3D Data Processing

Camera

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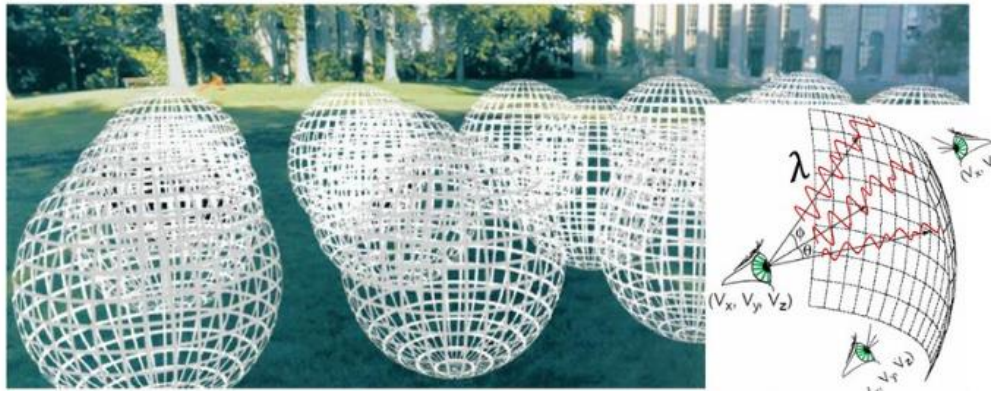
Basic Question

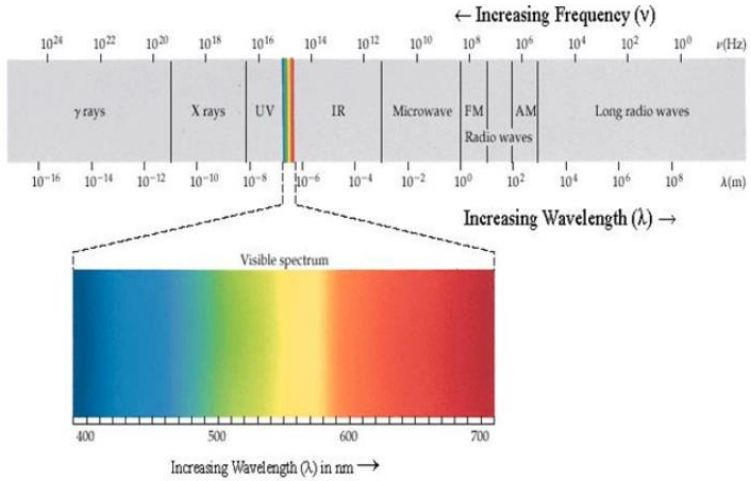
- Which of these sensors works the same way as a camera?
  - A. gyroscope
  - B. strain gauge
  - C. photoresistor
  - D. pressure sensor
  - E. Accelerometer

Light

- A form of electromagnetic radiation
  - Observable by human eye: Wavelengths between 380nm and 750nm
- Exhibits both wave-like and particle-like properties
- This lecture is based-on Ray Optics



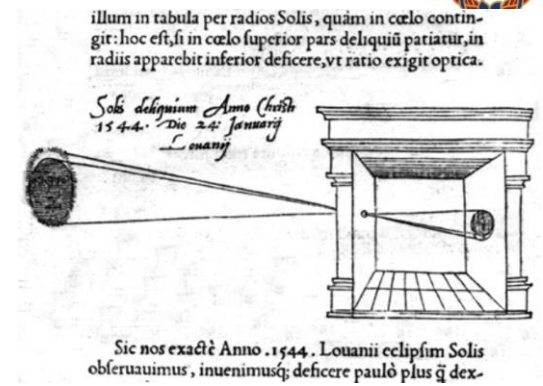
Concept of light field

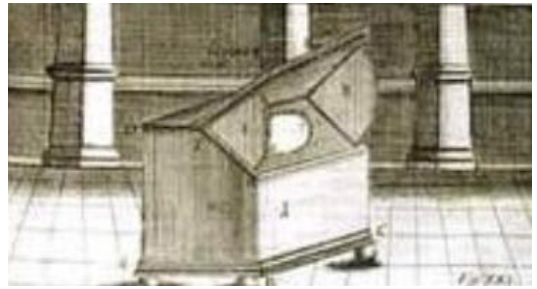


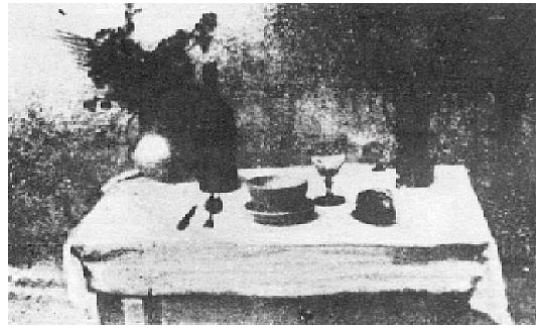
Electromagnetic Spectrum

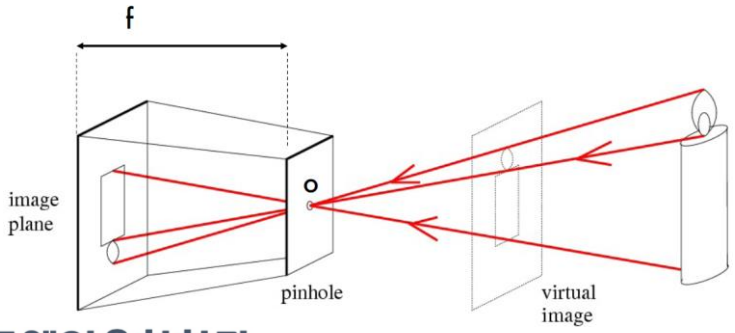
Camera obscura

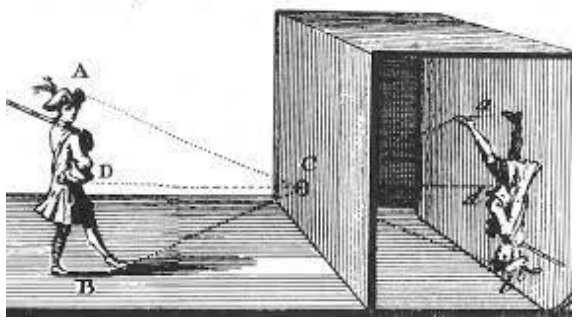
- Cameras generate a projected image of the world
- Leonardo da Vinci (1452-1519):
  - first record of camera obscura (1502)
- Johann Zahn (1685): first portable camera
- Joseph Nicéphore Niépce(1822)
  - first photo - birth of photography
- Most cameras are based-on pinhole model





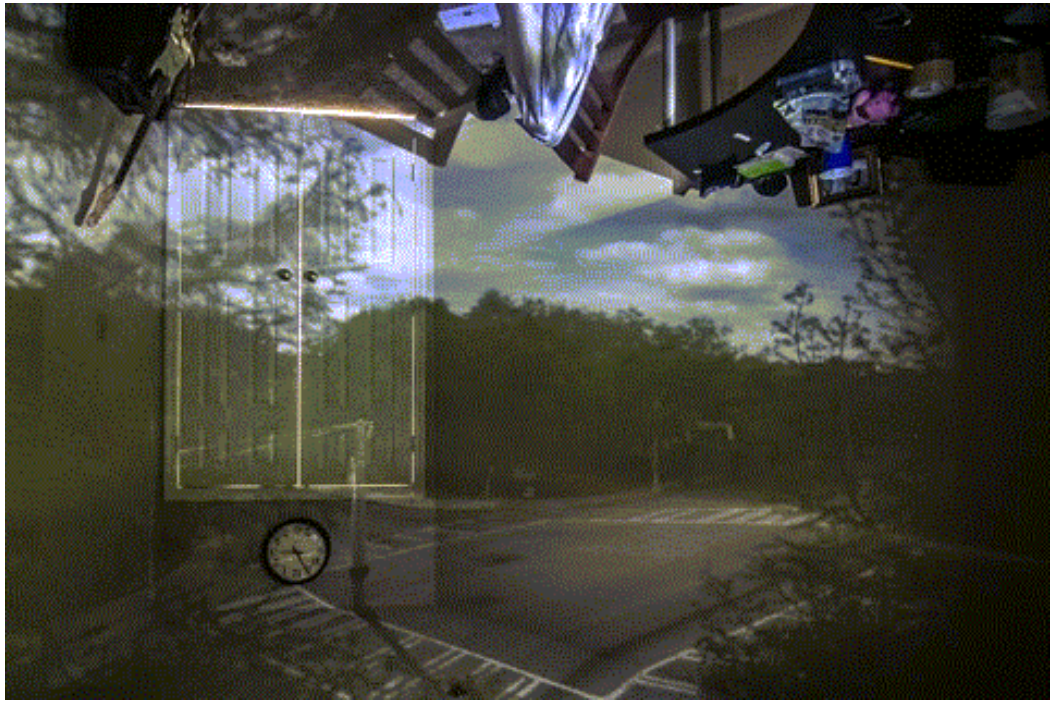






Camera obscura

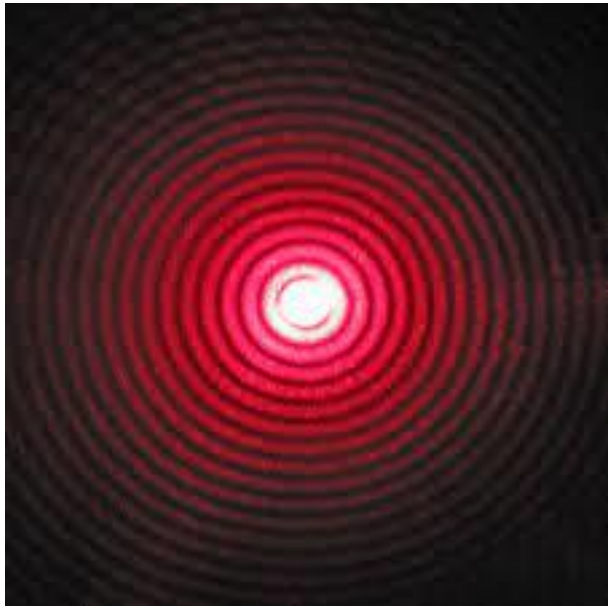
- Cameras generate a projected image of the world



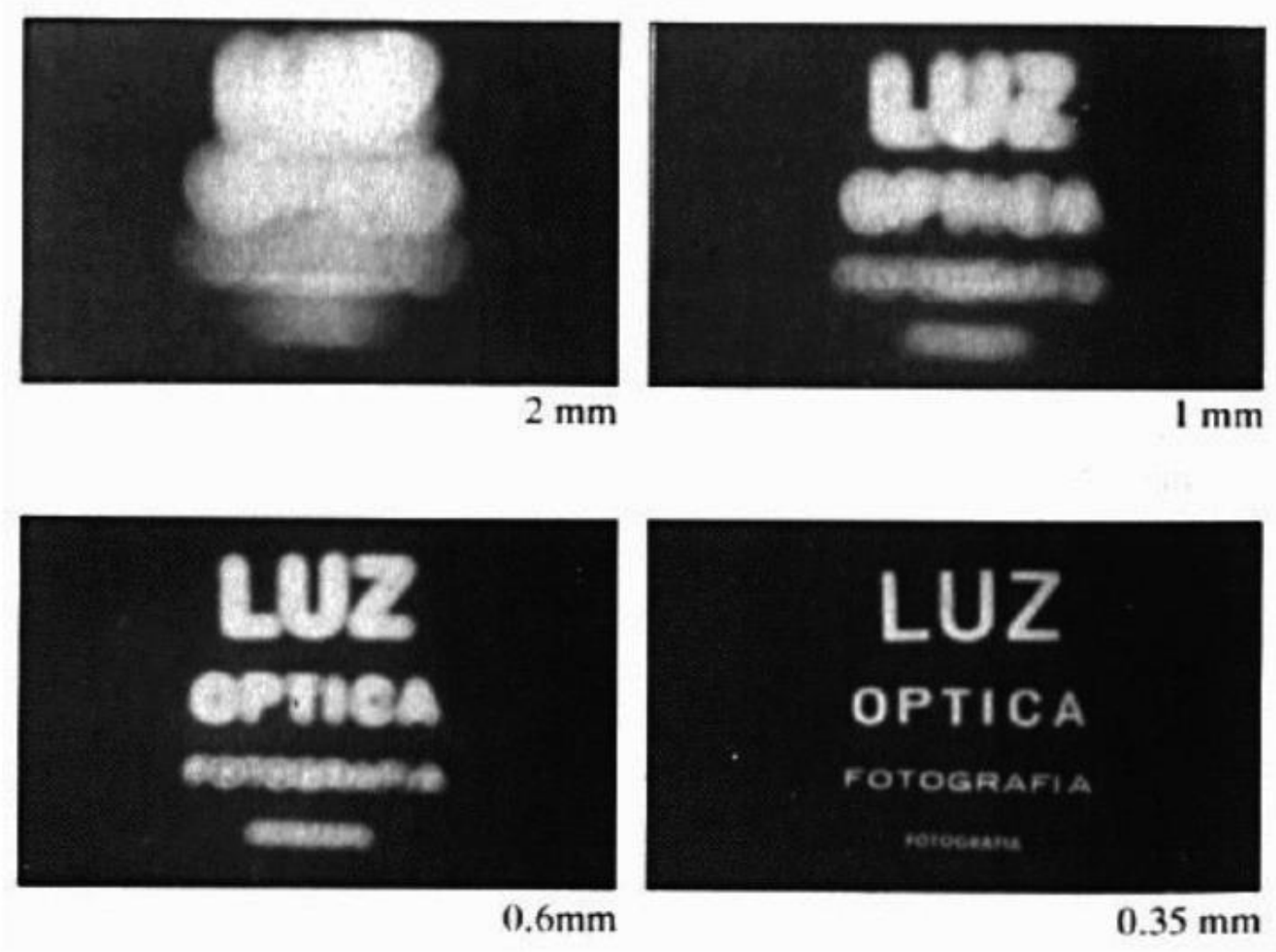
https://petapixel.com/2014/05/12/diy-tutorial-convert-room-camera-obscura/

Camera obscura

- Shrinking aperture size
  - Large: superposition
  - Small: less light, diffraction

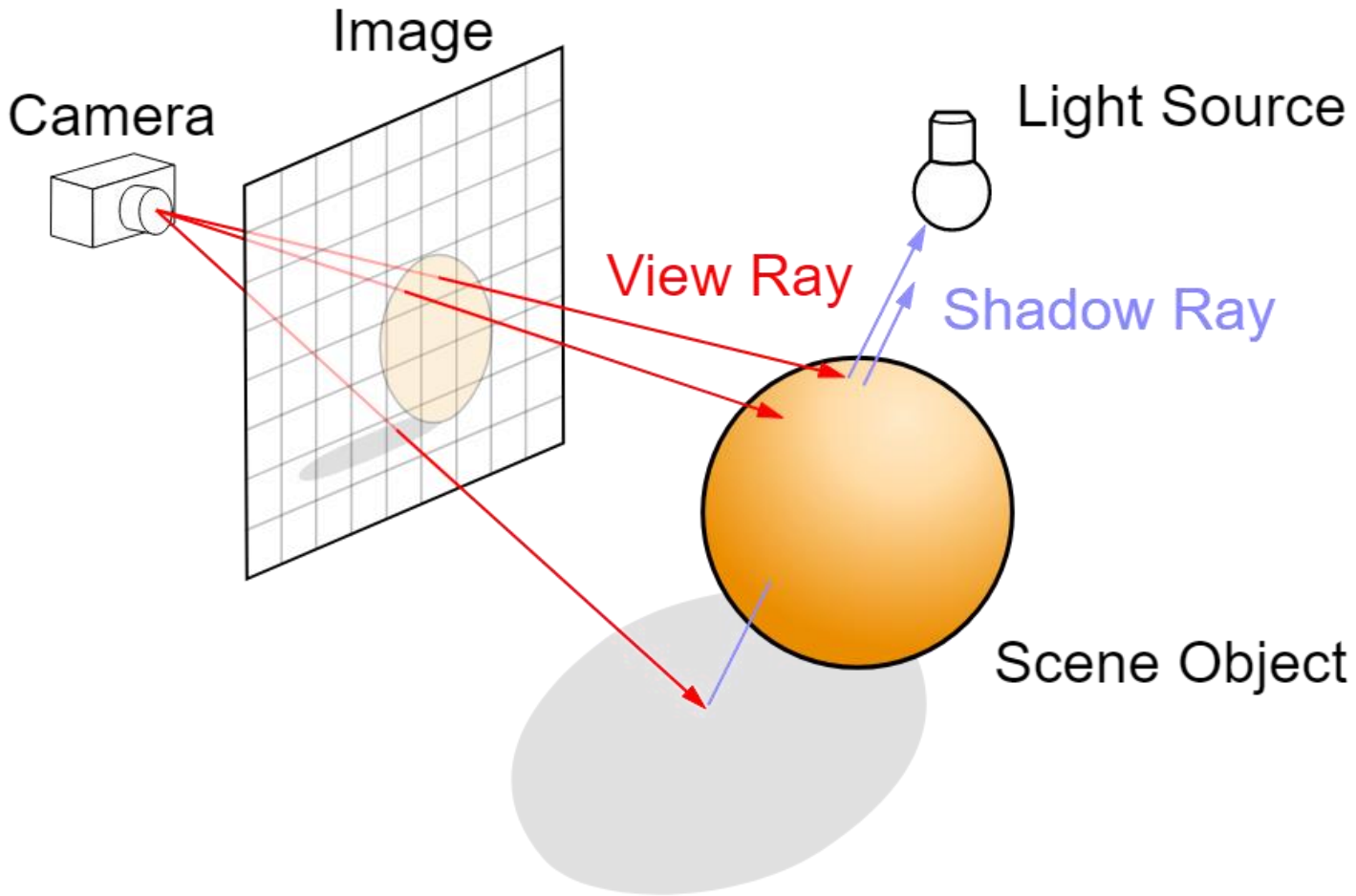


diffraction



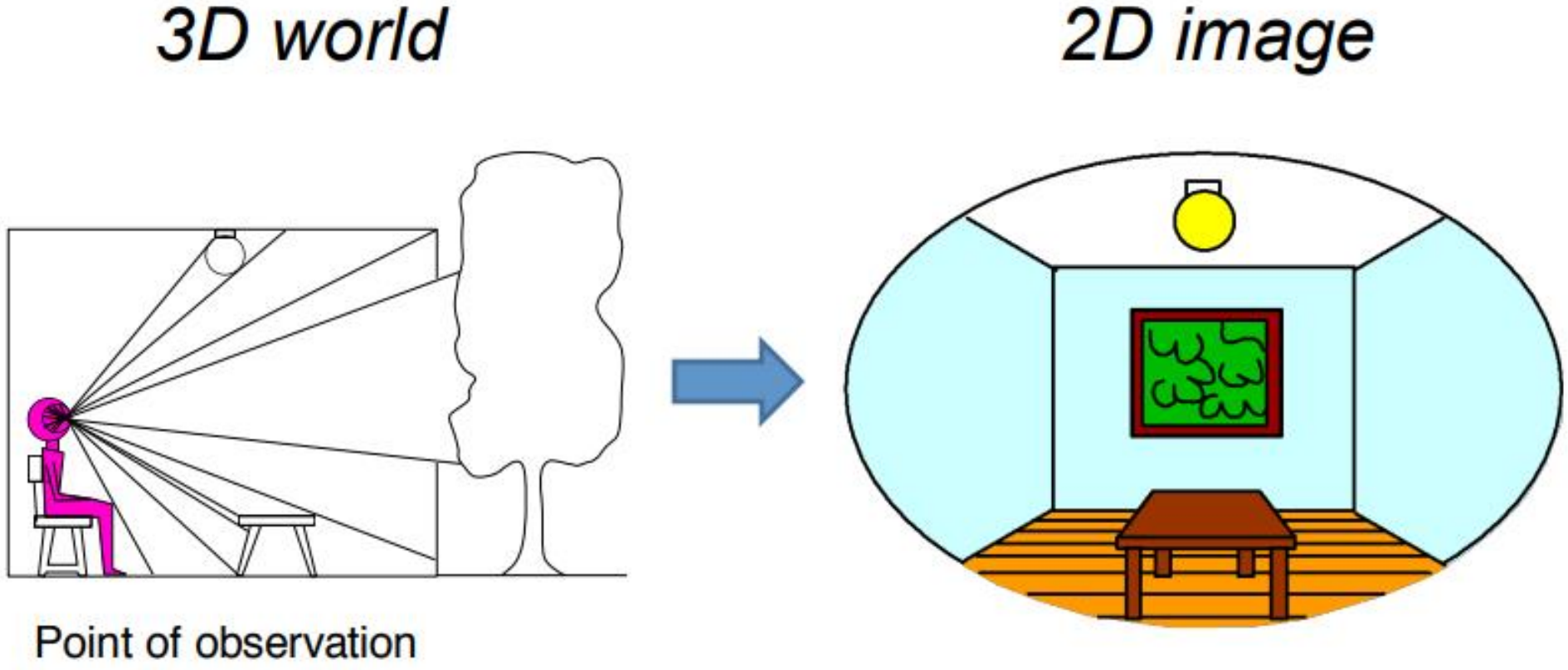
Camera

- Camera as sampling machine in the light field



Camera

- Camera as Dimensionality reduction machine



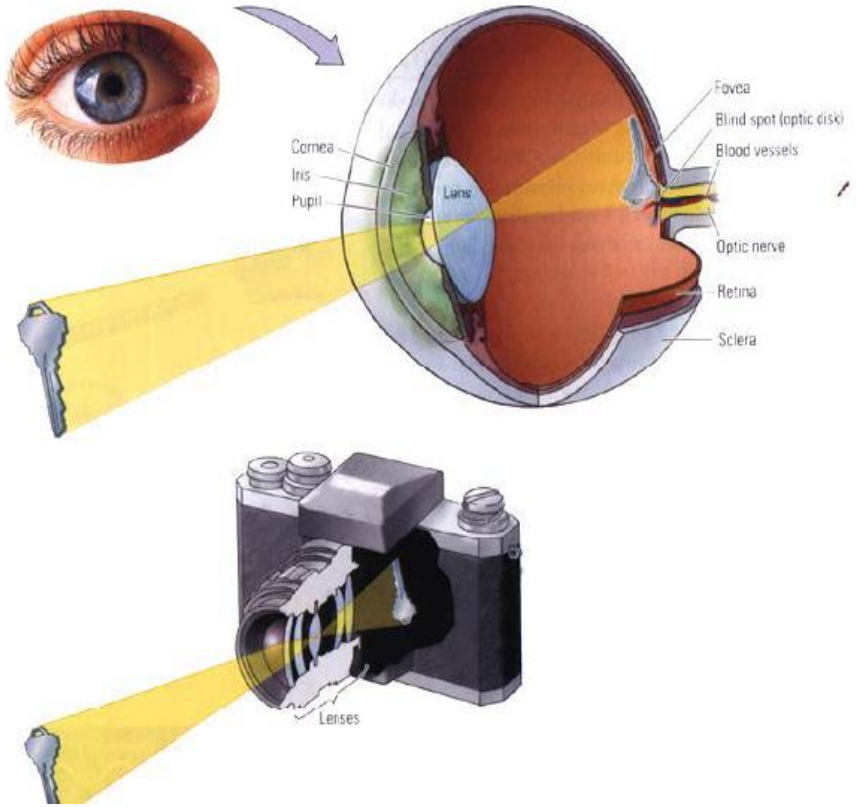
Camera

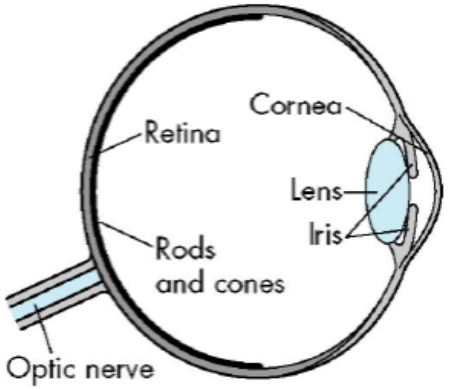
- Projection can be tricky.

- However, it's the same thing that happens to humans.

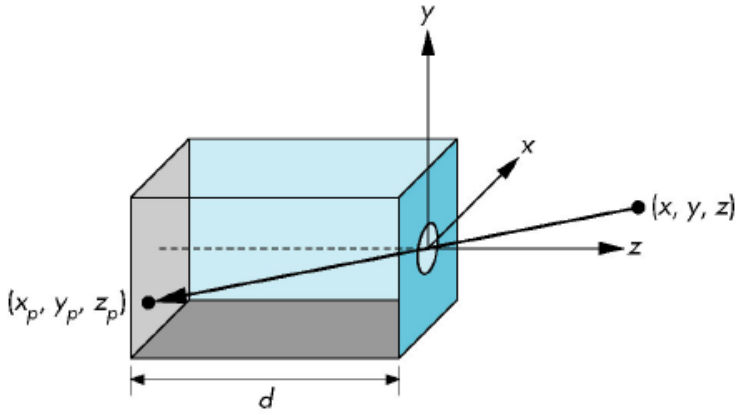
Camera obscura

- Cameras are a copy of the human eye
  - We make cameras that act “similar” to the human eye.





Human eye



camera

Camera obscura

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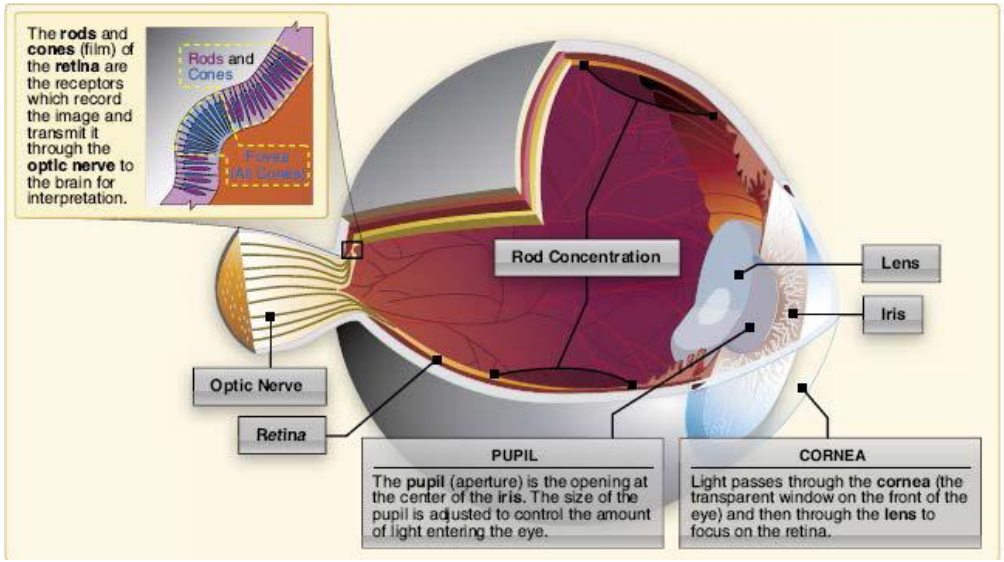
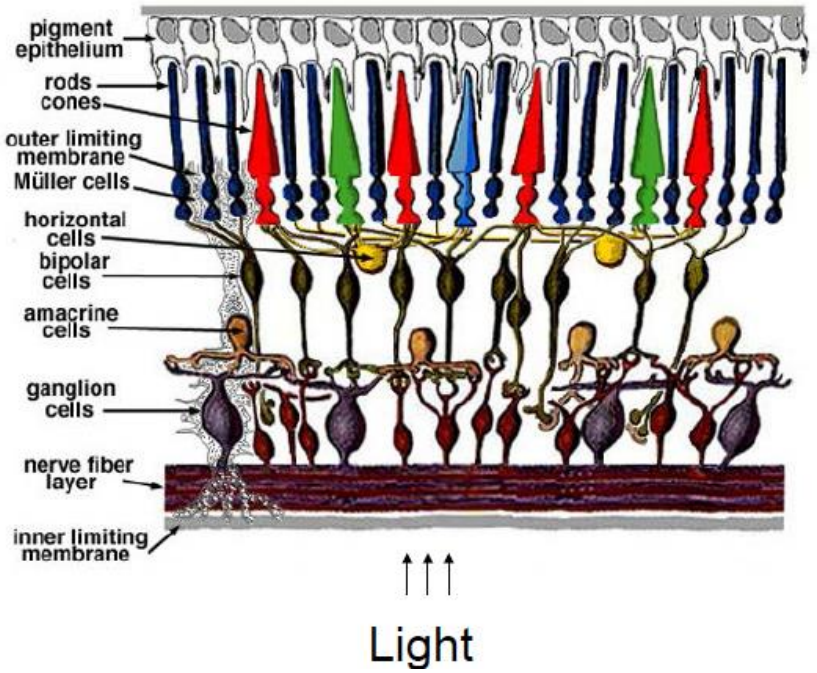
camera

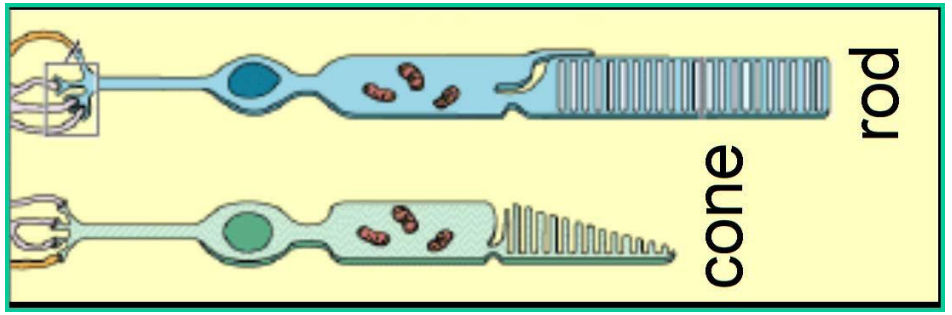
- Retina
  - Retina contains light sensitive cells that convert light energy into electrical impulses that travel through nerves to the brain
  - Brain interprets the electrical signals to form images

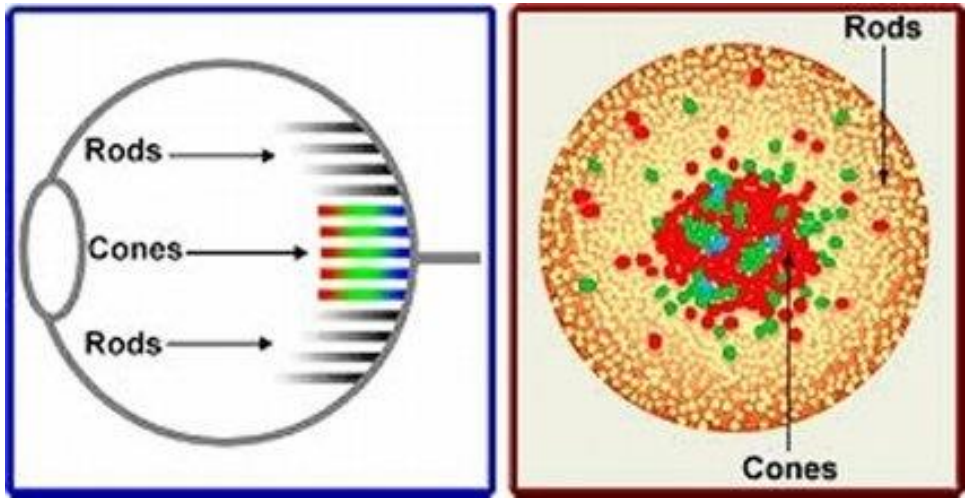




Camera

- Two types of light-sensitive receptors
  - Cones
    - cone-shaped less sensitive operate in high light color vision
  - Rods
    - rod-shaped highly sensitive operate at night gray-scale vision



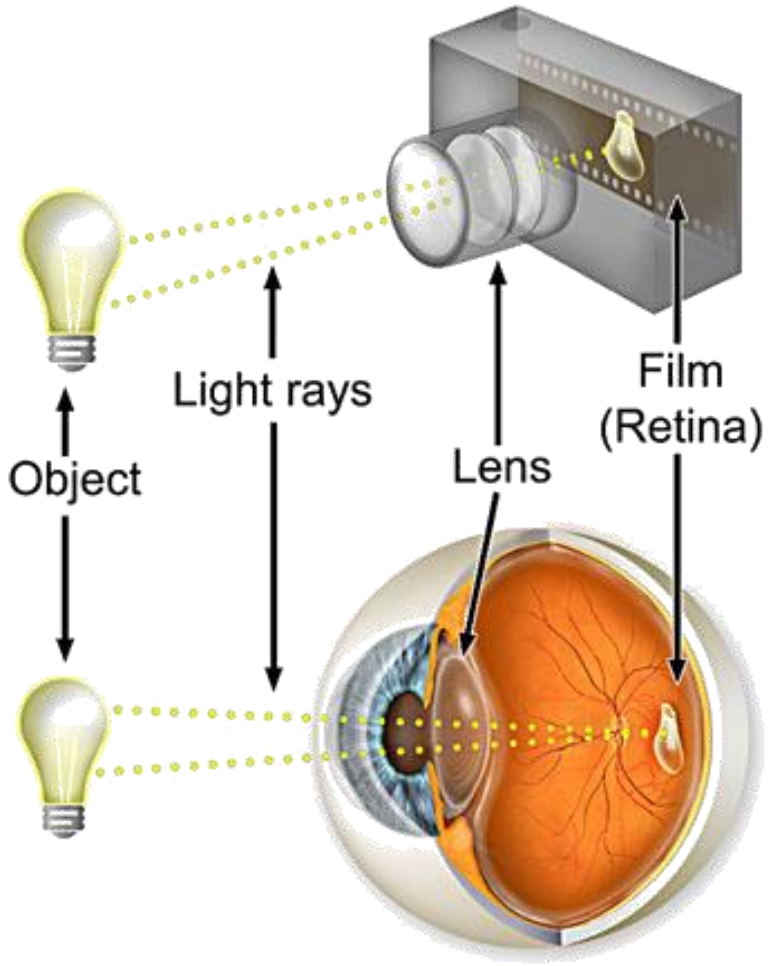


distribution of the rods and cones.

https://www.quora.com/Where-in-the-retina-are-rods-and-cone-found

Digital camera

- A digital camera is a camera that captures photographs in digital memory.
- Conceptually, it consists of a lens and an image sensor that replaces the film.
- An image sensor detects and conveys information used to make an image.



Digital Imaging

- Invented in 1969 at AT&T Bell Labs by Willard Boyle and George E. Smith.
- Originally working on memory →"Charge 'Bubble' Devices", can be used as a shift register and as a linear and area imaging devices
- CCDs are electronic devices, which work by converting light into electronic charge in a silicon chip (IC). This charge is digitised and stored as an image file on a computer.
- In 2009, they were awarded the Nobel Prize for Physics

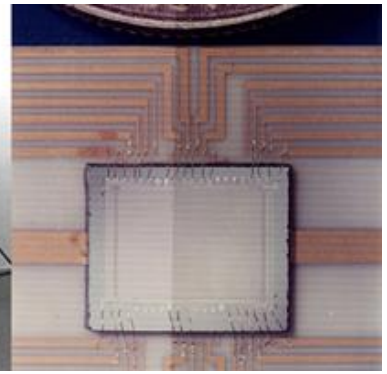
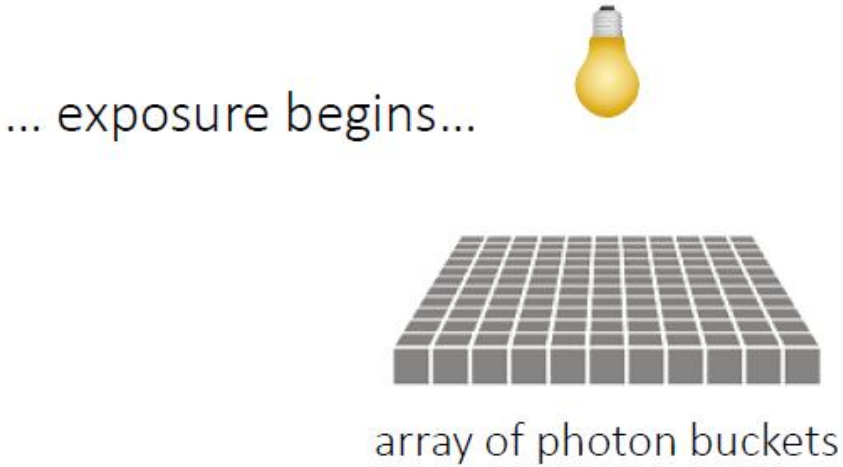
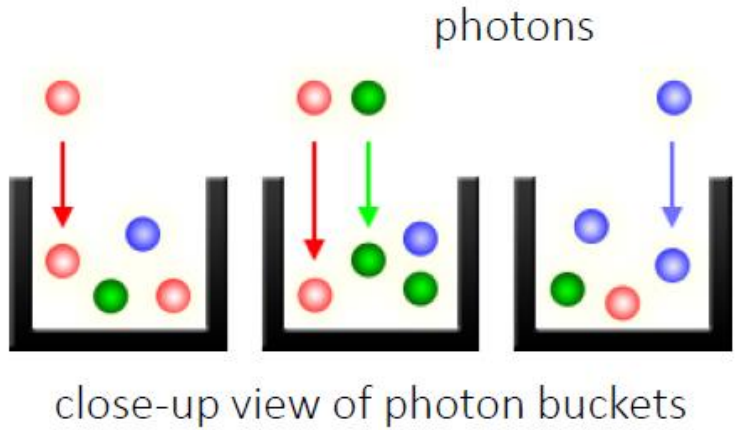


Image sensors

- When the camera shutter opens

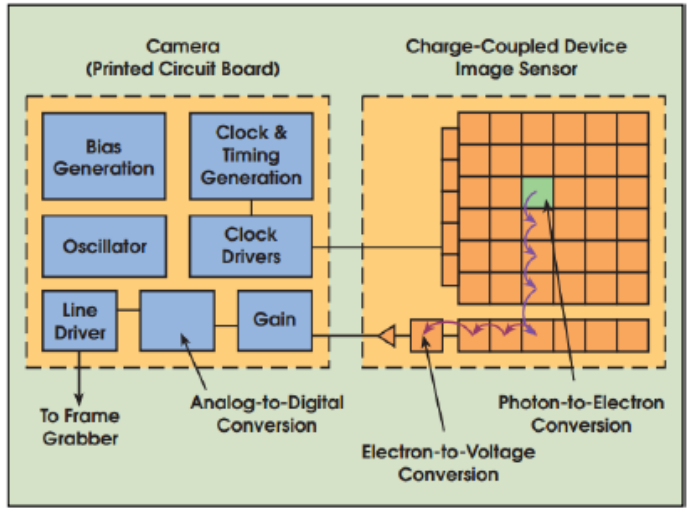




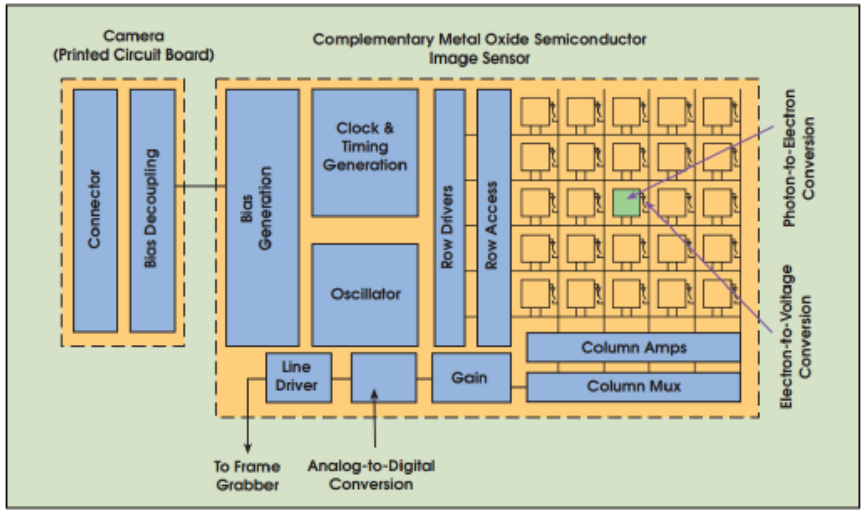
- Photon buckets (Cell) begin to store photons
- Until the camera shutter closes, then they convert stored photons to intensity values.

Image sensors

- Two main types of imaging sensors
  - CCD(Charged Coupled Device)
    - Convert electrons to voltage using readout circuitry separate from pixel
    - High sensitivity, lower noise
  - CMOS(Complementary Metal Oxide Semiconductor)
    - Convert electrons to voltage using per-pixel readout circuitry
    - Fast read-out, lower cost



CCD



CMOS

Camera types

- Monocular camera
  - Single camera
- Stereo camera
  - Fixed multi(two) camera
  - Various base-line, angle
- Fisheye camera
  - Using Fisheye lens
  - Extremely wide view angle

Monocular camera

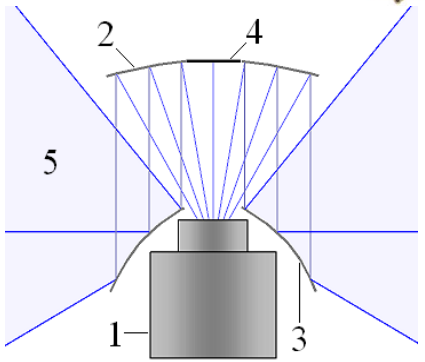
Stereo camera

Fisheye camera

Fisheye image

Camera 종류

- 360 camera
  - Multiple camera set
    - Panorama image after image processing
  - Omni-directional camera
    - Using mirror



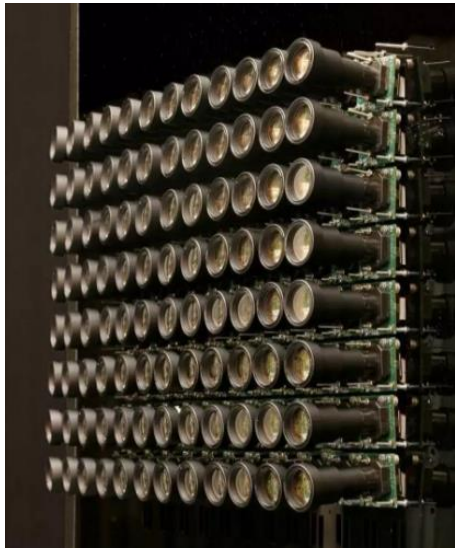
Omni directional camera and image

360 camera

Panorama image

Camera 종류

- Light-field camera
  - Sampling light field between two plane
  - Refocusing pictures
  - 3D scanning, modeling



LF camera system

Lytro

Refocusing example

Camera 종류

- Event camera
  - Novel sensor that measures only motion in the scene (x, y, t, θ)
  - Low-latency (~1us)
  - No motion blur, High Dynamic range

Event camera

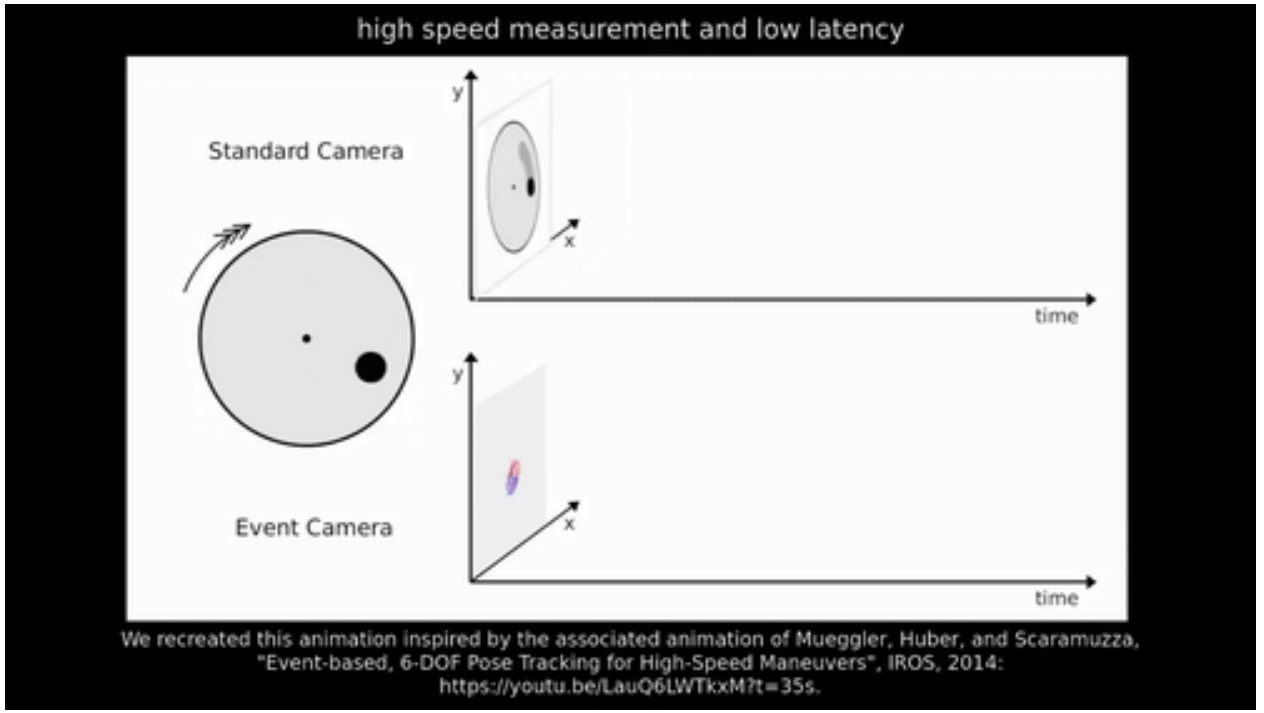
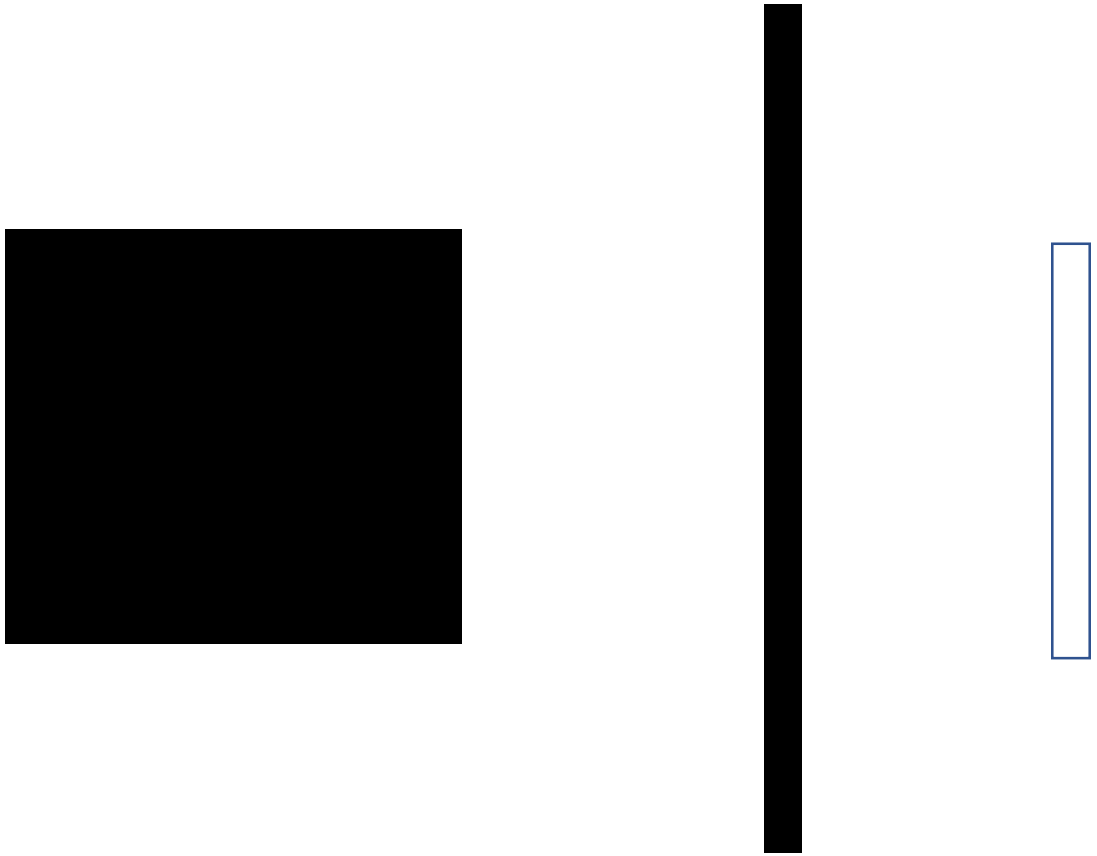


Image sensors

- In principle, an image sensor is a device that measures the **amount of light.**



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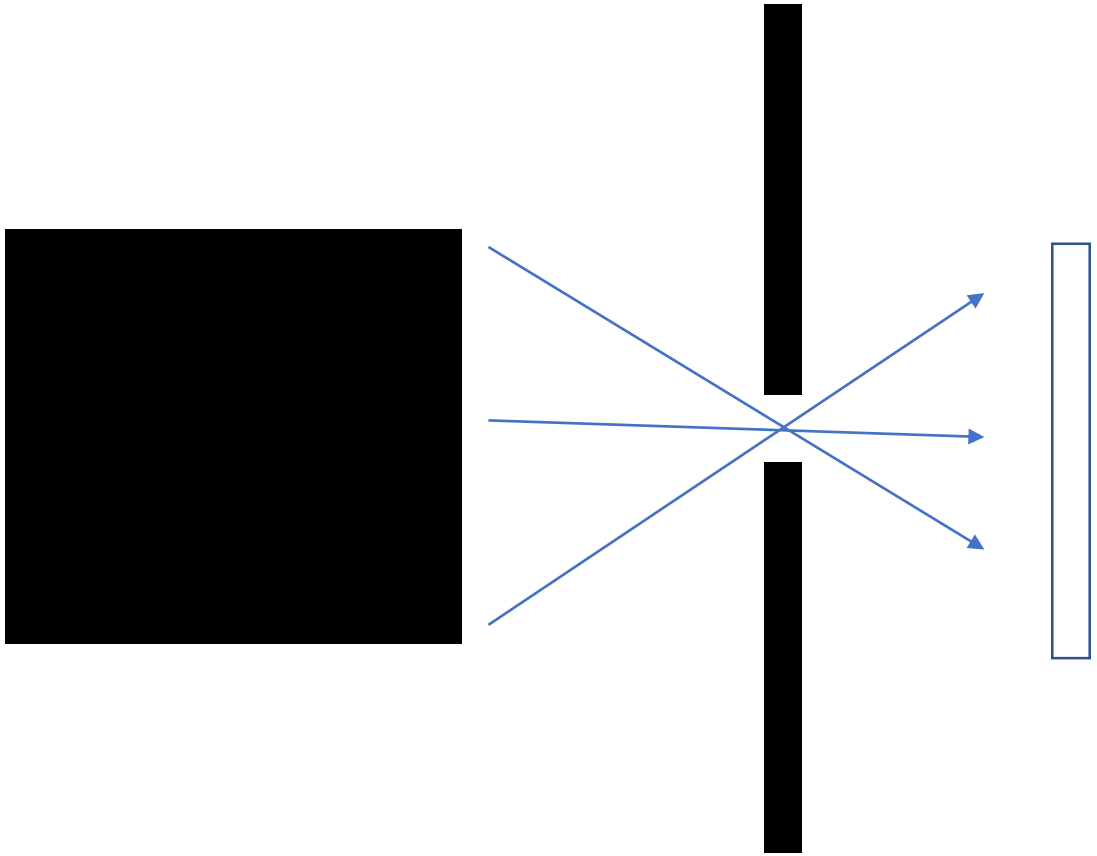

Image sensors

- In principle, an image sensor is a device that measures the **amount of light.**

Amount of photons: 100

Image sensors

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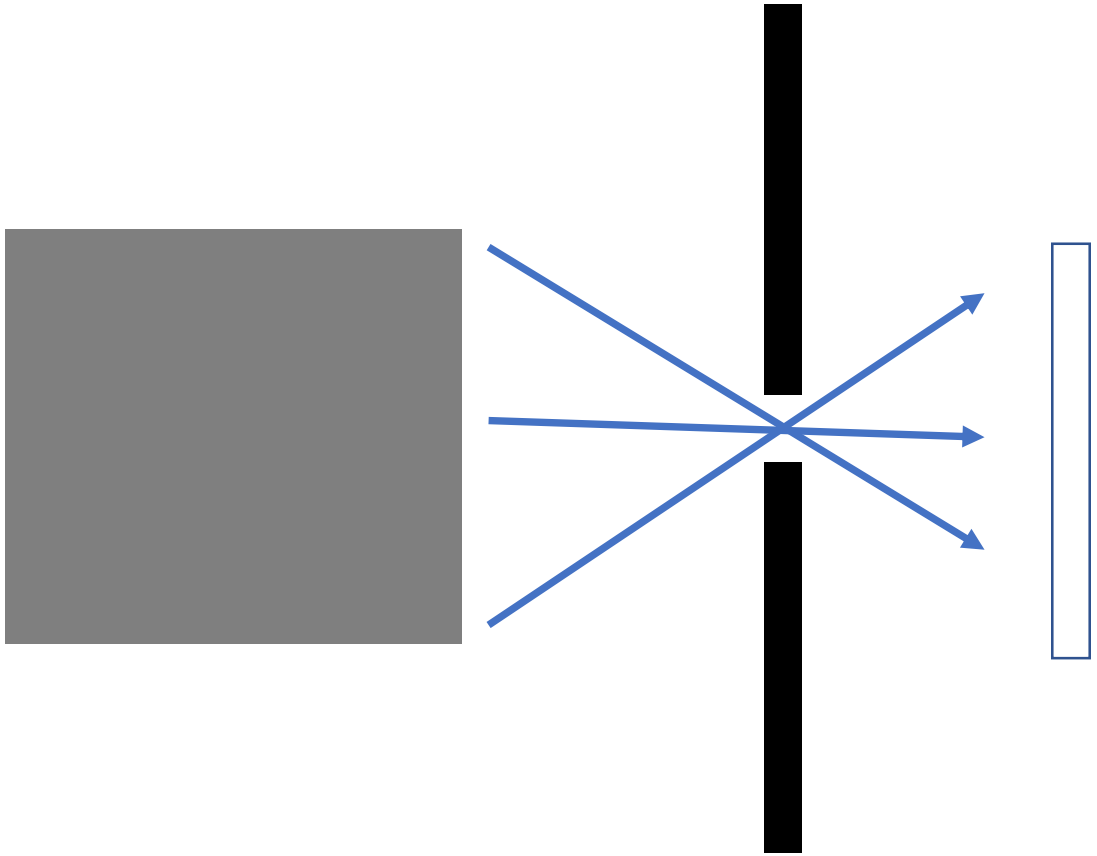

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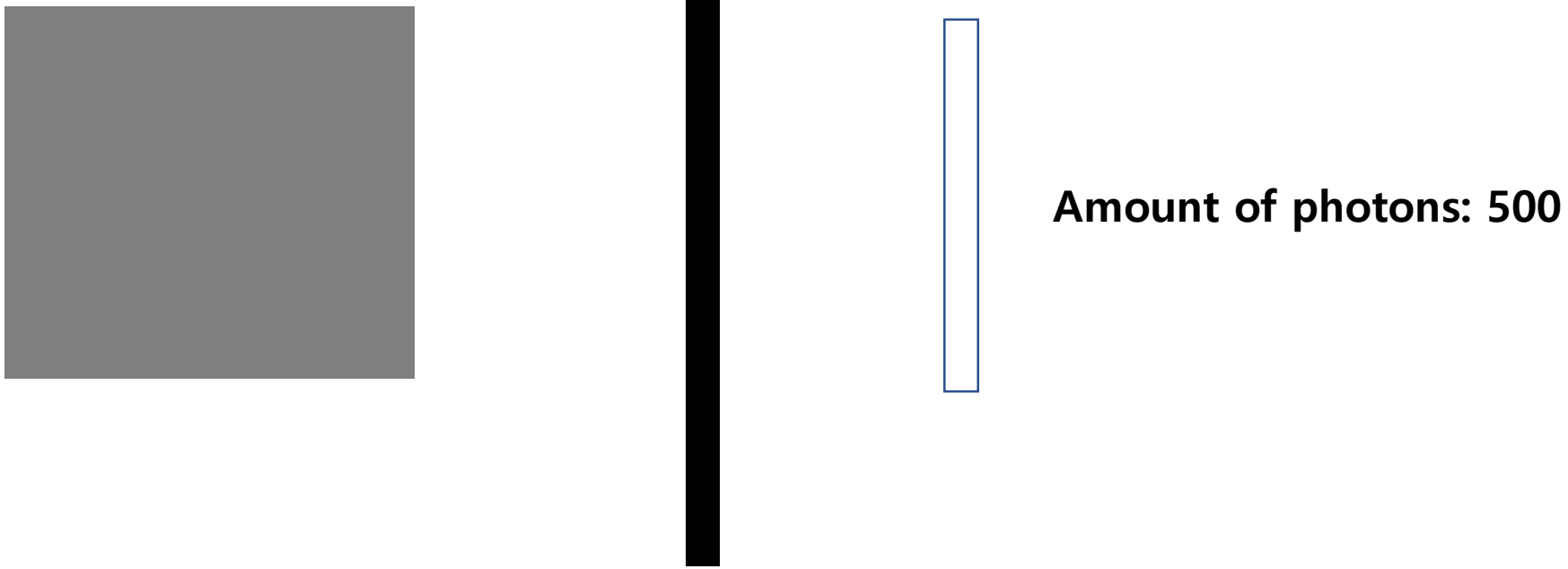

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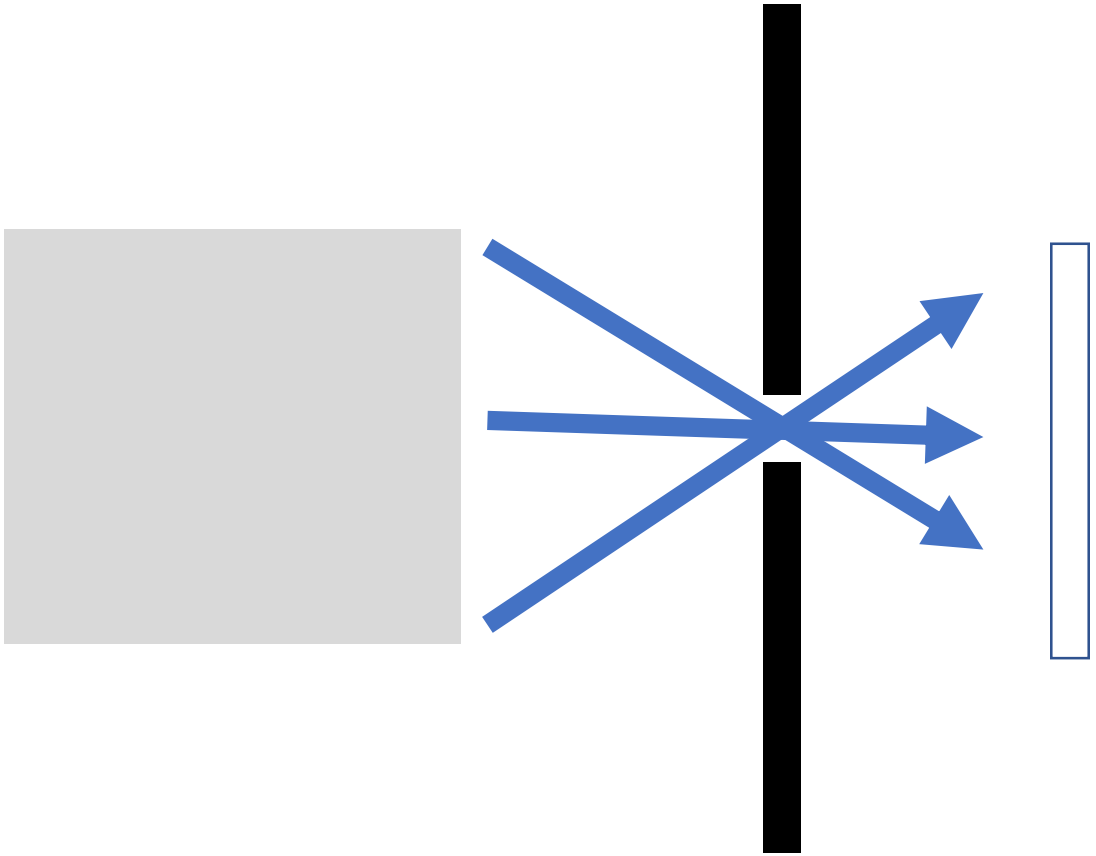


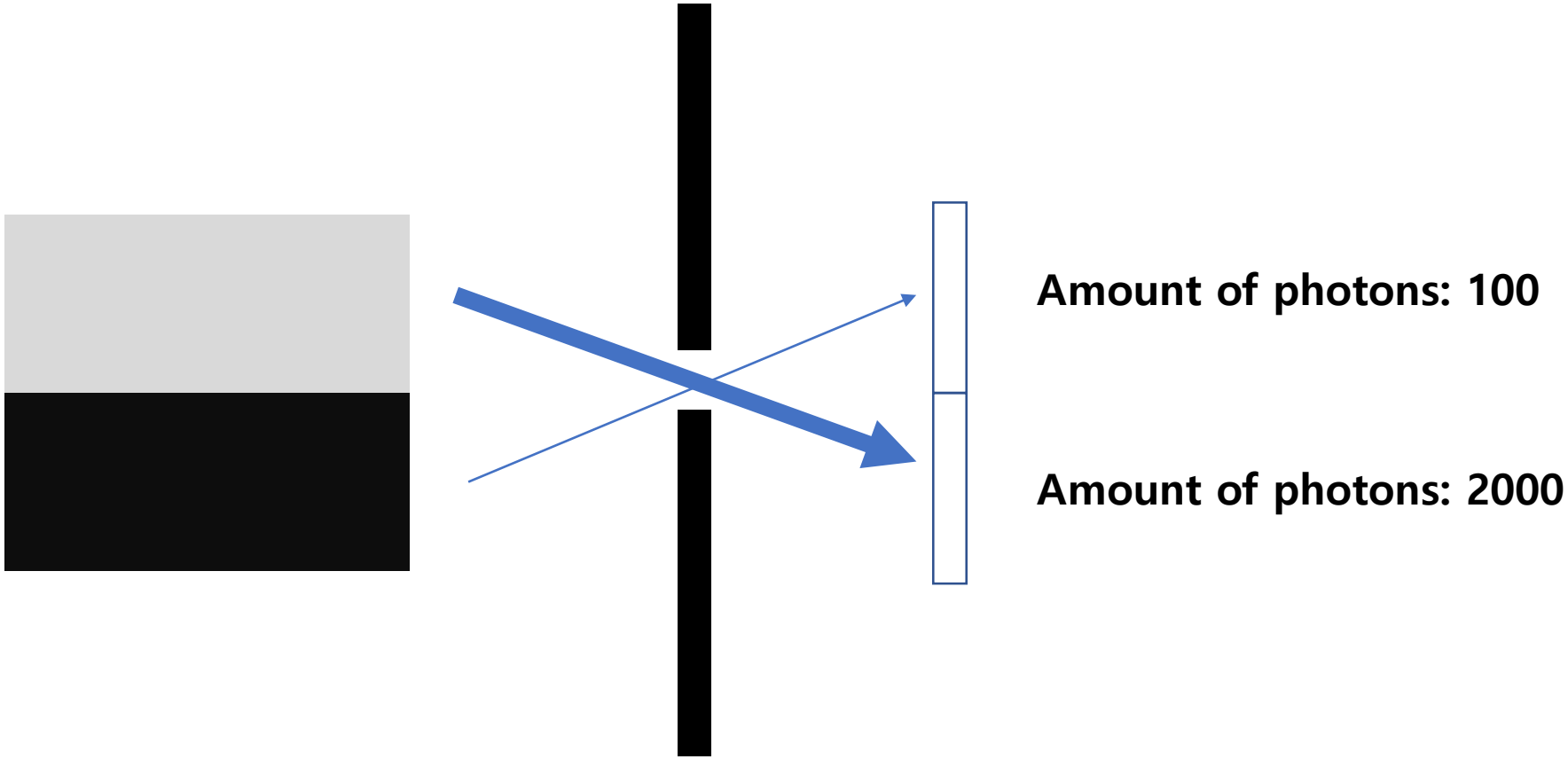
Image sensors

- In principle, an image sensor is a device that measures the **amount of light.**

Amount of photons: 2000

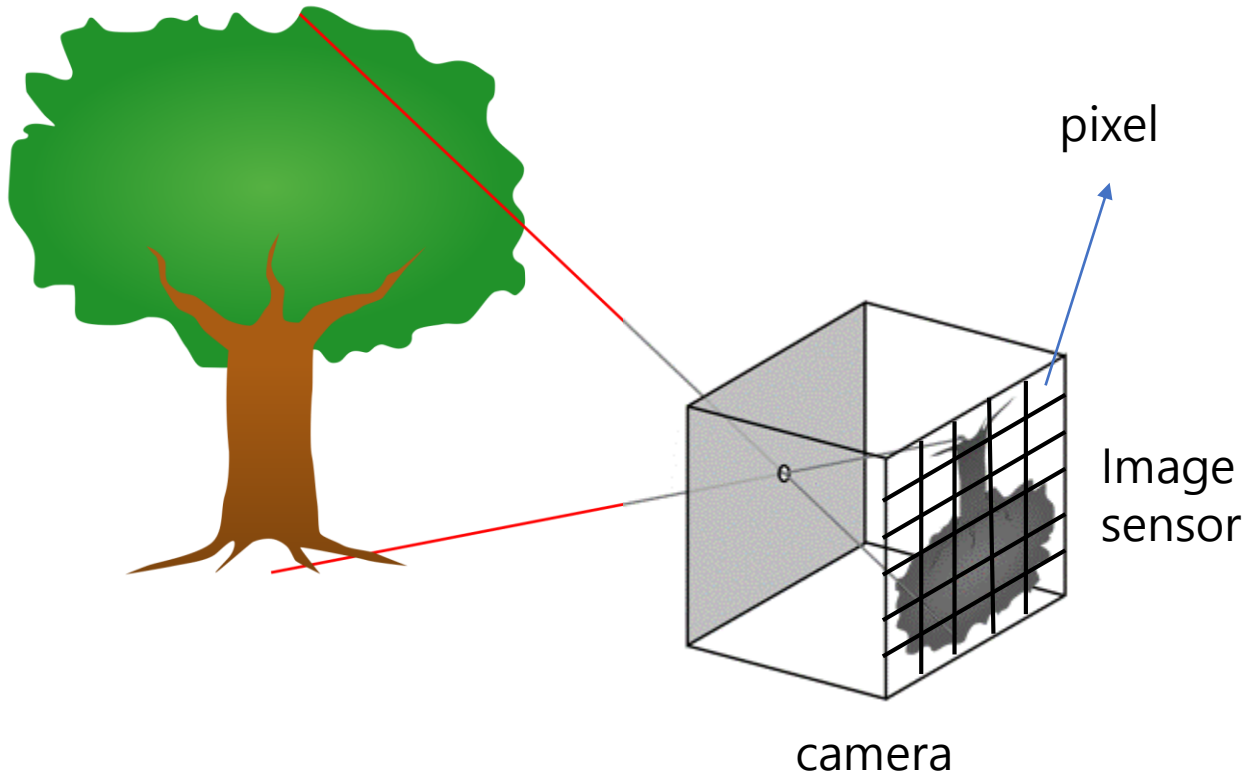
Image sensors

- Spatial division
  - 2D case



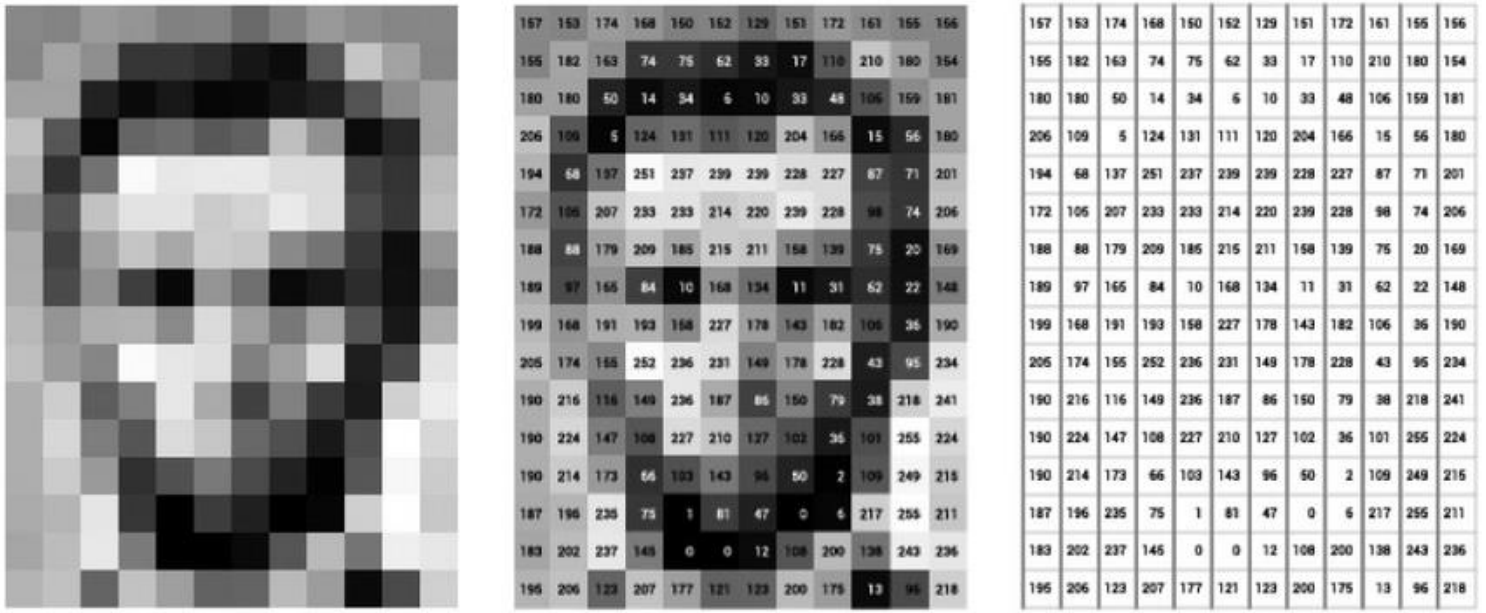
Digital image

- Image representation
  - Image sensors consist of a grid of cells which convert photons into electrical signals.
  - Each grid is called a pixel (picture + element)
  - a pixel, or picture element is a smallest addressable element of an image or display device



Digital image

- Image representation
  - All pixels are in the form of a grid.
  - It has a two-dimensional spatial resolution.
  - **Therefore, we can treat image data as a matrix, of which value means intensity**
  - Most of image processing can be conducted by matrix operation.



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206	109	5	124	131	111	120	204	166	15	56	180
194	68	137	251	237	239	239	228	227	87	71	201
172	105	207	233	233	214	220	239	228	98	74	206
188	88	179	209	185	215	211	158	139	75	20	169
189	97	165	84	10	168	134	11	31	62	22	148
199	168	191	193	158	227	178	143	182	106	36	190
205	174	155	252	236	231	149	178	228	43	95	234
190	216	116	149	236	187	86	150	79	38	218	241
190	224	147	108	227	210	127	102	36	101	255	224
190	214	173	66	103	143	96	50	2	109	249	215
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

157	153	174	168	150	152	129	151	172	161	155	156
155	182	163	74	75	62	33	17	110	210	180	154
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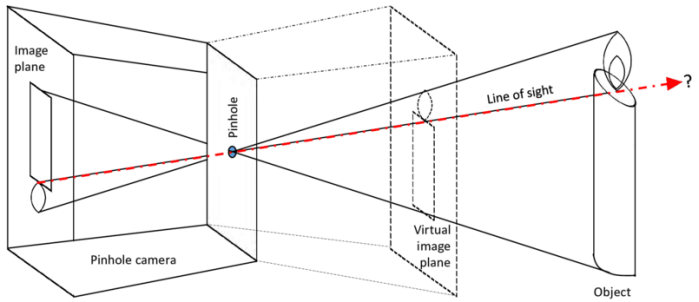
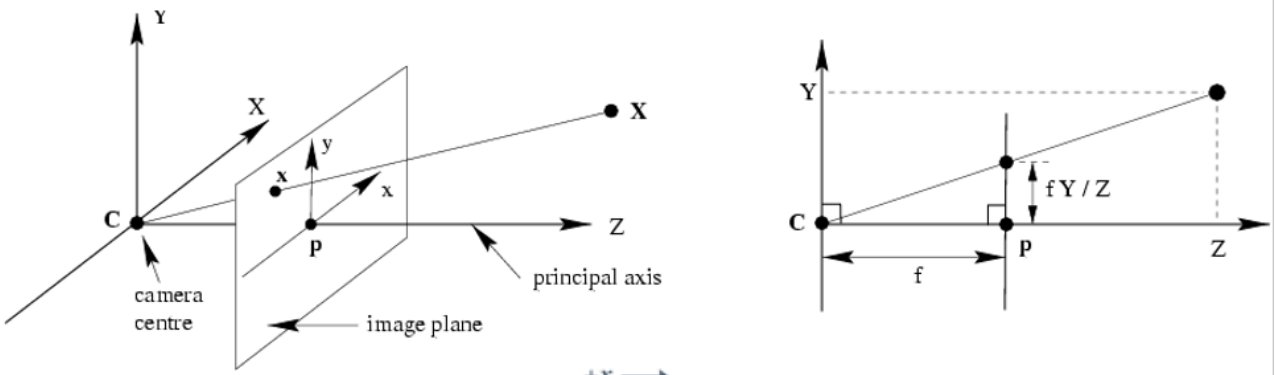
187	196	235	75	1	81	47	0	6	217	255	211
183	202	237	145	0	0	12	108	200	138	243	236
195	206	123	207	177	121	123	200	175	13	96	218

https://www.researchgate.net/figure/mage-of-Abraham-Lincoln-as-a-matrix-of-pixel-values_fig1_330902210

Pinhole camera model

- Image plane (virtual)
  - A plane that symmetrizes the actual projected plane (sensor) with respect to the origin (pinhole).
  - Intuitive and easy calculation
- Coordinate system
  - Camera coordinate (3D)
    - Center: pinhole
    - Image plane: (xk, yk, k)
  - World coordinate (3D, optional)
    - C_w to C_c → $\mathrm{X_c} = \mathrm{T_w^C} X_w$
  - Image(pixel) coordinate (2D, [u v])
  - **Focal length**: distance to image plane





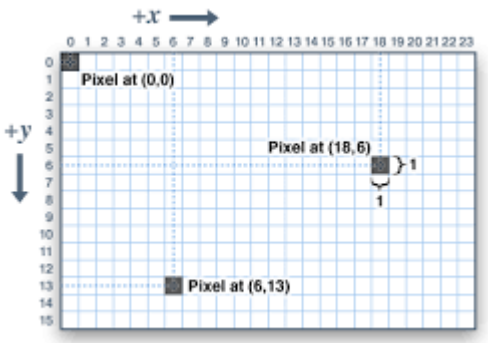


Image format

- Resolution
  - Precision of the sensor
  - Size of image
    - VGA: 640 x 480
    - HD: 1280 x 730
    - FHD: 1920 x 1080
    - UHD(4K): 3840 x 2160

- Aspect ratio
  - The ratio of its width to its height

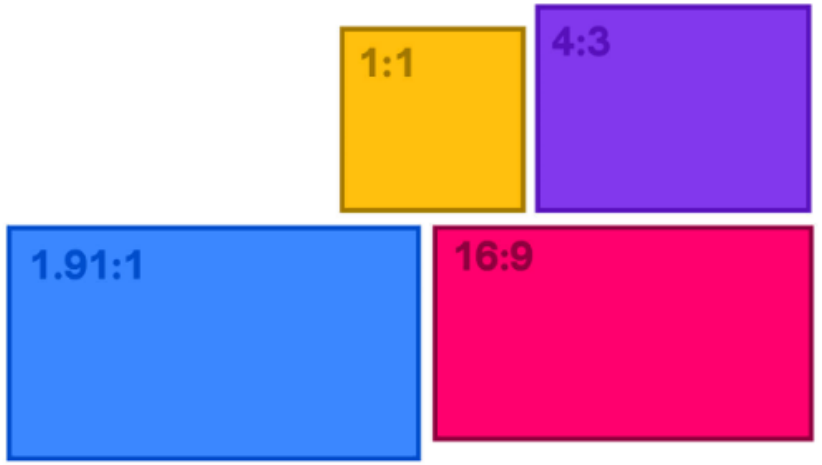
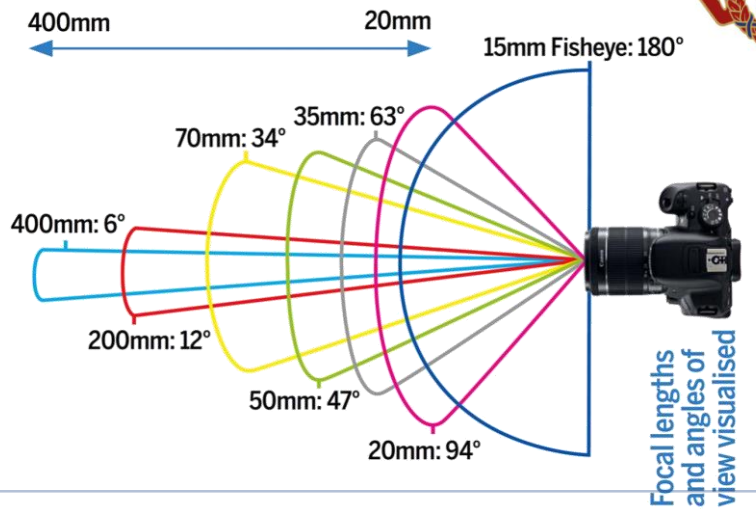
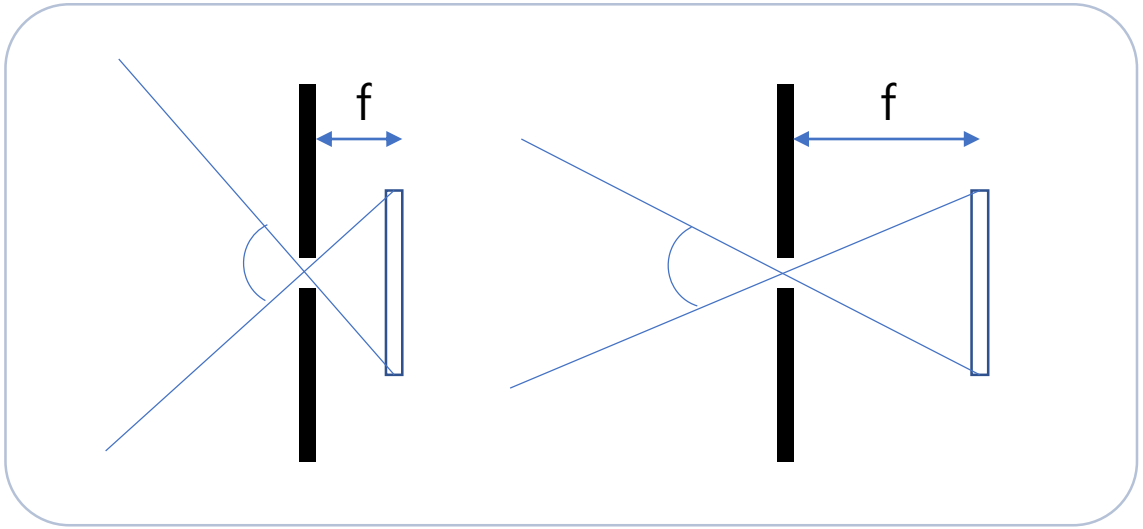


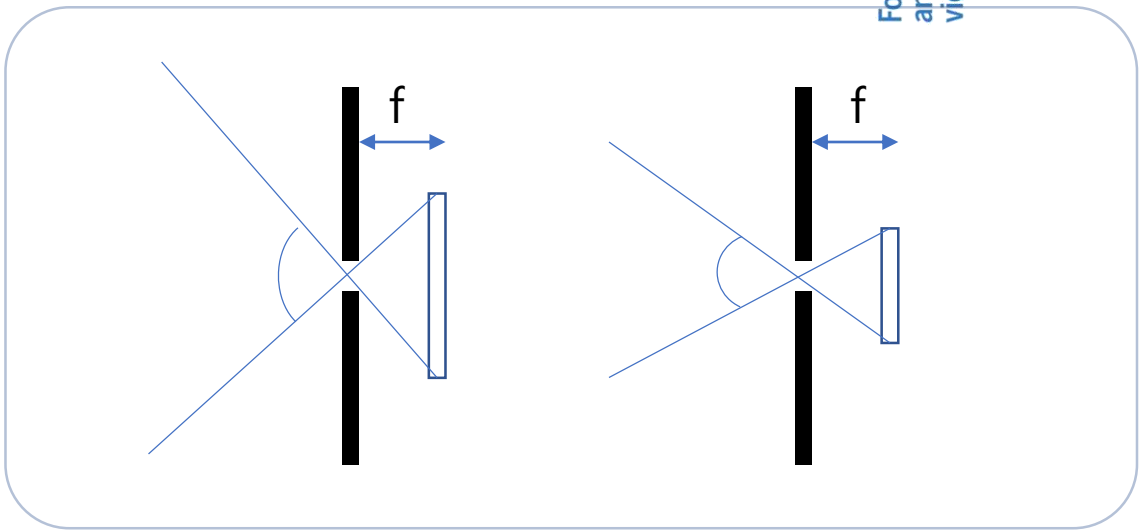
Image format

- Field of view (FOV)
  - The extent of the observable world
  - Expressed in degrees
  - It depends on the camera's sensor size and the lens's focal length





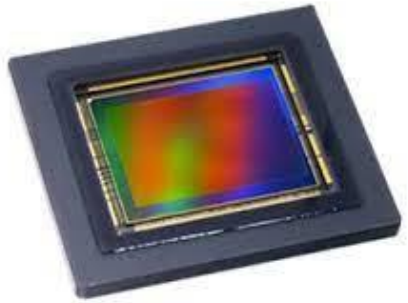
Different focal length
Same sensor size



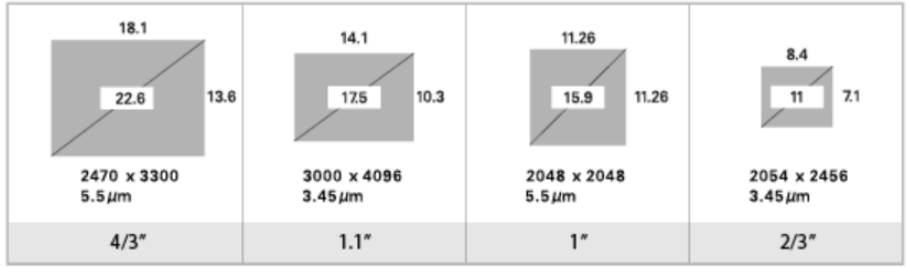
Same focal length
Different sensor size

Image sensor size

- Pixel size (= Cell size)
  - Size of each pixel(cell) of the image sensor
  - Larger pixel size : less noise, high dynamic range



- Sensor size
  - Sensor size = resolution x pixel size
  - 35mm(DSLR, Full frame) vs 8~10 mm (smart phone)
  - Large sensor: high resolution, large cell size

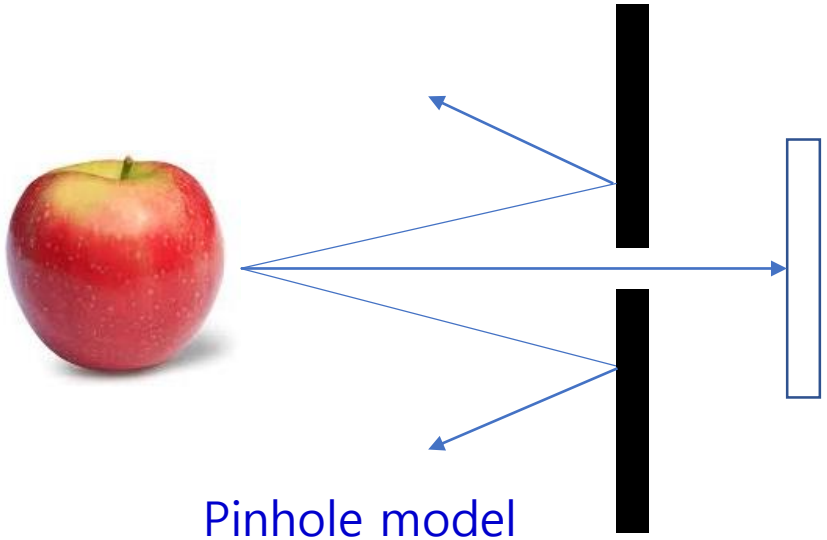


- Camera bump (카툭튀)
  - For high resolution
  - For high dynamic range

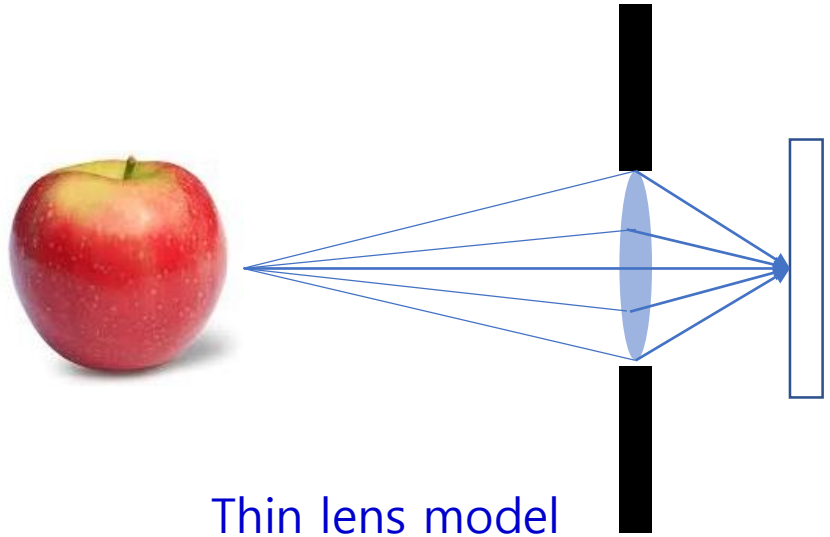
https://economictimes.indiatimes.com/magazines/panache/iphone-14-pro-to-feature-a-bigger-camera-bump-than-iphone-13-pro-heres-why/articleshow/90490125.cms?from=mdr

Lens

- Why lens?
  - A lens is a tool used to bring light to a fixed focal point.
  - **To collect more light rays in the same direction**
  - To implement FOV beyond linear model



Pinhole model

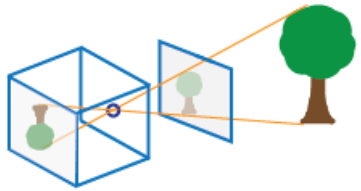


Thin lens model

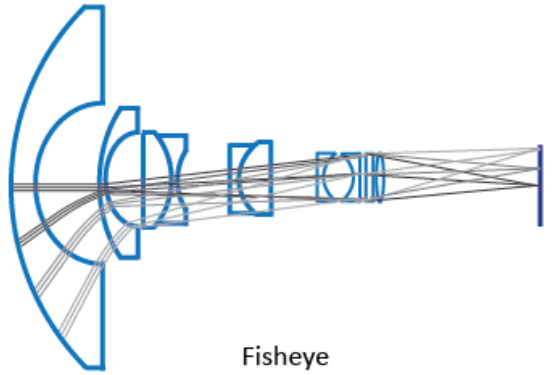
  - We can still consider a camera with a lens as a pinhole model.

Camera with lens

- Pros.
  - To implement FOV beyond linear model
  - Ex. fisheye camera, smartphone



Pinhole

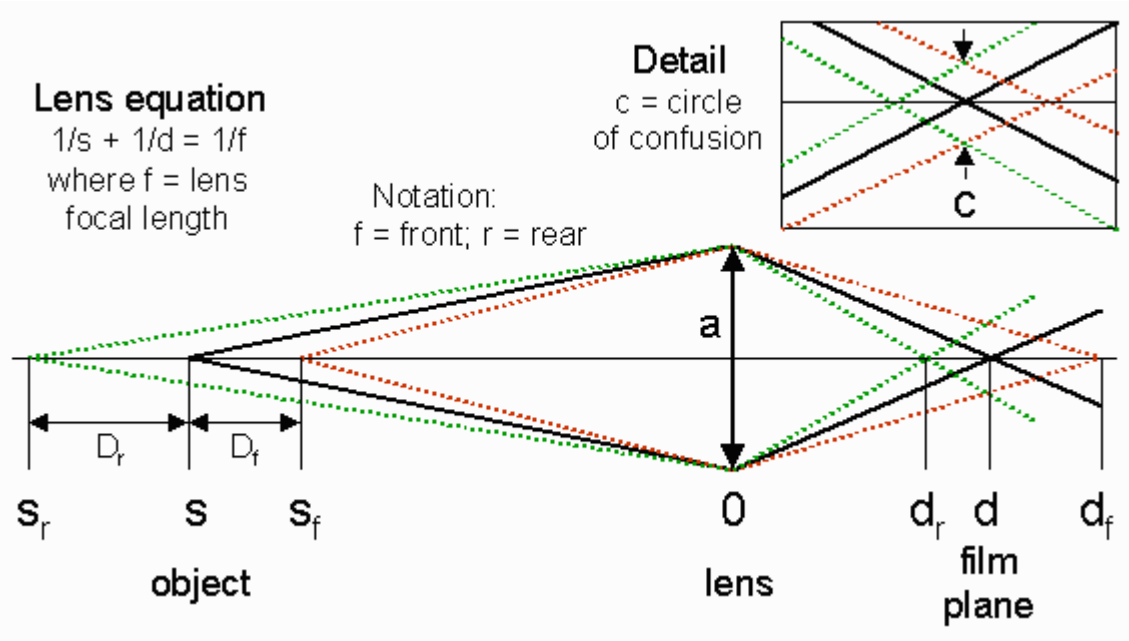


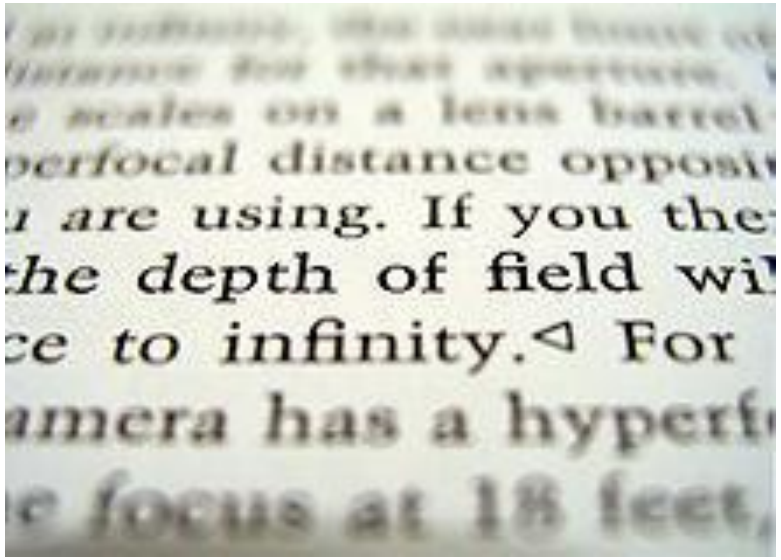
Fisheye

- Cons.
  - Lens has focal length → Out focusing
  - Chromatic aberration → Refraction varies with wavelength
  - Spherical aberration → Radial distortion

Camera with lens

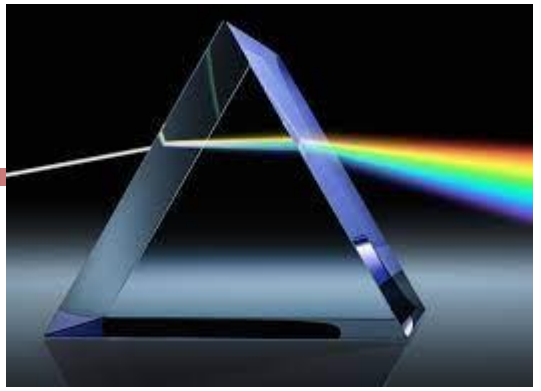
- Out focusing
  - Focal length is defined for each lens
  - Need to change the focal length depending on the distance of the object.



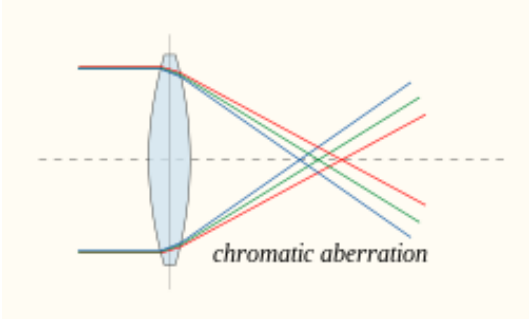


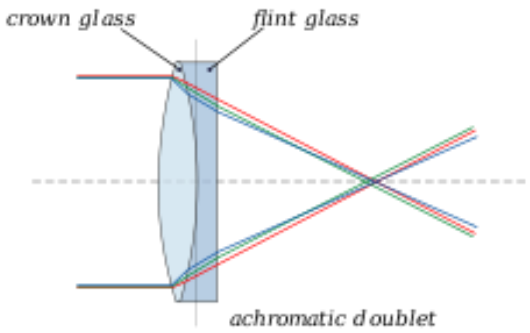
http://www.normankoren.com/Tutorials/MTF6.html

Camera with lens



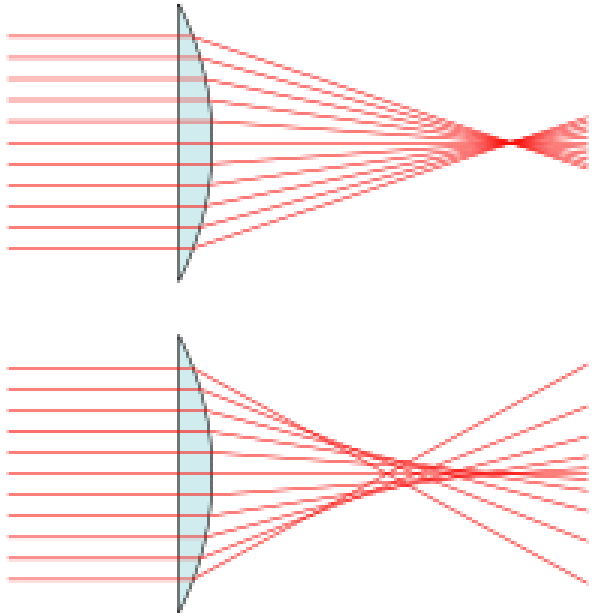
- Chromatic aberration
  - chromatic distortion and spherochromatism
  - Refraction varies with wavelength





Camera with lens

- Radial distortion
  - Spherical aberration
  - Solution: S/W calibration, Aspherical Lens, small aperture

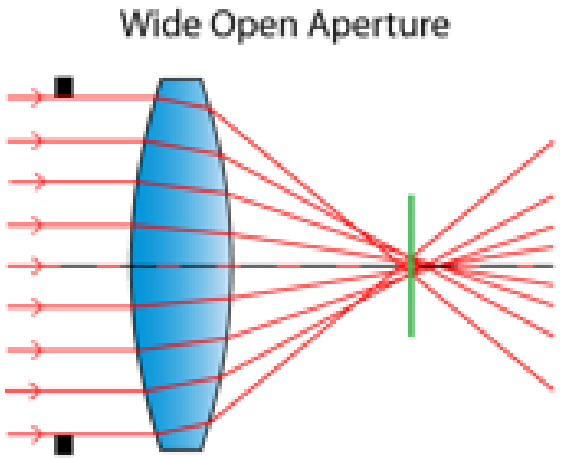


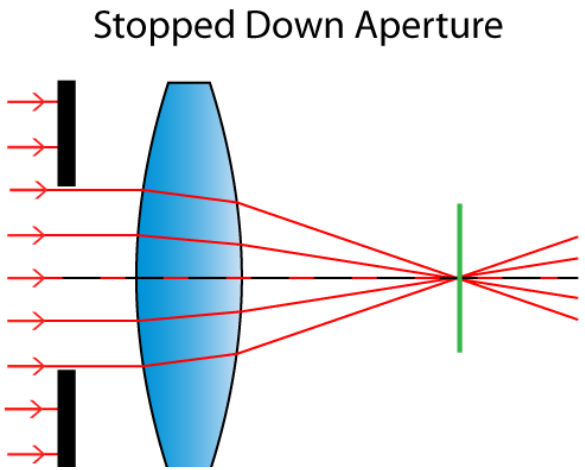
Spherical aberration

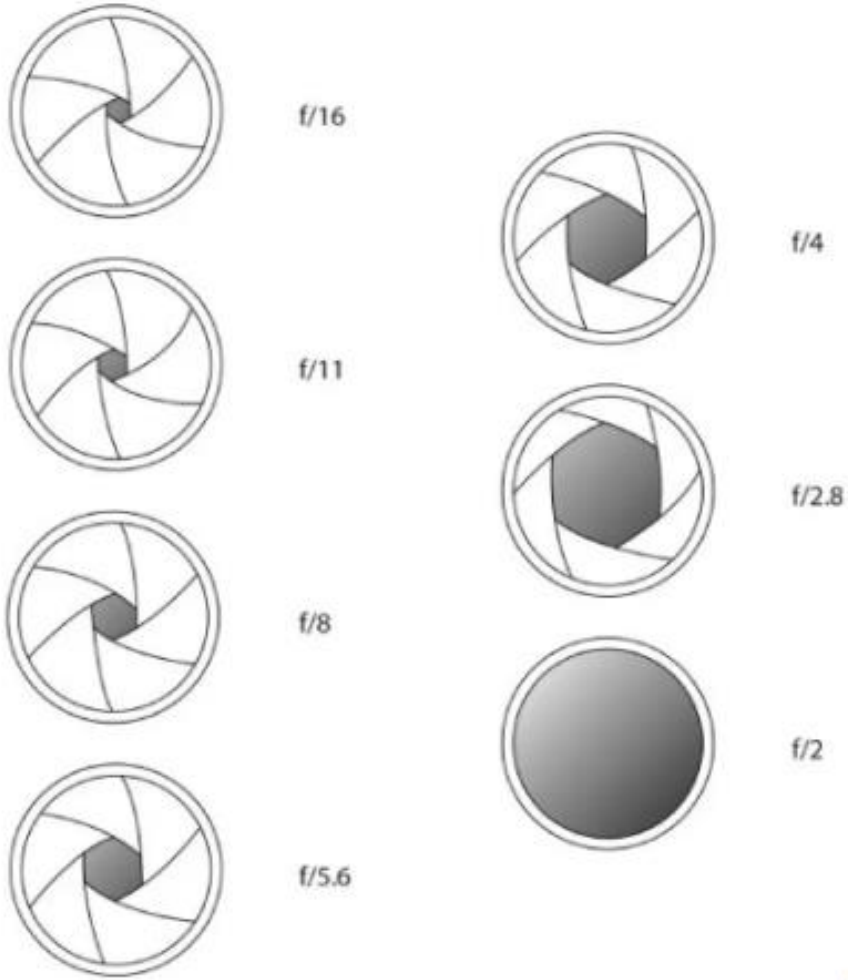
Radial distortion and warping image

Camera with lens

- Aperture (조리개)
  - Opening size of the lens
  - Wider: more light, more aberration, narrow depth of field
  - Aperture are notated as f/stops (F-number)

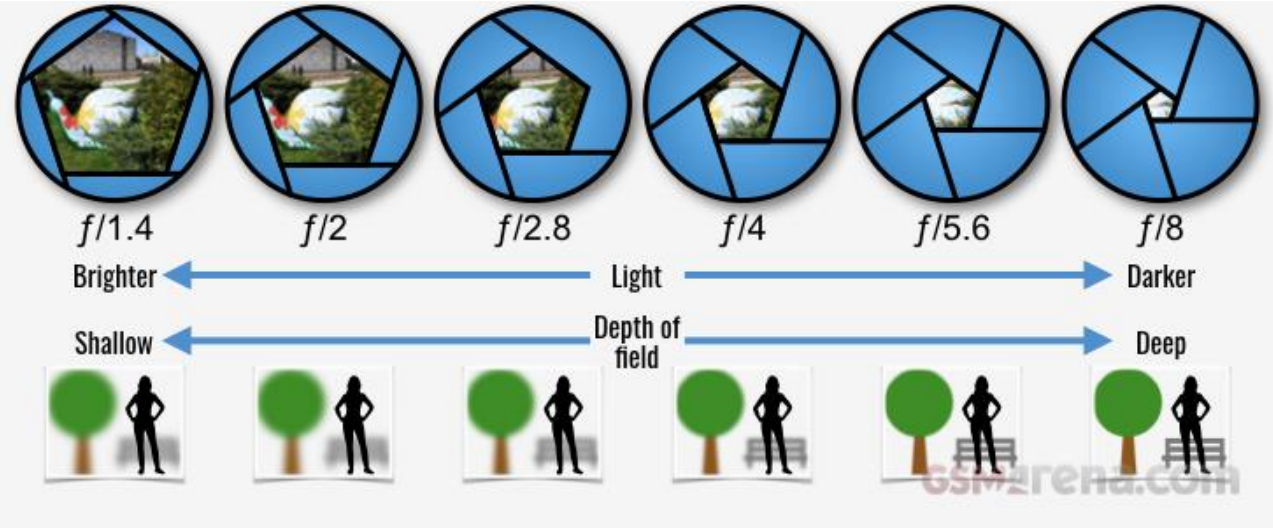






F number (F-stop)

- Represent amount of light to the sensor
  - Aperture size of f/x = Focal length(f) / x
  - Ex) f/2 of 50mm focal length camera: Aperture size (25mm)
  - Depth of field
    - the distance between the nearest and the furthest objects that are in acceptably sharp focus



Galaxy S23 5G

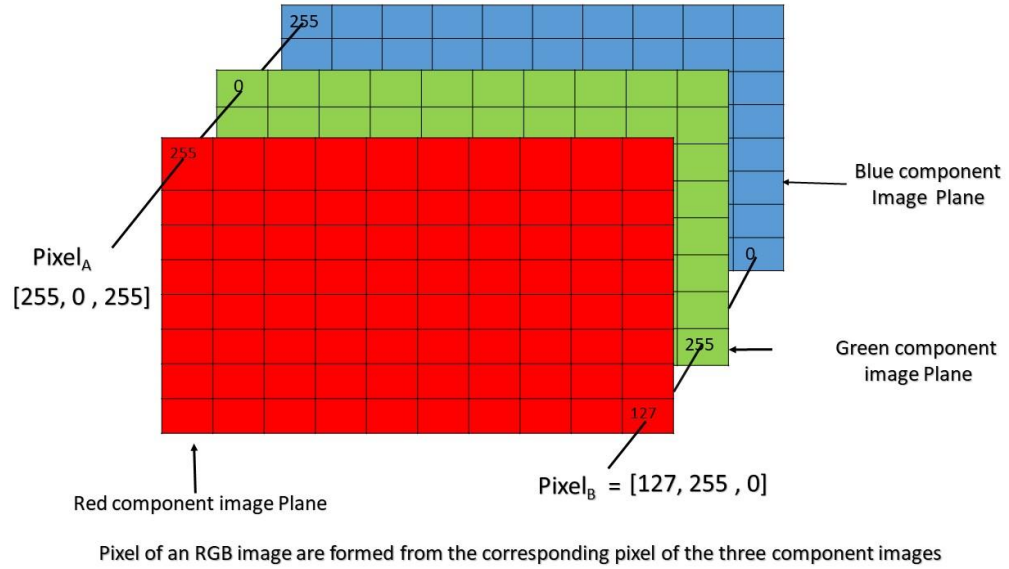
사이즈	6.1"
CPU	4nm, Snapdragon 8 Gen 2 for Galaxy
전면 카메라	12MP 2PD F2.2 1/3.2"
후면 카메라	초광각 12MP, F2.2 1/2.55" 광각 50MP(2PD) F1.8 1/1.56" 망원1 10MP(3x) F2.4 1/3.94"

Color image

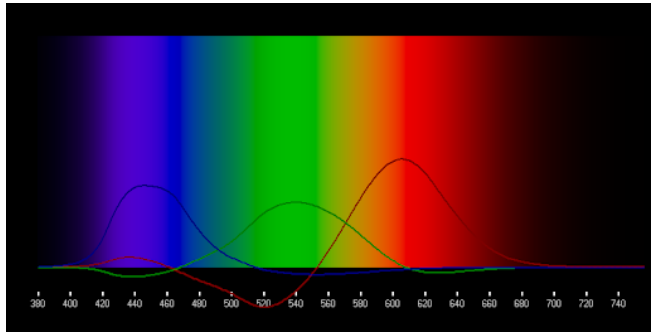
- We learned that each pixel value is the brightness value of light (=amount of photons)
- This means the image can represent intensity value only → grayscale
- Question) How can get color images?
  - Hint) Consider the human case.
- Solution
  - A. Use sensors that respond differently to different wavelengths.
  - B. Use another method

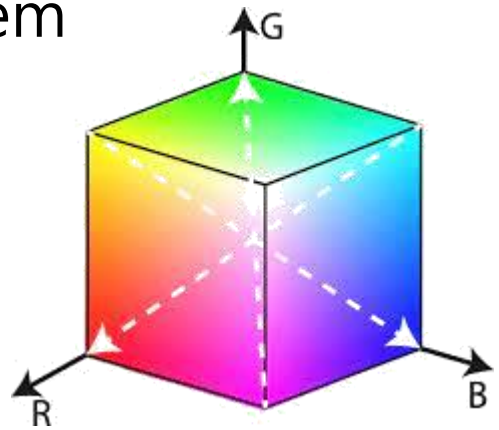
Color image

- Solution
  - B. Use another method
- Filtering
  - Capture Red wavelength
  - Capture Green wavelength
  - Capture Blue wavelength
  - Then, concatenate them



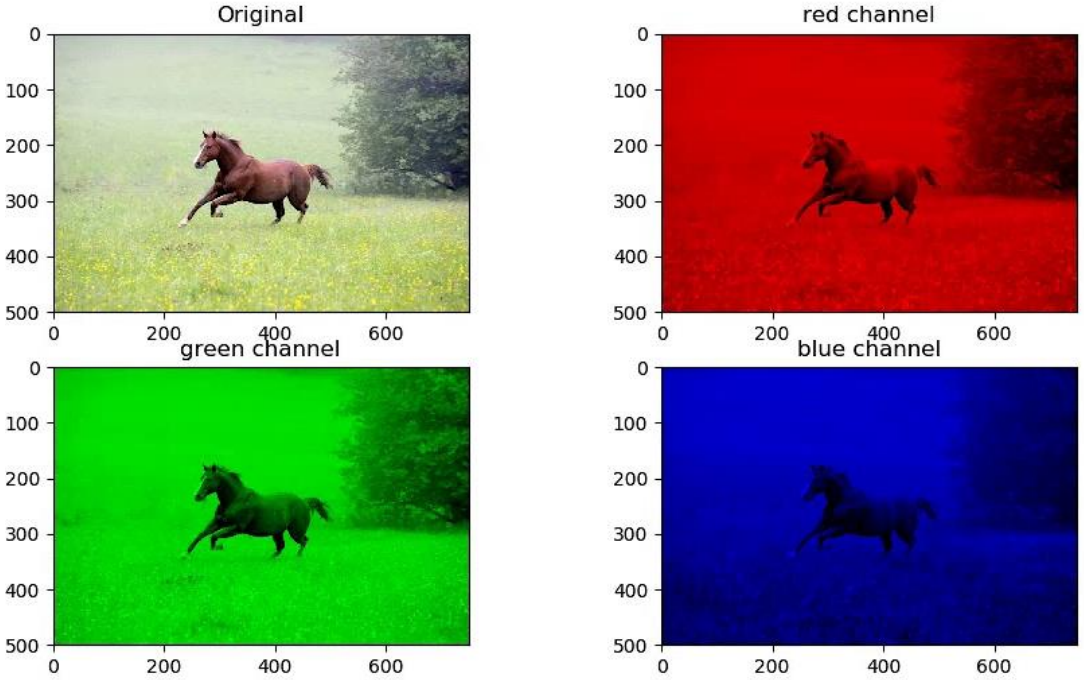
Pixel of an RGB image are formed from the corresponding pixel of the three component images

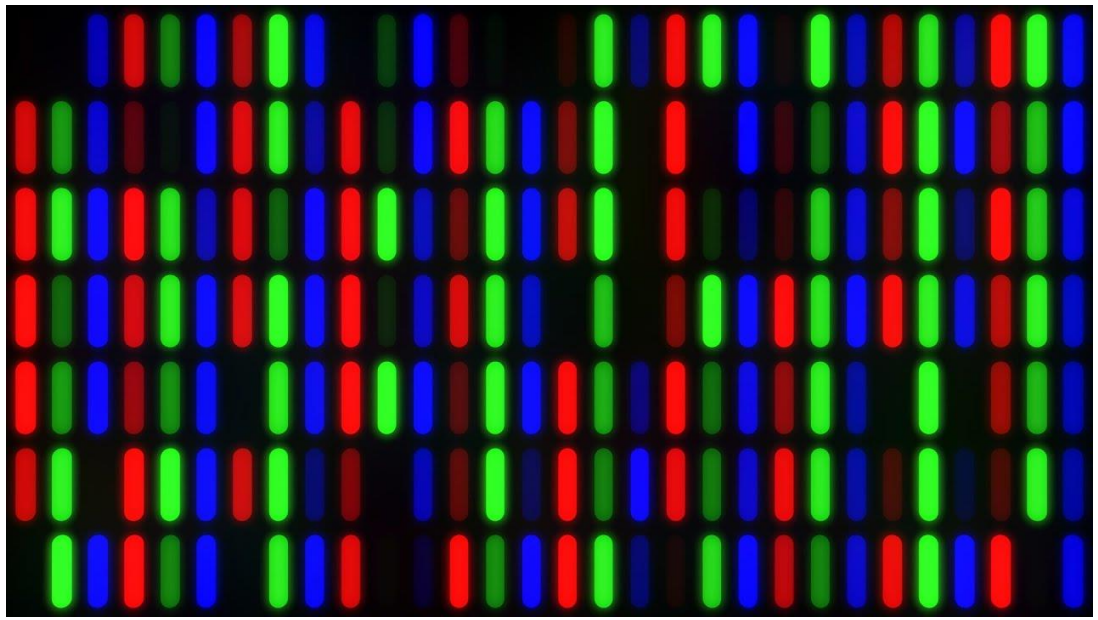




Color image

- Remember that
  - No color image is exist
  - We save and display brightness divided by R, G, B

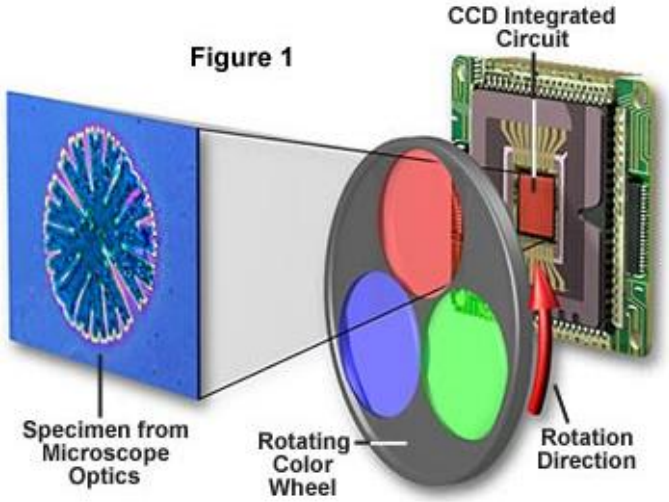




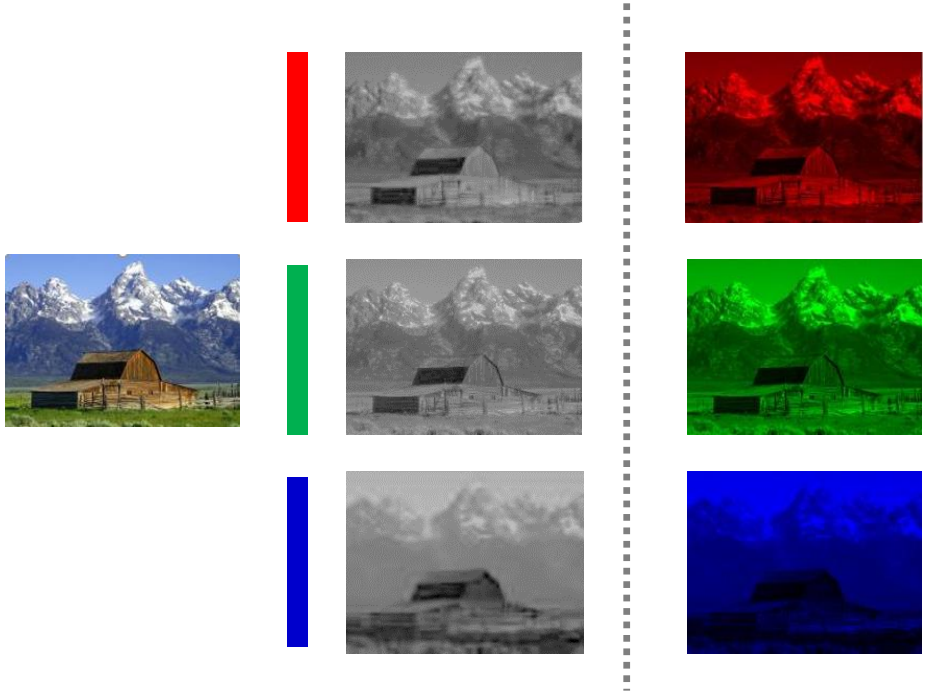
Display pixel

Color image

- Color filter
  - We filtering wavelength
  - Only pass rays, of which wavelength are red, green, blue

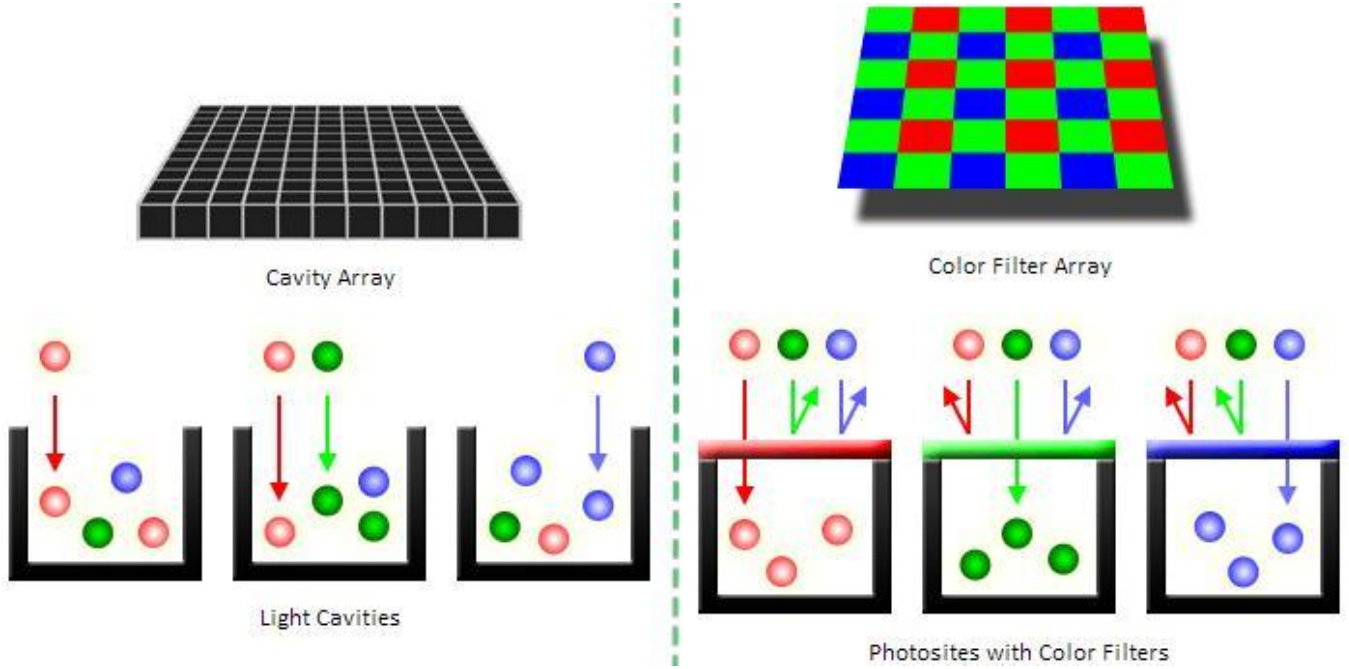


Sequential color filter



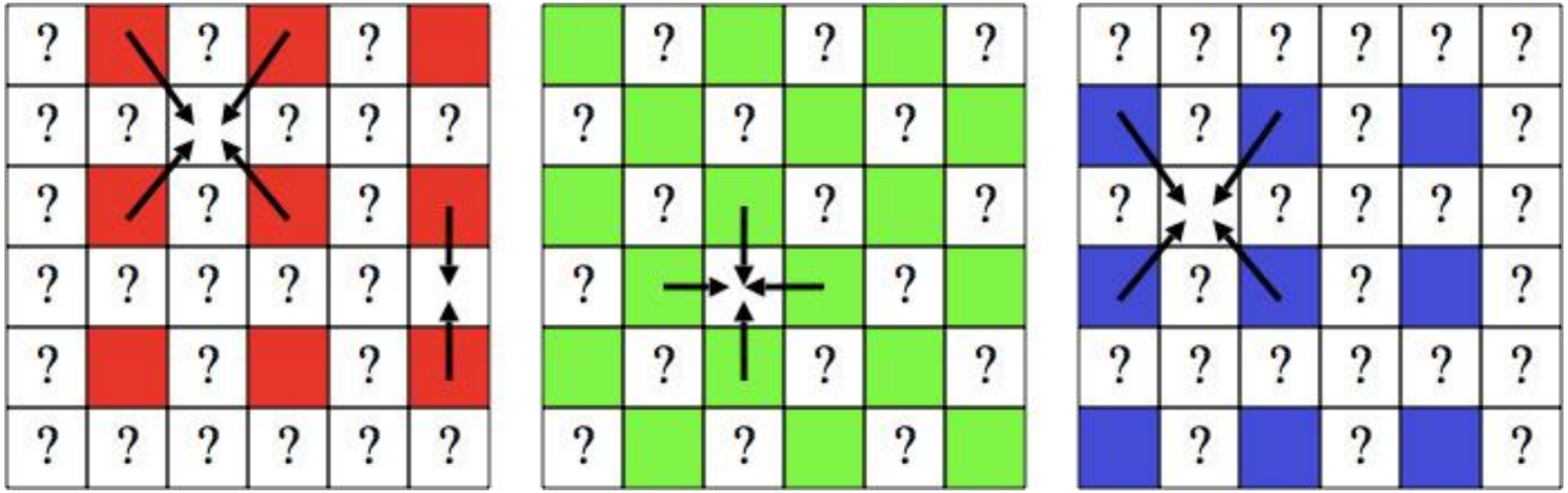
Color image

- Color filter array
  - A mosaic of tiny color filters placed over the pixel sensors of an image sensor to capture color information.
  - Get R, G, B images at once → Reduction of spatial resolution



Color image

- Color filter array
  - Pixels estimate their R, G, B values by interpolation
    - When a pixel has a R, B, or B value, the pixel use the value
    - When a pixel does not have R, G, or B value, mix up neighborhood values.



Color image

- Color filter array
  - Pixels estimate their R, G, B values by interpolation
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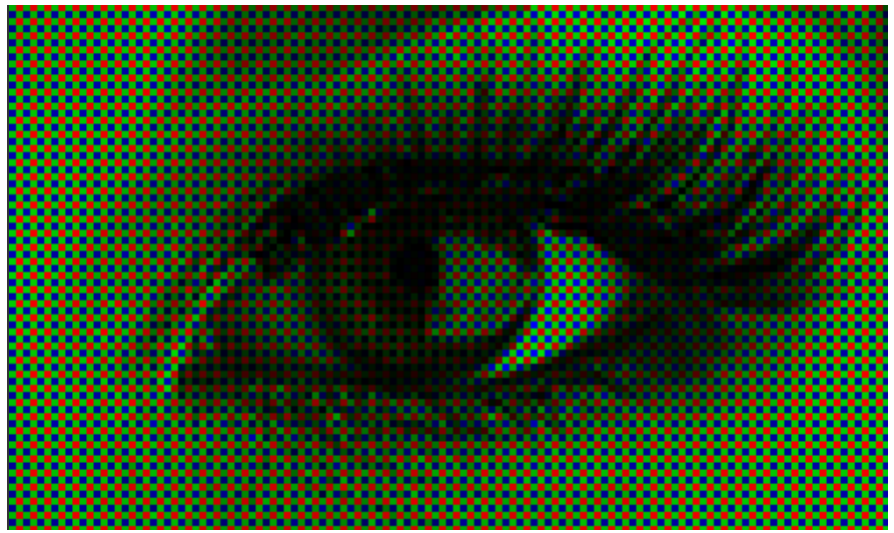
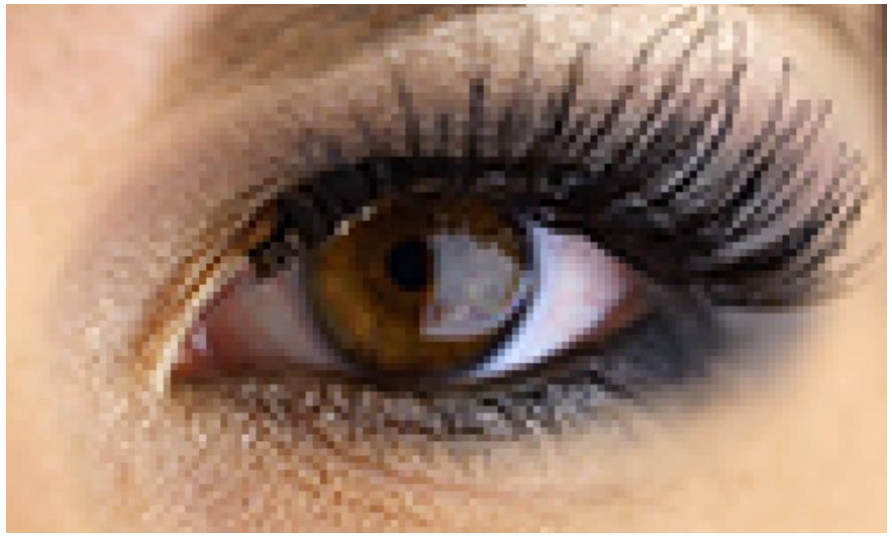


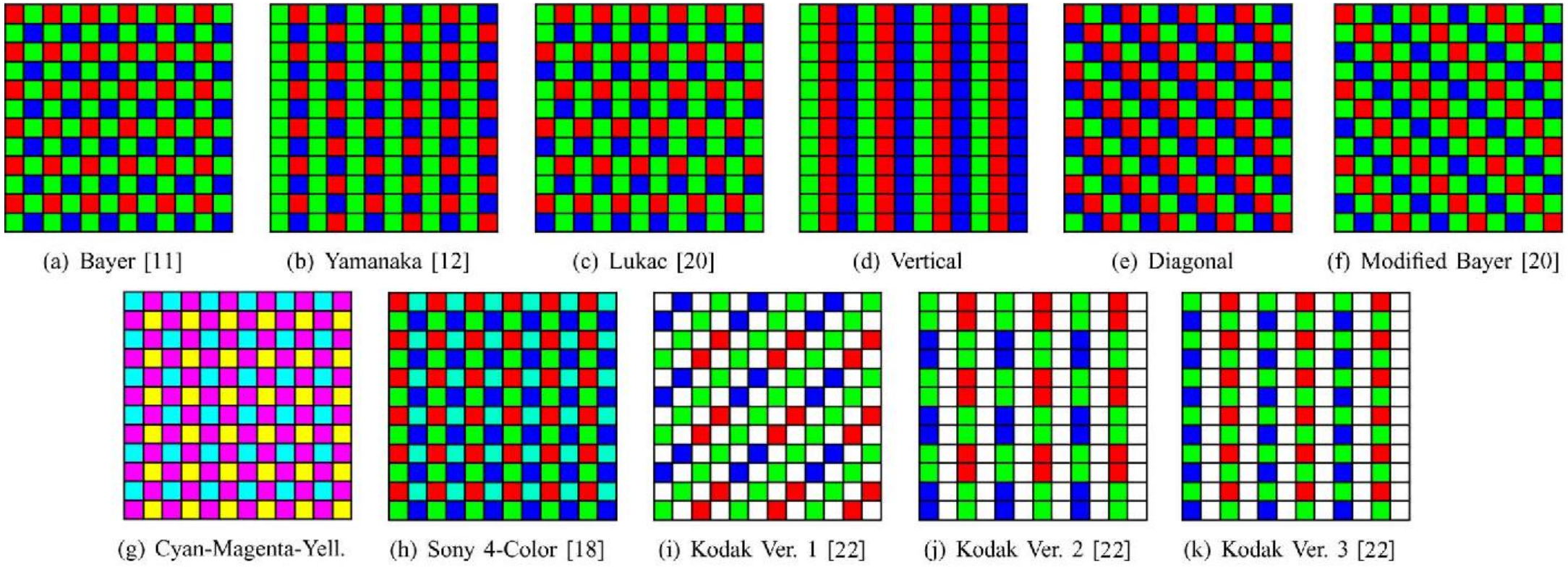
Bayer image



Interpolated image

Color image

- Various color filter array



(a) Bayer [11] (b) Yamanaka [12] (c) Lukac [20] (d) Vertical (e) Diagonal (f) Modified Bayer [20]

(g) Cyan-Magenta-Yell. (h) Sony 4-Color [18] (i) Kodak Ver. 1 [22] (j) Kodak Ver. 2 [22] (k) Kodak Ver. 3 [22]

End of the class

Q n A