Fundamentals of Computer Vision

Unit 2: Digital Image Formation

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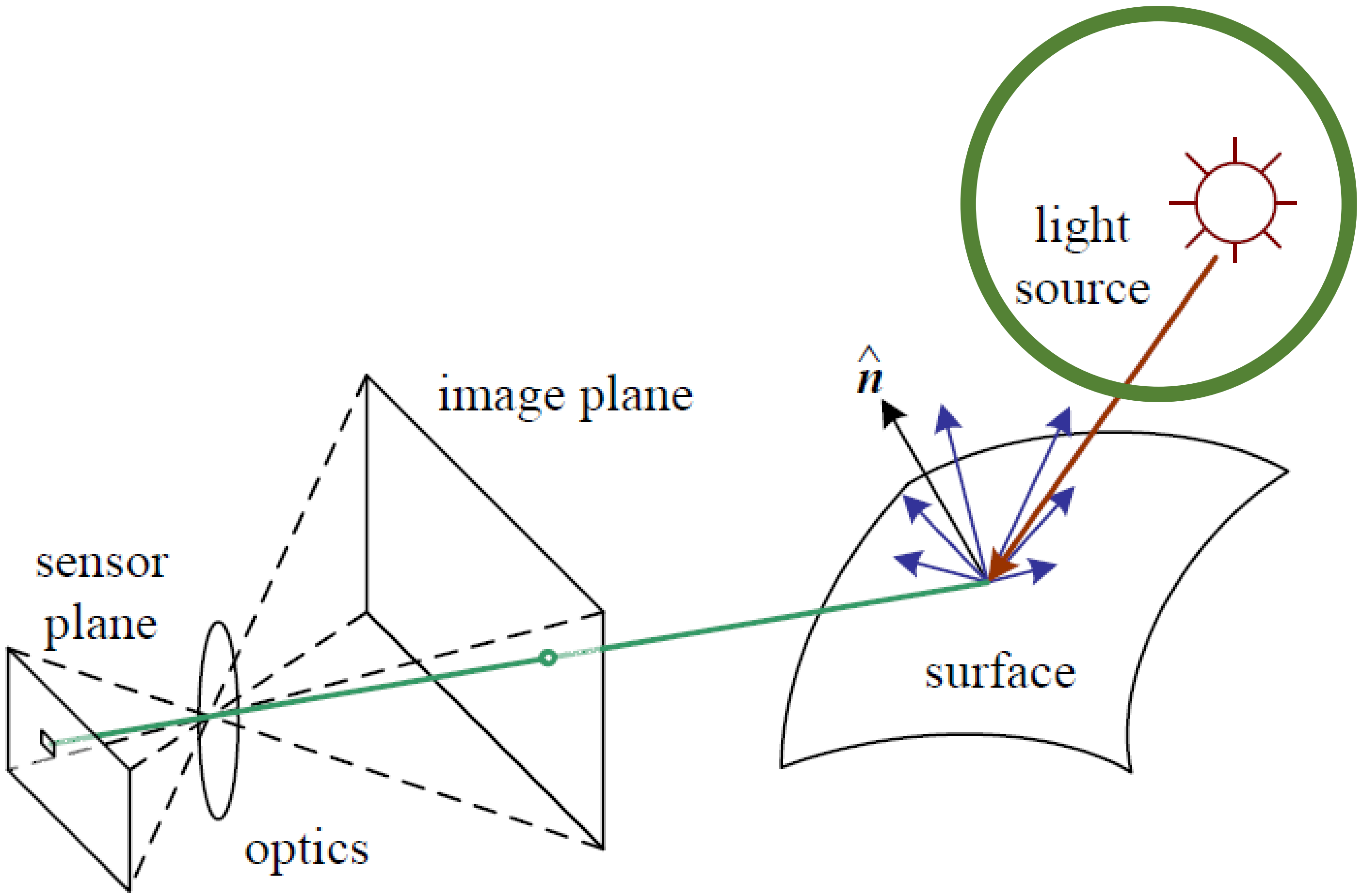
1

Light and Scene

Light and Scene



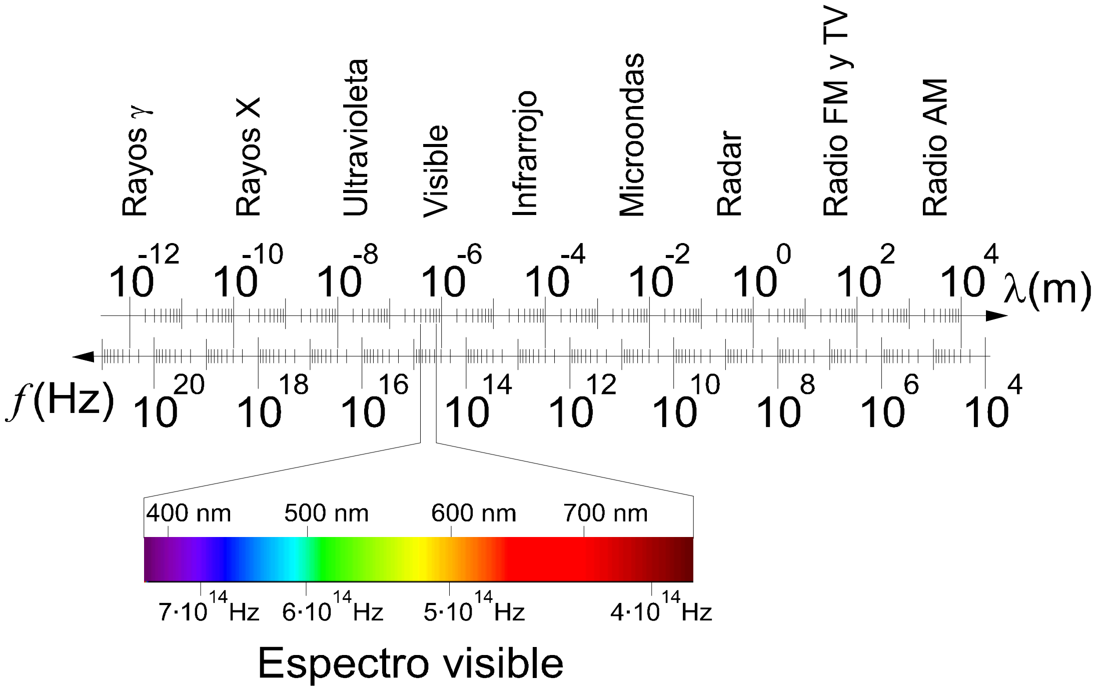
The elements needed to create an image are:

- Illumination
- Scence
- Camera / eye

The image captured will be later processed in a computer to perform a given task (object detection, recognition, classification …)

Light and Scene

Light is the energy with which we will interact with the scene and that will allow us to see it.
It is composed by EM waves that can also be seen as photons



We can obtain images from any given spectrum zone if we use the appropriate sensors (normally we aim for the visible spectrum)

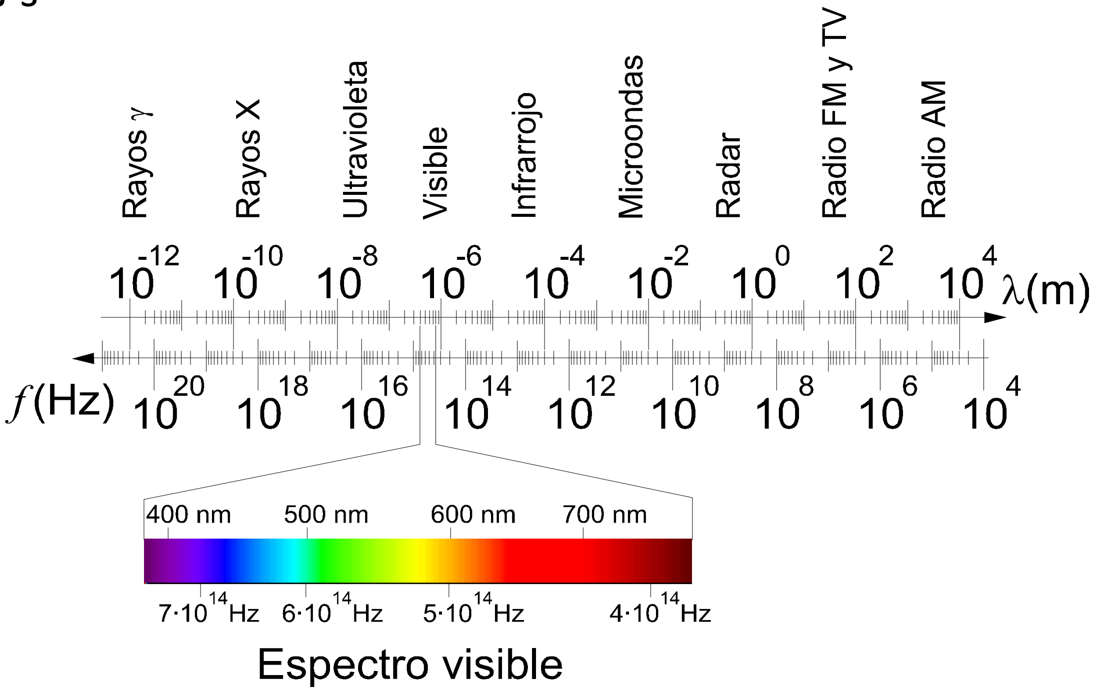
Light and Scene

EM waves have an energy associated and we can characterize them according to how they oscillate, how fast they oscillate (frequency) or by the amount of space they advance in each oscillation period (wavelength)

Planck constant: 6.626×10^{-34} J s

$$E = h\nu$$

EM wave frequency



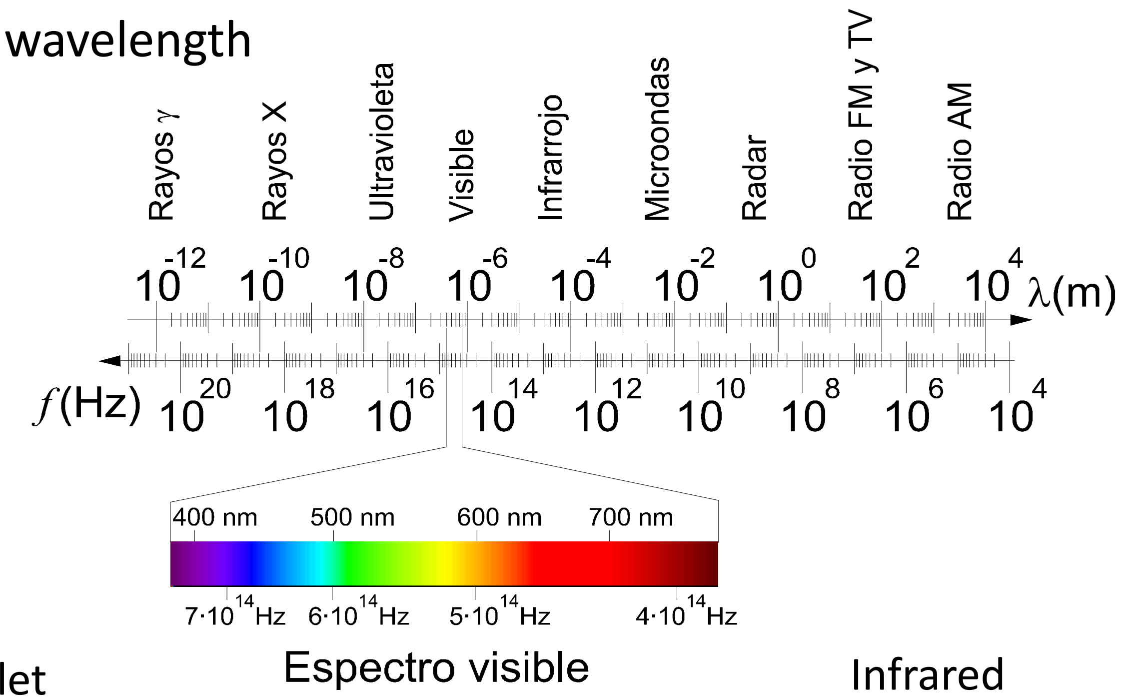
- Most energetic: gamma rays
- Less energetic: radio

Light and Scene

As light is an EM wave, it travels in space at lightspeed. There is a relationship between lightspeed, wavelength and frequency.

- Wavelength and frequency are one the inverse of the other
- More energetic waves → higher frequency → lower wavelength

$$c = \lambda \nu$$ → EM wave frequency



Ultraviolet

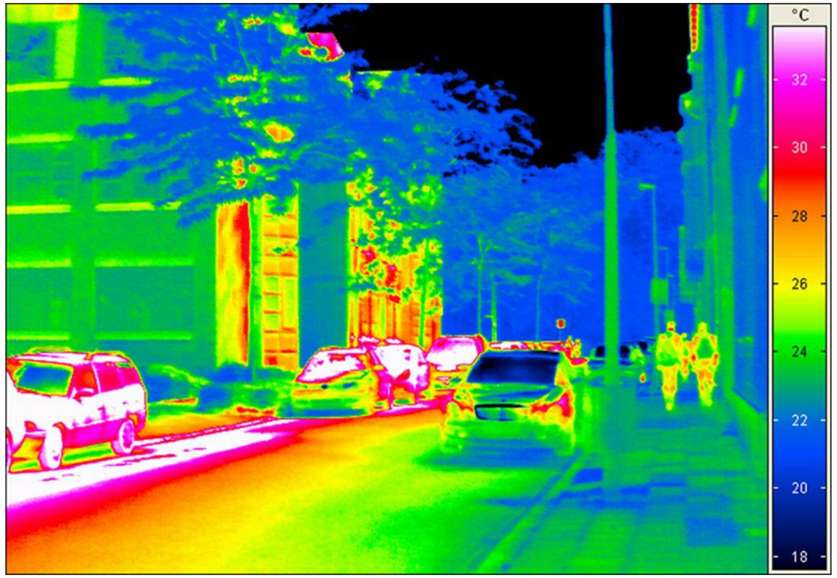
Infrared

Light and Scene

Examples of images in other light ranges:

X-ray image

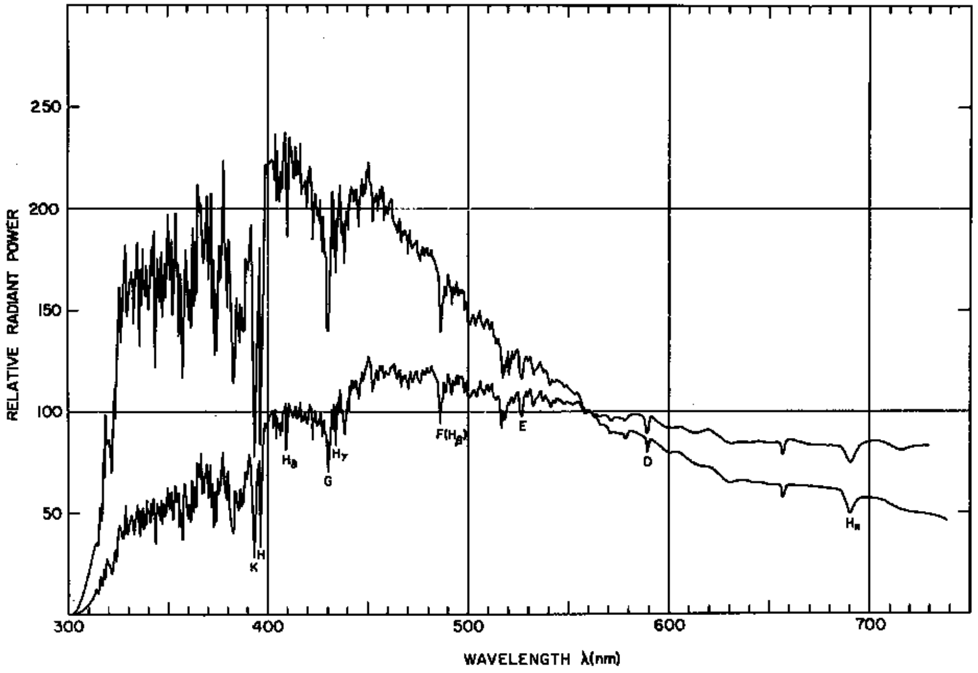
Ultraviolet image



Long wave infrared

Light and Scene

Spectral power distribution: power (energy per wavelength) radiating per wavelength unit

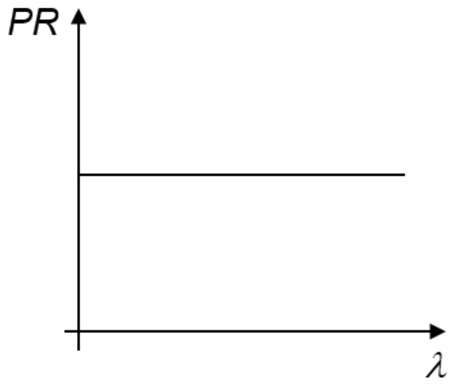


- Light emmited or reflected by an object in all wavelengths is defined as **color**
- In a given scene / object we have contribution from several wavelengths/ energies

Light and Scene

Two special cases:

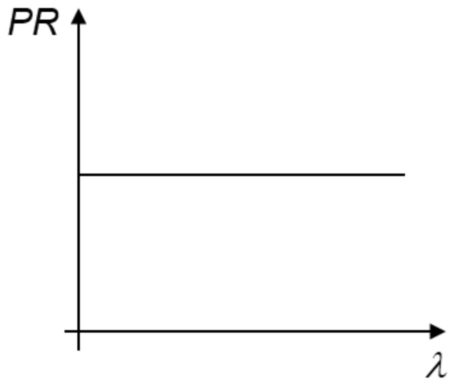
- White light: spectrum with the same amount of energy for each wavelength



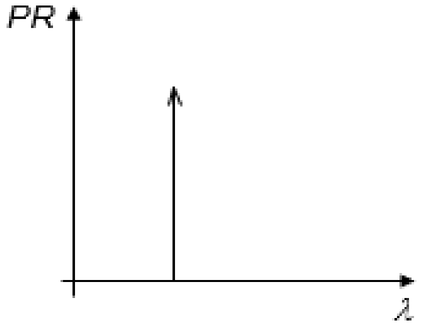
Light and Scene

Two special cases:

- White light: spectrum with the same amount of energy for each wavelength



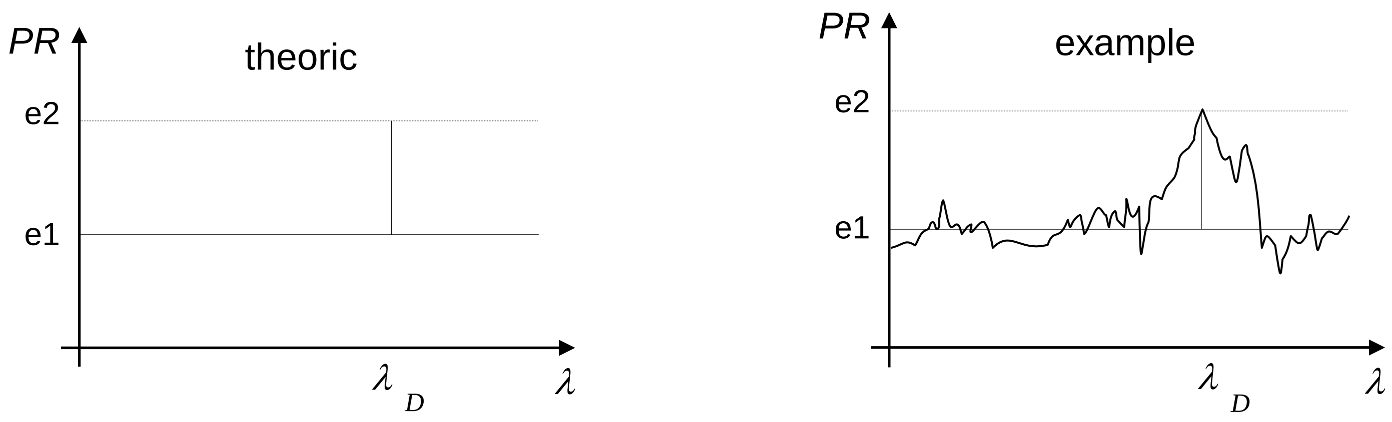
- Monochromatic light: energy of the spectrum is focused on a specific single wavelength. It does represent a pure spectral color



Light and Scene

Some definitions:

- Dominant wavelength (**hue**): wavelength with higher energy



Light and Scene

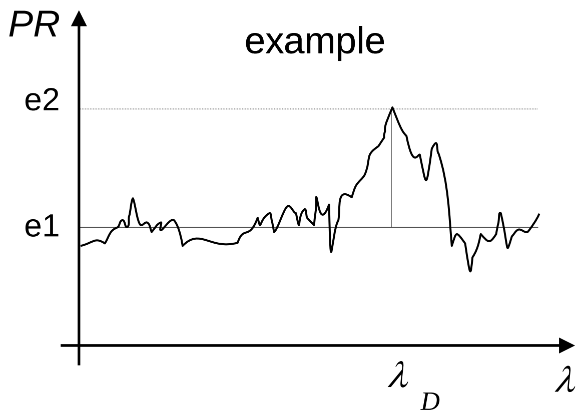
Some definitions:

- **Saturation**: rate between the energy of the dominant wavelength (e2) and the energy of the white light (e1)
  - In case e1=e2, saturation is zero
  - If e1=0, saturation is one (maximum value)

Light and Scene

Some definitions:

- **Brightness / luminance**: proportional to the area under the curve of the spectral distribution



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Color

Color

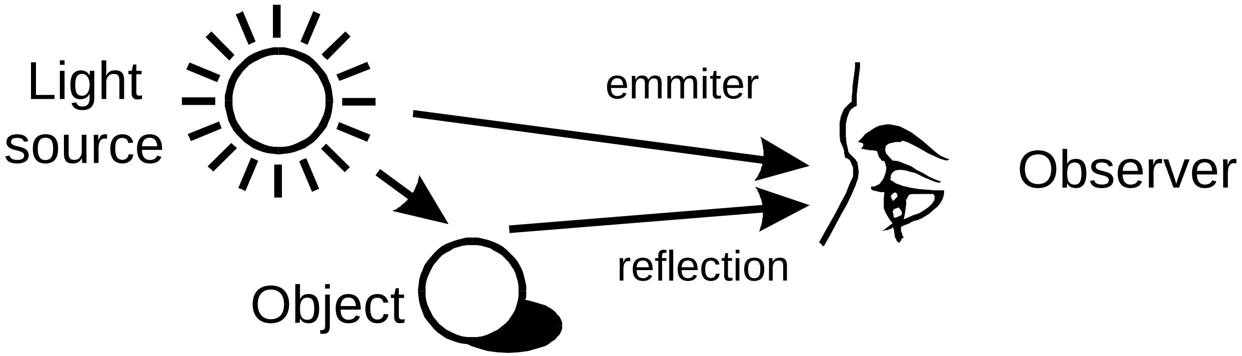
Human interpretation of an external stimuli. It is not only dependent on the energy that we perceive

What color is the hat of the girl? What about the triangle in the bottom right?

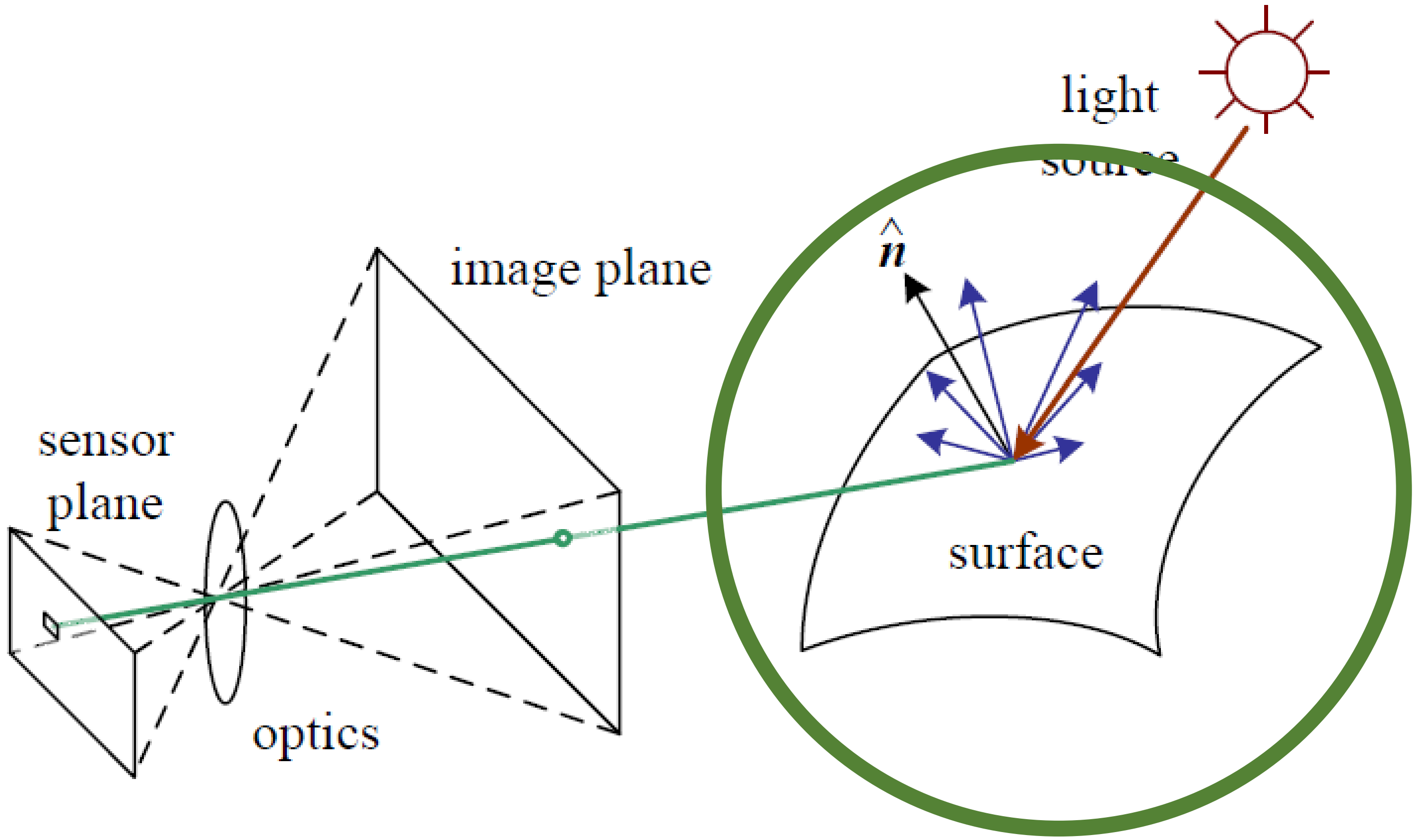
Color

There are several ways light can get to the human eye:

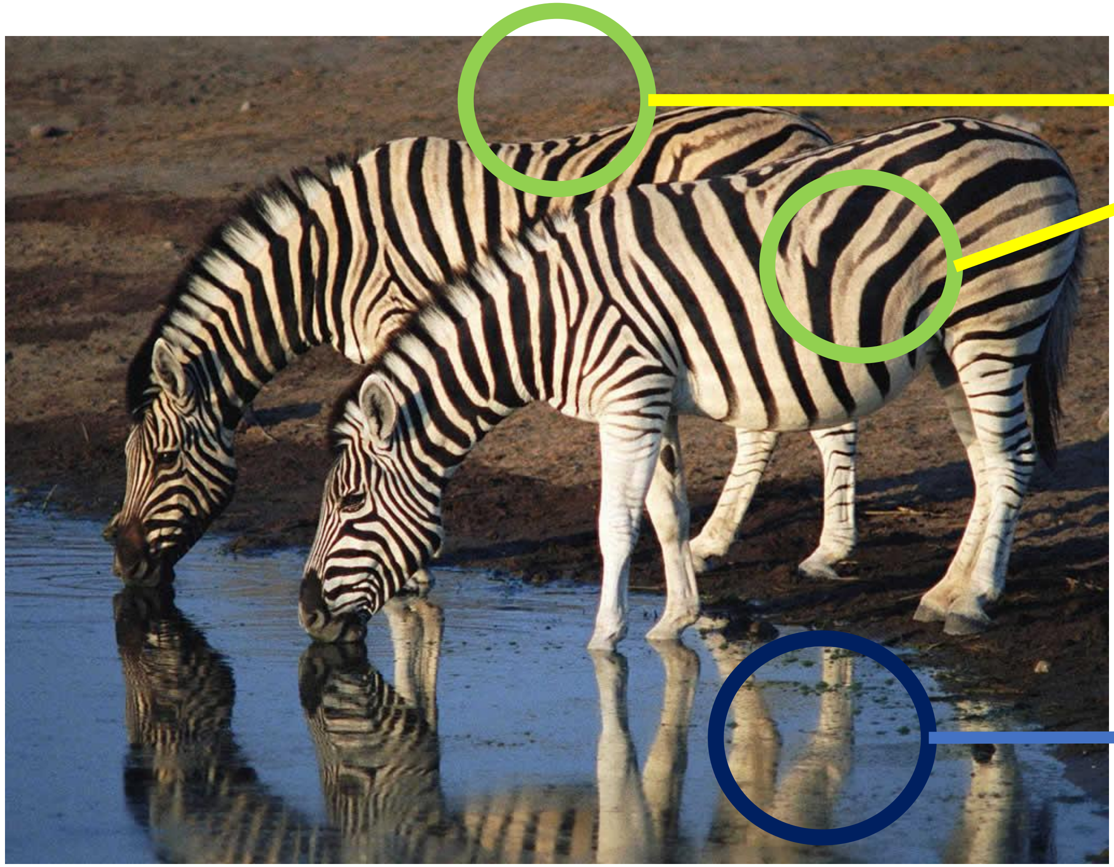
- Directly from the illumination source (it can have color or not)
- By reflection over object's surface



Color



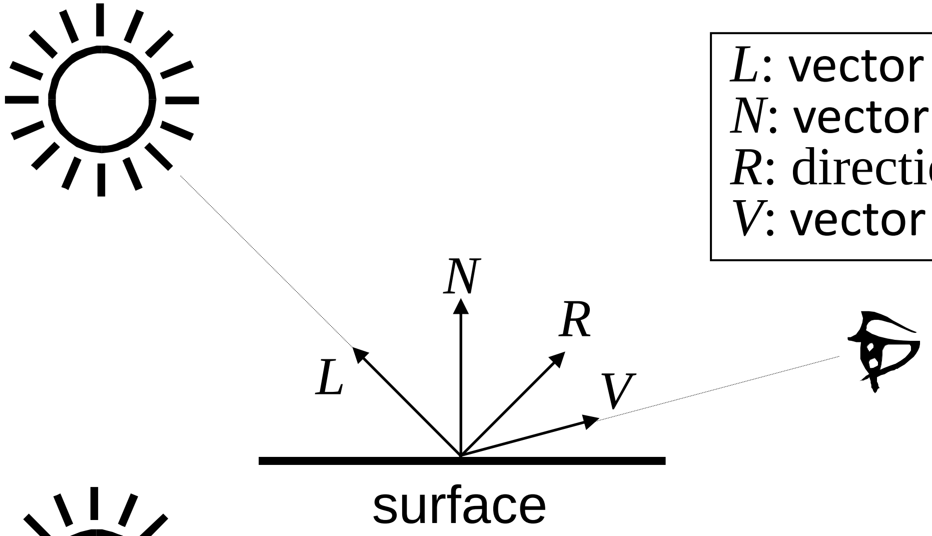
Color



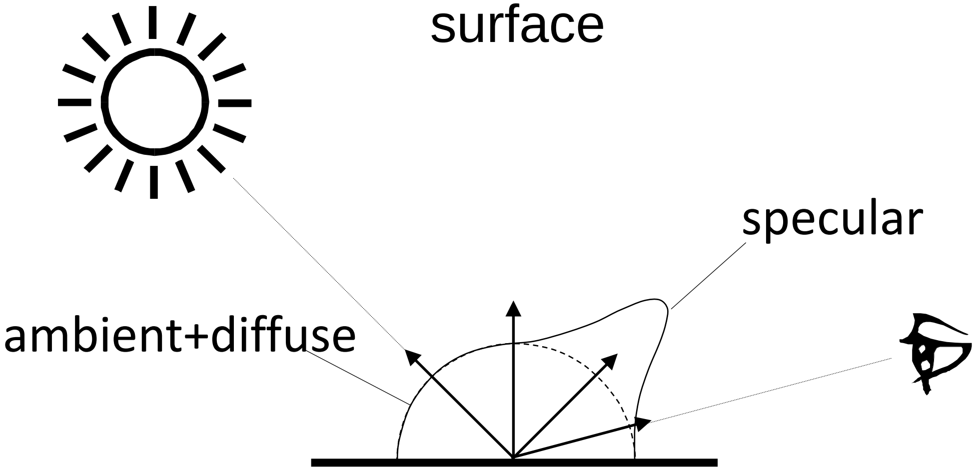
Diffuse surfaces: light reflects in all directions more or less equal

Specular component: light reflects better in a specific direction

Color

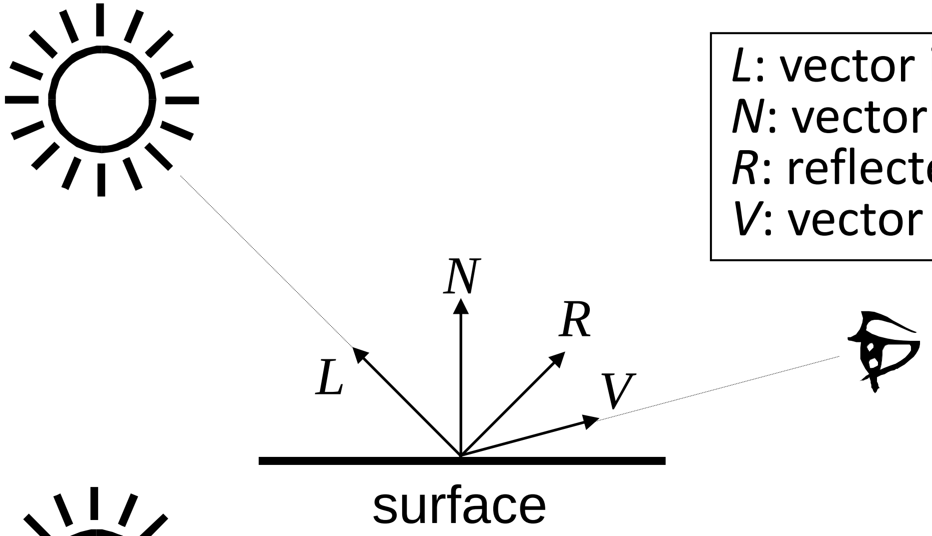


L: vector in the direction of light source
N: vector perpendicular to the surface
R: directional reflective
V: vector in the direction of the observer

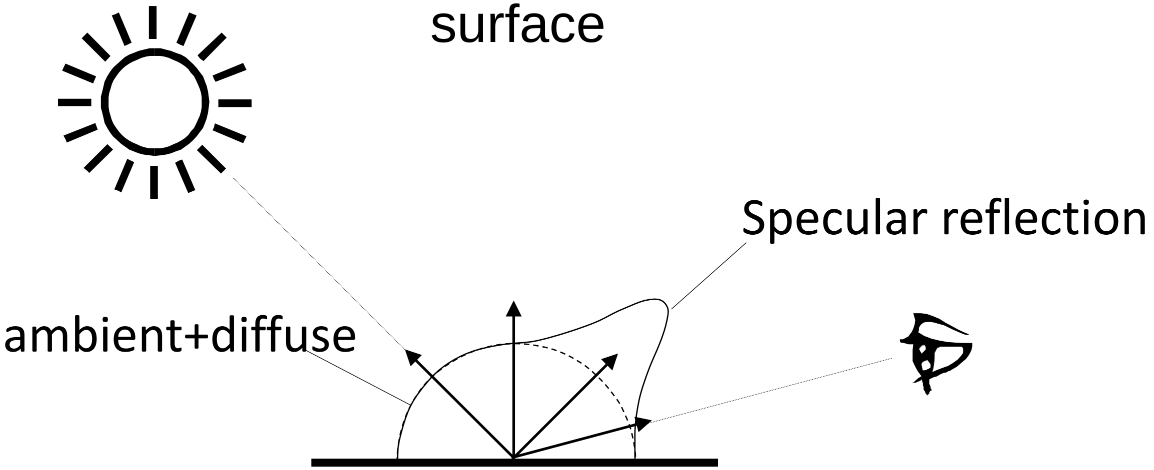


Diffuse light is spread equally in all directions and it only depends on the angle between L and N

Color



L: vector in the direction of light source
N: vector perpendicular to the surface
R: reflected vector
V: vector in the direction of the observer



Reflected vector has the opposite angle between L and N and represents the perfect rebound of the light in the Surface.

The reflection depends on the material: it can be more focused (metallic surfaces) or sparse (plastic surface). It depends on viewer's position

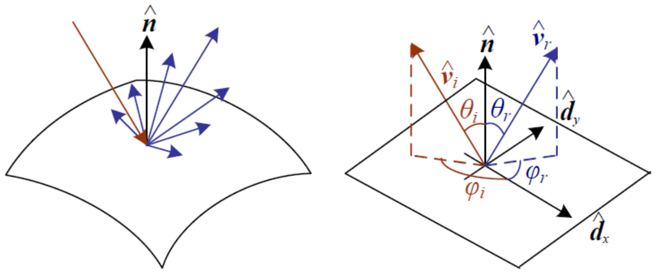
If R and V are equal, we could even get to see the light source

Color

- BRDF (bidirectional reflectance distribution function)

$$L_r(\hat{\boldsymbol{v}}_r;\lambda) = \sum_i L_i(\lambda) f_r(\hat{\boldsymbol{v}}_i, \hat{\boldsymbol{v}}_r, \hat{\boldsymbol{n}};\lambda)\cos^+\theta_i.$$

Isotropic materials



  - Difusa

$$L_d(\hat{\boldsymbol{v}}_r;\lambda) = \sum_i L_i(\lambda) f_d(\lambda)\cos^+\theta_i = \sum_i L_i(\lambda) f_d(\lambda)[\hat{\boldsymbol{v}}_i \cdot \hat{\boldsymbol{n}}]^+$$

  - Especular

$f_s(\theta_s;\lambda) = k_s(\lambda)\cos^{k_e}\theta_s$ (Phong) $f_s(\theta_s;\lambda) = k_s(\lambda)\exp(-c_s^2\theta_s^2).$ (Torrance Sparrow)

  - Phong

$$L_r(\hat{\boldsymbol{v}}_r;\lambda) = k_a(\lambda)L_a(\lambda) + k_d(\lambda)\sum_i L_i(\lambda)[\hat{\boldsymbol{v}}_i \cdot \hat{\boldsymbol{n}}]^+ + k_s(\lambda)\sum_i L_i(\lambda)(\hat{\boldsymbol{v}}_r \cdot \hat{\boldsymbol{s}}_i)^{k_e}$$

  - Dicromatic

$$\begin{aligned} L_r(\hat{\boldsymbol{v}}_r;\lambda) &= L_i(\hat{\boldsymbol{v}}_r, \hat{\boldsymbol{v}}_i, \hat{\boldsymbol{n}};\lambda) + L_b(\hat{\boldsymbol{v}}_r, \hat{\boldsymbol{v}}_i, \hat{\boldsymbol{n}};\lambda) \\ &= c_i(\lambda)m_i(\hat{\boldsymbol{v}}_r, \hat{\boldsymbol{v}}_i, \hat{\boldsymbol{n}}) + c_b(\lambda)m_b(\hat{\boldsymbol{v}}_r, \hat{\boldsymbol{v}}_i, \hat{\boldsymbol{n}}), \end{aligned}$$

r: reflectance
d: diffuse
s: specular
i: interface
b: surface body

Color

- Phong's illumination model

NL RV

$$L_r(\hat{\boldsymbol{v}}_r;\lambda) = k_a(\lambda)L_a(\lambda) + k_d(\lambda)\sum_i L_i(\lambda)[\hat{\boldsymbol{v}}_i \cdot \hat{\boldsymbol{n}}]^+ + k_s(\lambda)\sum_i L_i(\lambda)(\hat{\boldsymbol{v}}_r \cdot \hat{\boldsymbol{s}}_i)^{k_e}$$

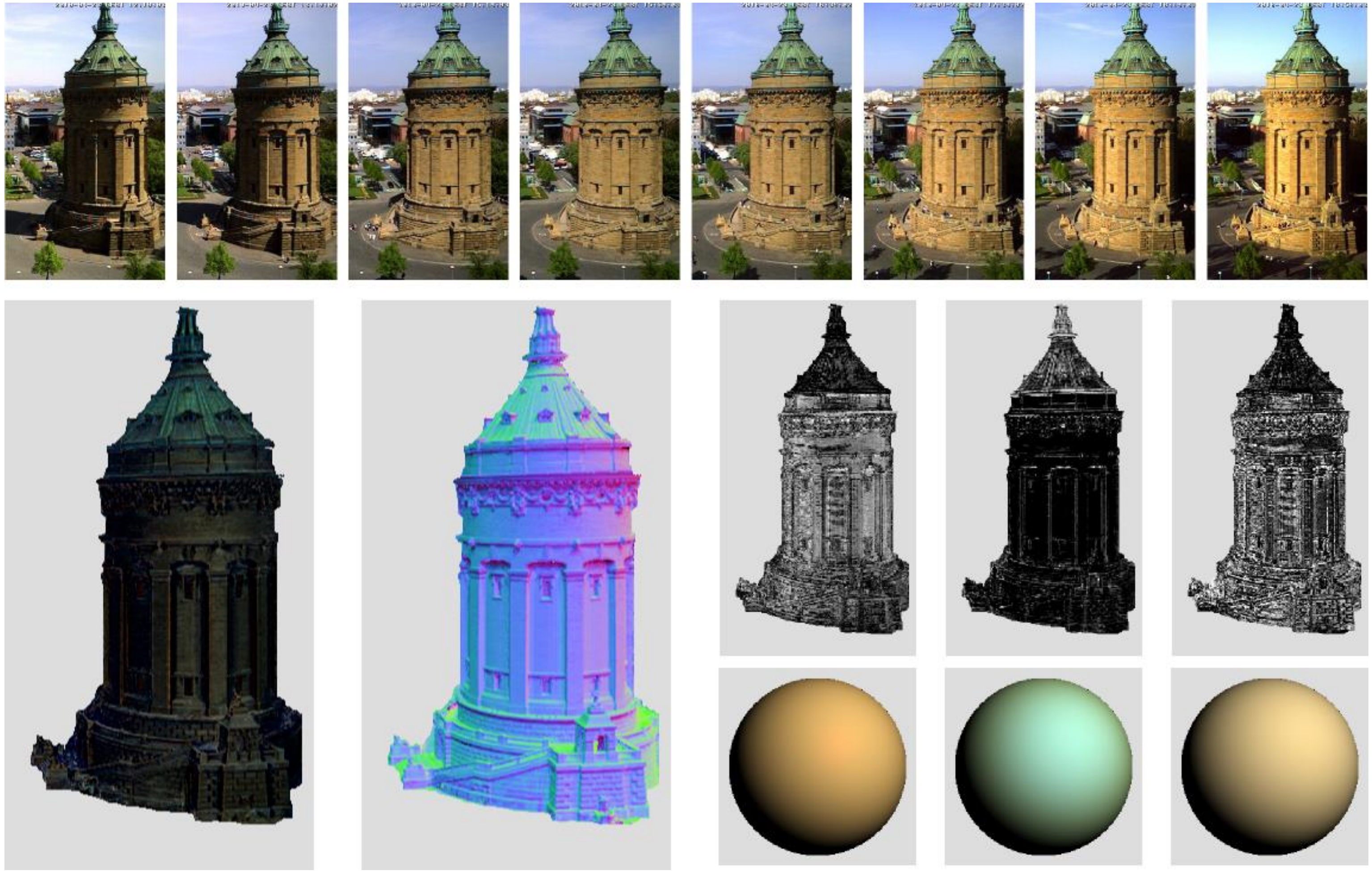
r: reflectance
d: diffuse
s: specular
i: interface
b: surface body

Three components of light:

- Ambient
  - K_a: ambient coefficient, L_a ambient intensity
- Diffuse
  - K_d: diffuse coefficient, L_i light that illuminates the scene
- Specular
  - Ks: specular coefficient, L_i light that illuminates the scene, K_e: shininess

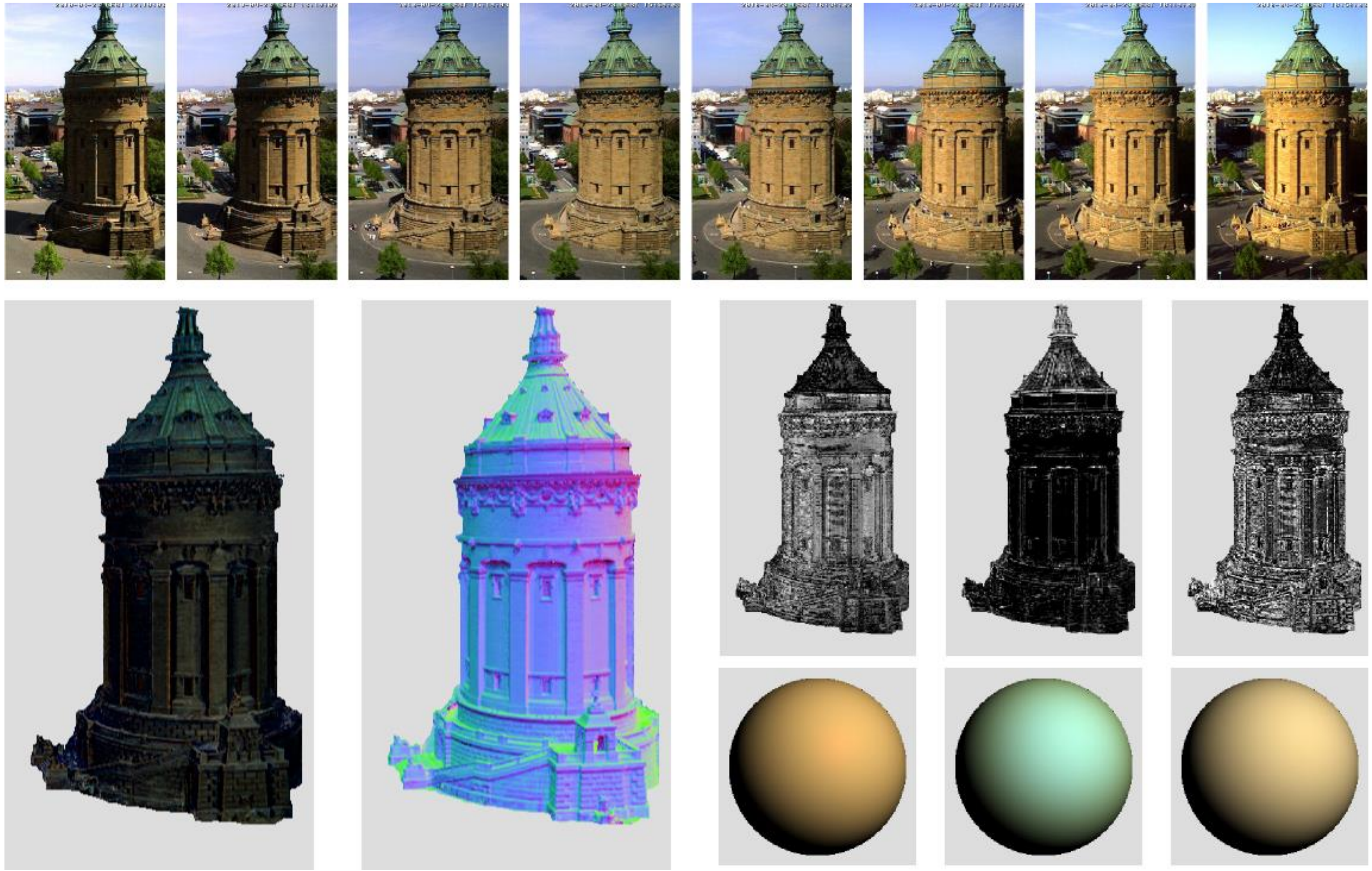
Lambert's law or rule of the cosine: formulae that defines diffuse term

Color



We assume:
- Scene is illuminated by a same light source (sun)
- The sun will move and the object (the tower) is static
- For each pixel we can use diffuse light model
    - We just need to calculate the N component

Color



We can obtain:
- N map → we could even get 3D from this
- Base colors K_d, albedo

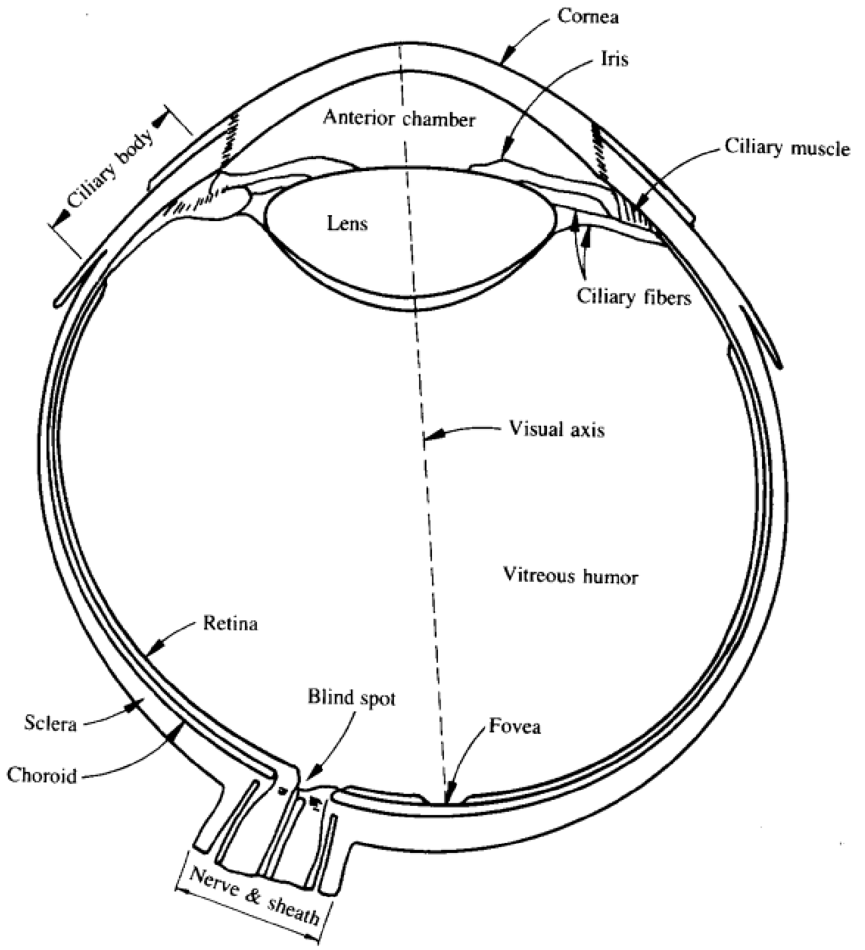
PHOTOMETRIC STEREO

Color

- Cornea, lens and vitreous humor are the ones that project the light into the retina → **lens, optics**

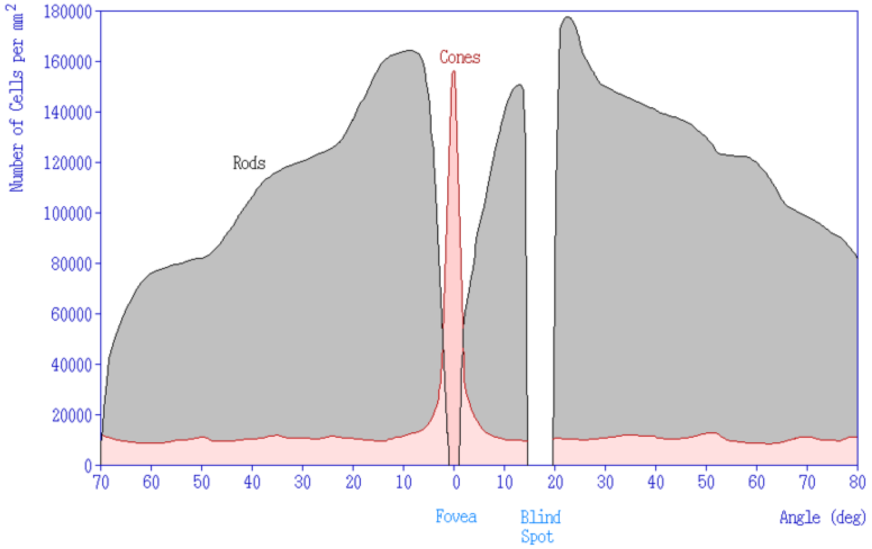
- Iris is a diaphragm that regulates the amount of light that enters the eye → **diaphragm**

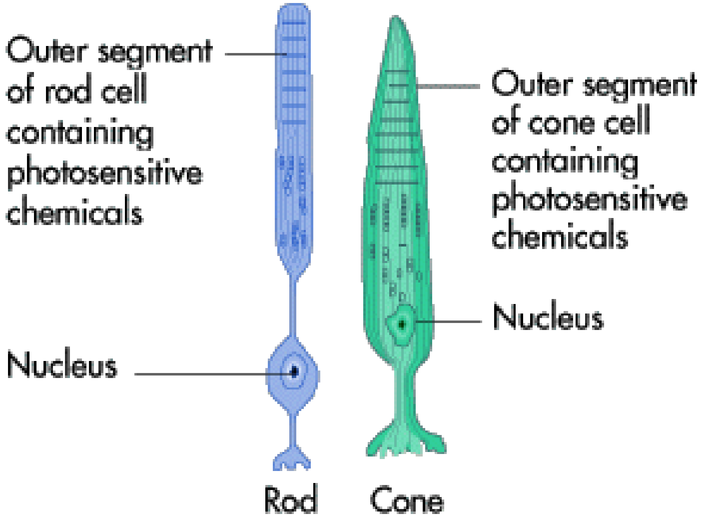
- Retina is a layer of nerve cells that transform luminus energy into electric pulses → **sensor**



Color

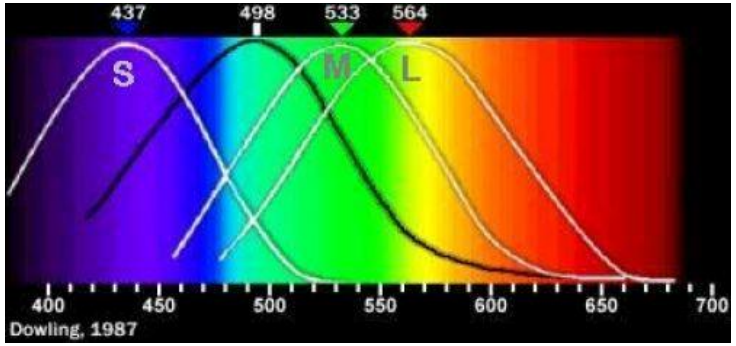
- Receptors:
  - Rods: sensitive to low intensity, not to color. Located at the farthest part of the fóvea
  - Cones: sensitive to higher intensities, to color.

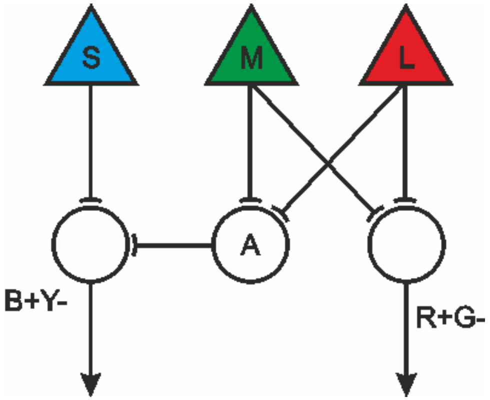


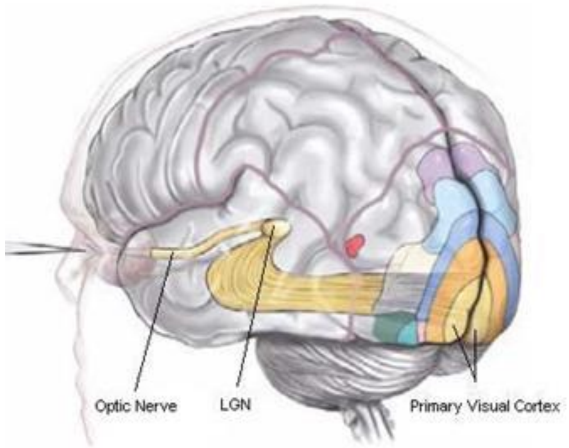


Name	Maximum sensitivity
S (*short*)	445 nm (purple)
M (*medium*)	535 nm (green)
L (*long*)	570 nm (yellow)

Color







All the information acquired from the cones is combined and codified in an opponent color space, with two channels:

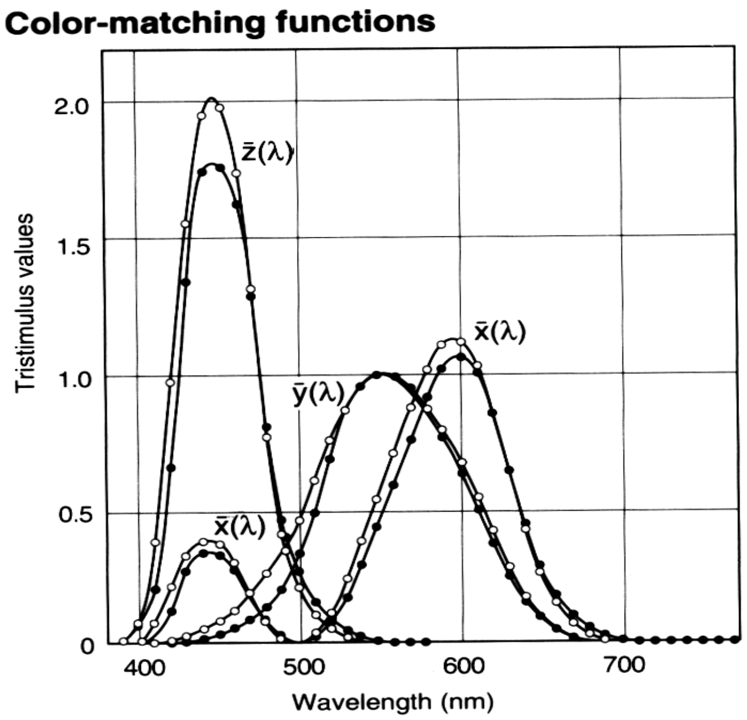
- Blue-yellow
- Red-Green

We can see colors in between, but never the combination of the opposite (a yellowish blue)

Color

How to measure color?

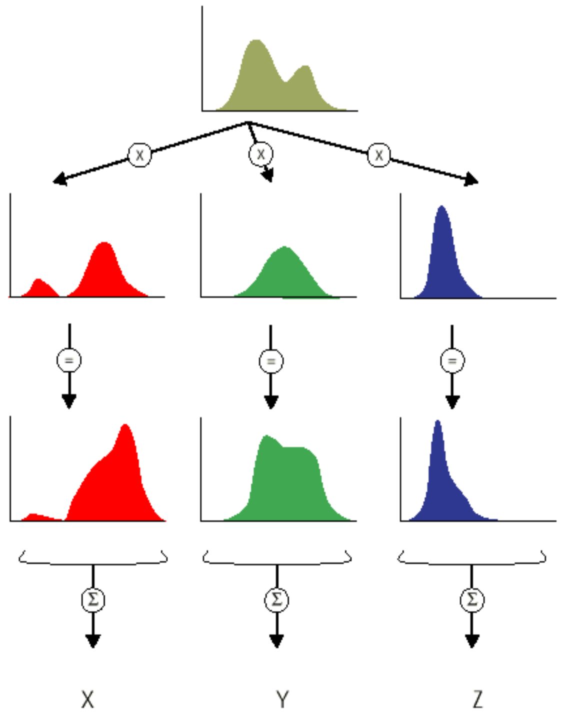
- In 1931 a standard observer was defined after doing color perception experiments with several people
- Three primary colors were defined: X, Y and Z → they do not exist in real life
- Curves $x(\lambda)$, $y(\lambda)$, $z(\lambda)$ are corresponding functions, always positive



Color

How to calculate the correct values

- From spectral distribution of a given stimuli we can obtain X, Y and Z
  - We multiply the stimuli by the separate corresponding funcions
  - We integrate the area under the curve

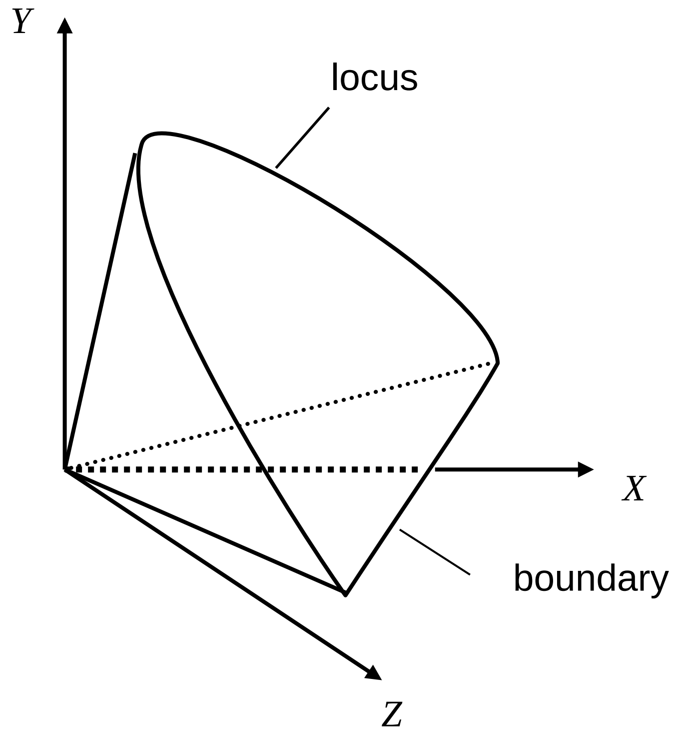


$$X = \int L(\lambda)\bar{x}(\lambda)d\lambda\,;\ \ Y = \int L(\lambda)\bar{y}(\lambda)d\lambda\,;\ Z = \int L(\lambda)\bar{z}(\lambda)d\lambda$$

Color

Color space XYZ

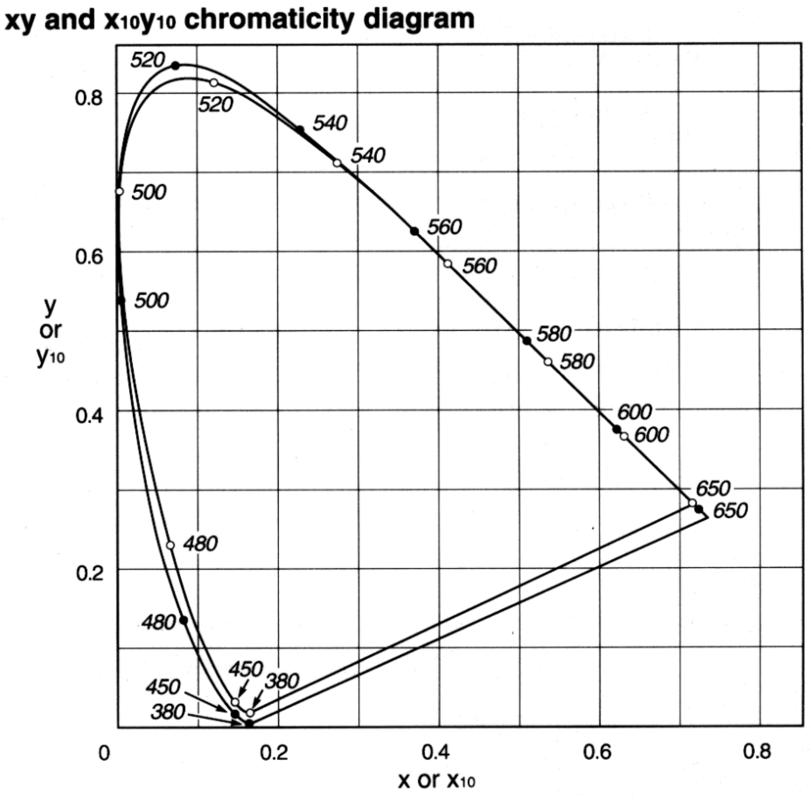
- XYZ values of each of the possible colors define a solid cone of color
- The axis represent imaginary colors, not under the cone where real colors are
- Origin is black
- The boundary of the cone represent pure spectral colors



Color

Diagram XY

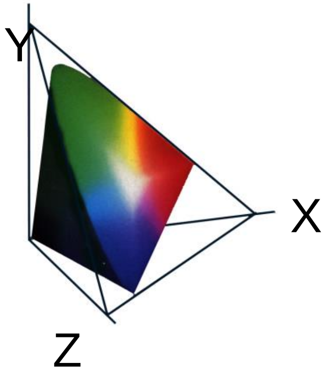
- Separate illumination component from color
  - $x=X/(X+Y+Z)$
  - $y=Y/(X+Y+Z)$
  - $z=Z/(X+Y+Z)$
- As $x+y+z=1$, we can remove redundancy by supressing one of them



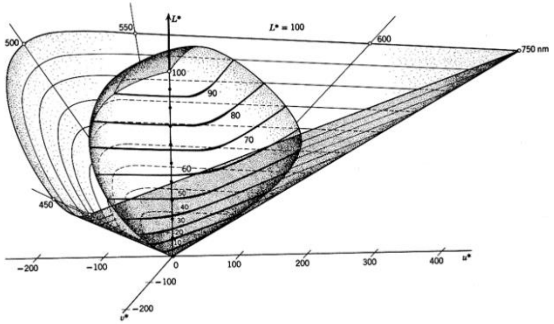
Color

Color spaces

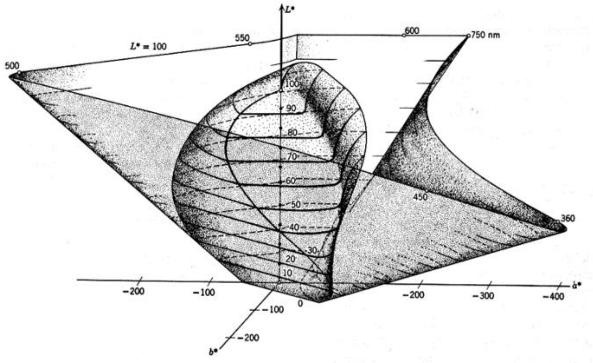
- Device independent
  - CIEXYZ (1931,1964): basic, good to measure
  - CIELUV: uniform, used by emitters
  - CIELAB: uniform, used for painting and reflected colors



CIEXYZ



CIELUV

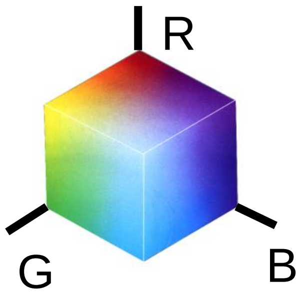


CIELAB

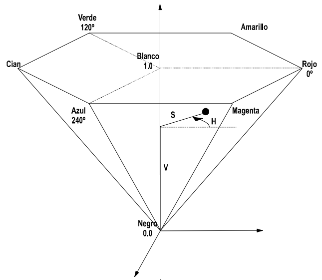
Color

Color spaces

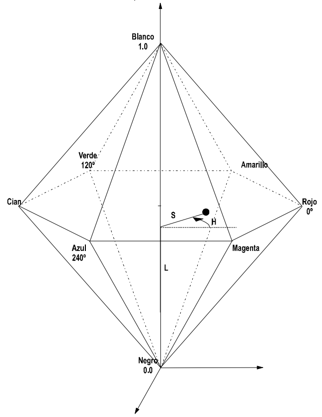
- Device dependent
  - RGB: monitors, cameras, images
  - CMY / CMYK: printers
  - Y’U’V’ and Y’I’Q’: TV and video
  - HSV: emit perceptual spaces. Useful to define colors and for color image processing
  - HLS: similar to HSV



RGB



HSV

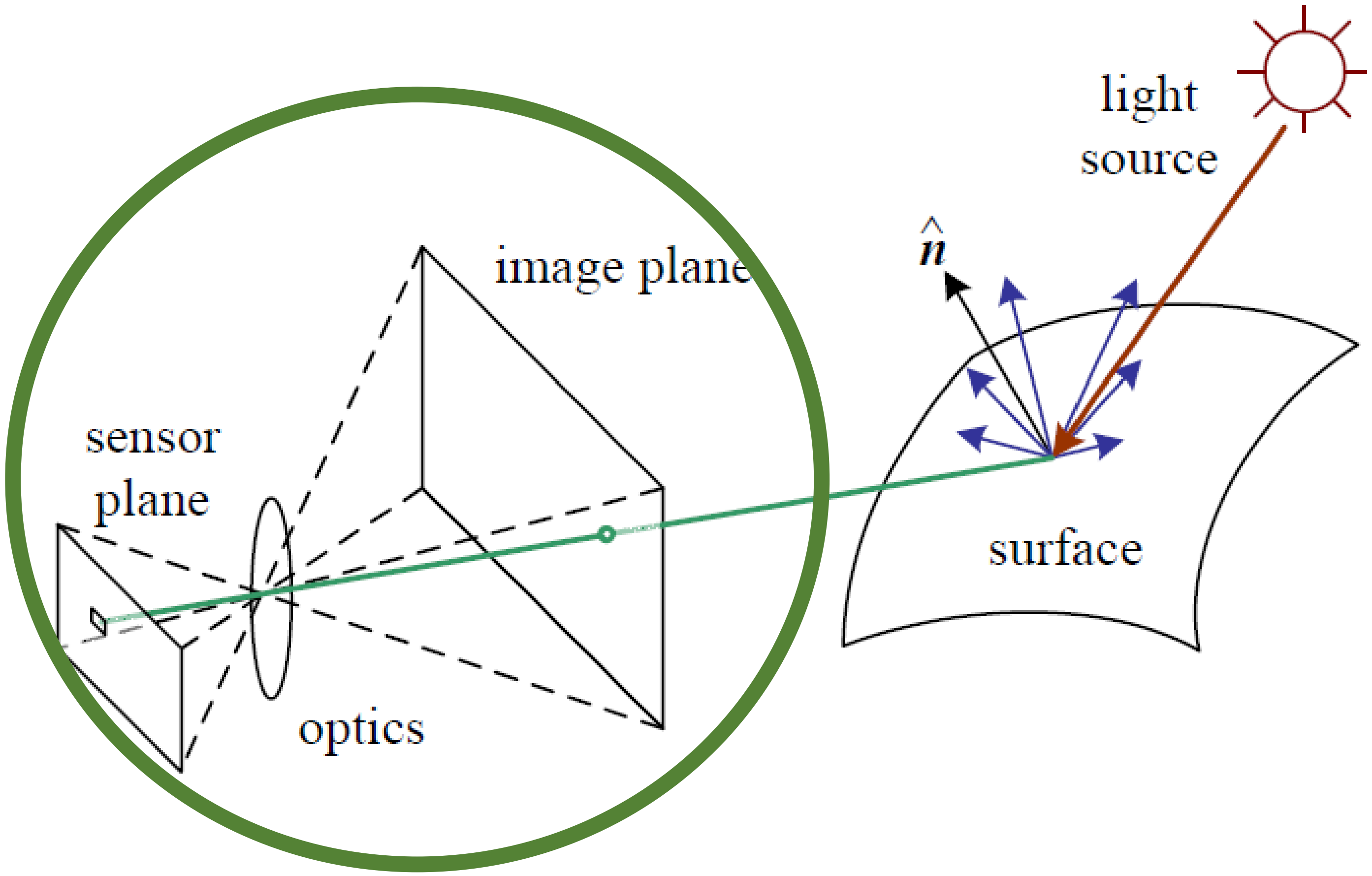


HLS

3

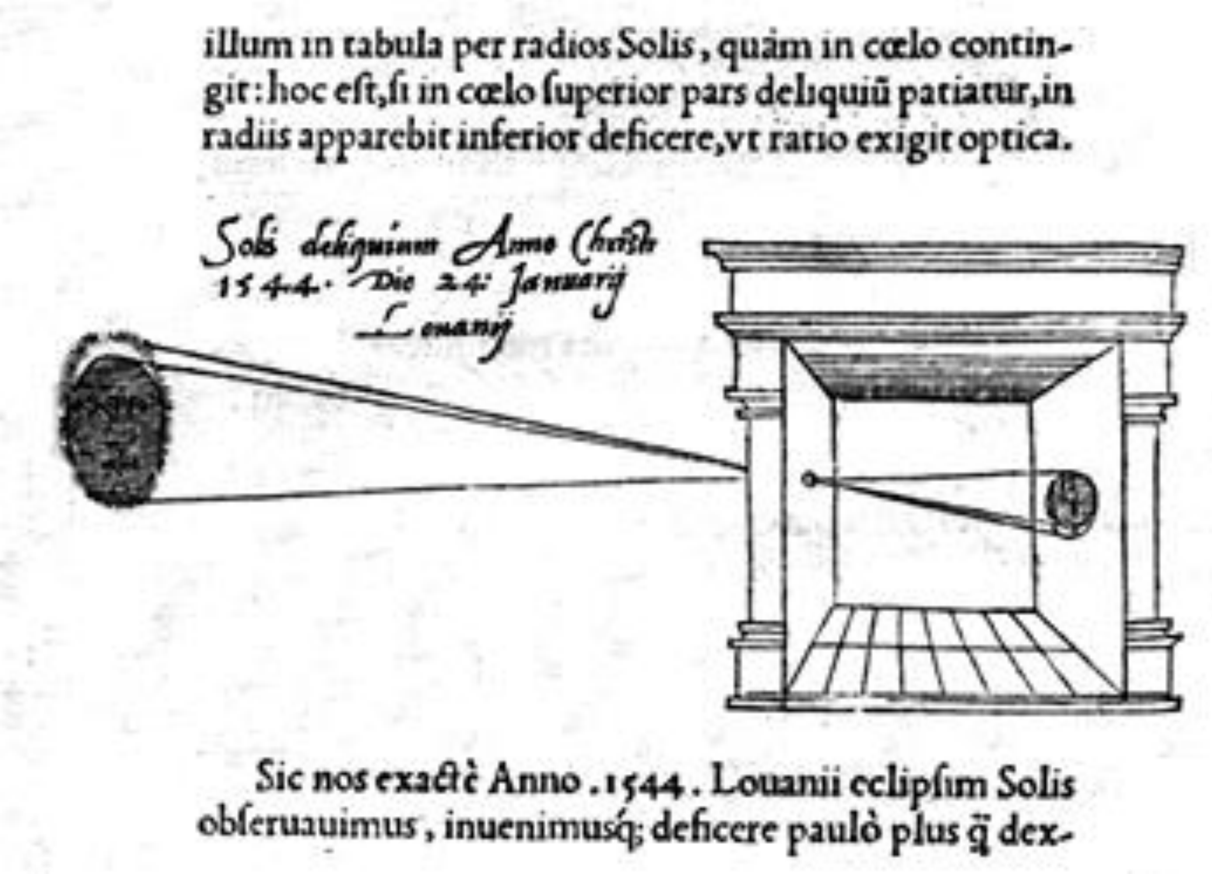
Cameras

Camera



Camera

Simple model:
- Pinhole
- Central projection



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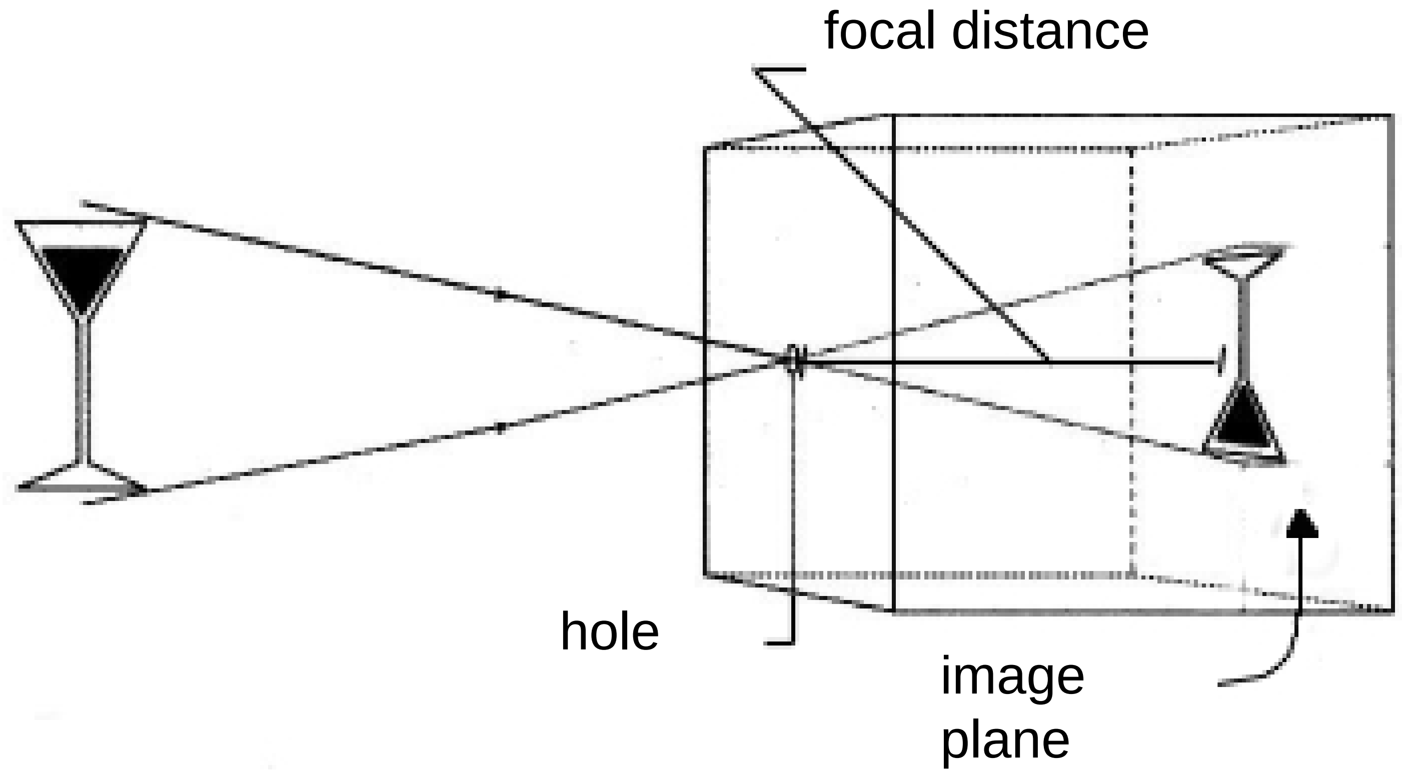
Camera

Simple model:

- Pinhole
- Central projection



Camera

Simple model:

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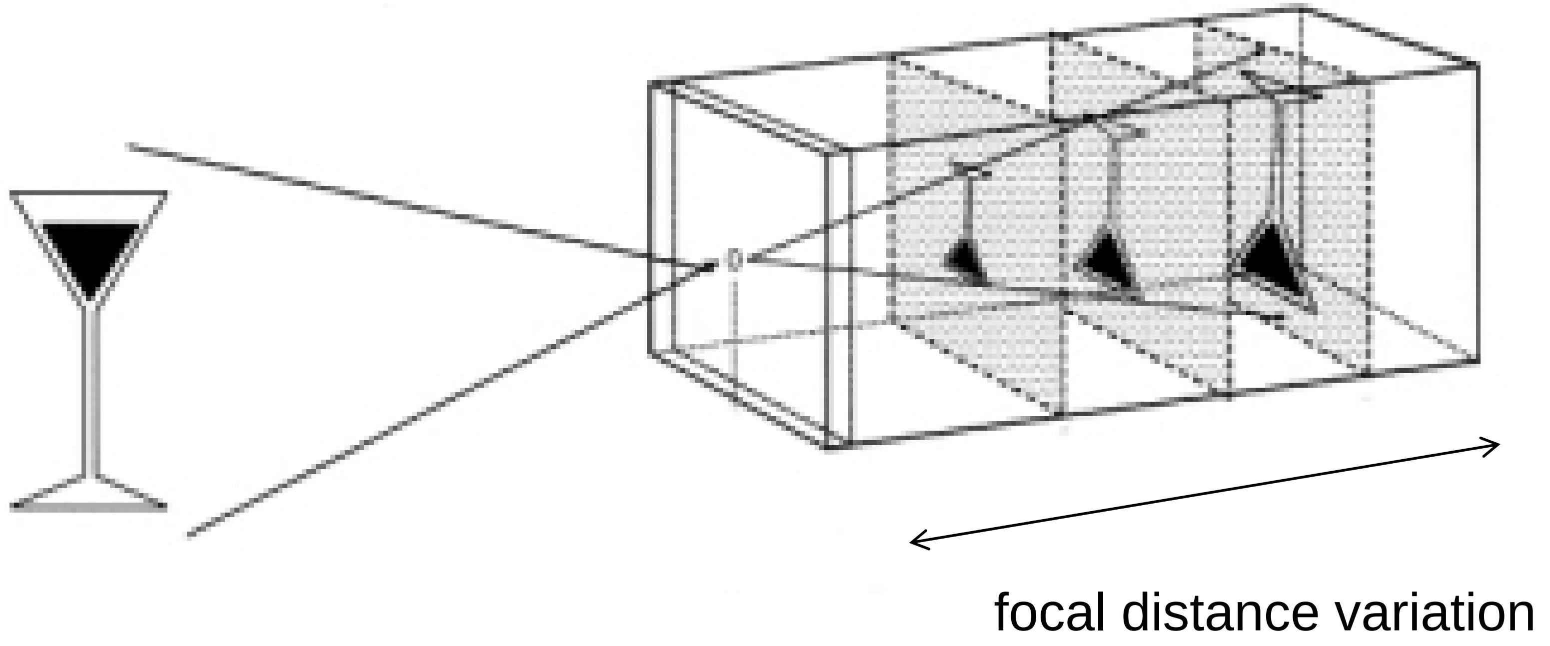
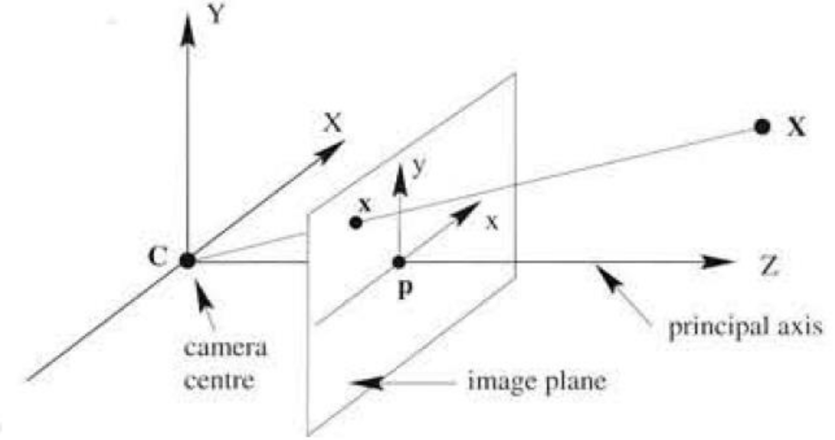
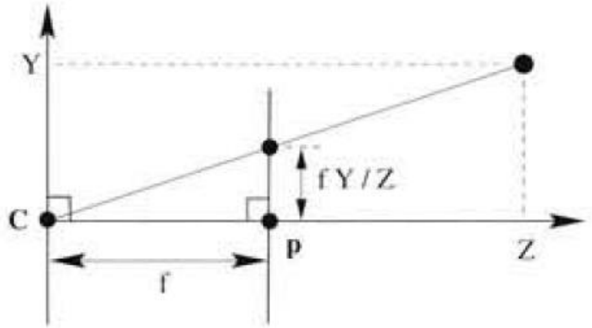


Camera

Simple model:

- **Pinhole**
- Central projection





$$(X,Y,Z)^T \rightarrow (fX/Z, fY/Z, f)^T$$

Homogeneous coordinates

$$\begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix} \rightarrow \begin{pmatrix} fX \\ fY \\ Z \end{pmatrix} = \begin{bmatrix} f & & & 0 \\ & f & & 0 \\ & & 1 & 0 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

$$\mathbf{x} = P\,\mathbf{X}$$

Camera

Simple model:
- **Pinhole**
- Central projection

Optical center (principal point)

$$\begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix} \rightarrow \begin{pmatrix} f X + Z p_x \\ f Y + Z p_y \\ Z \end{pmatrix} = \begin{bmatrix} f & & & p_x \\ & f & & p_y \\ & & 1 & 0 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

$$K = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}$$

Intrinsec parameters

$$\mathbf{x} = K[I \mid \mathbf{0}]\, \mathbf{X}_{\mathrm{cam}}$$

Camera rotation and traslation

$[R \mid \mathbf{t}]$

Extrinsec parameters

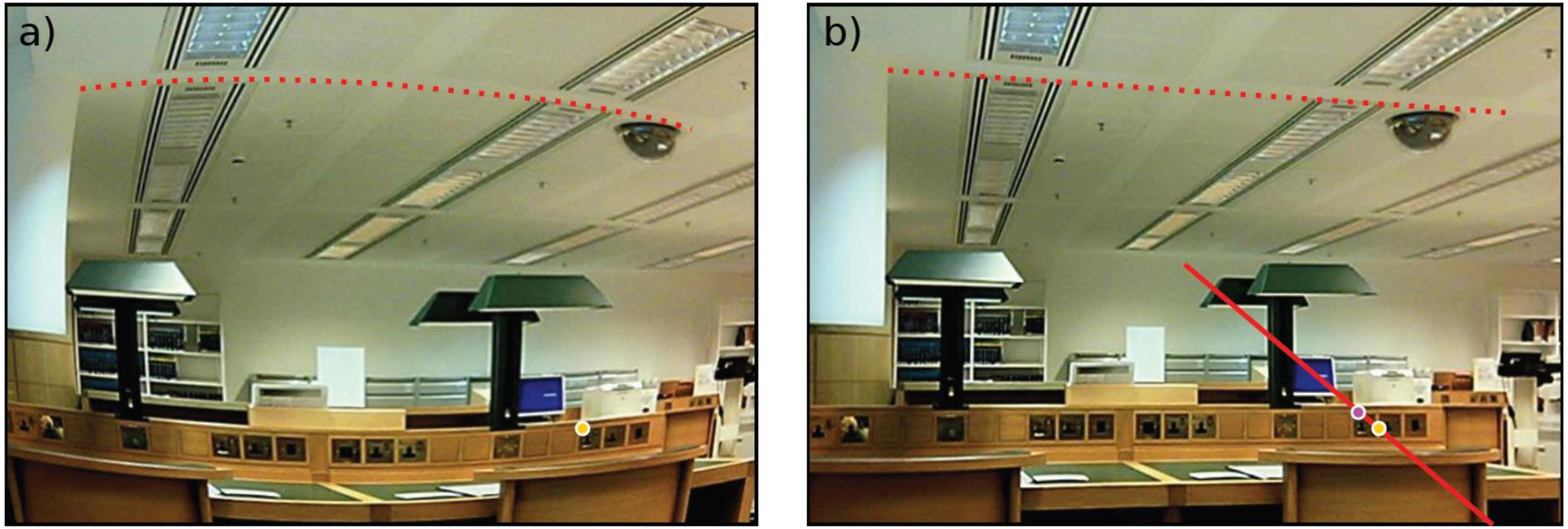
$P = K[R \mid \mathbf{t}]$

Projection matrix

$$\mathbf{x} = K[R \mid \mathbf{t}]\, \mathbf{X}$$

Camera

Radial distortion

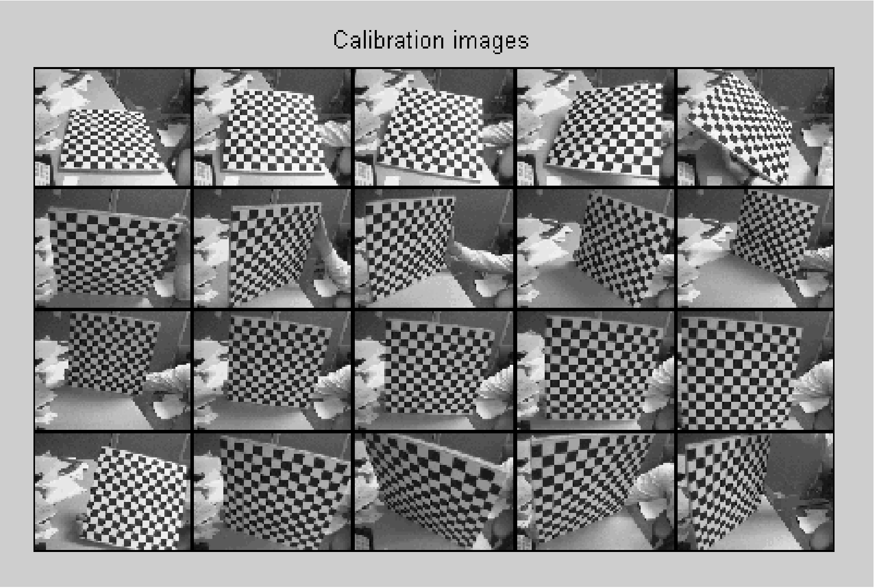


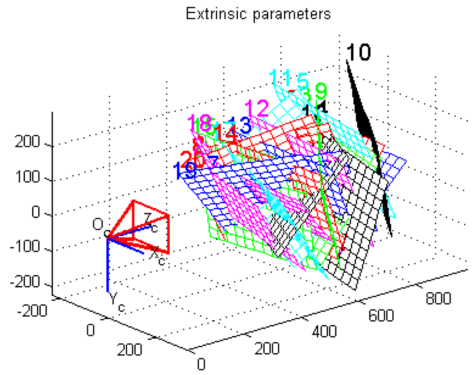
$$x' = x(1 + \beta_1 r^2 + \beta_2 r^4)$$
$$y' = y(1 + \beta_1 r^2 + \beta_2 r^4)$$

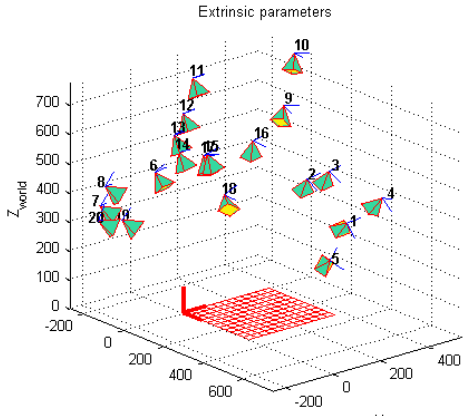
Camera

Camera calibration

- Intrinsec :
  - focal (in pixels),
  - Principal point (center)
  - distortions
- Extrinsec
  - Rotation
  - Traslation

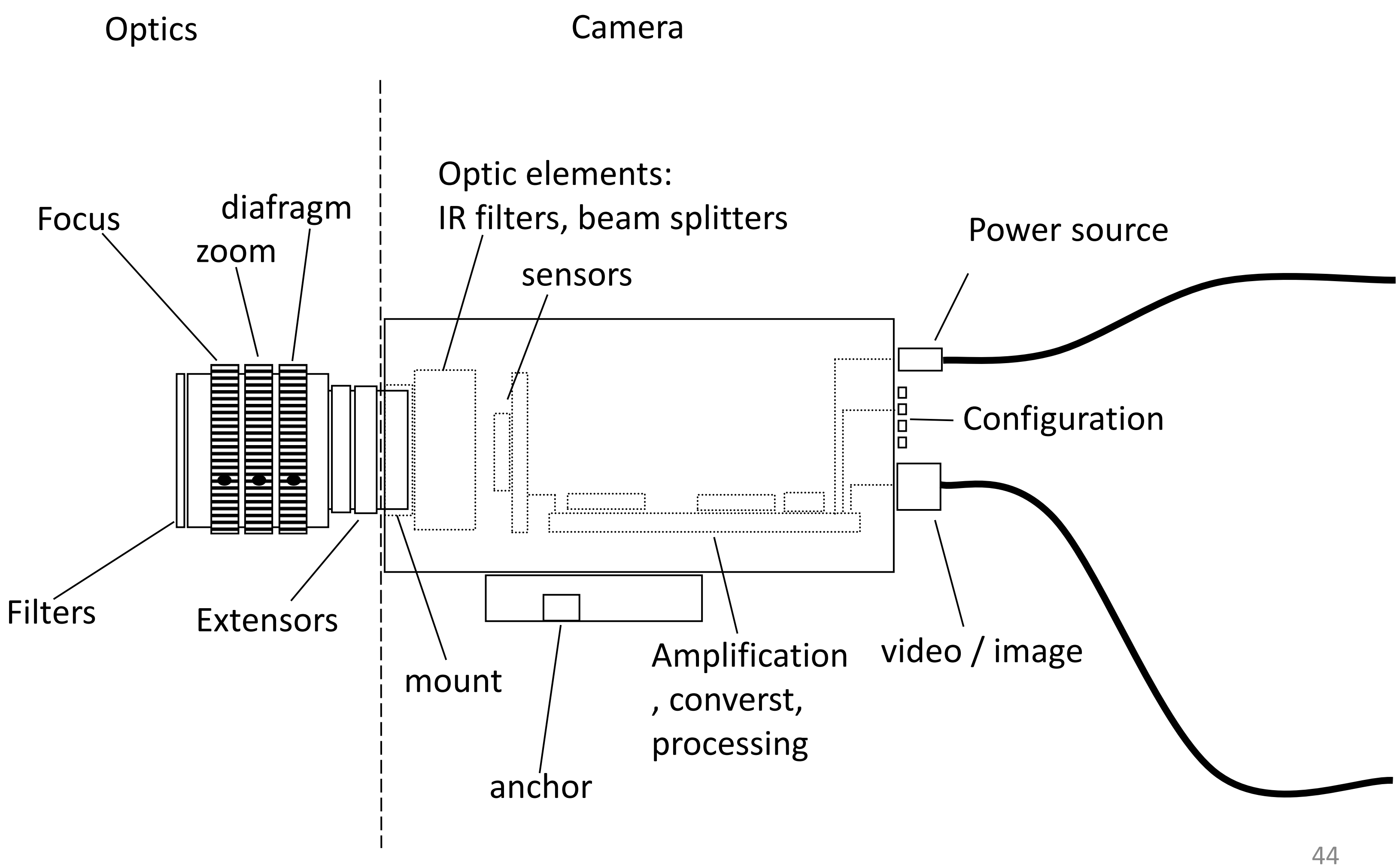






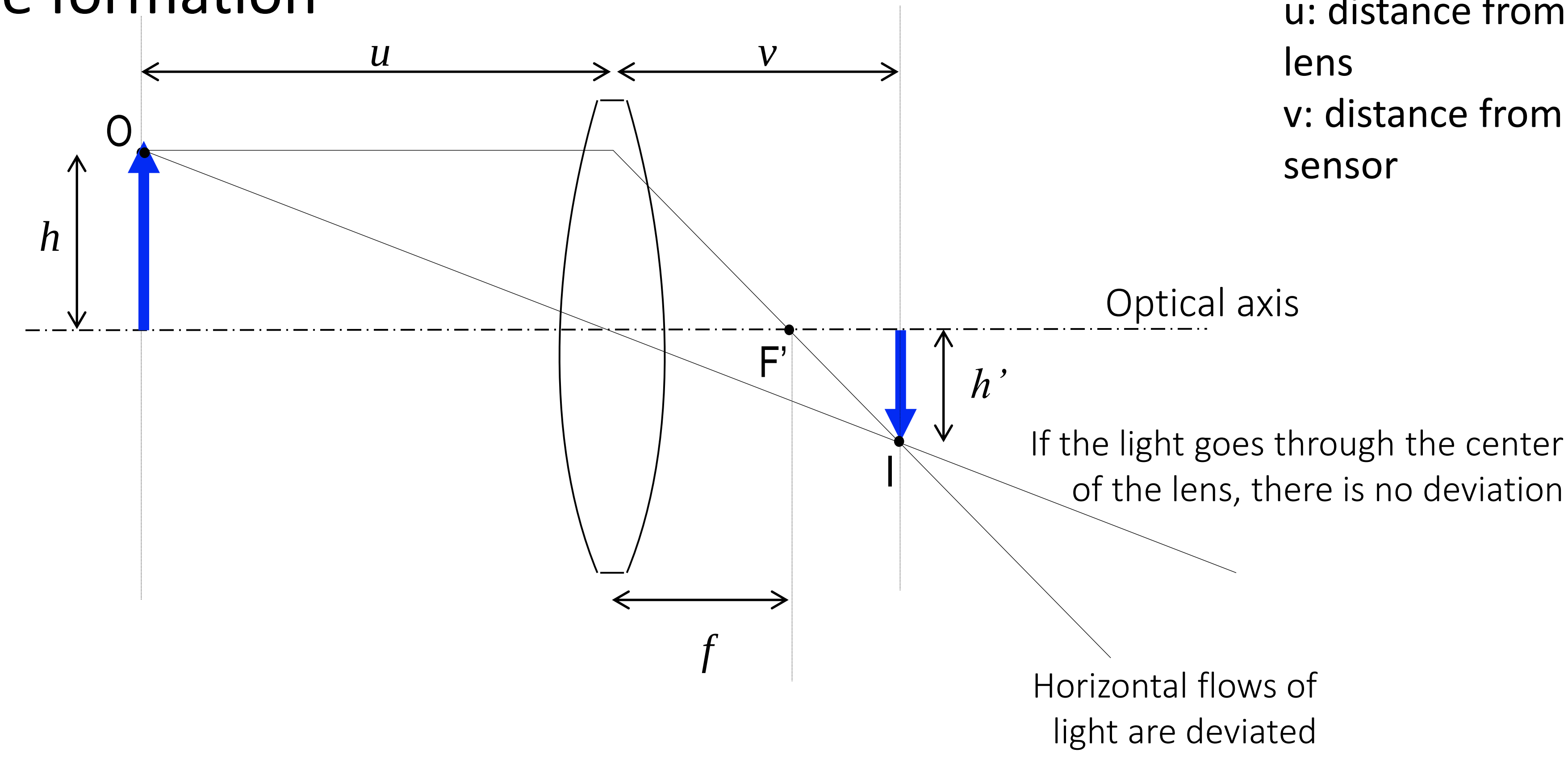
Camera

- Image acquisition



Camera

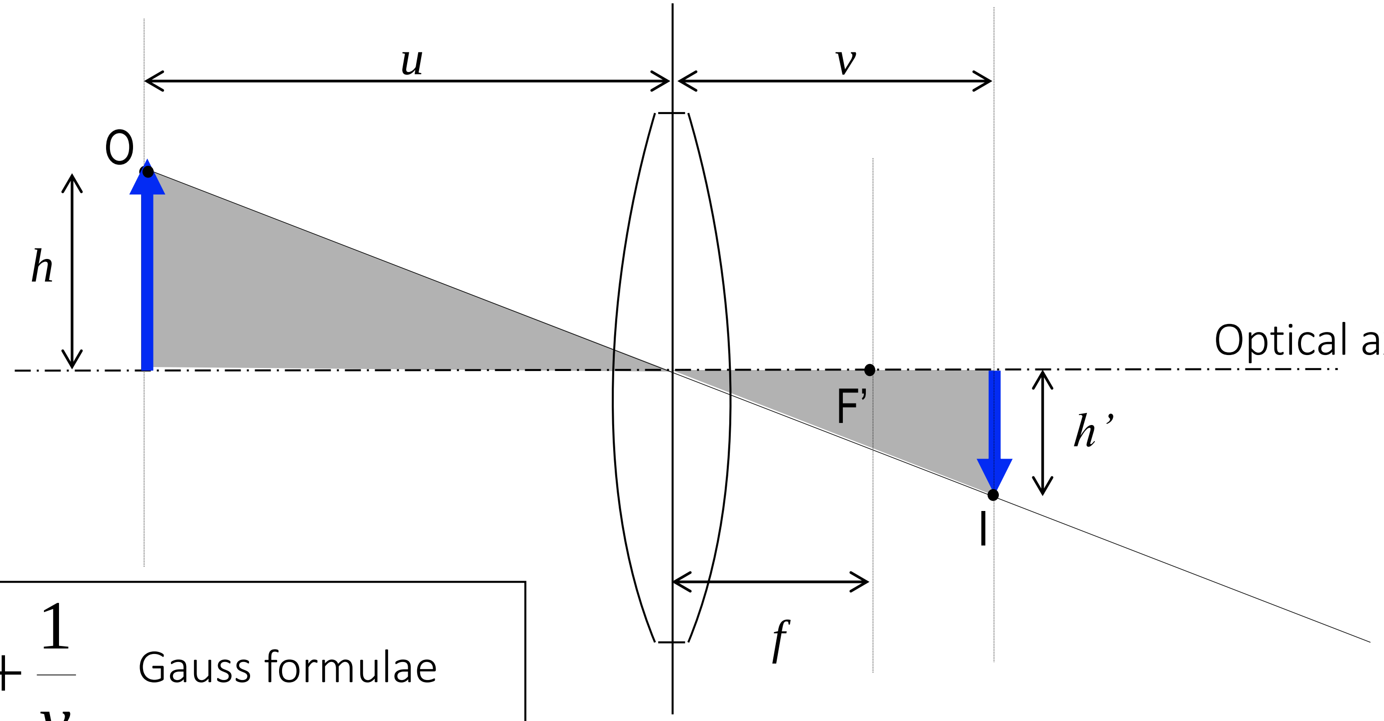
- Image formation



u: distance from the object to the lens
v: distance from the lens to the sensor

Camera

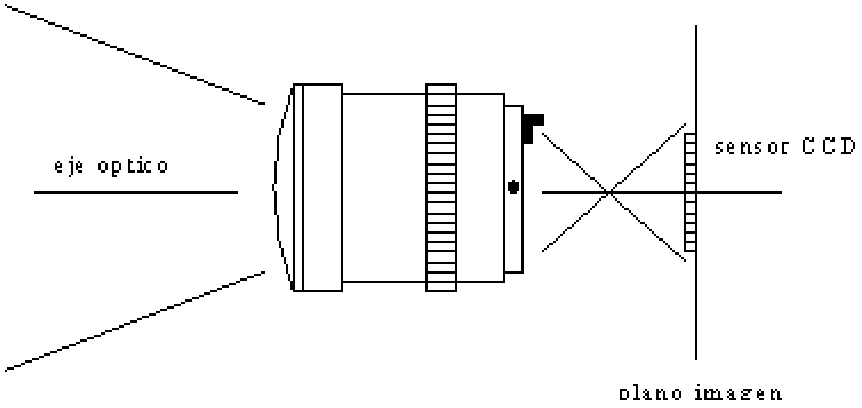
- Objectives: group of elements that generate the image in the sensor



$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$ Gauss formulae

Camera

- Image formation

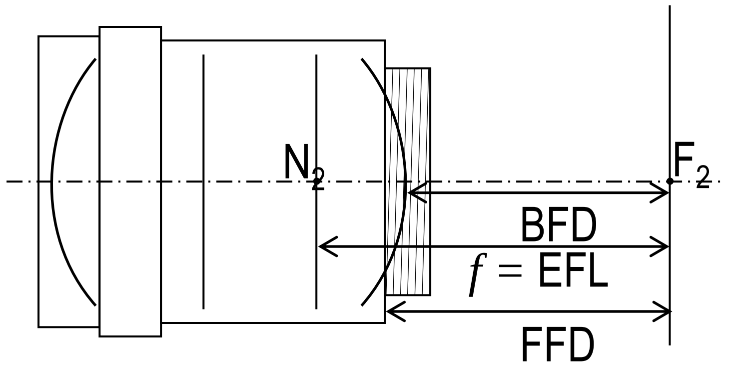


  - Features:
    - Focal distance: f
    - Aperture: f-number, N.A., $\varnothing$
    - Depth of field
    - Field of view
  - Types
    - Fix or variable focal
    - Wide angle, fisheye
    - Zoom
  - Mounts
    - Video-specific: C, CS
    - Microlenses
  - Other elements
    - Extensors
    - Filters
    - Screws

Camera

- Focal distance
  - Objectives are composed by optical groups in which previous conditions do not apply (we can still simplify calculations)
  - We refer to Effective Focal Length (EFL)
    - BFD: back focal distance
    - FFD: flange focal distance (contact between objective and camera)

For a fixed sensor size, focal distance is related to the angle covered by the image
The less the focal distance, the higher the angular field



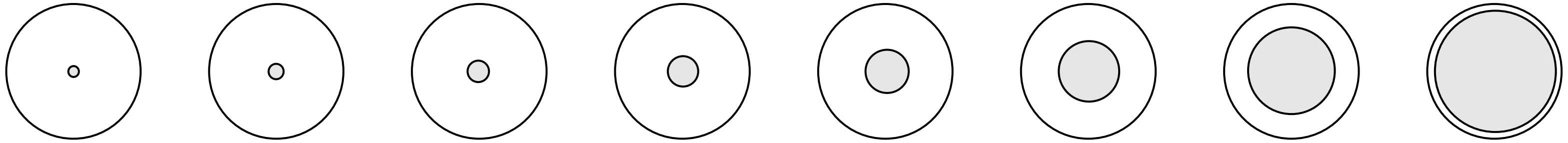
Camera

- Aperture
  - Relative aperture:
    - Related to the brightness the acquired image will have
      - Objective diameter → light that comes in
      - Focal distance → image size

$$N = \frac{f}{D}$$

f = focal
D = ∅ of the lens

    - The light that arrives to the sensor is proportional to D^2



N: 16 11 8 5.6 4 2.8 2 1.4

Camera

- Aperture
  - Relative aperture:
    - Related to the brightness the acquired image will have
      - Objective diameter → light that comes in
      - Focal distance → image size

$$N = \frac{f}{D}$$

f = focal
D = ∅ of the lens

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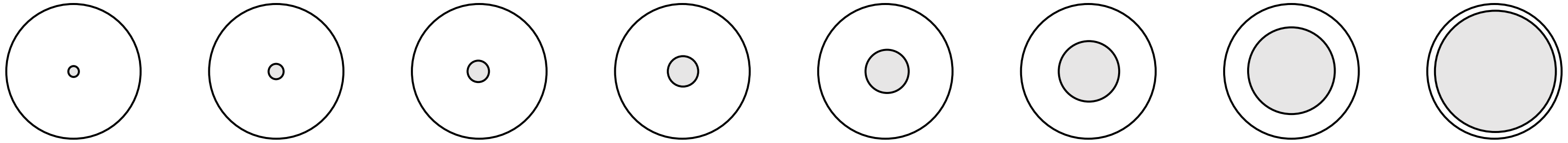


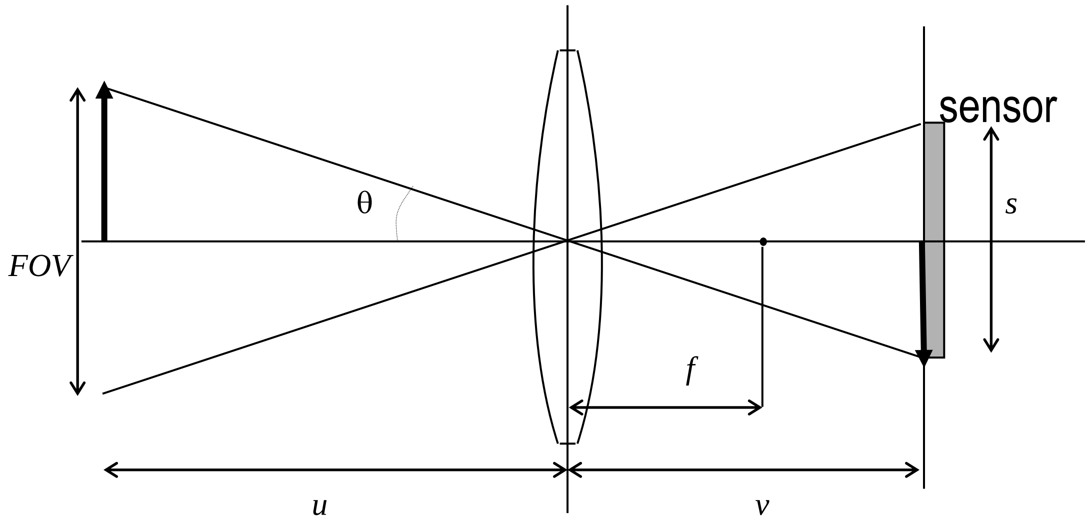
N: 16 11 8 5.6 4 2.8 2 1.4

Camera

- Focus
  - Objectives adjust distance from the lens to the sensor with the focus so the image is shown clean at the sensor
  - As the lens is closer to the sensor, it is positioned in the focal plane of the system (distant object can be properly seen)

Camera

- Field of view:
  - Area of the scene, at working distance *u,* that creates the image in the sensor
  - Depends on three factors:
    - Focal distance *f*
    - Working distance *u*
    - Sensor size

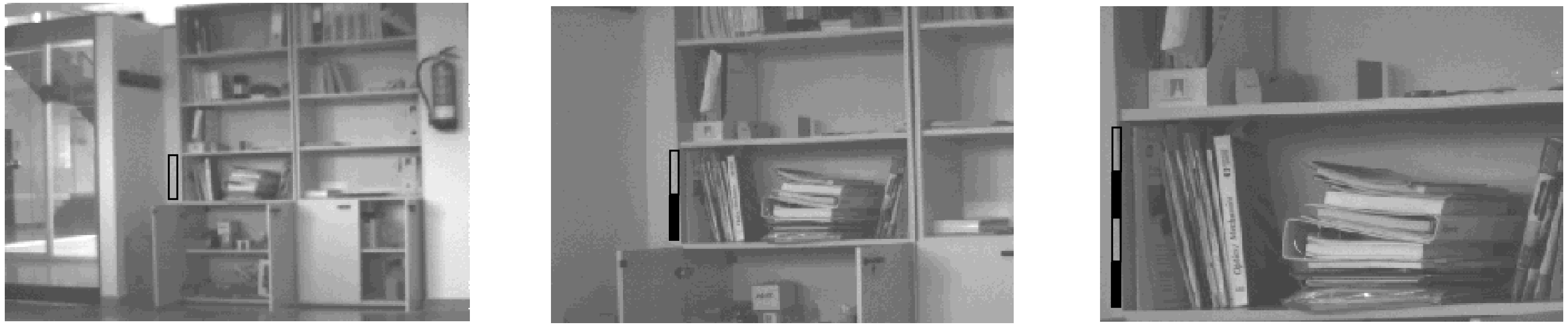


$$\theta = 2\arctan\frac{s/2}{v}$$

$$FOV = s\frac{u}{v}$$

Camera

- Magnification and field of view:
  - The field of view varies significantly if we vary *f* with a fixed *u*



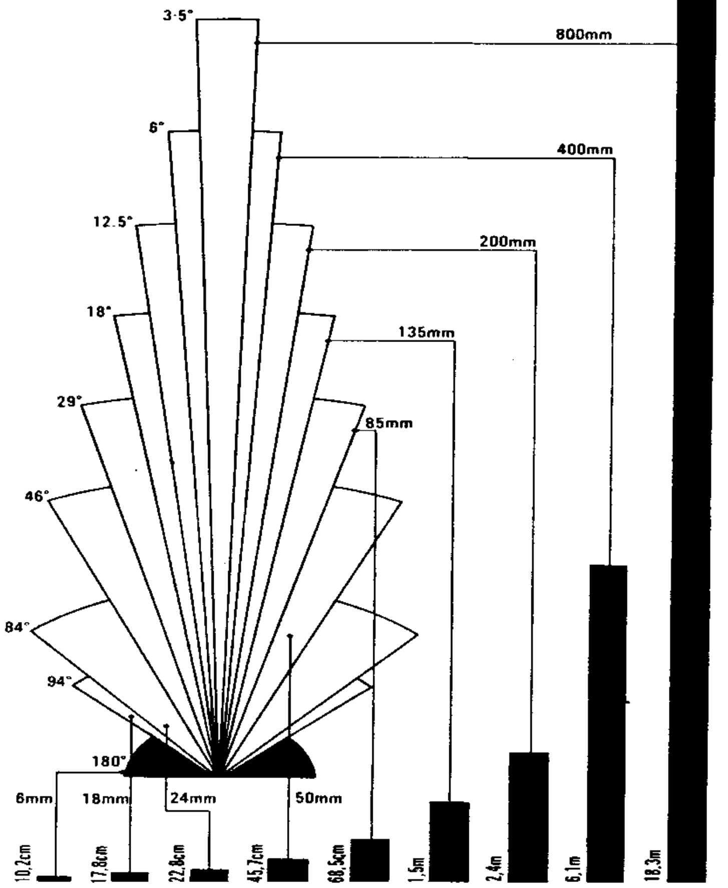
f = 12 mm f = 25 mm f = 50 mm

Camera

- Field of view:
  - The greater focal distance, the less field of view

100°	super-wide angle
65°	wide angle
35°	standard wide angle
20°	standard
12°	light telephoto
6°	telephoto

Cuanto mayor es la distancia focal de un objetivo, menor es su ángulo de visión. Al aumentar la distancia focal, se incrementa la distancia mínima de enfoque; para un objetivo de 50 mm esta última puede ser de 45 cm, pero el objeto más cercano que puede enfocar un teleobjetivo de 250 mm ha de estar a 6 m.



Camera

- Depth of field:
  - Main axioma: human eye (and any other sensor) is not able to distinguish finer details smaller than the element used to acquire them
  - Depending on the sensor, we will have a different circle of confusion (usually 10μm - 30μm)

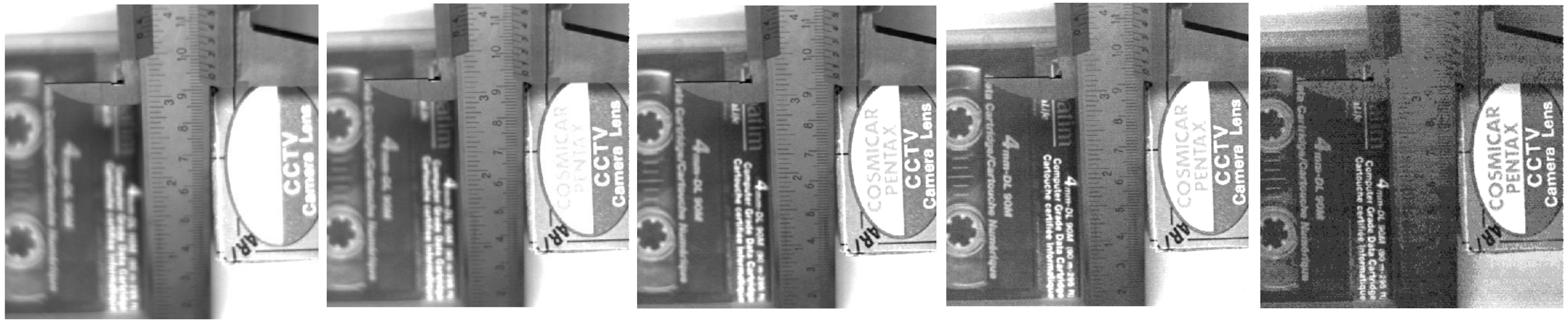
Camera

- Depth of field:
  - Range of positions in which the object is correctly focused (size of an image point is equal or smaller to confusion circle)
  - Important factors:
    - Aperture: the less aperture, the higher Depth of field
    - Distance to the object: the higher the distance, the higher Depth of field
    - Focal distance: the less focal distance, the higher Depth of field

Camera

- Depth of field:
  - Example of Depth of field variation according to aperture

$$f = 25mm$$



$f/\#1.4$ $f/\#2$ $f/\#2.8$ $f/\#4$ $f/\#8$

Camera

- Extensors:
  - Placed between the objective and the camera to increase the distance between the lense and the sensor
  - Useful when we want to see something that is very close to the camera
  - Consequences of their use:
    - Decrease in DoF
    - Decrease in minimum working distance
    - Decrease in FoV

Camera

- Type of objectives:
  - Fix
  - Teleobjectives
  - Wide angle
  - Zoom
  - Macro
  - Telecentric

Camera

- Mount:
  - Distance from the posterior part of the optic and the sensor
  - Two standards:
    - Type C (industry, science) distance = 17.5 mm
    - Type CS (surveillance) distance = 12.5 mm

Camera

- Sensor:
  - Convert radiant energy into an electric signal
  - Light is composed by photons → sensor “just” count photons

Light (photons) → Sensor → Electric charge (electrons)

  - Quantum Efficiency (QE): number of electrons generated per incoming photon
  - Well Capacity (WC): number of electrons that the sensor cell can accumulate

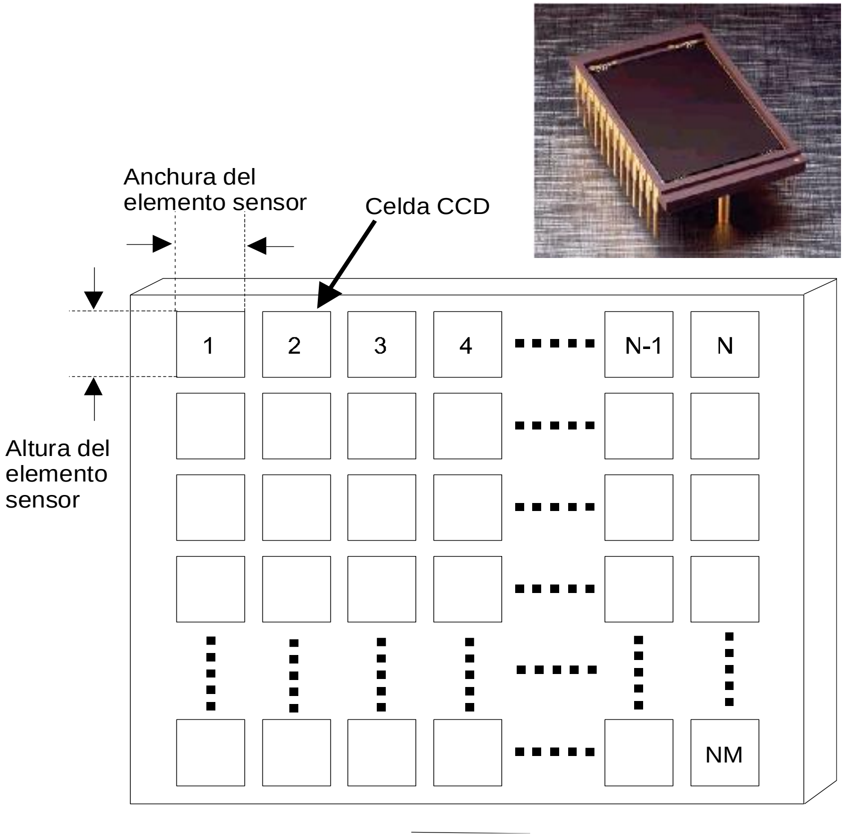
Camera

- Sensor features:
  - Chip architecture
  - Integration time
  - Integration type
  - Transfer
  - Spectral sensitivity
  - Signal to noise ratio, dark current
  - Response, Saturation
  - Color
  - Technology

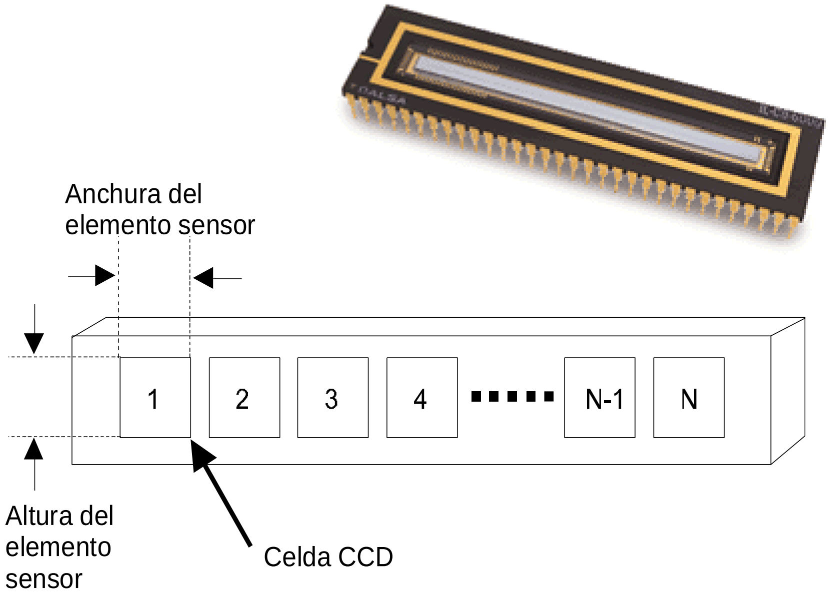
Camera

- Architecture:

Matrix cameras



Linear cameras

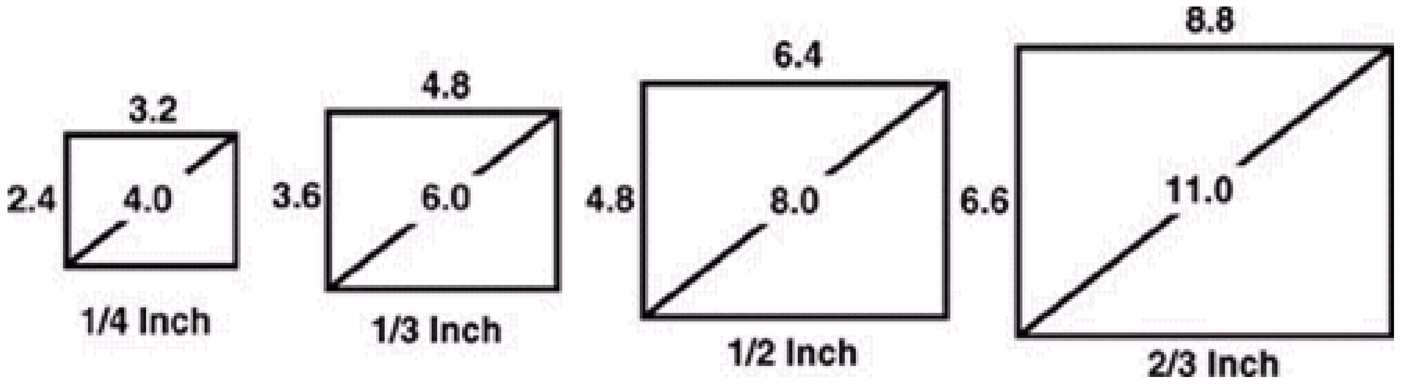


Camera

- Matrix cameras:
  - Effective number of cells: HxV
  - Size of the cells: (THxTV)
  - Shape of the cells (TH/TV). Ideal = 1 (square)
  - Matrix format (1’’, 2/3”,1/2”,1/3”,1/4”)

SPECIFICATIONS

	XC-75CE
Optical size	1/2-inch format
Effective picture elements	752(H) x 582(V)
Total number of pixels	795(H) x 596(V)
Chip size	7.95mm(H) x 6.45mm(V)
Unit cell size	8.6µm(H) x 8.3µm(V)



Camera

- Effective number of cells:

SPECIFICATIONS

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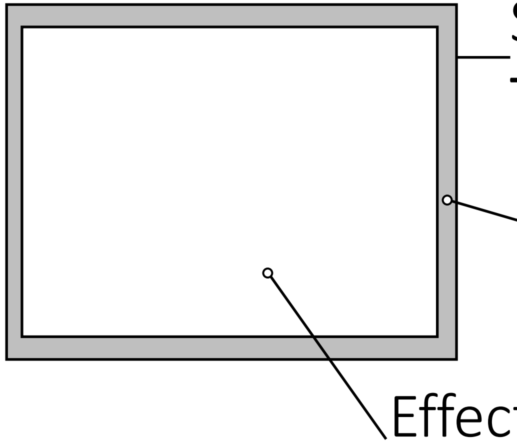
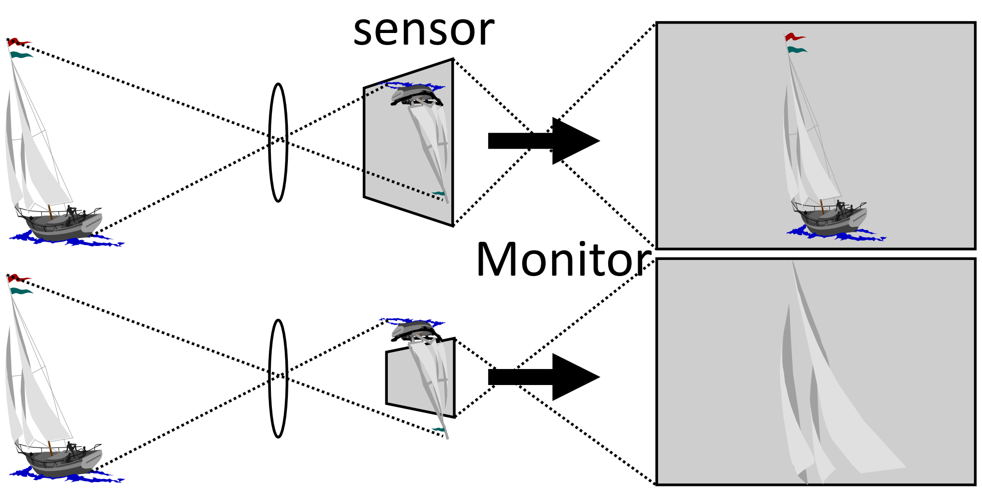


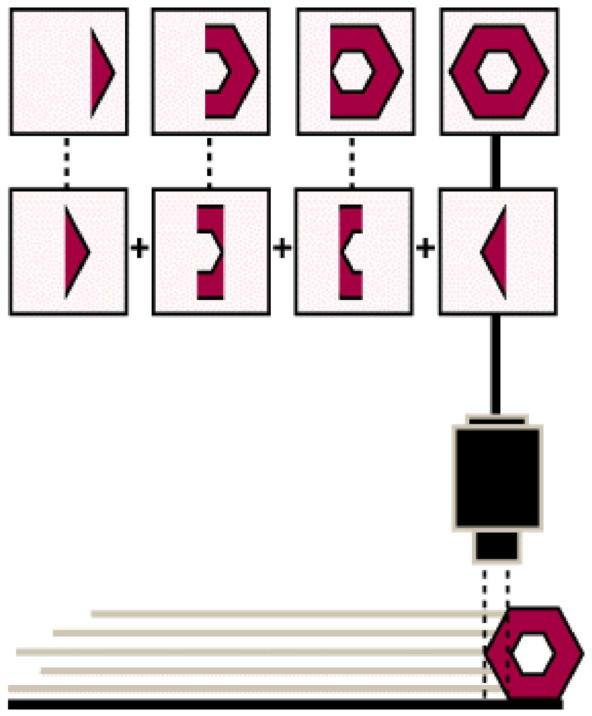
Camera

- Matrix format:
  - Related to size and aspect ratio of the sensor
  - It is related to:
    - Field of View
    - Global magnification



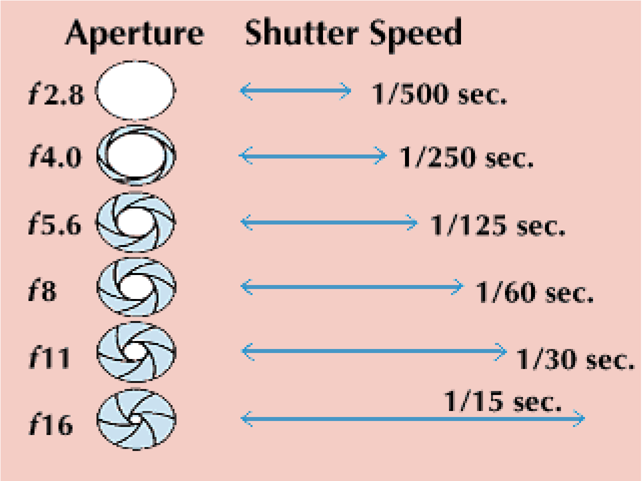
Camera

- Linear sensor:
  - Several discharge architectures: linear, bilinear, trilinear
  - Huge resolution of the line: from 128 to 8800 pixels
  - ☹ Not standard output



Camera

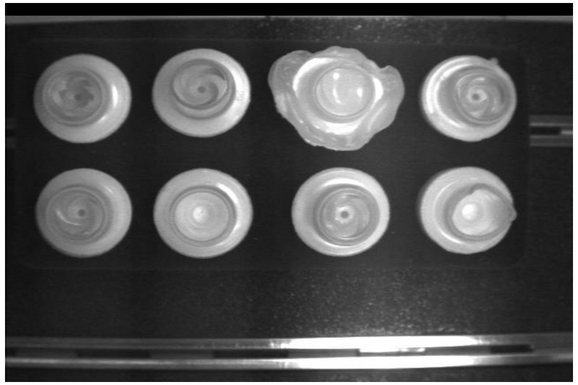
- Integration time:
  - Allows us to work with different lighting and movement conditions
  - It is controlled by a signal called *shutter*
  - The less the amount of light, the higher the integration time



Camera

- Integration time:
  - Affects the number of electrons stored during time
  - It allows us to perform motion blur

Camera



Static object

1/250 s

1/1000 s

1/10000 s

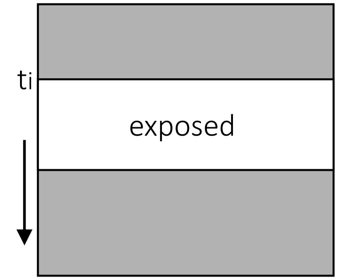
Camera

- Smaller integration time can be compensated by:
  - Increasig the amount of light in the scene → HEAT
  - Opening the iris of the objective

Camera

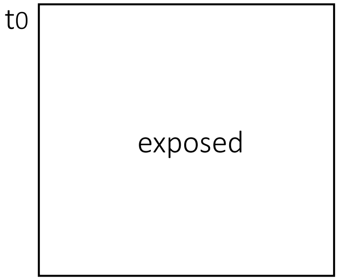
- Integration type:

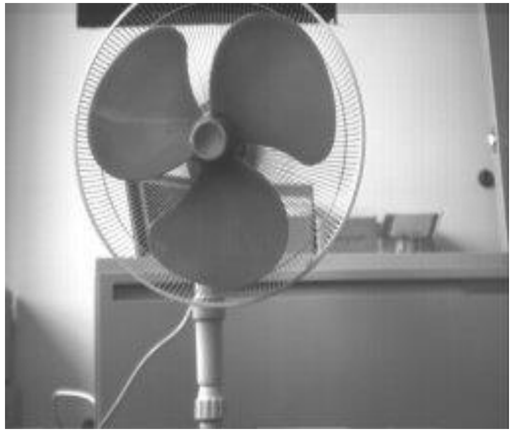
Rolling shutter



Majority of CMOS

Frame shutter

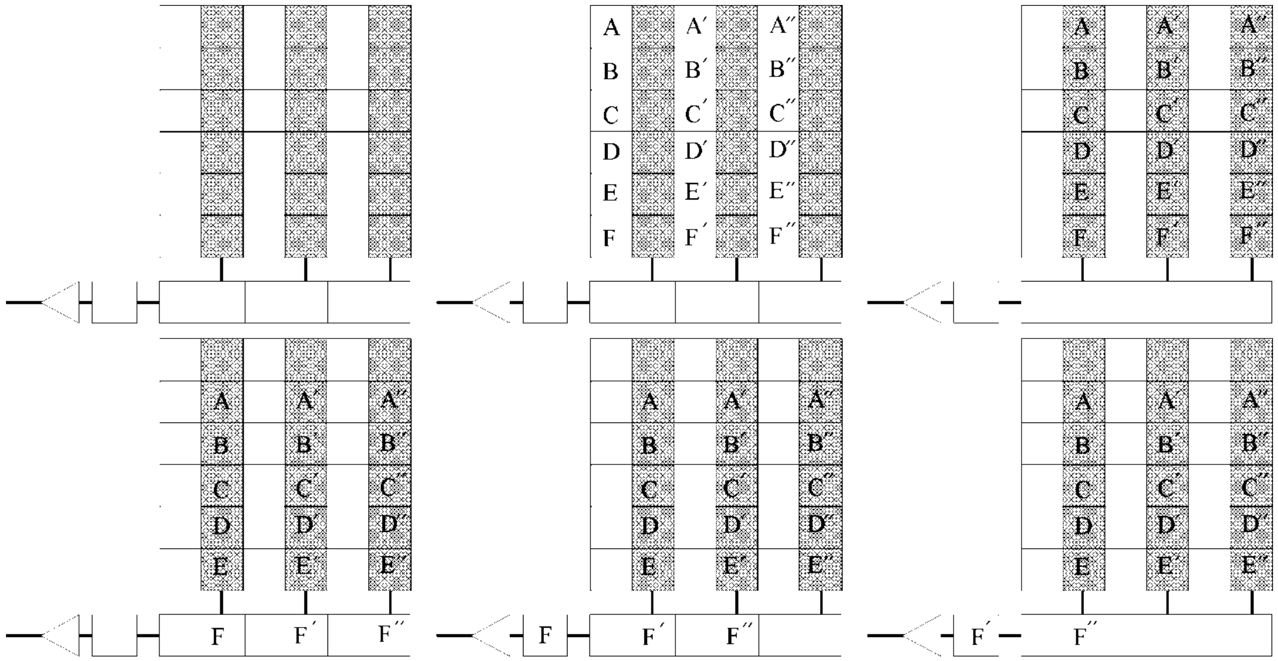




CCD and some CMOS

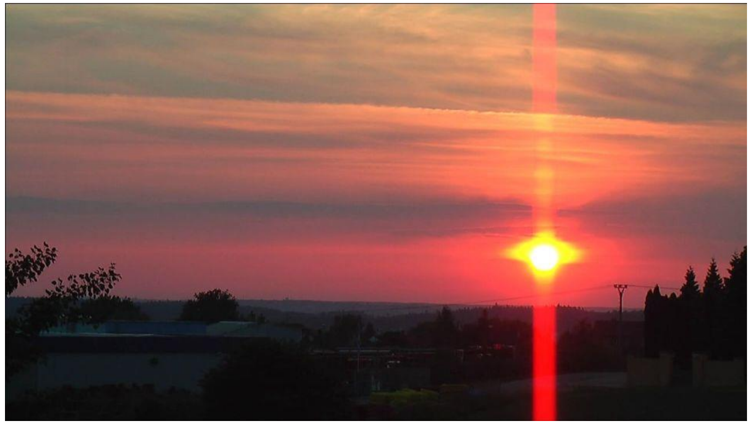
Camera

- Transfer (CCD):
  1. Acquisition (image integration time)
  2. Readout
  3. Reset (photocells discharge)

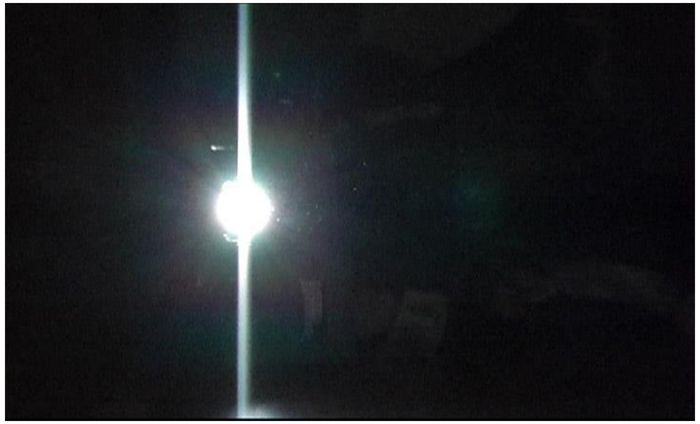


Camera

- Transfer (CCD):
  - Problems associated:
    - Blooming: charge overload
    - Smear: light arrives in reading stage



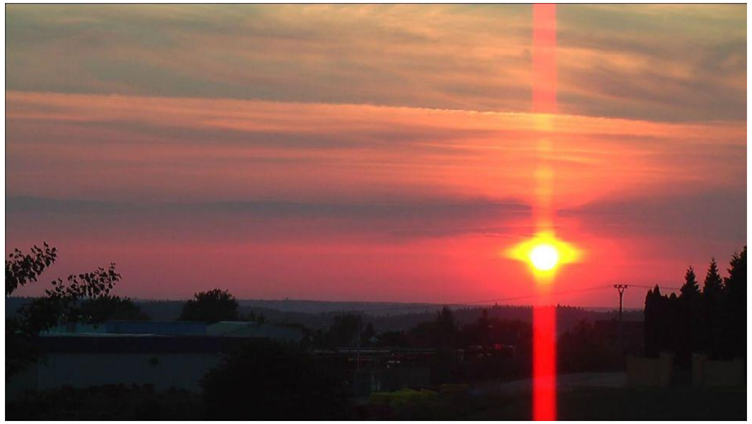
Blooming



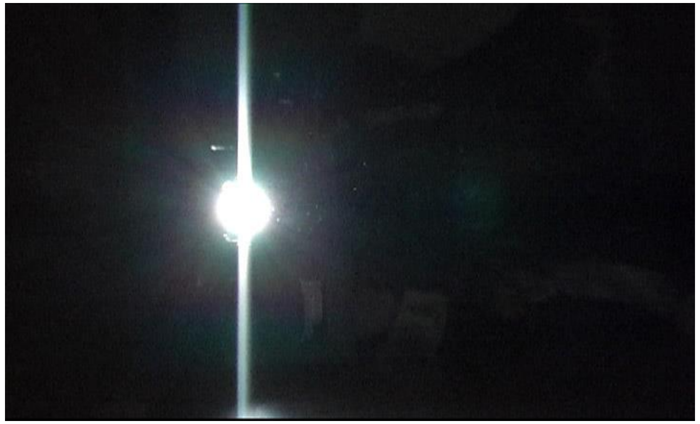
Smearing

Camera

- Transfer (CCD):
  - Solutions:
    - Blooming: charge overload → less integration time
    - Smear: light arrives in reading stage → block the sensor when reading



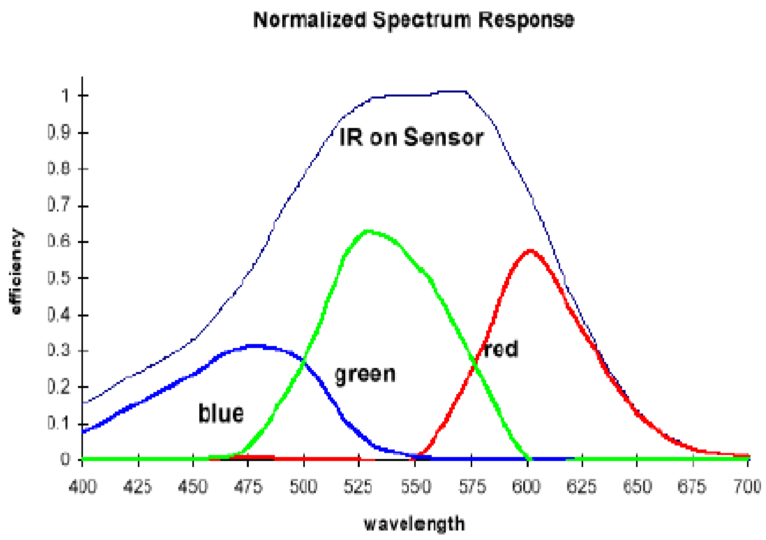
Blooming



Smearing

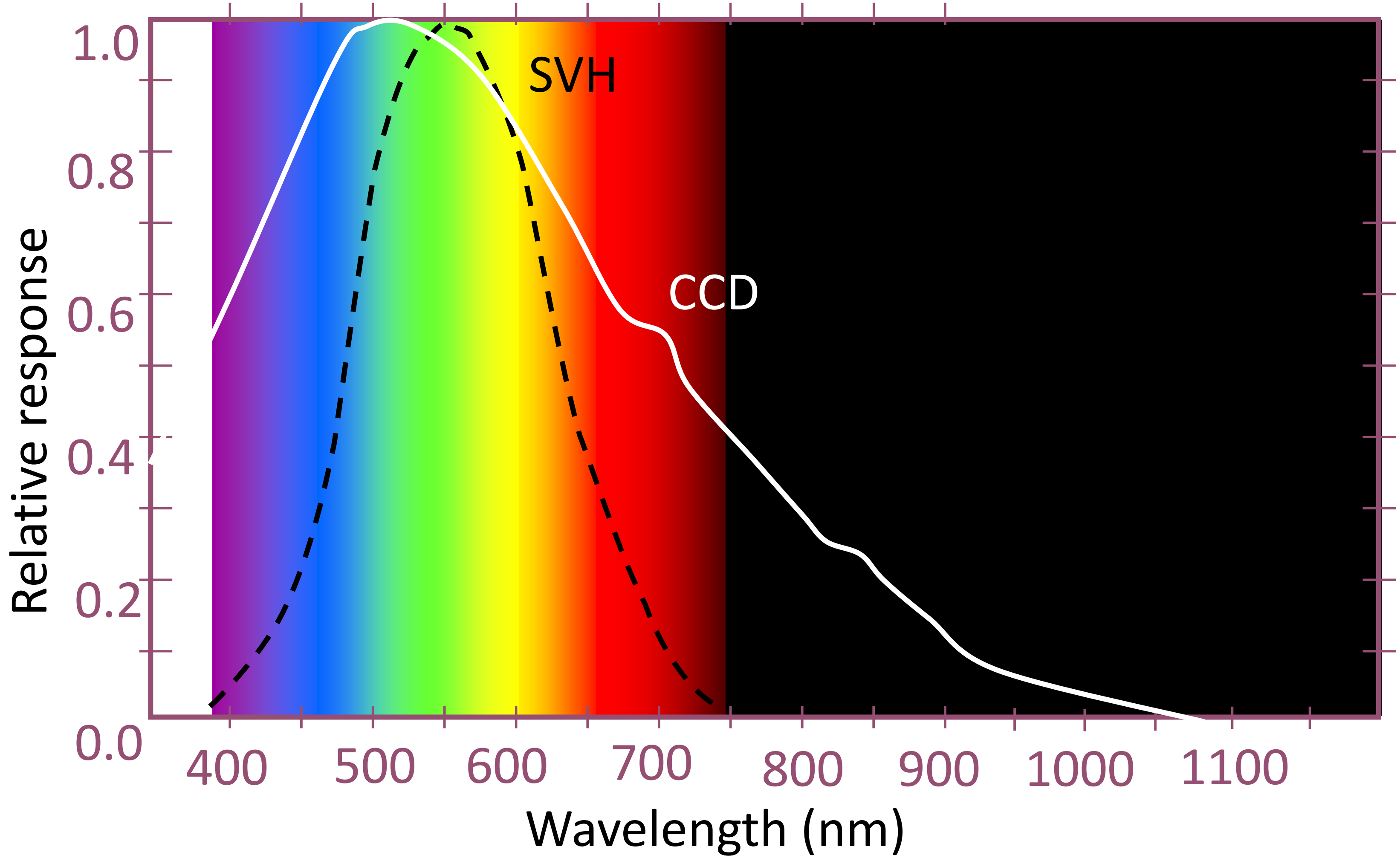
Camera

- Spectral sensitivity
  - Sensor sensitivity depends on the materials it is made of. The semiconductor gives us sensitivity contour
  - In case we have associated and adjacent filters, they will limit the range



  - To generate a pair electron-hole, photon energy has to be higher to semiconductor gap

Camera

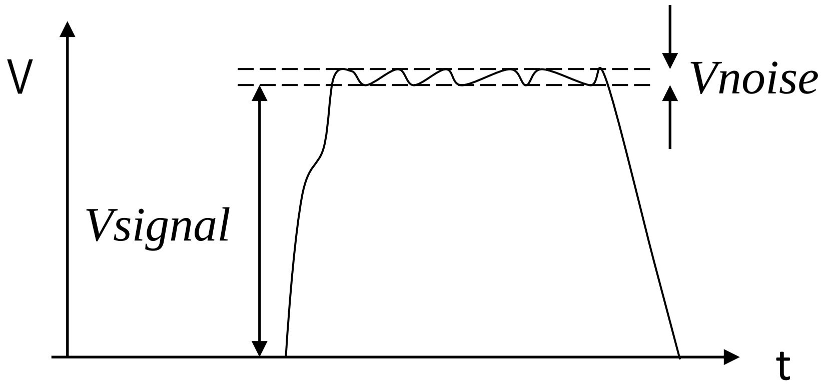


1.0
0.8
0.6
0.4
0.2
0.0
Relative response
SVH
CCD
400
500
600
700
800
900
1000
1100
Wavelength (nm)

Camera

- Signal to Noise ratio
  - Relative amount of noise in a given signal

$$SNR = 20\log\left(\frac{V_{señal}}{V_{ruido}}\right)$$



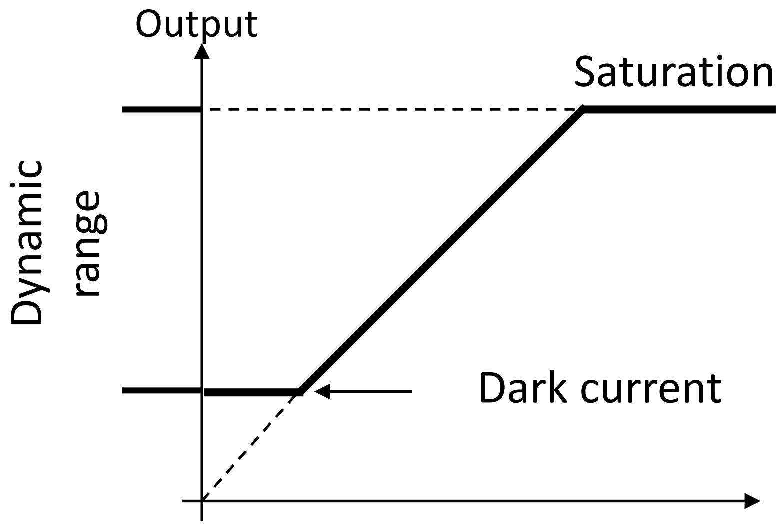
Camera

- Dark current
  - If we are at a determinate temperature, an electron-hole pair is generated (a small signal) **even if there is no light → dark current**
  - Non effective pixels are used to quantify and mitigate this signal
  - We can also mitigate this decreasing the temperature

Camera

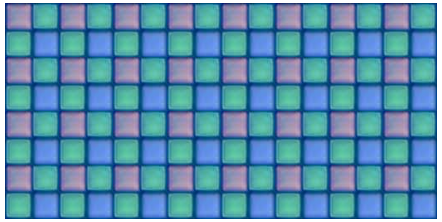
- Response
  - For a given wavelength and a general intensity range, sensor response is linear
  - We can alter this response in non linear devices (CRT) → gamma correction

  - Image processing → linear signal
  - If we need big differences between dark and clear areas (High Dinamic Range) → non linear or logaritmic response sensors



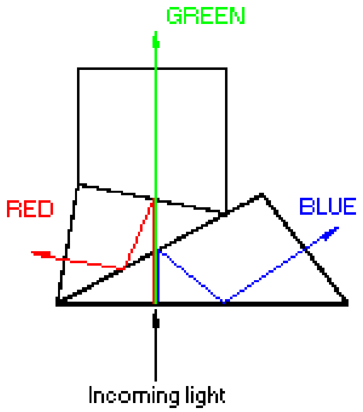
Camera

- Color
  - Bayer pattern (a single sensor)
    - The most used system
    - We do not have R, G or B in any pixel. We need to interpolate (demosaicing)



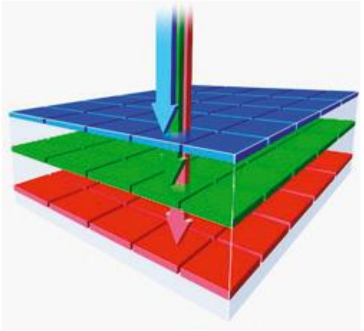
Camera

- Color
  - 3 independent sensors
    - Prisms and filters divide light into three components that illuminate three monochromatic sensors



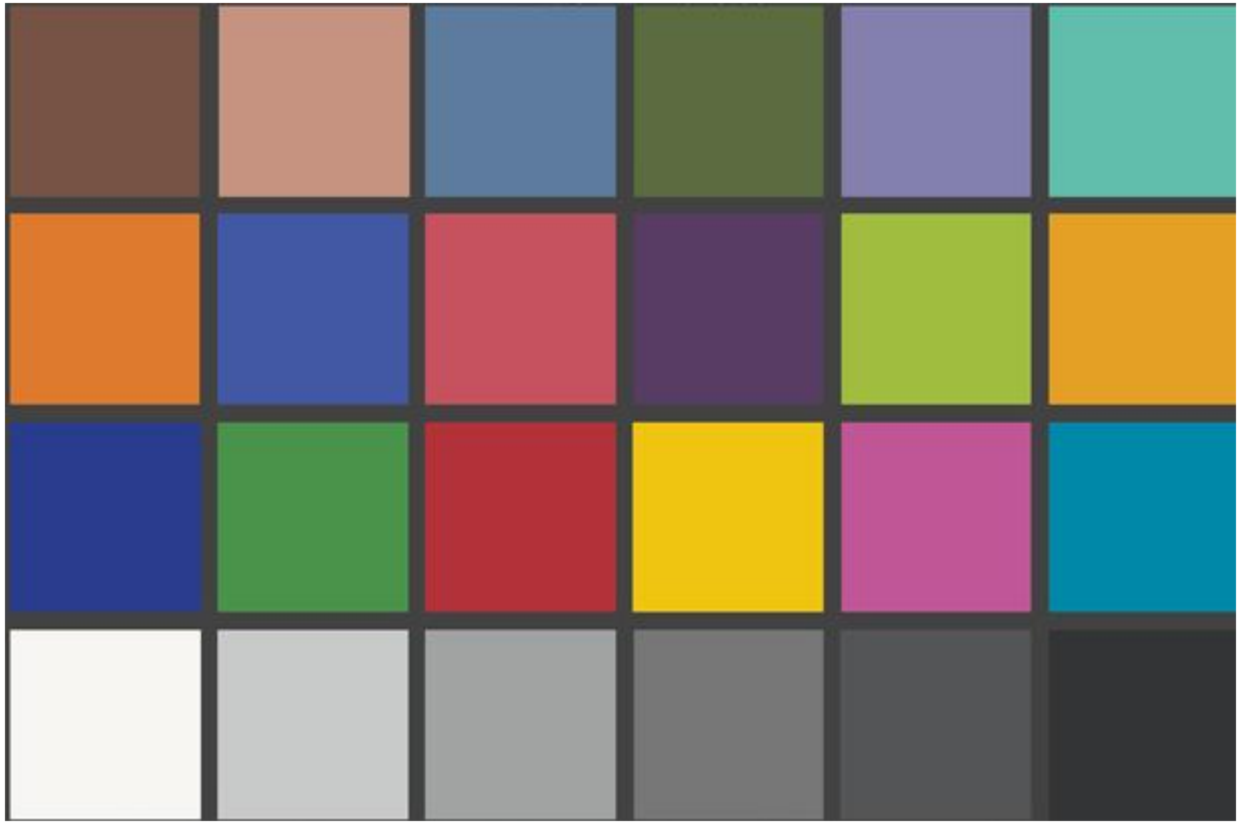
Camera

- Color
  - Stacked sensors
    - Depending on its energy, color gets to different depths



Camera

- Color callibration

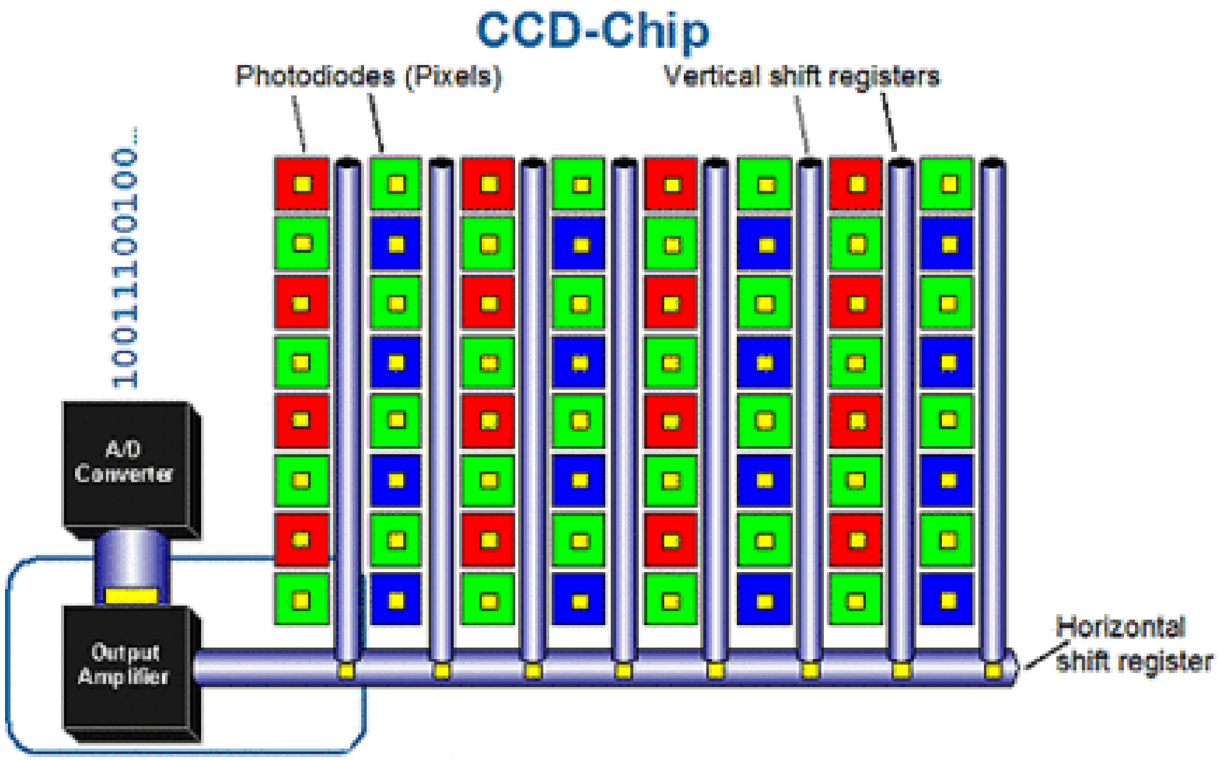


Camera

- Sensor types
  - **CCD (Charge-Coupled Device)**
    - CCD-specific technology.
    - It needs extra electronics to get the signal from the sensor.
  - **CMOS (Complementary Metal Oxide Semiconductor)**
    - Same technology as for other electronic devices.
    - Low cost
    - Extra electronics can be integrated in the same chip (converters, image processing,...).

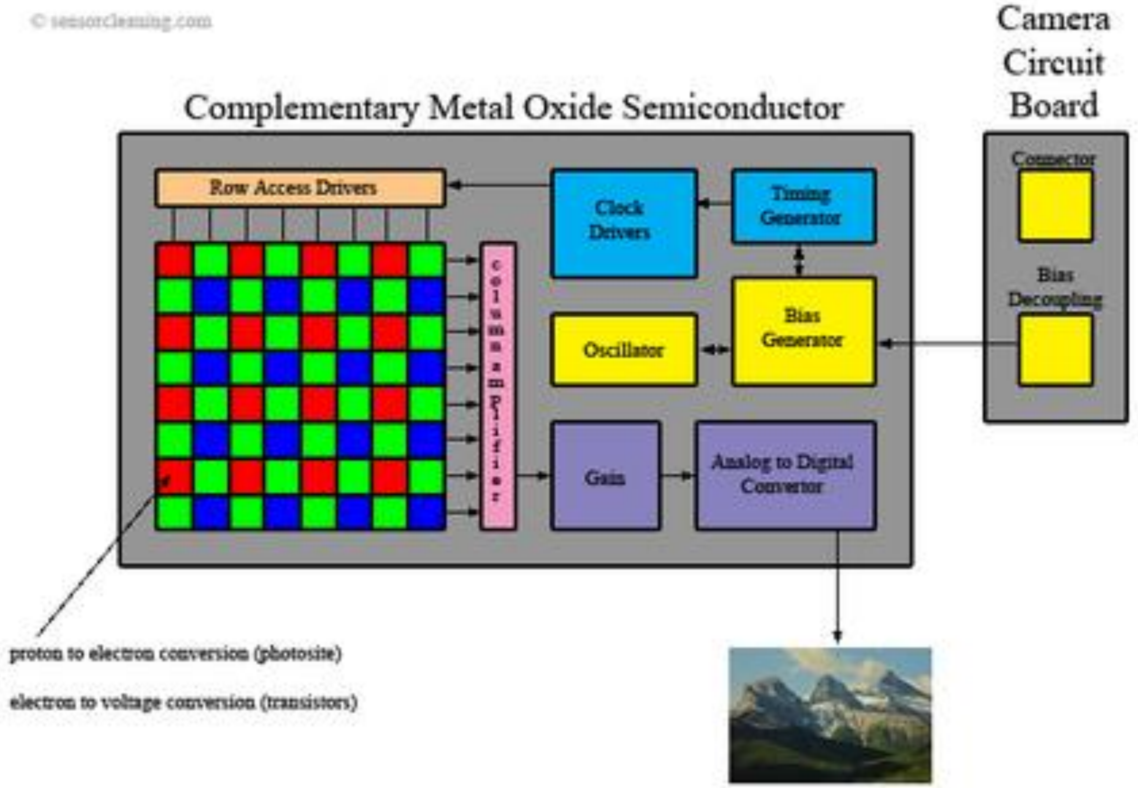
Camera

- Sensor types
  - **CCD (Charge-Coupled Device)**



Camera

- Sensor types
  - **CMOS (Complementary Metal Oxide Semiconductor)**



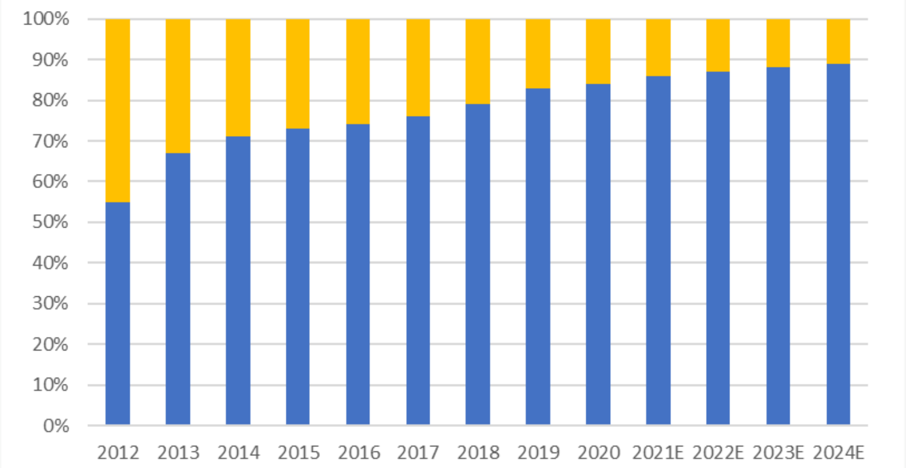
Camera

- Sensor types
  - **CCD vs CMOS**

Feature	CCD	CMOS
Windowing	Restricted	Yes
Consumption	High	Low
Integration	Low	High
Speed	Low	High
Blooming and smear	Yes	Low
Cost	High	Mid, Low
Fill Factor	High	Mid/Low
Noise	Low	Mid/High(FPN)
Shuttering	Easy	Some problems

Camera

- Sensor types
  - **CCD vs CMOS (trends)**
    - They are complementary technologies
    - Mid / Long term:
      - Use CCD when you need high image quality
      - Use CMOS for:
        - Low quality applications
        - When you need to transfer some areas
        - If you need high speed
        - To obtain HDR
      - CMOS will improve noise problems over time



CMOS higher market share

Camera

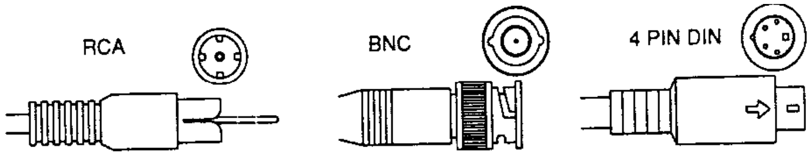
- Signal, connectivity
  - **Analogue**
    - Advantages:
      - Ilimited cable length (100 m)
      - Low Price
    - Disadvantages
      - Lower resolution
      - Frame grabber commonly required
      - Sync problems when using multiple cameras
      - Interlacing

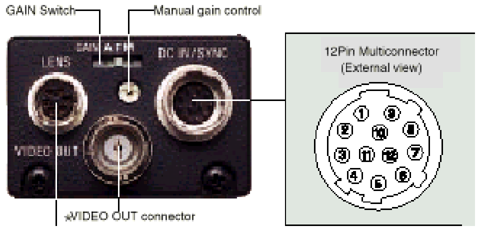
Camera

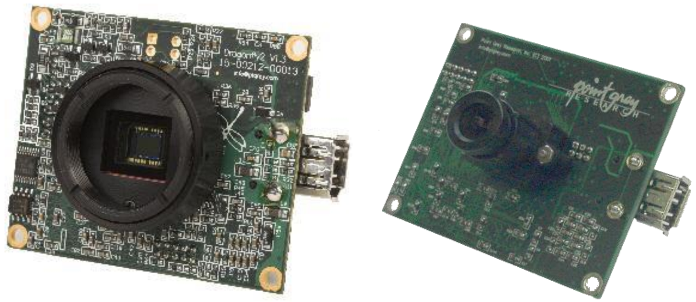
- Signal, connectivity
  - Analogue
  - **Digital**
    - They do not originate from TV standard
      - Higher resolution
      - Higher speed
      - Variable window
    - Several systems
      - Firewire
      - CameraLink
      - USB
      - GigaEthernet
      - CoaXPress

Camera

- Signal, connectivity
  - Connectors
    - Analogue:
      - BNC
      - RCA
      - Manufacturer specific
    - Digital:
      - USB 2, USB 3
      - FireWire
      - Cameralink
      - Ethernet

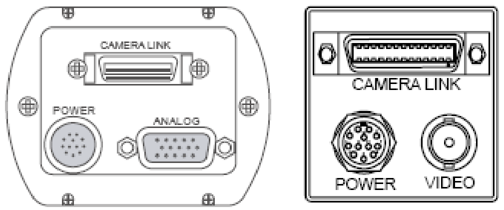






Rear Panel

TMC-6700CL/TMC-1000CL AccuPiXEL™ Series



Camera

- Smart cameras
  - Capture and process integrated in the same product. Integrated machine vision system:
    - Lens + sensor (CCD, CMOS, matrix, linear) + digitization + memory (image).
    - Processor (CPU, DSP) + program memory
    - Communications, inputs and outputs: RS232, Etherner, optocoupled i/o.
    - Lighting system (LED)
  - Perform simple vision tasks in a production line, without the need for external hardware.
  - Programming with languages (C, C++), or from libraries supplied by the manufacturer.


Camera

- Emerging technologies
  - sCMOS (scientific) sensor: low framerate. High framerate, dynamic range, quantum efficiency, resolution, field. Alternative to CCD, EMCCD.
  - Event based camera: Responds to light changes. There is no image, only event in the time when the light changes.

Fundamentals of Computer Vision

Unit 2: Digital Image Formation (I)

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