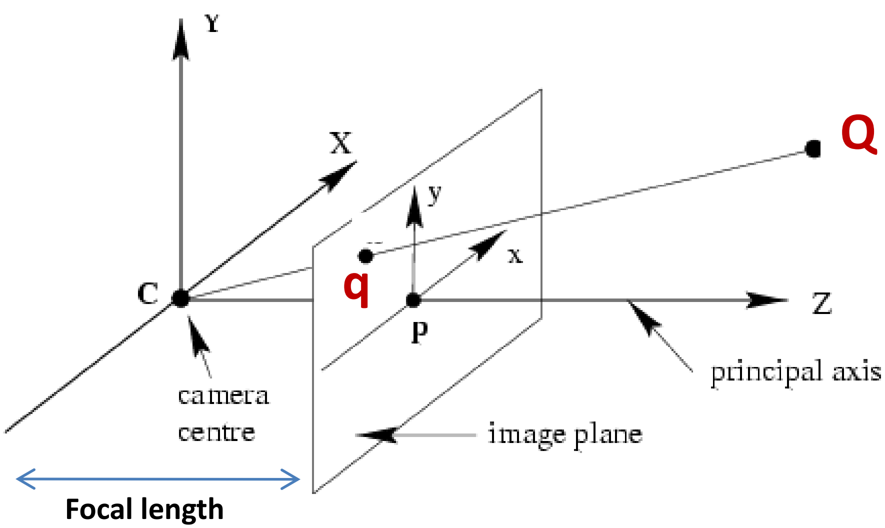
Camera geometry model

- The pinhole (central imaging) camera model
  - Perspective projection of 3D points (the scene) onto a 2D plane (image plane / retina)
  - Camera parameters
    - Camera center **c**
    - Focal length **f**



Camera geometry model

- The pinhole (central imaging) camera model
  - Perspective projection of 3D points (the scene) onto a 2D plane (image plane / retina)
  - Camera parameters
    - Camera center **c**
    - Focal length **f**
- Question
  - Given a point Q(X, Y, Z) in the 3D space,
    what is the coordinates of its image q(x, y)
    (on the image plane)



- This topic will be covered in "Computer Vision" lecture

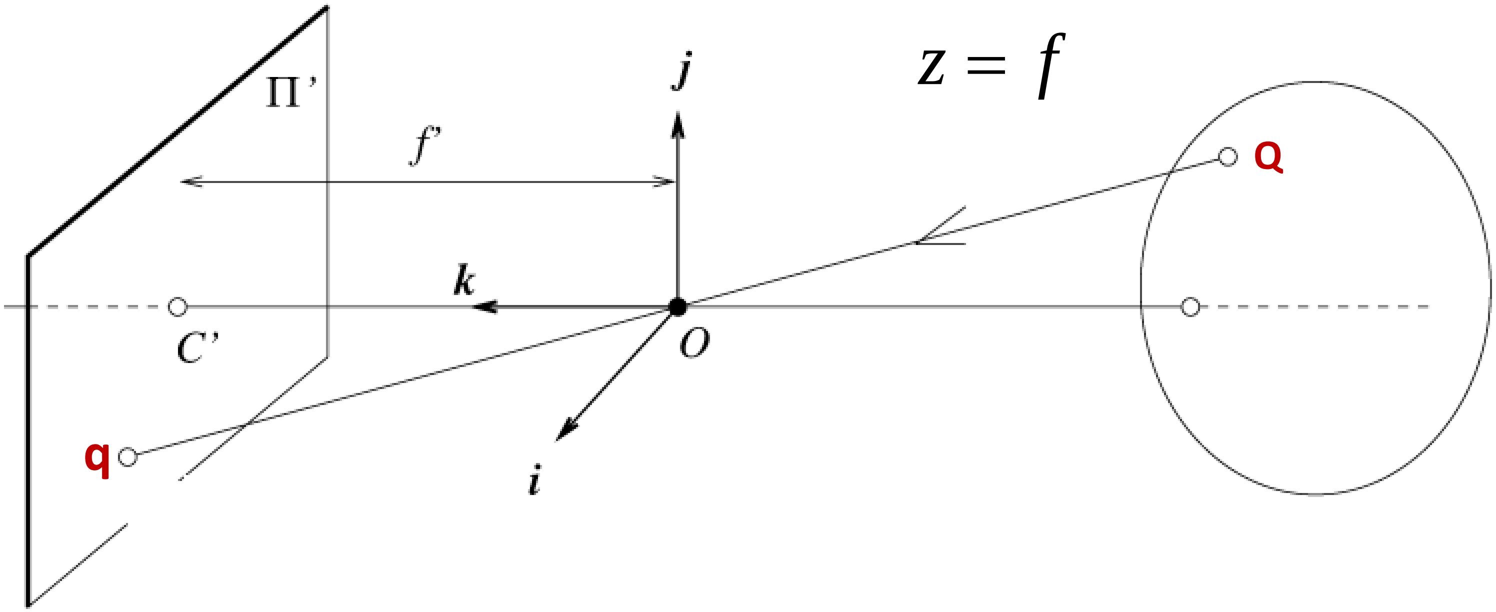
The pinhole camera model

- Answer
  - Since q is on the image plane $z = f$
  - Since q, O, and Q are colinear
    - **x/ X = y / Y = z / Z = f / Z**

$$x = f\,\frac{X}{Z}$$

$$y = f\,\frac{Y}{Z}$$

$$z = f$$



The pinhole camera model

- Answer
  - If you ignore the 3rd coordinates

$$(X, Y, Z) \rightarrow \left(f\frac{X}{Z}, f\frac{Y}{Z} \right)$$

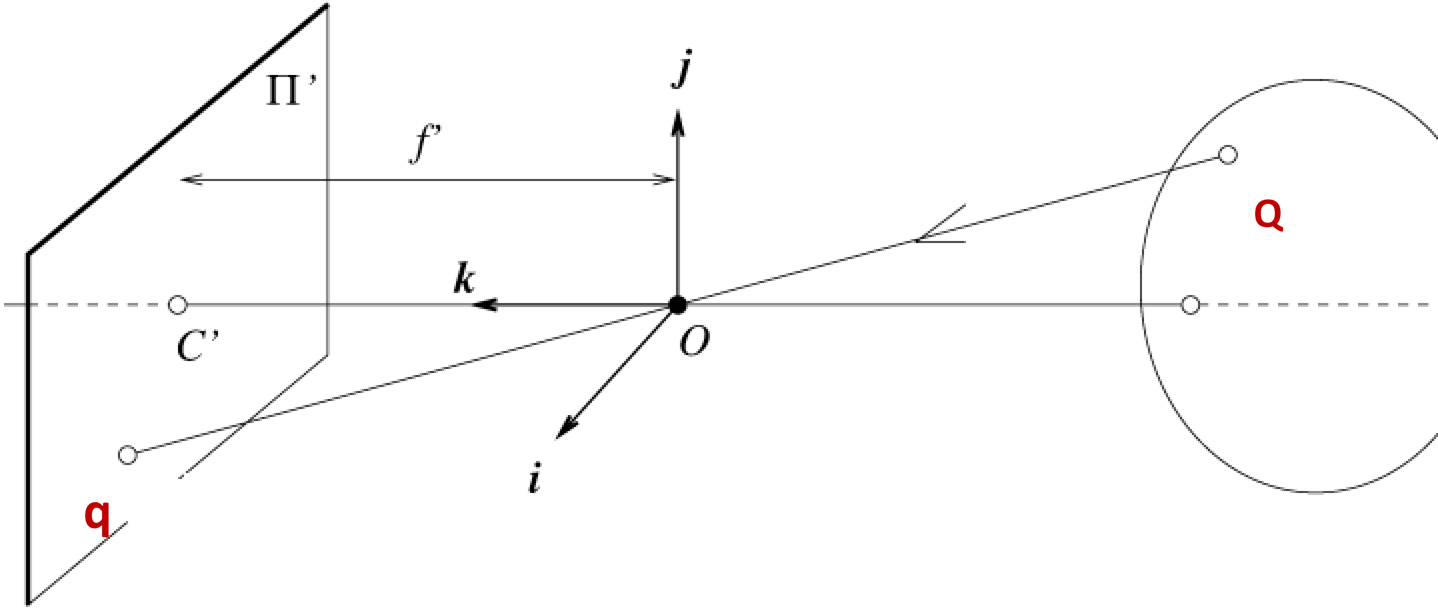
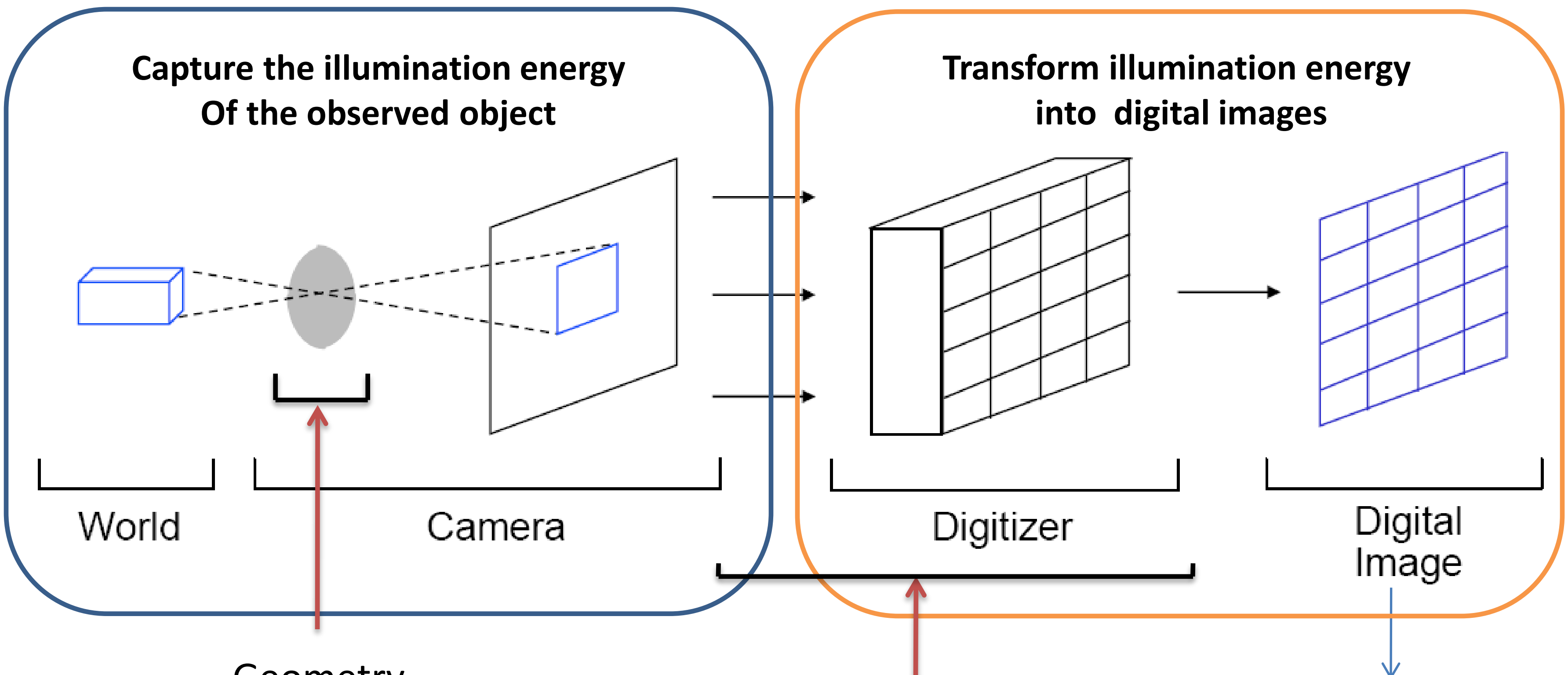


Image formation model



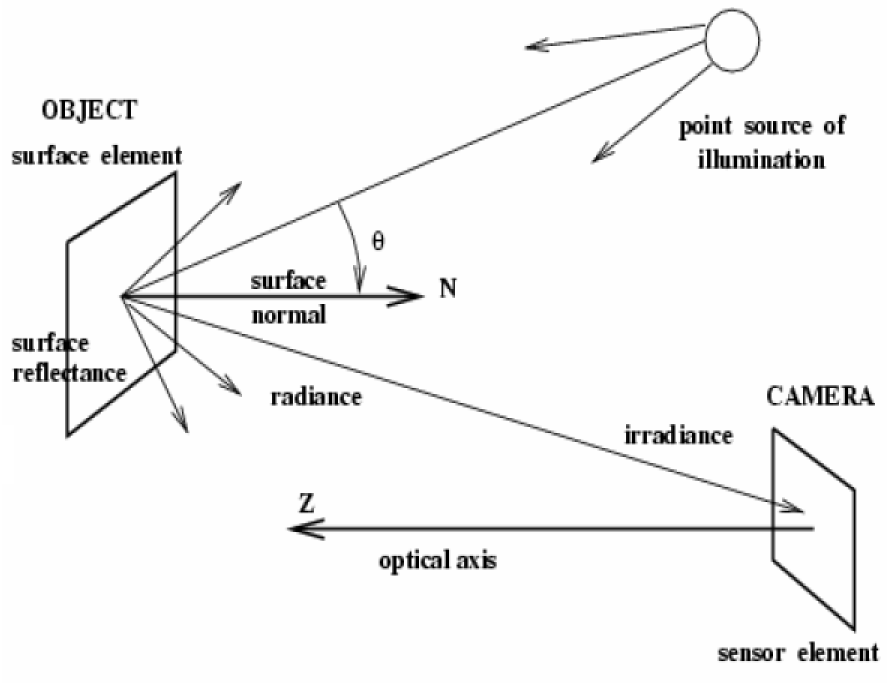
Computer

Geometry
(referred as *camera geometry*,
Studied in detail in
Computer vision lecture)

Colors
(referred as *image formation model)*

Image formation model

- A simple model
  - Light reaches surfaces in 3D
  - Surfaces reflect the light
  - Sensor elements receive the reflected lights
  - Light intensity is important
  - Angles (light, surface, cam.) are important
  - Surface materials are important



- What is an image
  - A 2D function *f(x, y)* from $R^2 \rightarrow R$:
    - *f(x, y)* gives the intensity at position (x, y)
  - A color image is just three functions pasted together
    - $f(x, y) = [r(x,y)\ g(x,y)\ b(x,y)]$

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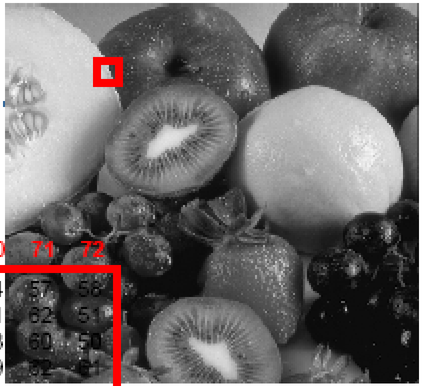
Representing digital images

- We usually operate on **digital (discrete)** images
  - **Sample** the 2D space on a regular grid
  - **Quantize** each sample (round it to the nearest integer)
  - The image is then represented as a matrix of integer values.



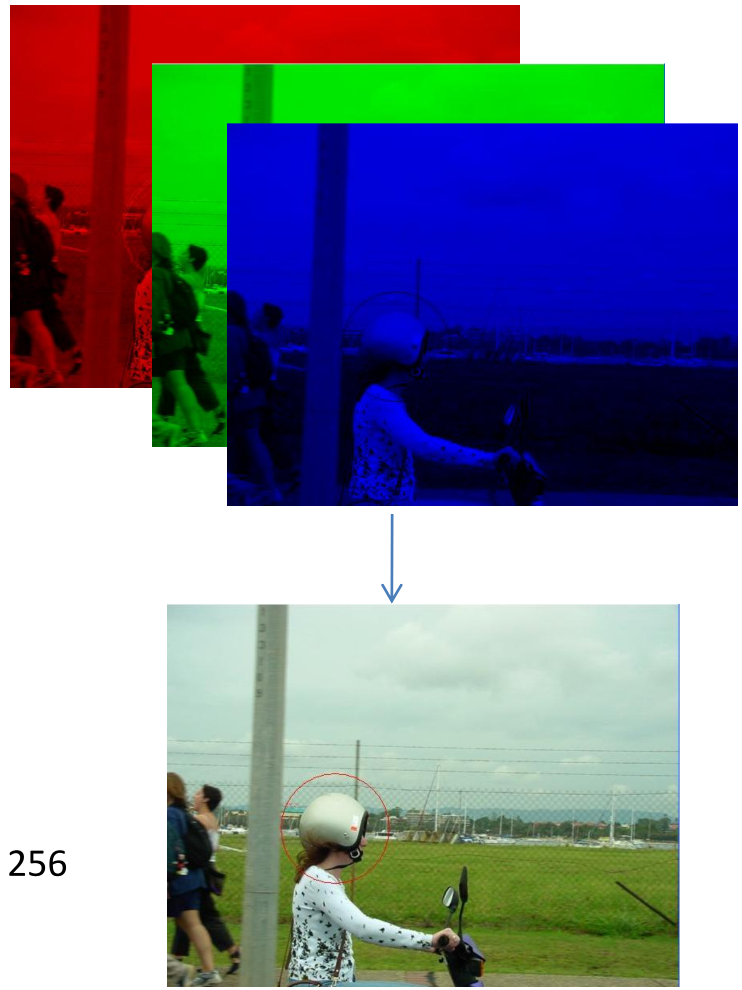
y \ x =	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
41	210	209	204	202	197	247	143	71	64	80	84	54	54	57	58
42	206	196	203	197	195	210	207	56	63	58	53	53	61	62	51
43	201	207	192	201	198	213	156	69	65	57	55	52	53	60	50
44	216	206	211	193	202	207	208	57	69	60	55	77	49	[illegible]	[illegible]
45	221	206	211	194	196	197	220	56	63	60	55	46	97	58	106
46	209	214	224	199	194	193	204	173	64	60	59	51	62	56	48
47	204	212	213	208	191	190	191	214	60	62	66	76	51	49	55
48	214	215	215	207	208	180	172	188	69	72	55	49	56	52	56
49	209	205	214	205	204	196	187	196	86	62	66	87	57	60	48
50	208	209	205	203	202	186	174	185	149	71	63	55	55	45	56
51	207	210	211	199	217	194	183	177	209	90	62	64	52	93	52
52	208	205	209	209	197	194	183	187	187	239	58	68	61	51	56
53	204	206	203	209	195	203	188	185	183	221	75	61	58	60	60
54	200	203	199	236	188	197	183	190	183	196	122	63	58	64	66
55	205	210	202	203	199	197	196	181	173	186	105	62	57	64	63

Example of a grayscale image

Source: http://www.cs.brown.edu/courses/cs143/lecture2.pdf

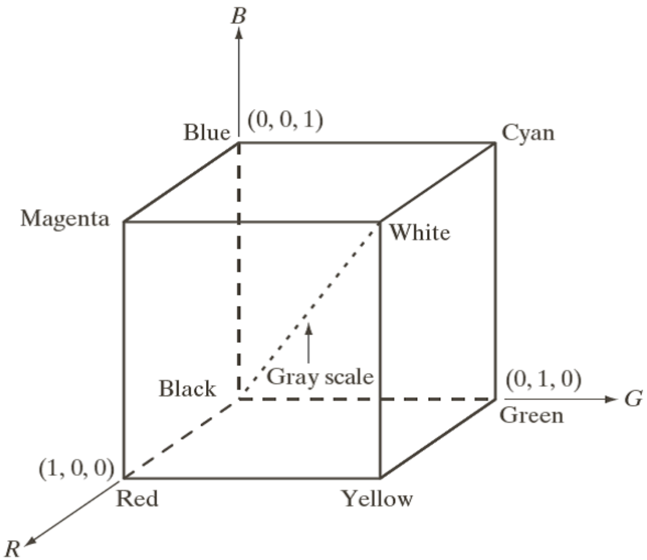
Representing colors

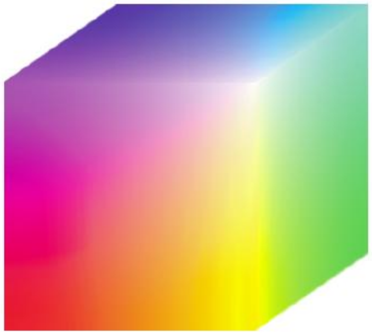
- Gray-scale image
  - A matrix of values between 0 and 255 (the gray-scales)
  - Sometimes it is represented with real values between 0 and 1.
  - Matrix elements are called pixels.
- Color image
  - Three (03) matrices encoding Colors (ex.: RGB: Red – Green – Blue)
  - Each matrix is called color band
- Spatial resolution = Number of pixels
  - Width x Height of the image
- Intensity resolution
  - Number of intensity levels
    - Usually 256 for grayscale images, 256 x 256 x 256 for color images Larger is better



Color spaces

- RGB color space
  - Each pixel in the image is a tuple (r, g, b) corresponding to the amount of red, green, and blue color.
  - It can be seen as a point in the 3D space (the RGB space) where each axis is one color component
  - RGB space is linear
- Can the RGB space represent all the set of colors visible by the human eye ?
  - NO
  - Let's see why !!!





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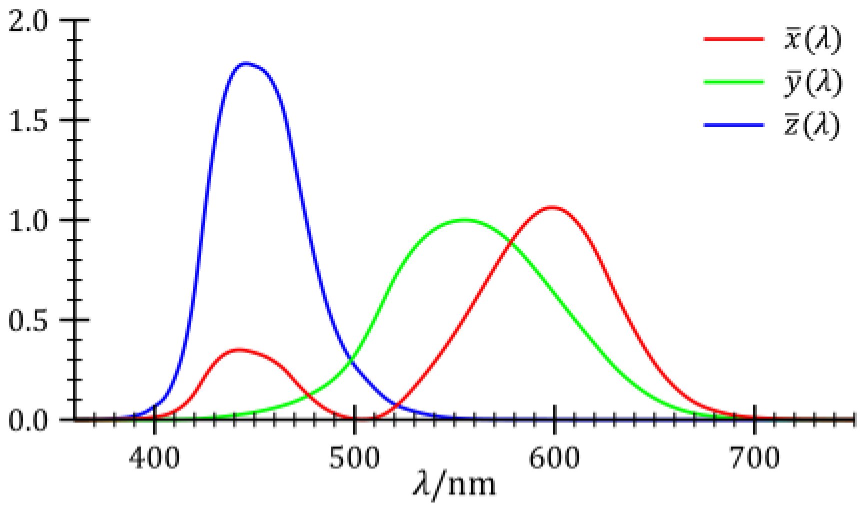
Color spaces

- The eye has photoreceptors (cones) of 3 types
  - S: for medium to high-brightness vision (wave lengths between 420-440nm) ~ Blue
  - M: middle (530-540nm) ~ Green
  - L: (560-580nm) ~ red



Color spaces

- The eye has photoreceptors (cones) of 3 types
  - S: for medium to high-brightness vision (wave lengths between 420-440nm) ~ Blue
  - M: middle (530-540nm) ~ Green
  - L: (560-580nm) ~ red
- Color can be divided into two parts
  - Brightness (luminance) and Chromaticity
    Ex.: White and Gray have the same chromaticity but differ in brightness
  - Chromaticity is specified with two values **x** and **y**
  - And luminance with one value **L**

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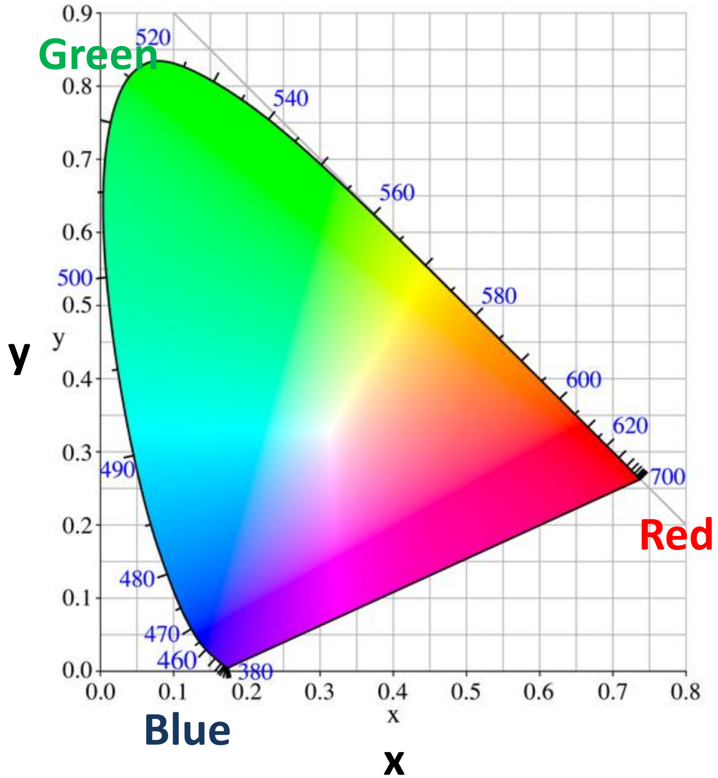
Color spaces

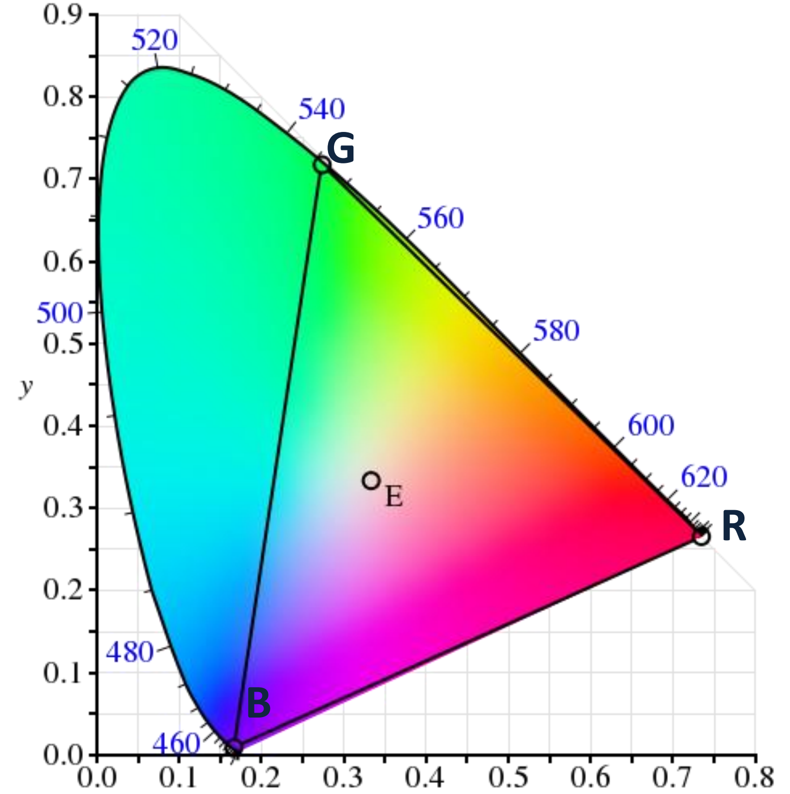
- Chromaticity diagram



The CIE 1931 color space chromaticity diagram.

Color spaces – RGB color space

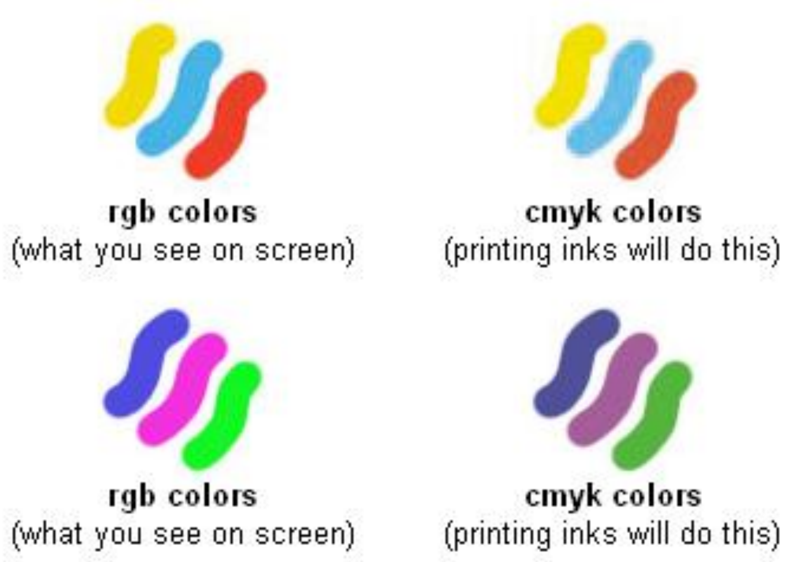
- Can the RGB space represent all the set of colors visible by the human eye ?
  - NO
- Monitors use RGB space

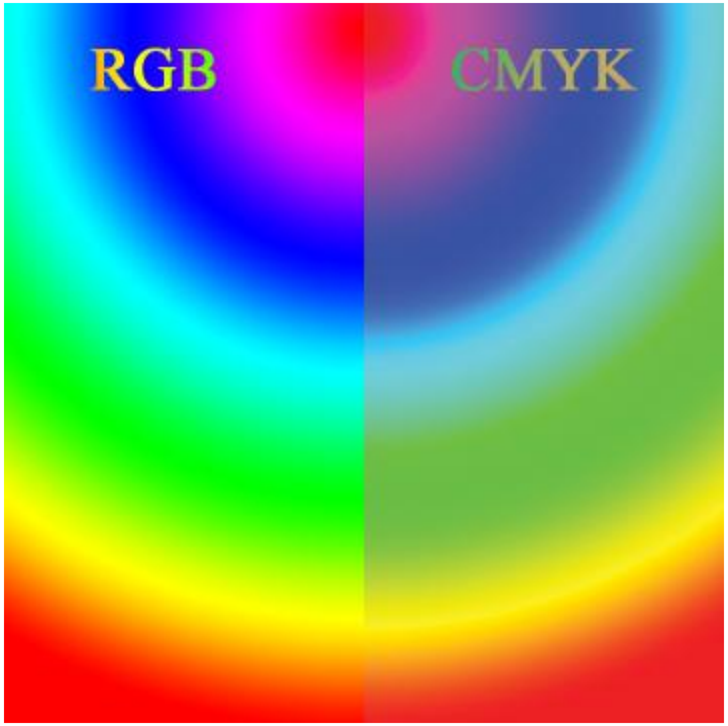


Gamut of the CIE RGB primaries and location of primaries on the CIE 1931 *xy* chromaticity diagram

Color spaces – CMYK color space

- Printers use Cyan, Magenta, Yellow, and Black (CMYK) color space (linear)

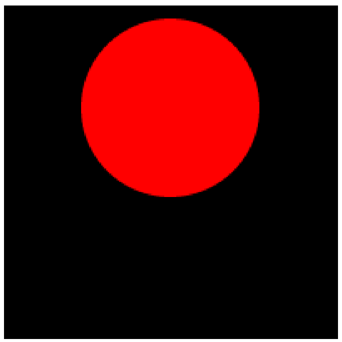




A comparison of RGB and CMYK color models. This image demonstrates the difference between how colors will look on a computer monitor (RGB) compared to how they will reproduce in a CMYK print process

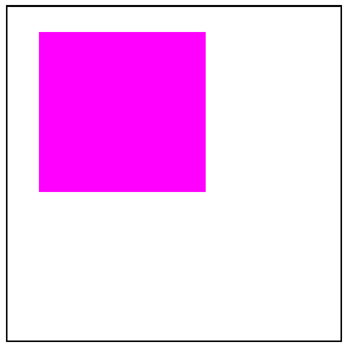
Color spaces – RGB vs CMYK

- RGB is additive because monitors emit light
- CMYK is subtractive because paper absorbs ink



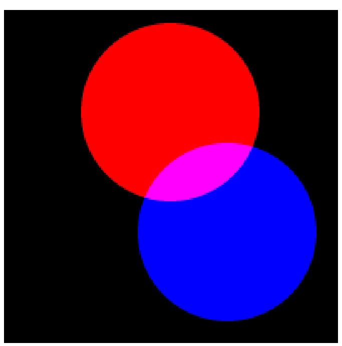
Red, Green, Blue

Additive color space



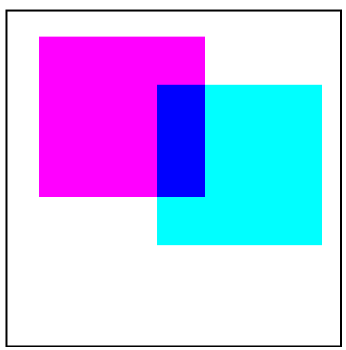
Cyan, Magenta, Yellow

Subtractive color space



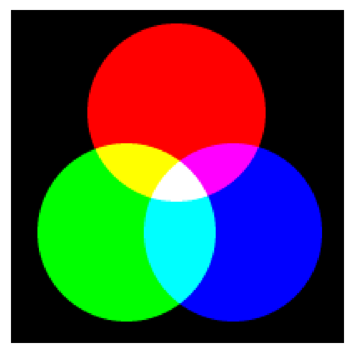
Red, Green, Blue

Additive color space



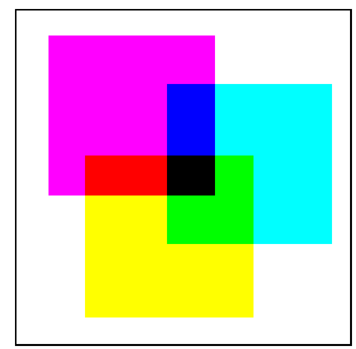
Cyan, Magenta, Yellow

Subtractive color space



Red, Green, Blue

Additive color space



Cyan, Magenta, Yellow

Subtractive color space

Transformation between color spaces

- There are many other color spaces (linear, non-linear) which we will cover in a different lecture
- Transformations exist between color spaces

Summary

- Things you should keep in mind
  - Colors are the results of the interaction of light with the surface as observed by a sensor from a viewing point
    (the surface absorbs some light, depending on the material properties)
  - An image is a 2D function which encodes the color at each location of the image plane
  - In the discrete case, an image is a 2D matrix, each entry is called a pixel, it can have a single value (grayscale) or a vector of 3 values (color)
  - There are many color spaces, from now we will use the RGB color space.
    - If we need to use another color space I will mention it explicitly

Next

- Intensity transformations
  - Basics
  - Histogram processing

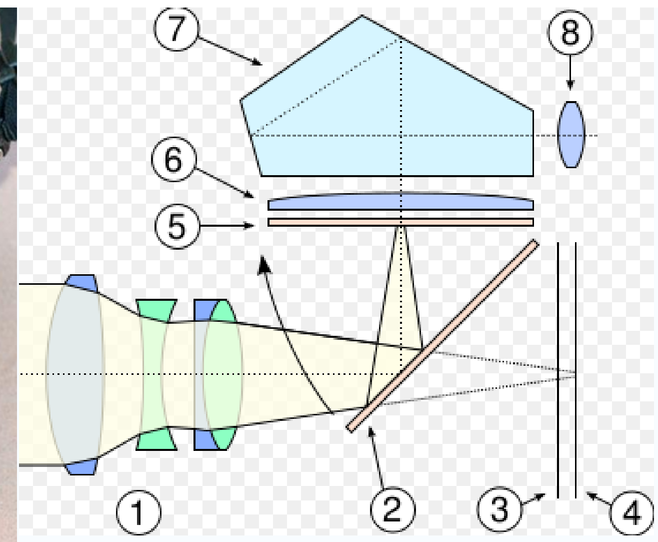
Further reading

- Camera geometry

- Image sampling and quantization

Nowadays digital cameras

- Complex optical, electronic and mechanical components



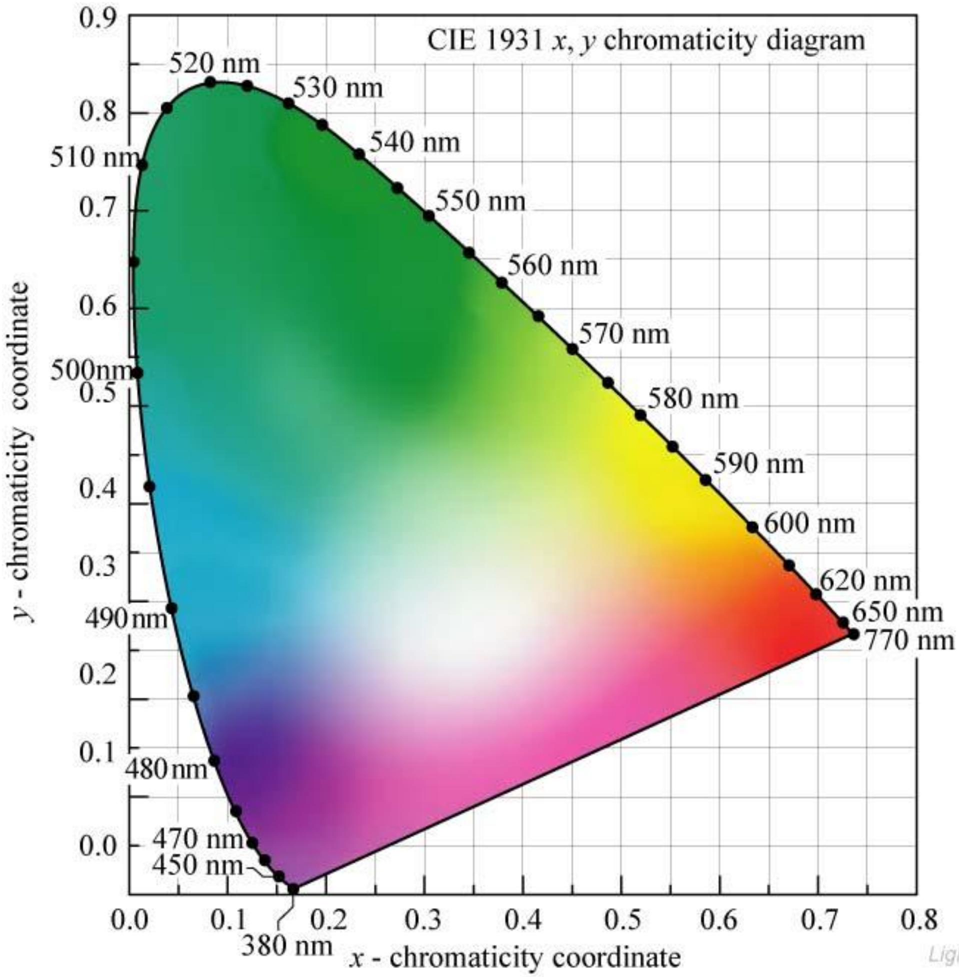


Fig. 17.2. CIE 1931 (x, y) chromaticity diagram. Monochromatic colors are located on the perimeter and white light is located in the center of the diagram.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

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