Summer term 2024 – Cyrill Stachniss

5 Minute Preparation Video

https://www.youtube.com/watch?v=ViCqs7J2yi0

Photogrammetry & Robotics Lab

Camera Basics and Propagation of Light

Cyrill Stachniss

The slides have been created by Cyrill Stachniss.

How to Obtain an Image?

Image Courtesy: Leonardo Garcia

What Does a Camera Measure?

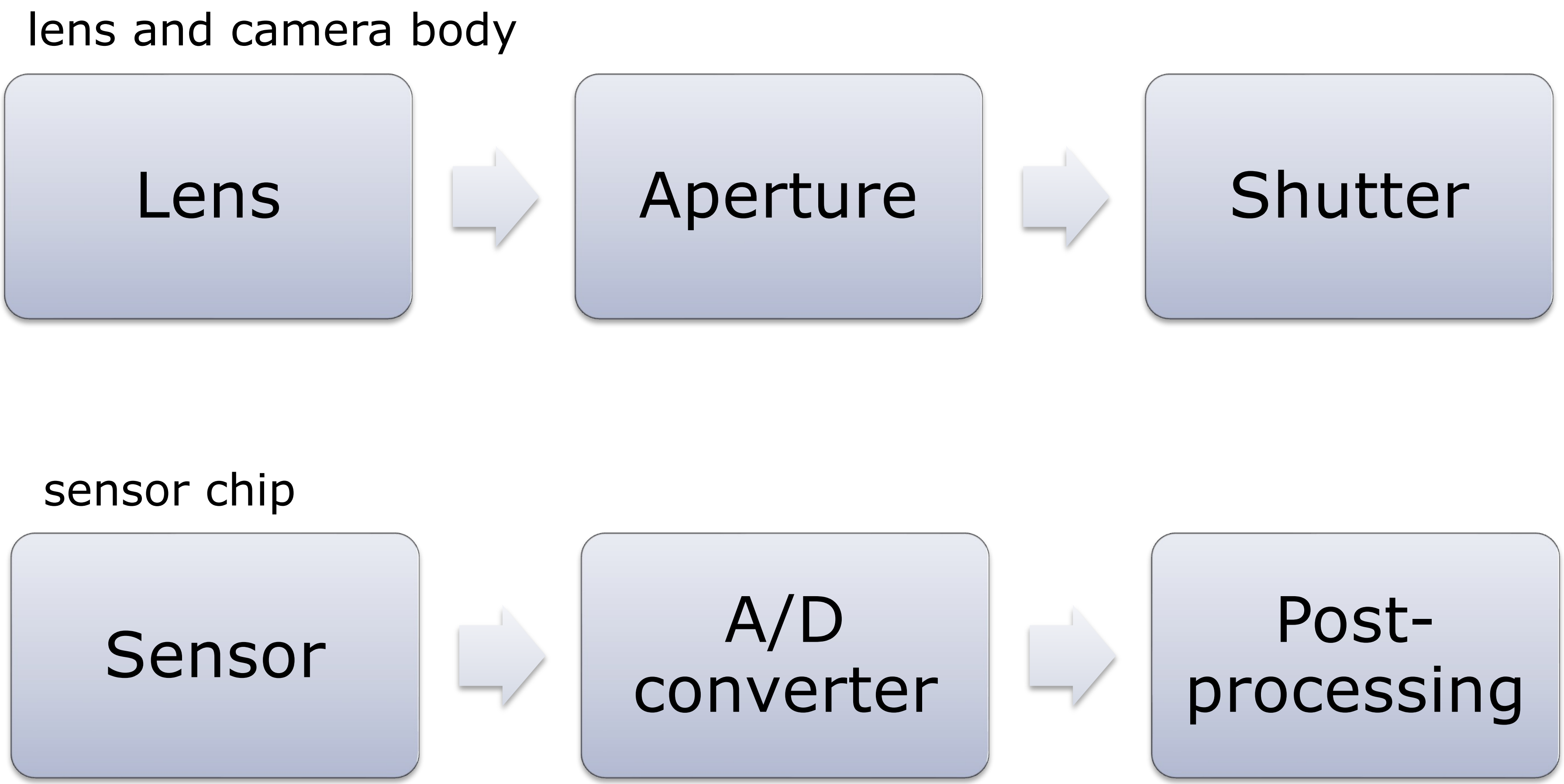
Image Courtesy: D. Yun

What do Cameras Measure?

- Cameras provide 2D images consisting of pixels (“picture elements”)
- Cameras measure the **light intensity** for each pixel
- Each position in an image (=**pixel**) corresponds to a **specific direction** in the 3D world

Each pixel measures the amount of light coming from a certain direction.

Elements of a Digital Camera



Sensor

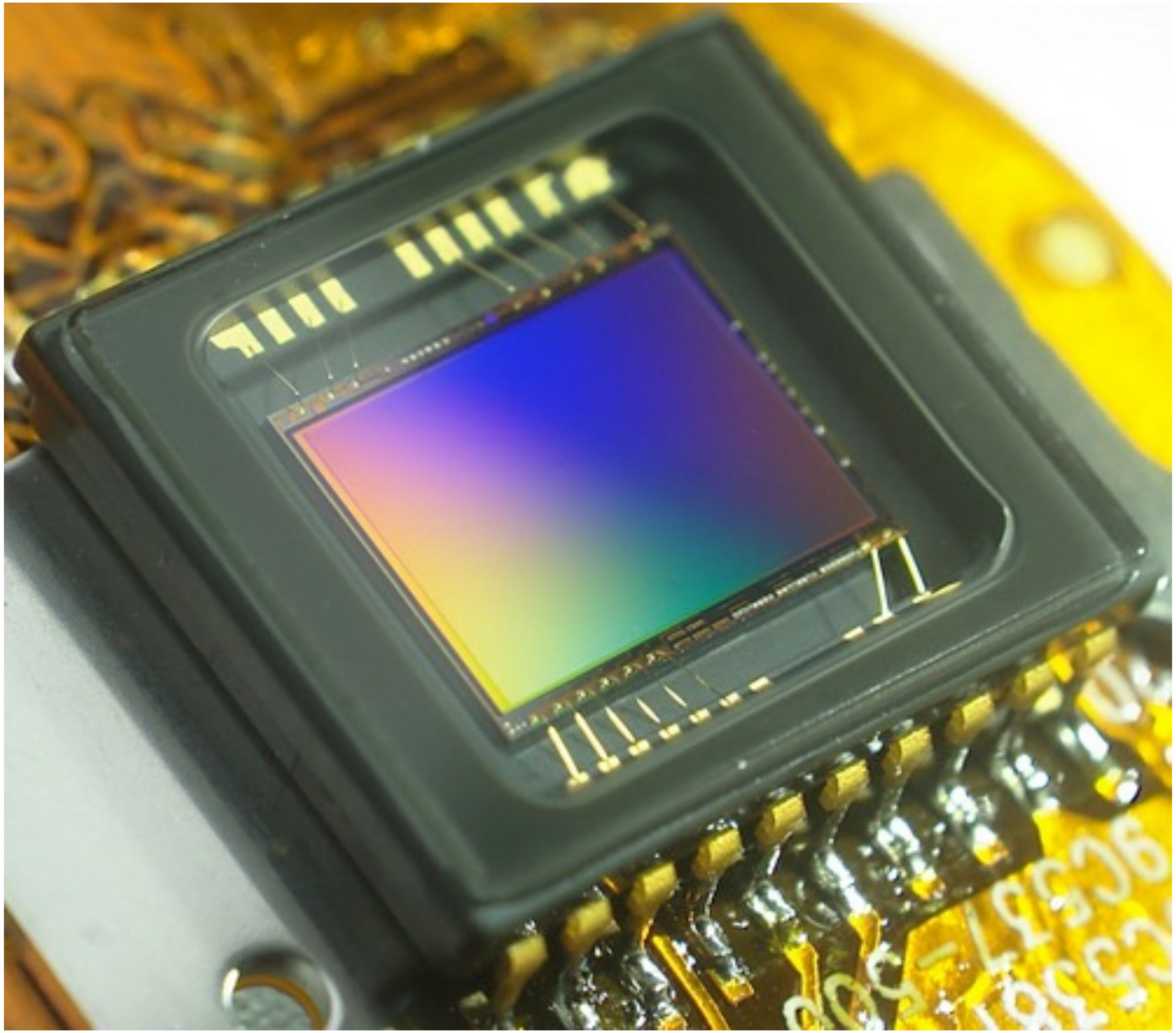


Image Courtesy: TechHive

Sensor

- The image sensor converts the incoming light to intensity values
- Array of light-sensitive cells
- Larger sensor cells can collect more light per time interval
- Larger chips are more expensive to produce
- Larger chips require larger (and thus more expensive) lenses

Typical Sensor Sizes

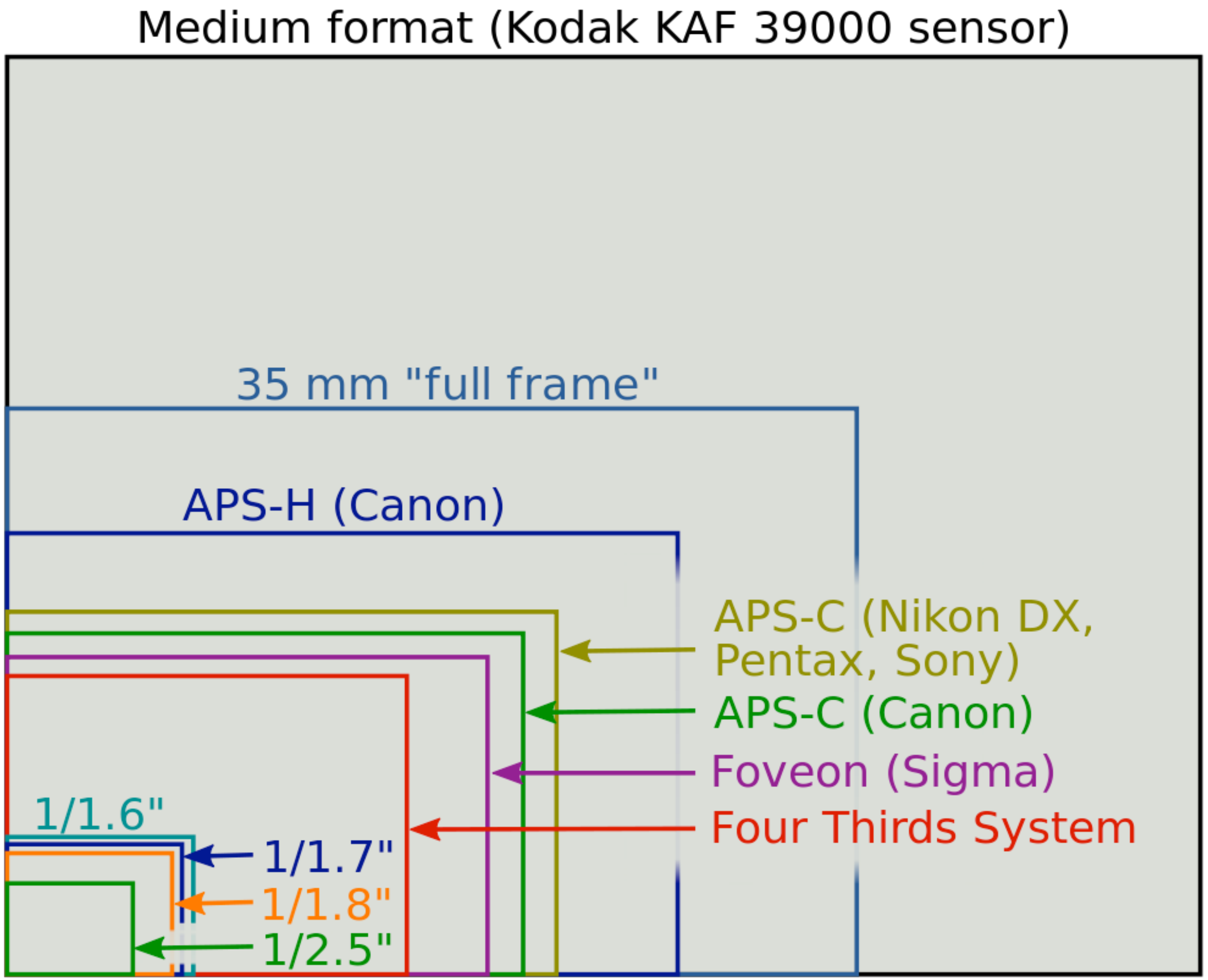


Image Courtesy: MarcusGR

How to obtain
color information?

Three-Chip Camera

- Three chips with separate filters for red, green, and blue
- Light is separated with a beam splitter

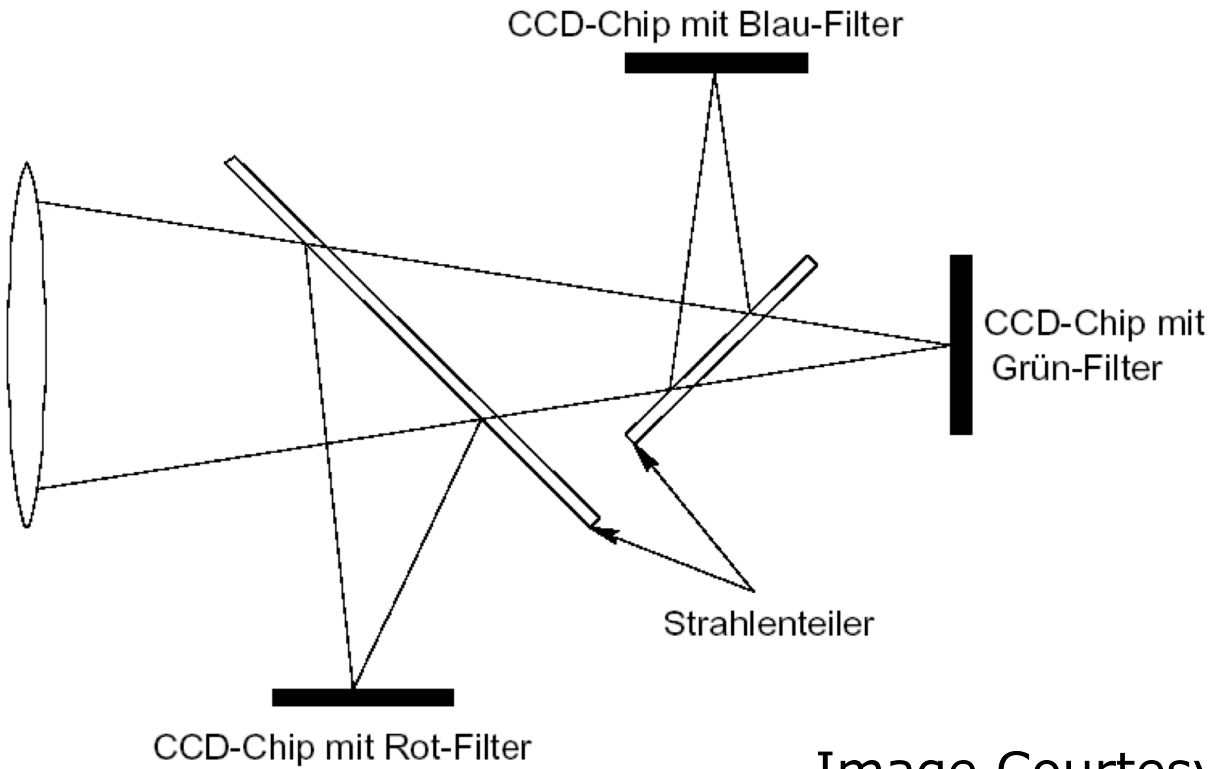
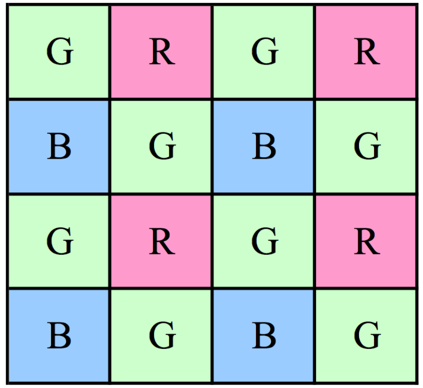


Image Courtesy: Förstner

Single-Chip Camera

- A single chip is used to obtain the RGB values
- Uses small, pixel-dependent color filters



Compared to a three-chip design

- Cheaper
- 1 vs. 3 chips: few measurements
- Interpolation leads to lower quality

Color Filter Array (CFA)

- Single chip, alternating sensors are covered by different colored filters
- Bayer pattern

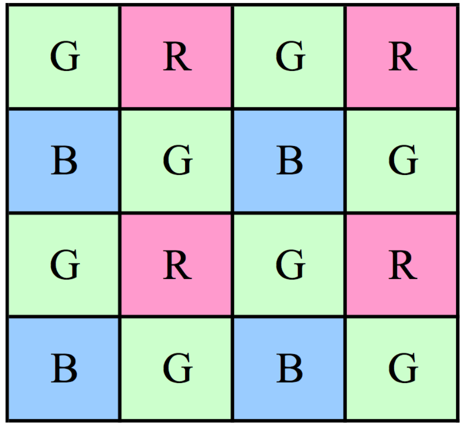
G	R	G	R
B	G	B	G
G	R	G	R
B	G	B	G

CFA layout

rGb	Rgb	rGb	Rgb
rgB	rGb	rgB	rGb
rGb	Rgb	rGb	Rgb
rgB	rGb	rgB	rGb

generated pixel (lower-case means interpolated values)

Bayer Pattern



- 50% green
- 25% red and blue

- Luminance (perceived relative brightness) is strongly influenced by green values
- Human visual system is very sensitive to high-frequency details in luminance

Other Patterns

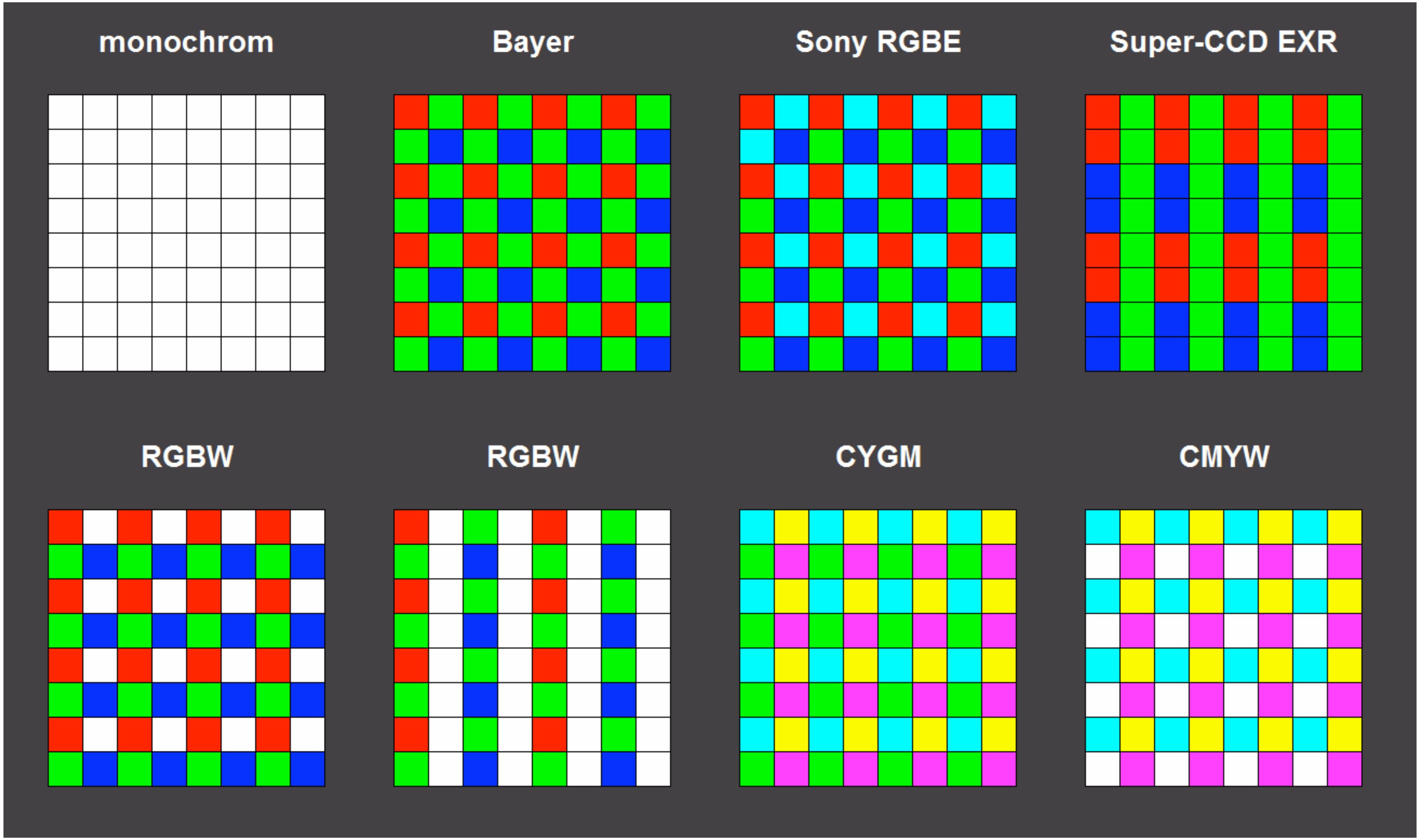
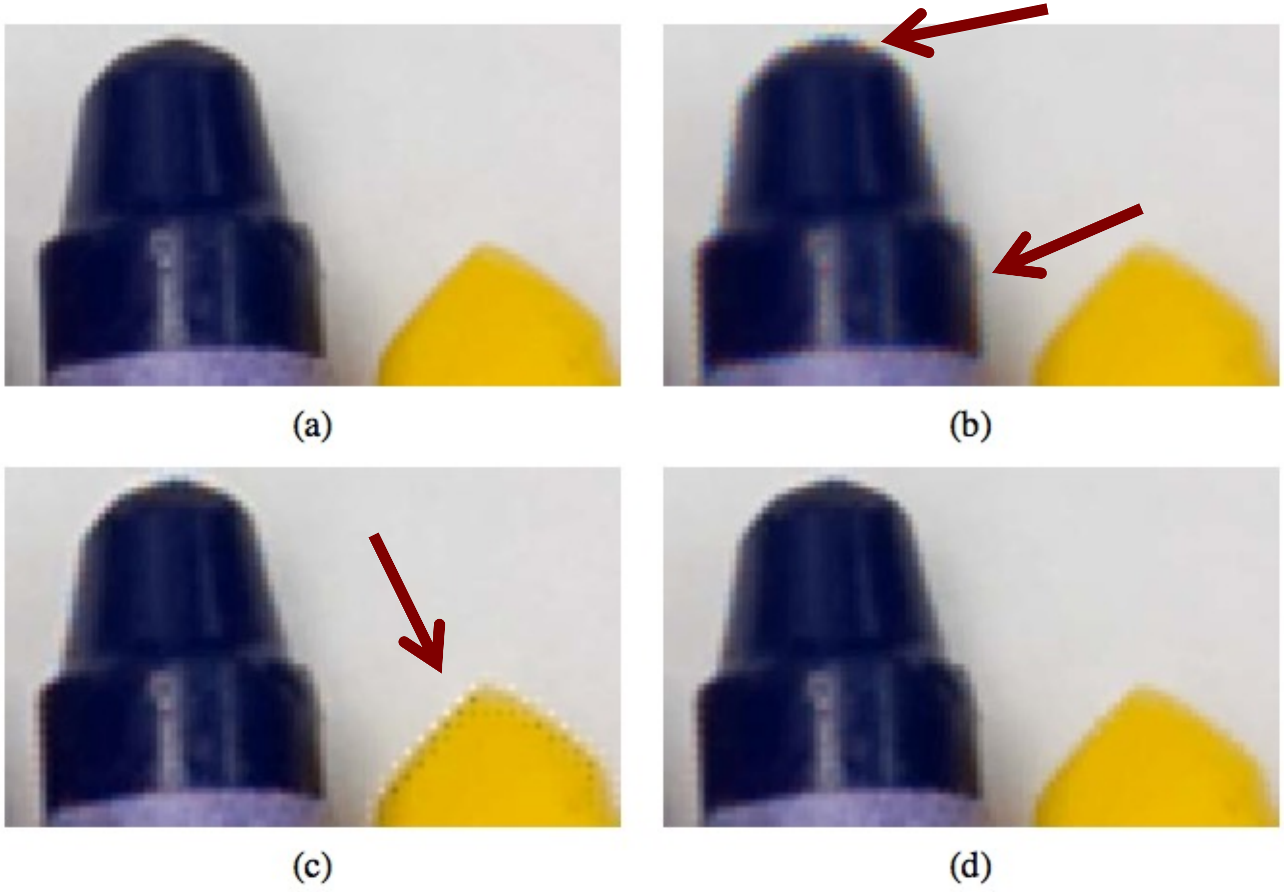


Image Courtesy: Frank Klemm

Demosaicing

Interpolating the missing color values to obtain RGB values for all the pixels is called **demosaicing**



(a) original full-resolution image

(b) bilinear interpolation

(c) the high-quality linear interpolation

(d) using the local two-color prior

Image Courtesy: Szeliski

Errors from Demosaicing

- Color interpolation leads to errors
- Errors typically occur around edges

Image Courtesy: Dubois

Comparison

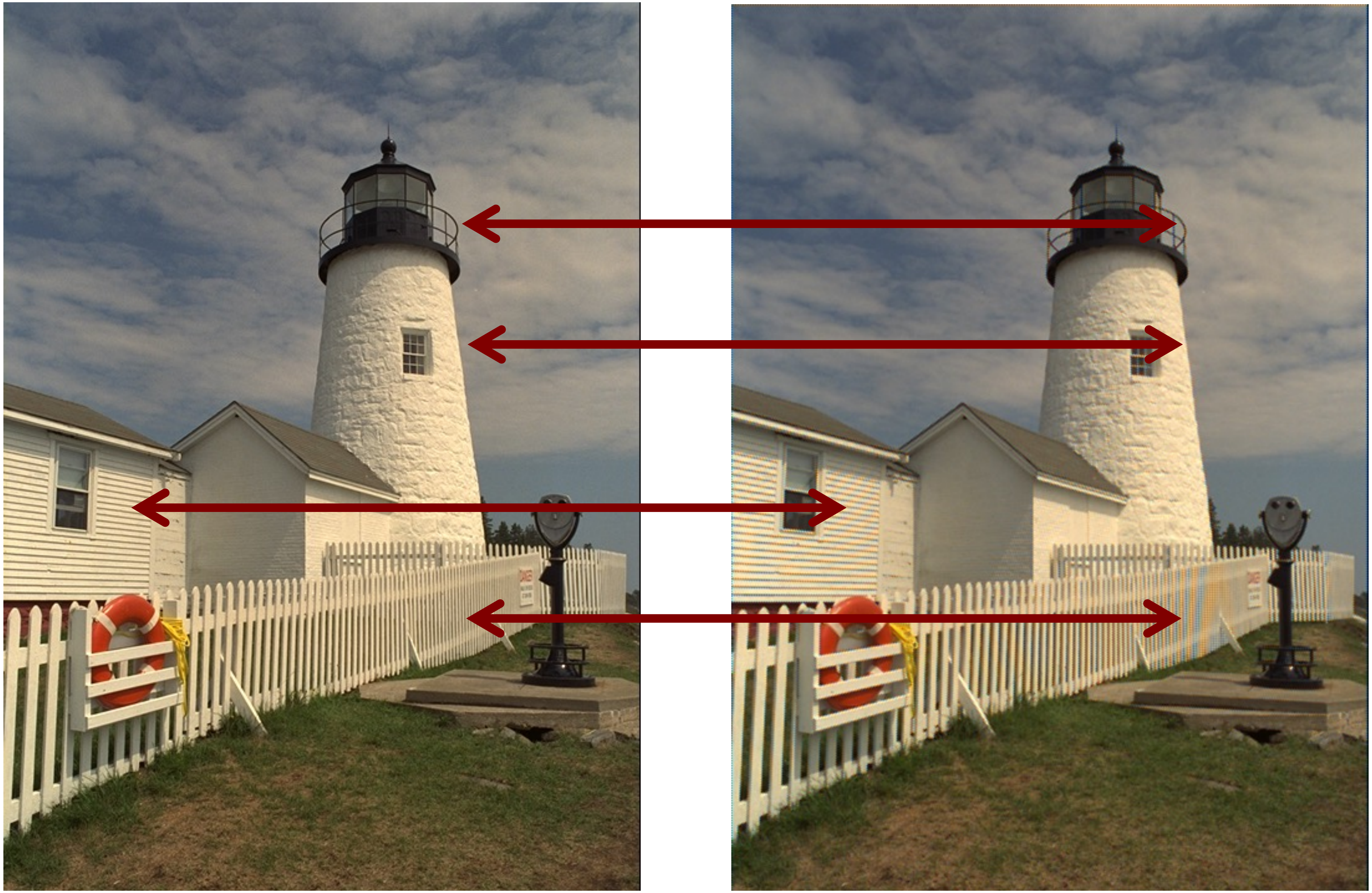


Image Courtesy: Dubois

Comparison (Zoomed-in view)

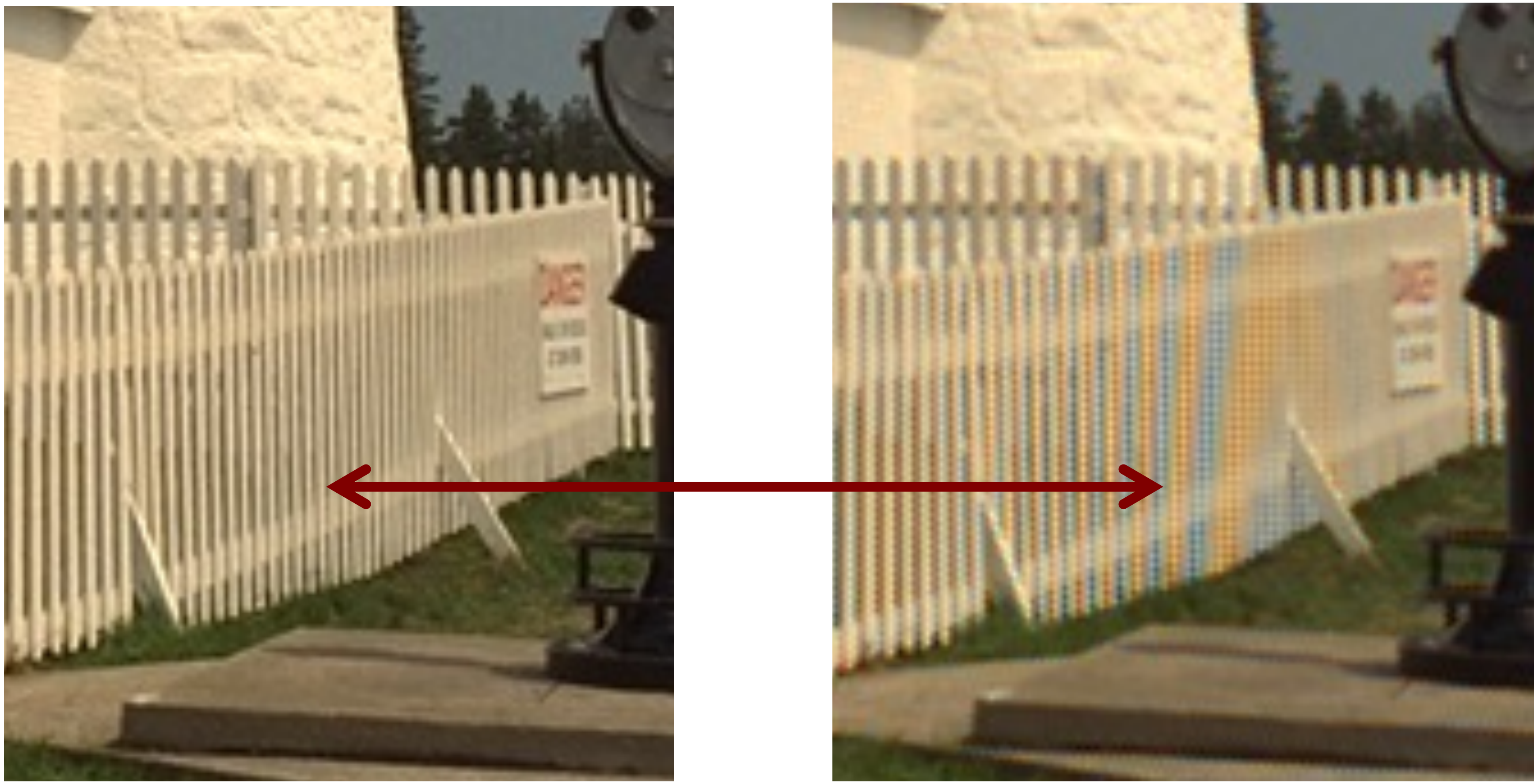
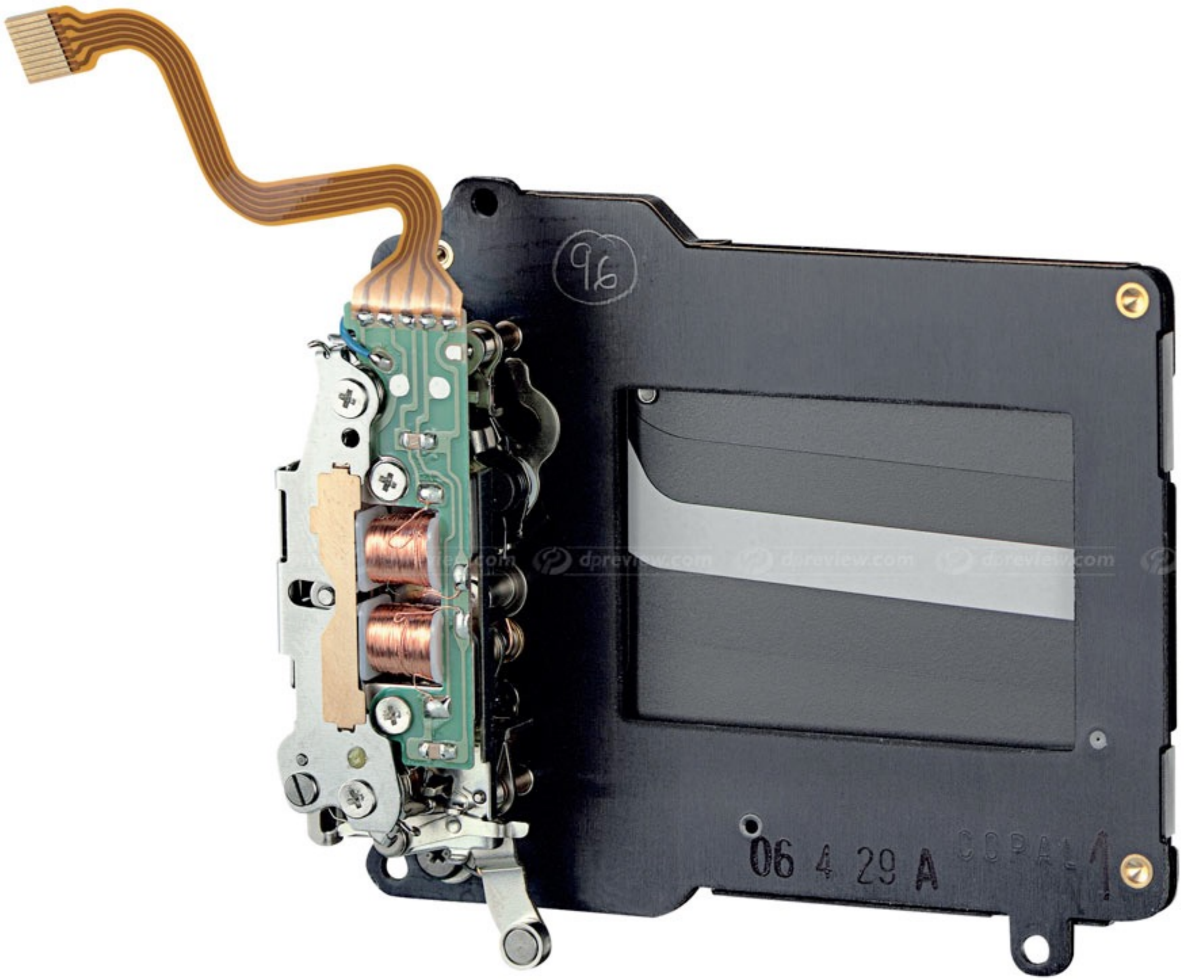


Image Courtesy: Dubois

Shutter



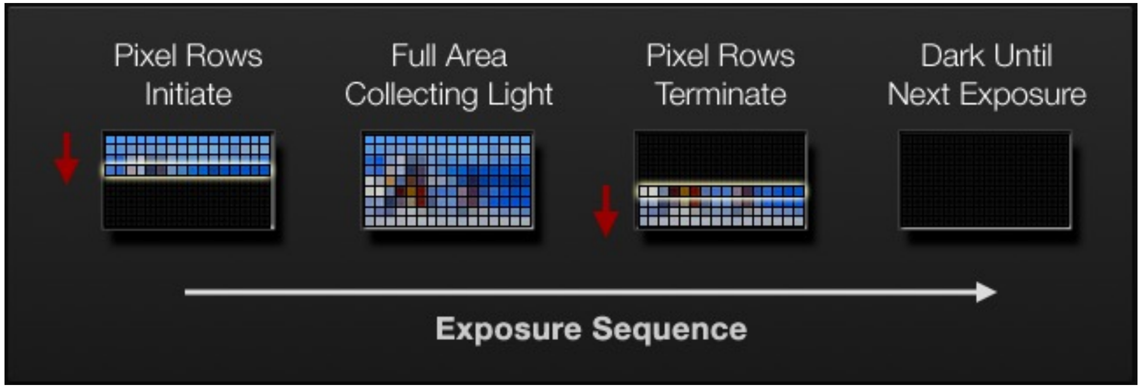
Shutter Speed / Exposure Time

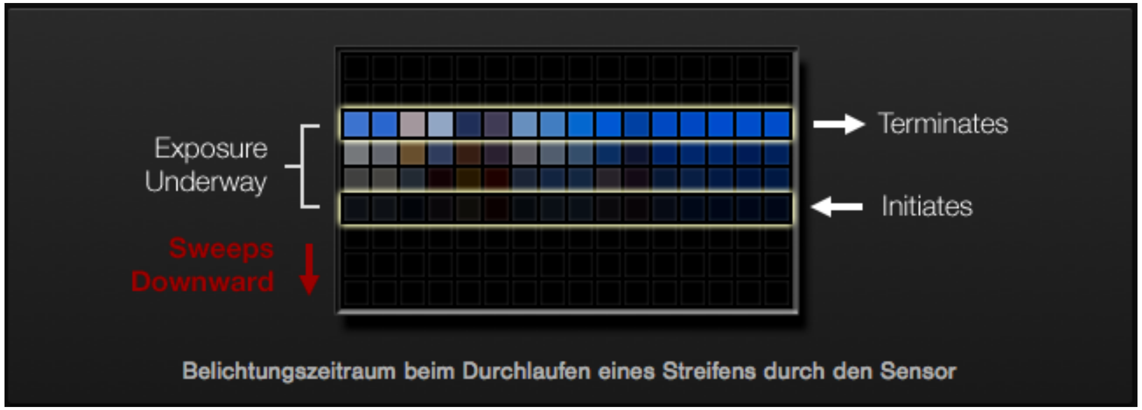
- Controls the amount of light reaching the sensor
- Longer exposure time = more light = brighter images
- Long exposure time leads to motion blur

Rolling Shutter

- The shutter rolls (moves) across the exposable image area
- The pixels at the same line of the image are recorded at the same time
- Produces distortions in case of fast-moving objects or cameras
- Often found in CMOS cameras

Rolling Shutter





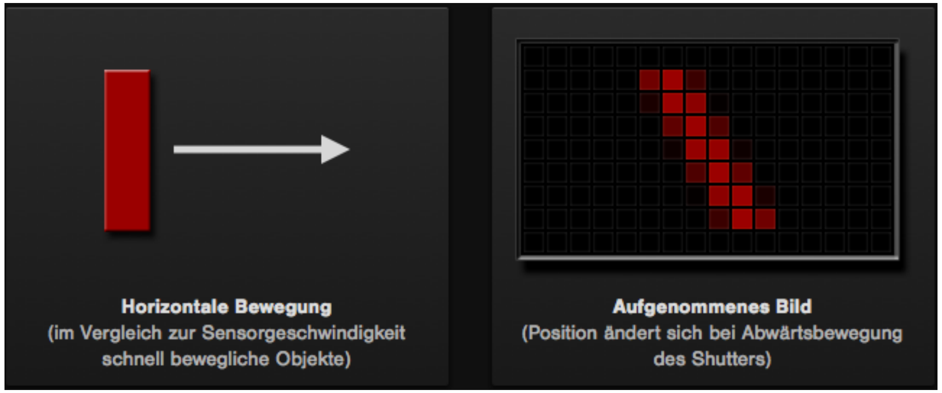


Image Courtesy:
Red.com, Inc.

Rolling Shutter Effects

Image Courtesy: Axel1963 (wikipedia)

Image Courtesy: Richmilliron (wikipedia)

Global Shutter

- The whole image is recorded at exactly the same time
- No rolling shutter distortions
- Preferable for geometric reconstruction task
- More expansive to produce

Global Shutter

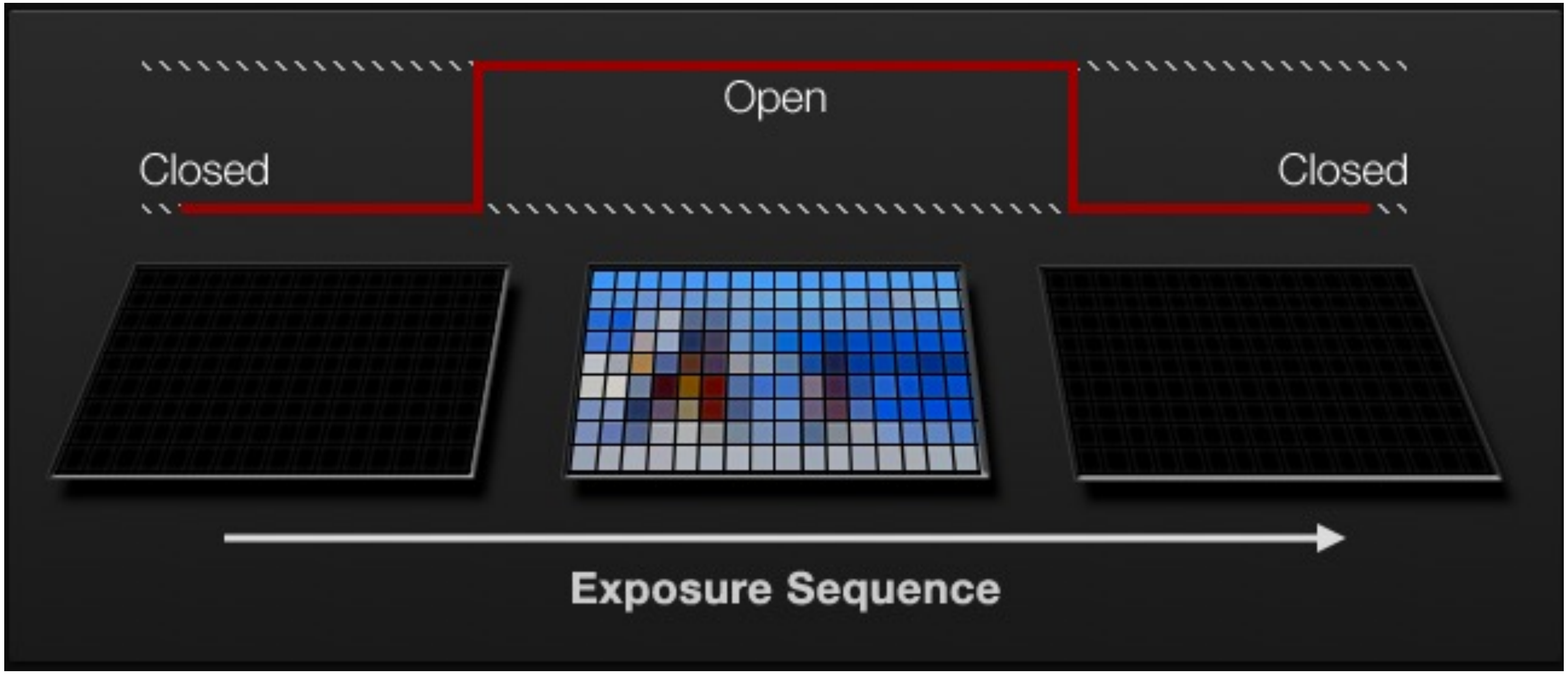


Image Courtesy: Red.com, Inc.

Rolling vs. Global Shutter

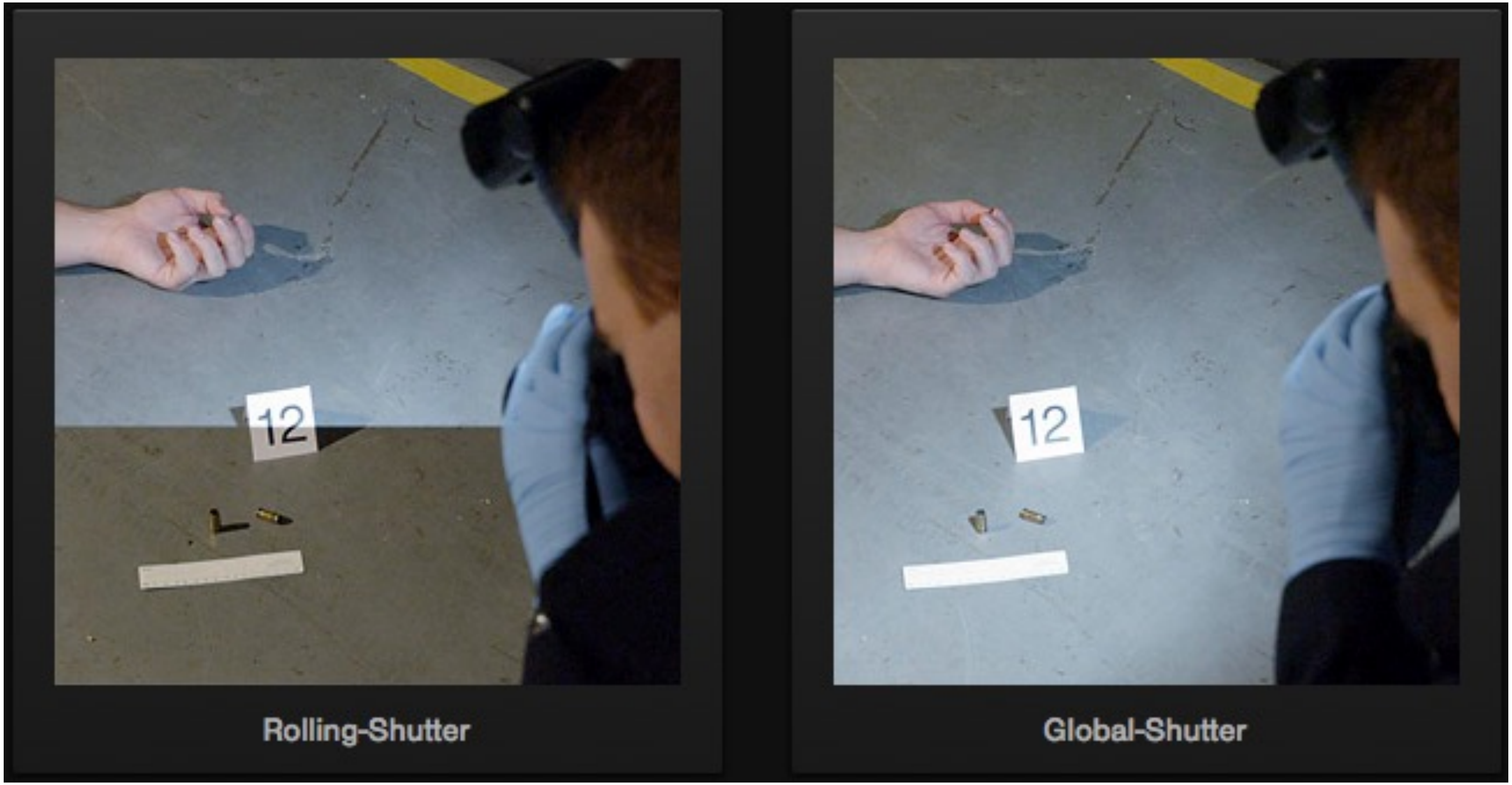


Image Courtesy: Red.com, Inc.

Lens & Aperture

Image Courtesy: A. Chizhov

How does light propagation work?

Models for Light Propagation

There are three models to describe light propagation in physics:

- Geometric or ray optics
  (DE: Geometrische Optik)
- Wave optics based on Maxwell's equations (DE: Wellenoptik)
- Particle/quantum optics based on the wave–particle duality
  (DE: Quantenoptik)

Geometric/Ray Optics

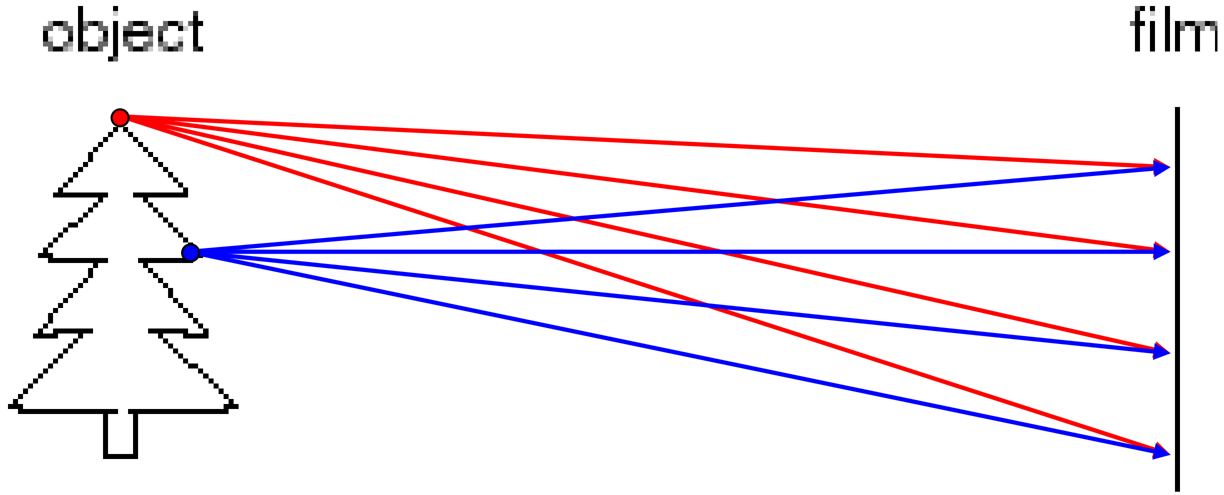
Four Axioms of Geometric Optics

1. A light ray is a straight line in homogenous material
2. At the border between two homogenous materials, the light is reflected (Fresnel reflection) or refracted (Snell's law; DE: Brechung)
3. The optical path is reversible
4. Intersecting light rays do not influence each other

Geometric Optics

- Light propagation is described by rays from the light sources
- Light travels with $c \approx 2.998 \times 10^8 \frac{m}{s}$ in vacuum
- Different speeds in different materials
- Each material has an index of refraction n (DE: Brechungsindex)
- Speed $v = \frac{c}{n}$
- Light travels along the fastest path

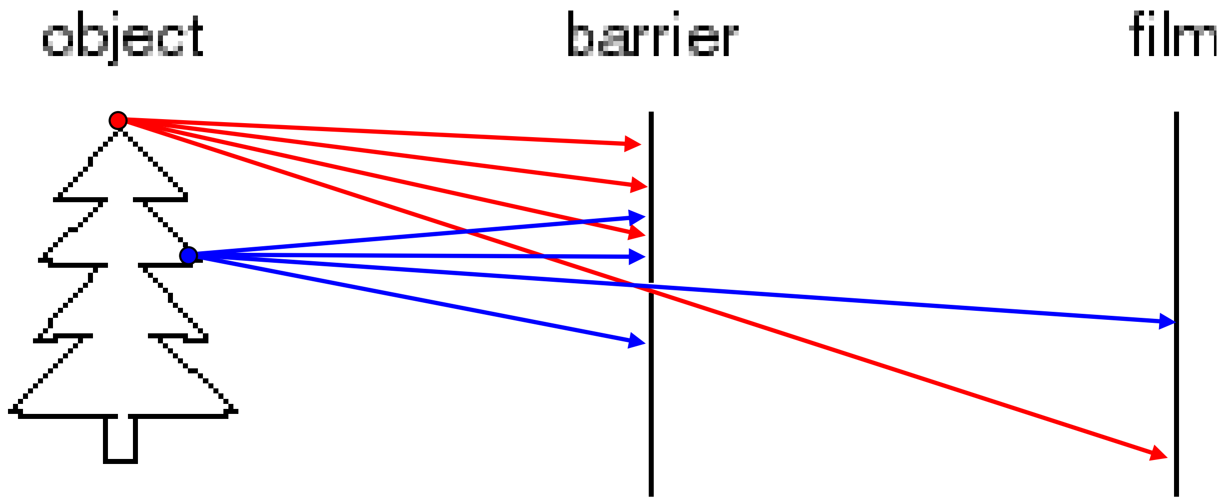
Image Formation



Let’s design a camera

- Put a piece of film in front of an object
- Do we get a reasonable image?

Pinhole Camera



- Add a barrier to block off most of the rays
- This reduces blurring
- The opening is known as the aperture
- How does this transform the image?

Pinhole Camera

- Pinhole camera is a simple model to approximate the imaging process
- If we treat pinhole as a point, only one ray from any given point can enter the camera

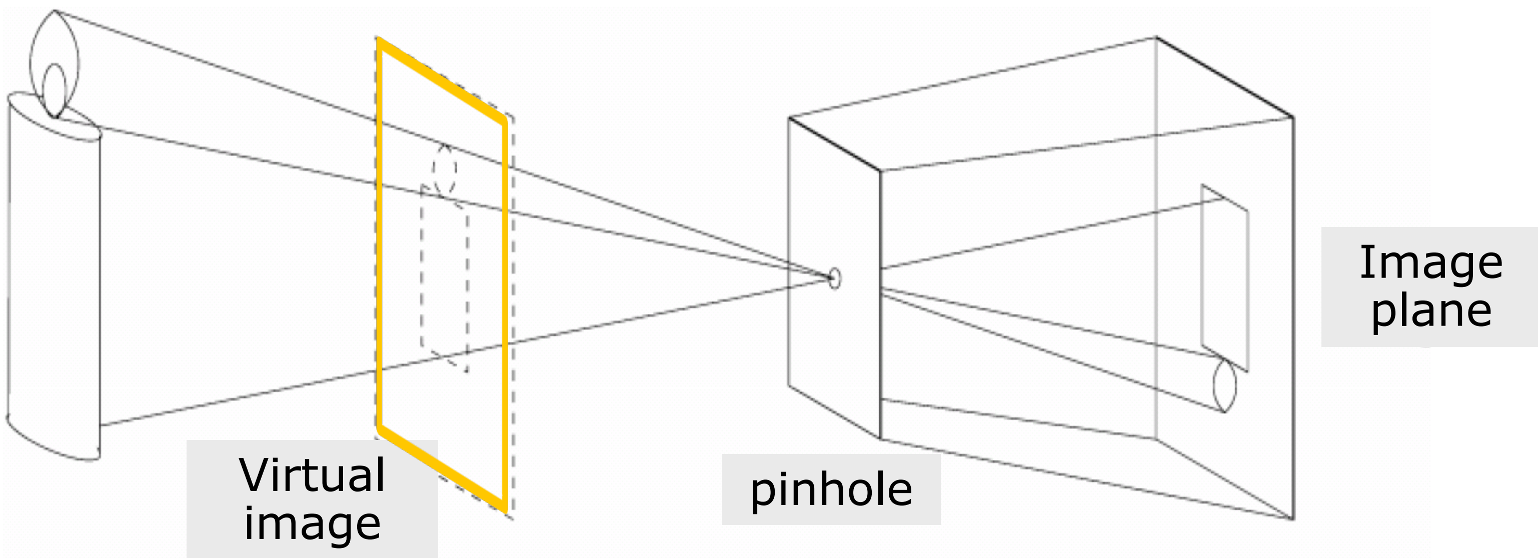
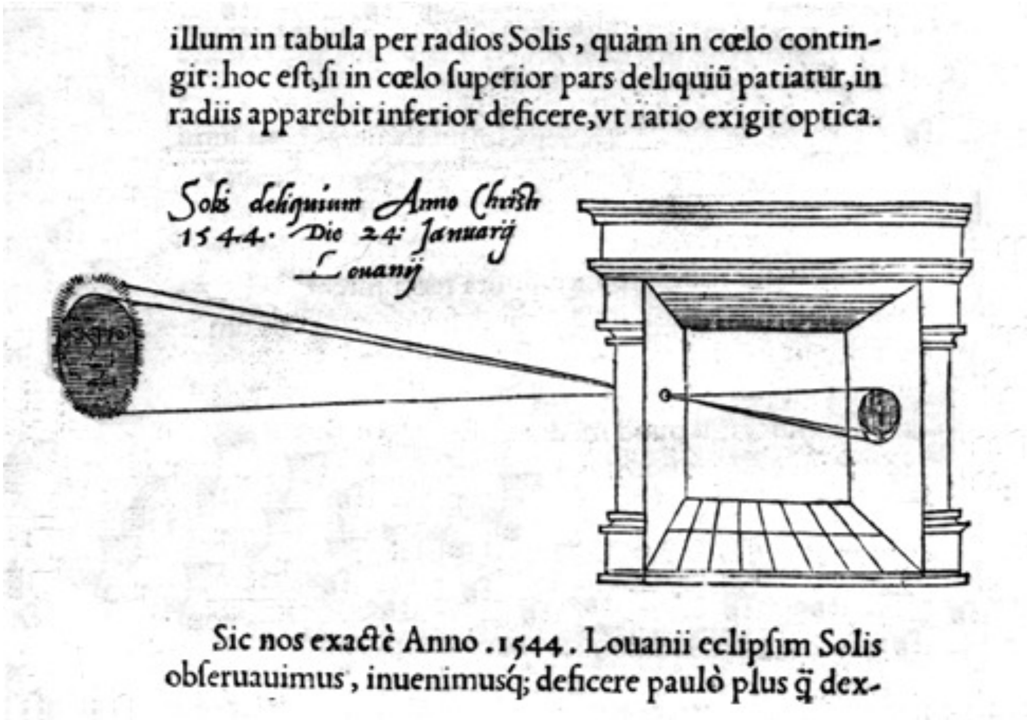


Image Courtesy: Forsyth and Ponce

Camera Obscura (1544)


illum in tabula per radios Solis, quàm in cœlo contingit: hoc est, si in cœlo superior pars deliquiũ patiatur, in radiis apparebit inferior deficere, vt ratio exigit optica.

Sic nos exactè Anno .1544. Louanii eclipsim Solis obseruauimus, inuenimusq; deficere paulò plus q̃ dex-

In Latin, means "dark room"

"**Reinerus Gemma-Frisius**, observed an eclipse of the sun at Louvain on January 24, 1544, and later he used this illustration of the event in his book <u>De Radio Astronomica et Geometrica</u>, 1545. It is thought to be the first published illustration of a camera obscura..."

Hammond, John H., <u>The Camera Obscura, A Chronicle</u>

Image Courtesy: http://www.acmi.net.au/AIC/CAMERA_OBSCURA.html

Camera Obscura at Home

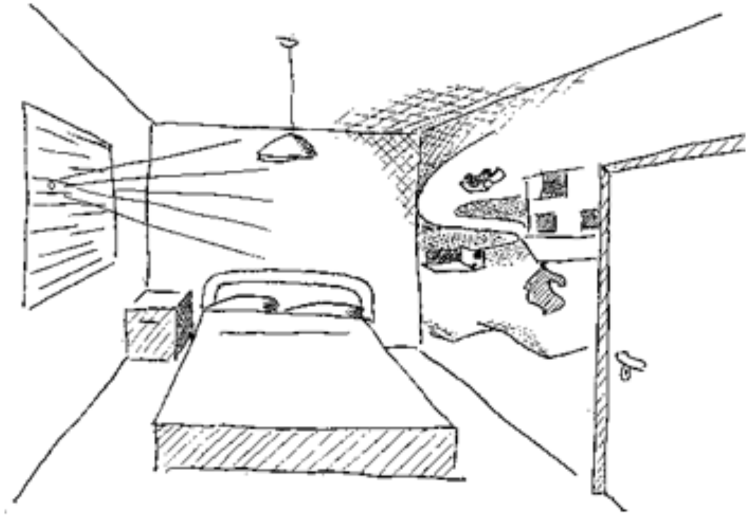
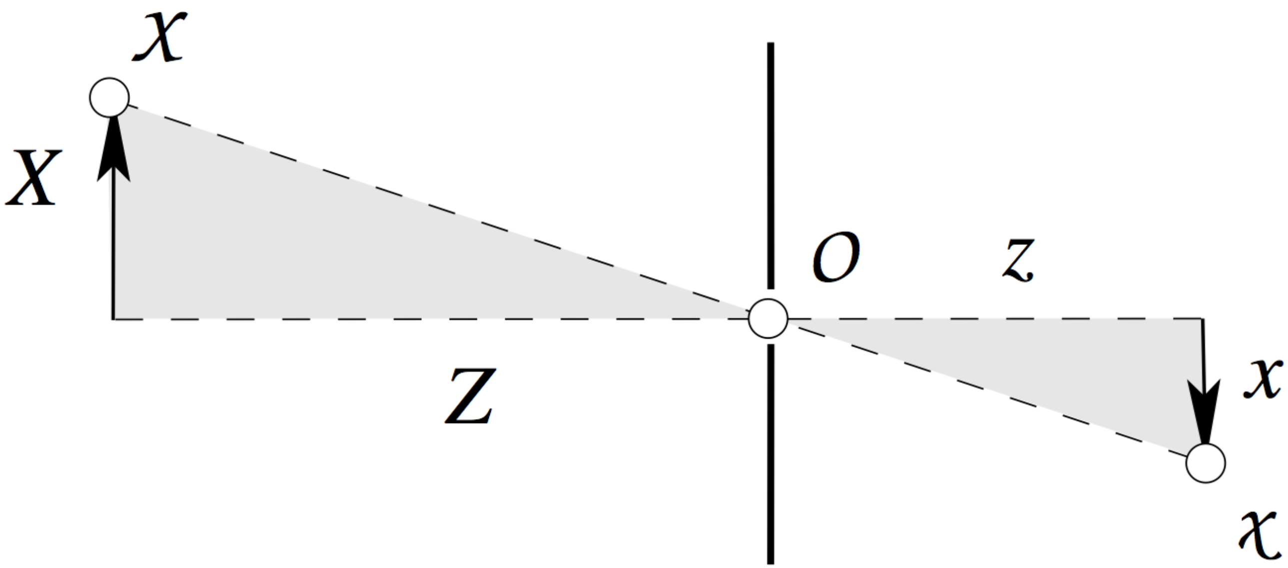


Figure 1 - A lens on the window creates the image of the external world on the opposite wall and you can see it every morning, when you wake up.

Sketch from:
http://www.funsci.com/fun3_en/sky/sky.htm

Image Courtesy:
http://blog.makezine.com/archive/2006/02/how_to_room_sized_camera_obscu.html

Pinhole Camera Model



- Similarity of the gray triangles
- Image scale $m = \frac{z}{Z}$
- Mapping $x = -mX$

Image courtesy: Förstner

Pinhole Camera Model

- Small hole: sharp images but requires large exposure times
- Large hole: short exposure times but blurry images
- Solution: replace pinhole by lenses

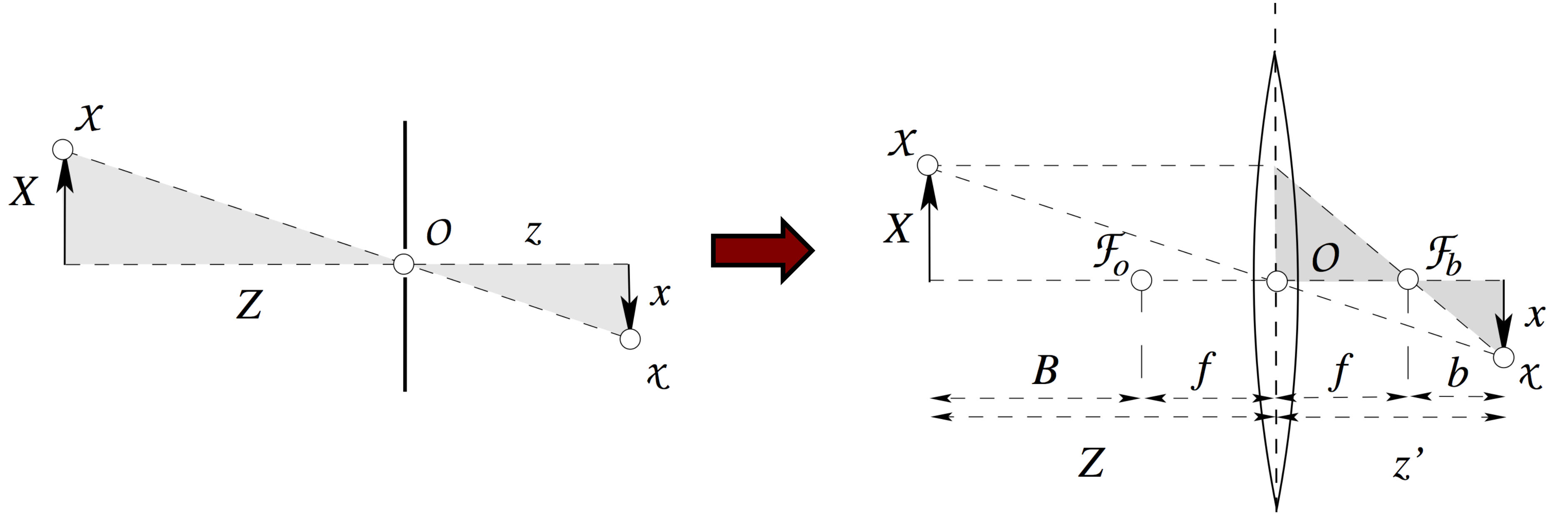
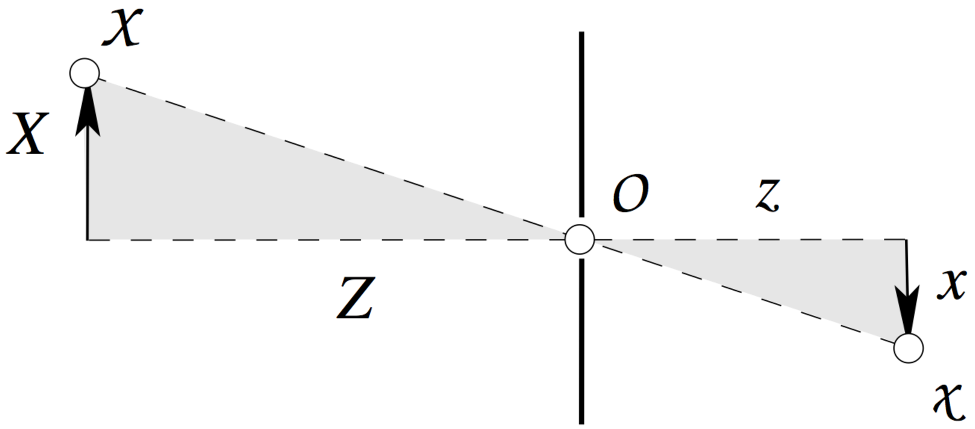
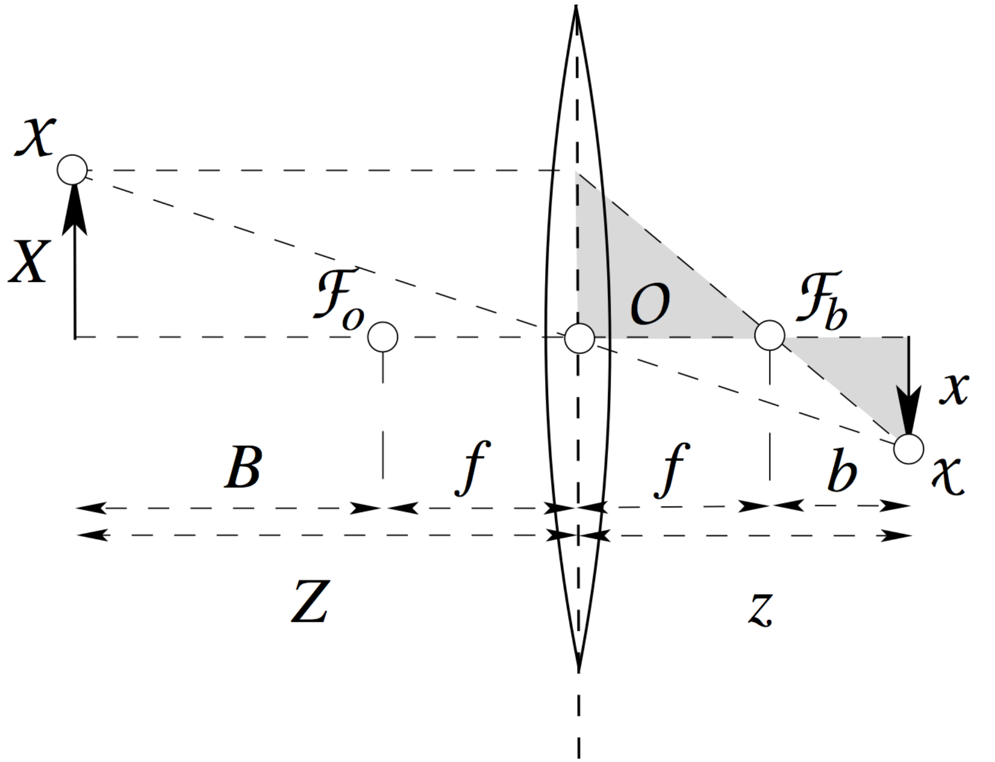


Image courtesy: Förstner

Camera with a Thin Lens





law for thin lenses:
(DE: Linsengleichung)

$$\frac{1}{f} = \frac{1}{z} - \frac{1}{Z}$$

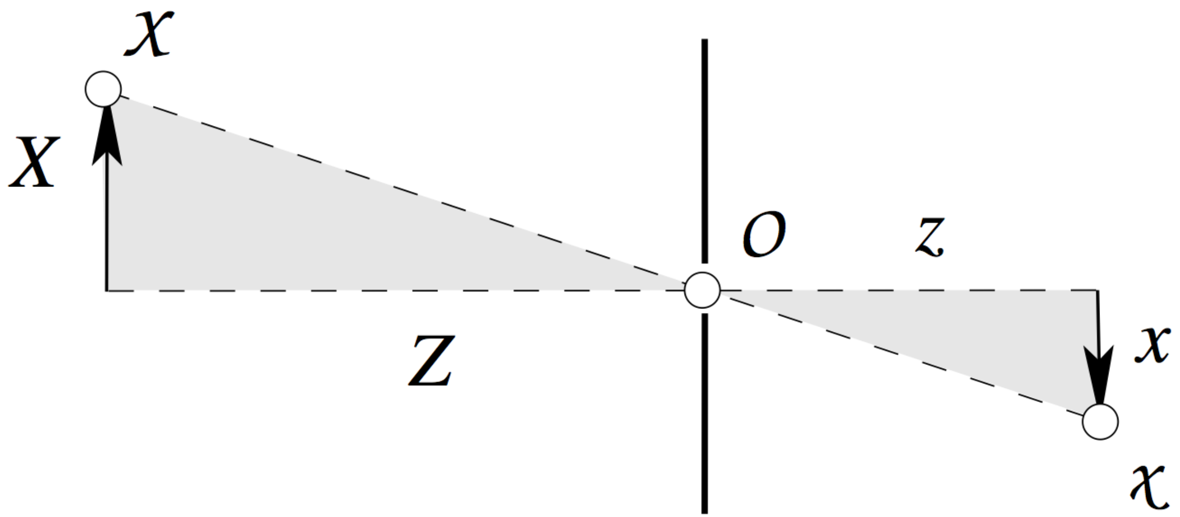
Image courtesy: Förstner

Lens Approximates the Pinhole

- A lens is only an approximation of the pinhole camera model
- The corresponding point on the object and in the image and the center of the lens should lie on one line
- The further away a beam passes the center of the lens, the larger the error
- Use of an aperture to limit the error (trade off between the usable light and price of the lens)

Pinhole Model

- Pinhole camera model is the most commonly used model for camera
- Simplicity makes it popular
- Note: unsuitable in some cases, e.g., for large fields of view



Three Assumptions Made in the Pinhole Camera/Thin Lens

1. All rays from the object point intersect in a single point
2. All image points lie on a plane
3. The ray from the object point to the image point is a straight line

Aperture

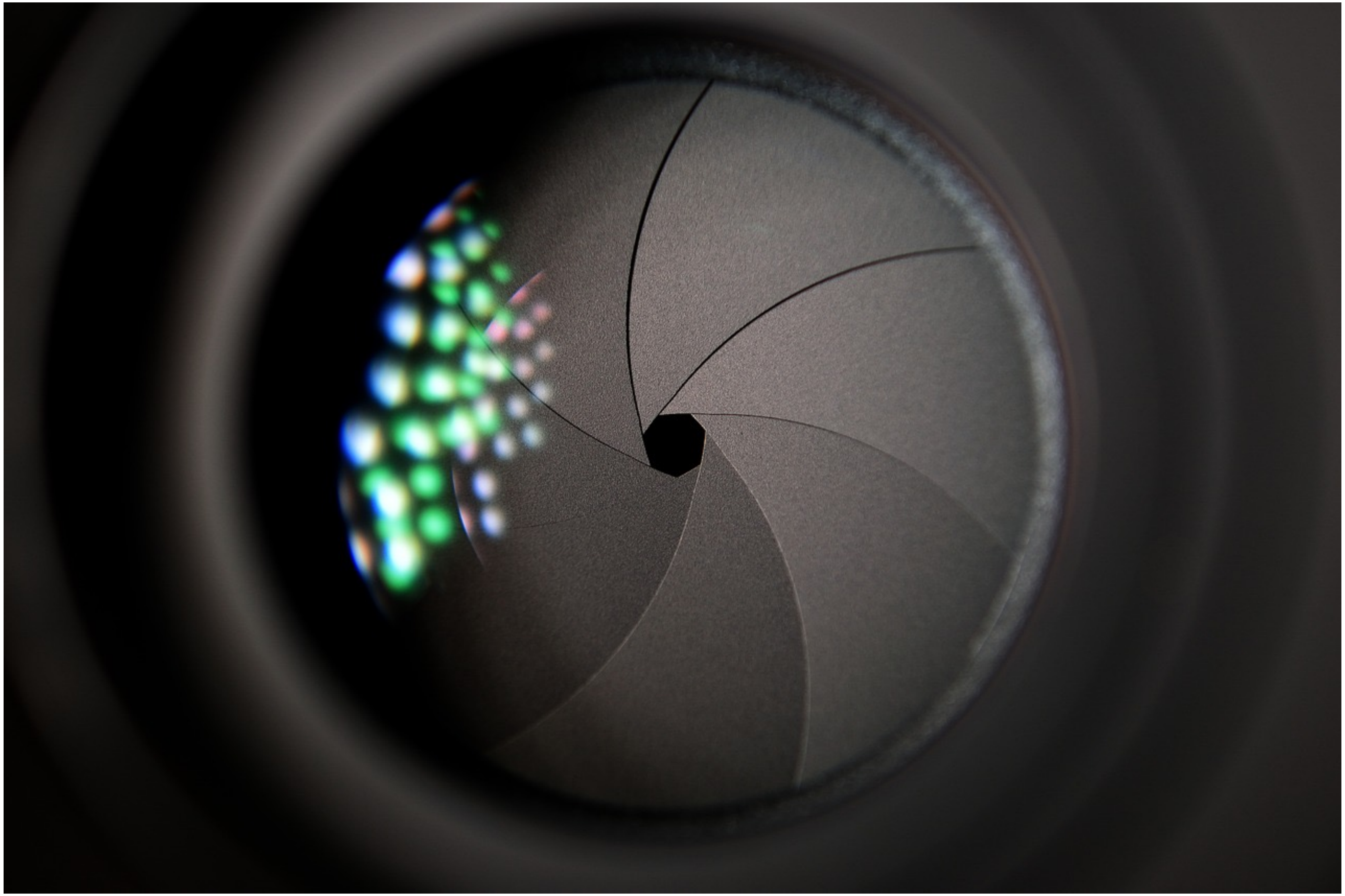


Image Courtesy: F. Krejci 46

Aperture is the "Pinhole Size"

Image Courtesy: VERSATILE SCHOOL OF PHOTOGRAPHY

Aperture is the "Pinhole Size"

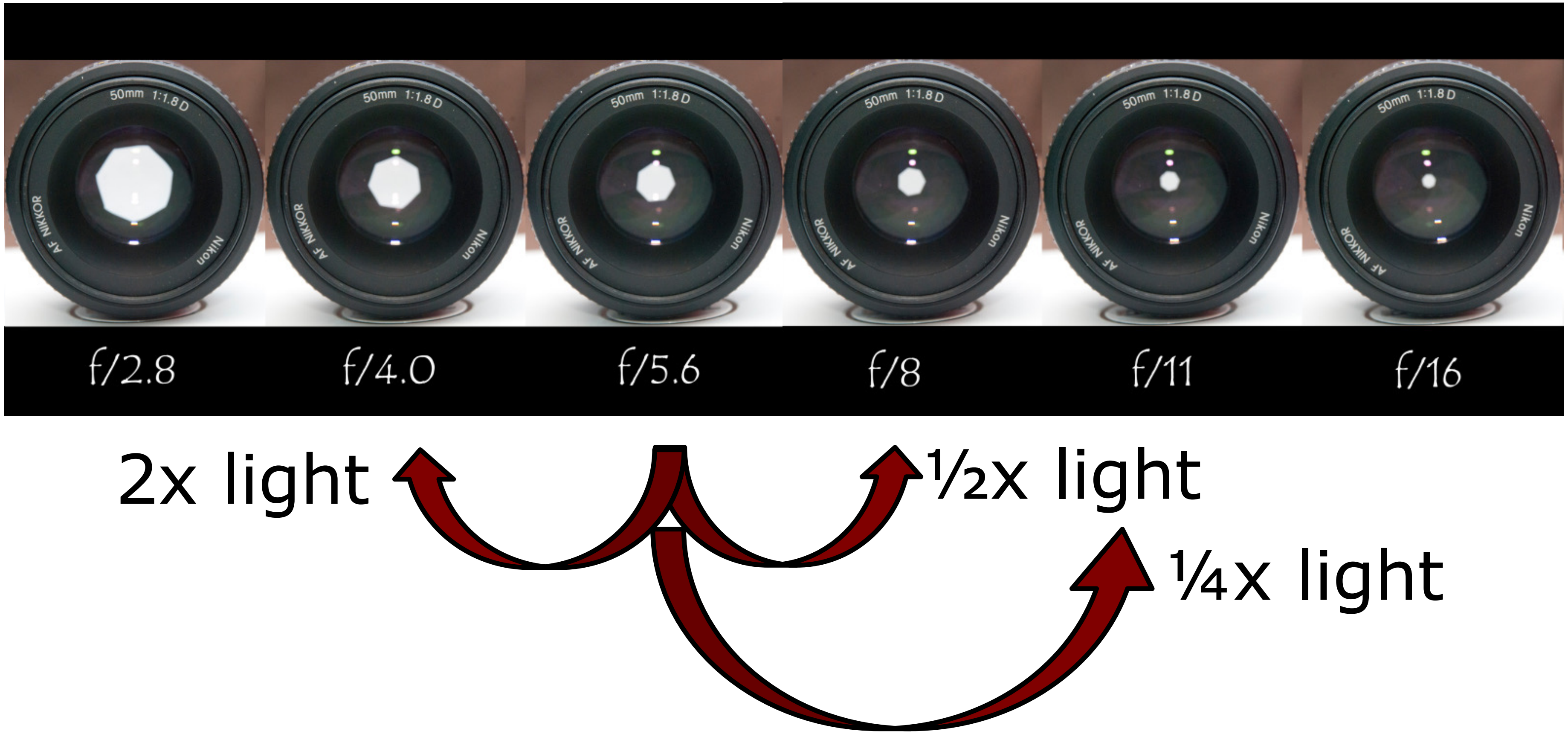


Image Courtesy: VERSATILE SCHOOL OF PHOTOGRAPHY

Aperture Reduces Lens Errors

- The error of a lens increases with the distance from the optical axis
- Aperture limits this maximum distance

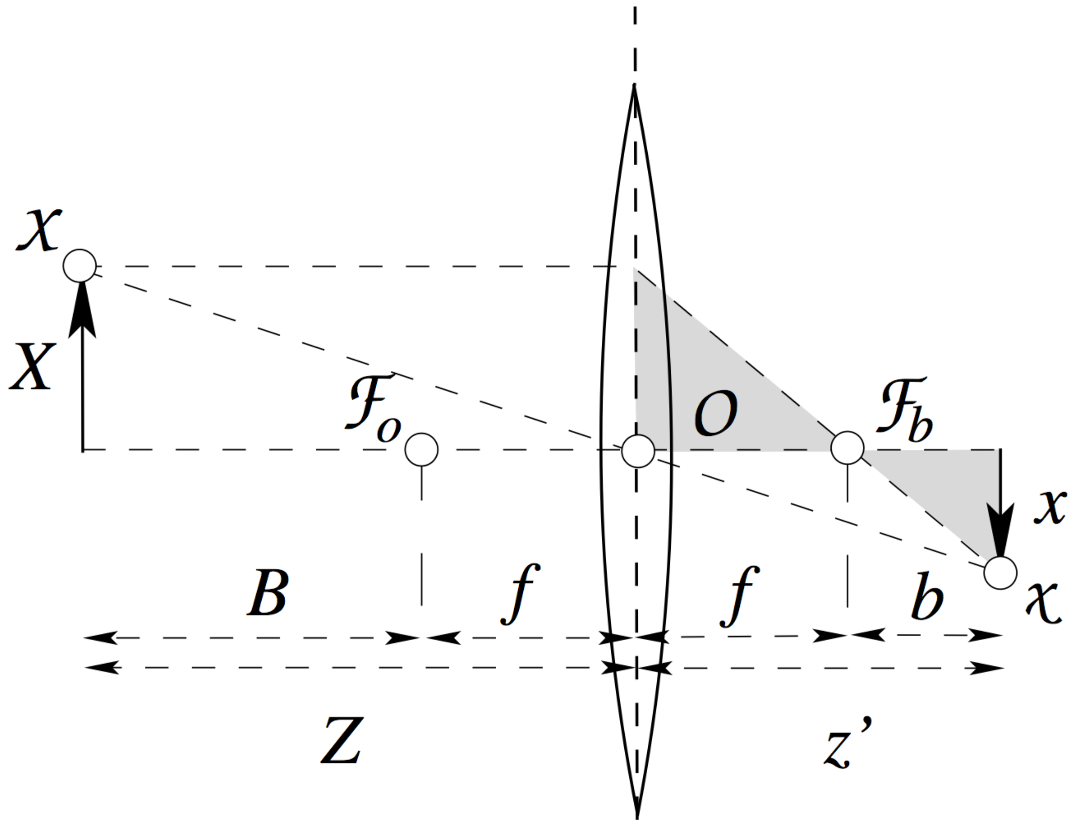


Image courtesy: Förstner

Aperture and Depth-of-Field

- The aperture controls the amount of light on the sensor chip and the depth-of-field
- Depth-of-field refers to the range of distance that appears acceptably sharp.

Image Courtesy: http://www.cambridgeincolour.com/tutorials/depth-of-field.htm

Depth-of-Field Example

f/8.0

f/5.6

f/2.8

Image Courtesy: http://www.cambridgeincolour.com/tutorials/depth-of-field.htm

Try yourself: http://www.cambridgeincolour.com/tutorials/dof-calculator.htm

Lens

Goal is to obtain images that are

- not distorted
- sharp
- contrast intensive

The choice of the lens depends on

- field of view
- distance to the object
- amount of available light
- price

Typical Lenses

Telephoto lens, normal lens, wide-angle lens, fisheye lens, …

telephoto

normal

wide-angle

fisheye

Image courtesy: Canon

Moderate Tele Lens

- Narrow field of view
- Minimal perspective distortions
- Parallel lines remain parallel

Image courtesy: Förstner

Wide Angle Lens

- Useful for application that require a large field of view (70 and 120 deg)
- Straight lines in the world are mapped to roughly straight in the image
- Perspective distortions
- Proportions are not correct anymore

Image courtesy: Förstner

Fisheye Lens

- Field of view of 130+ deg
- Straight lines in the world are not straight anymore in the image

Image Courtesy: Ashley Ringrose

Three Assumptions Made in the Pinhole Camera/Thin Lens

1. All rays from the object point intersect in a single point
2. All image points lie on a plane
3. The ray from the object point to the image point is a straight line

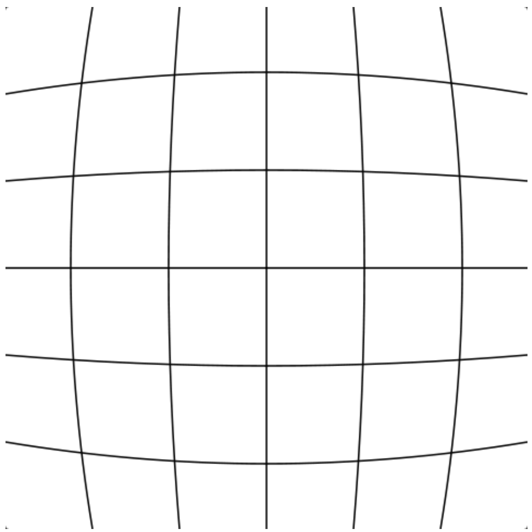
Often these assumption do not hold and leads to imperfect images

Aberrations

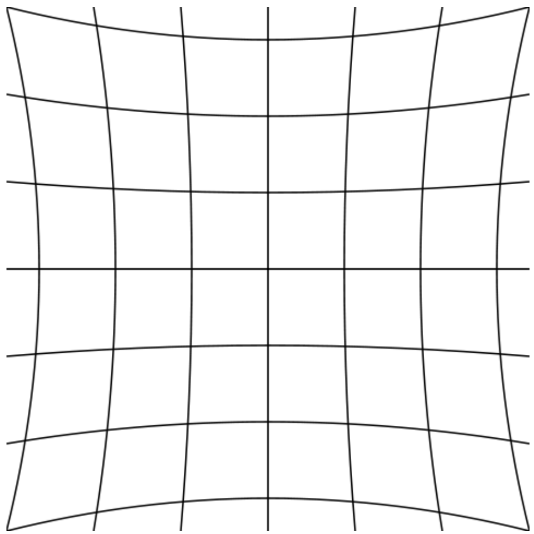
- A deviation from the ideal mapping with a thin lens is called aberration
- Main types of aberrations:
  - Distortion
  - Spherical aberrations
  - Chromatic aberrations
  - Astigmatism
  - Comatic aberrations
  - Vignetting
  - ...

Distortion

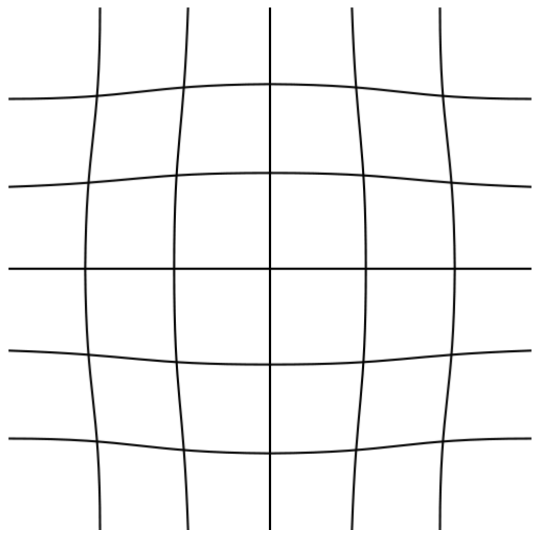
Deviation from rectilinear projection, a projection in which straight lines in a scene remain straight in an image



barrel distortion



pincushion distortion

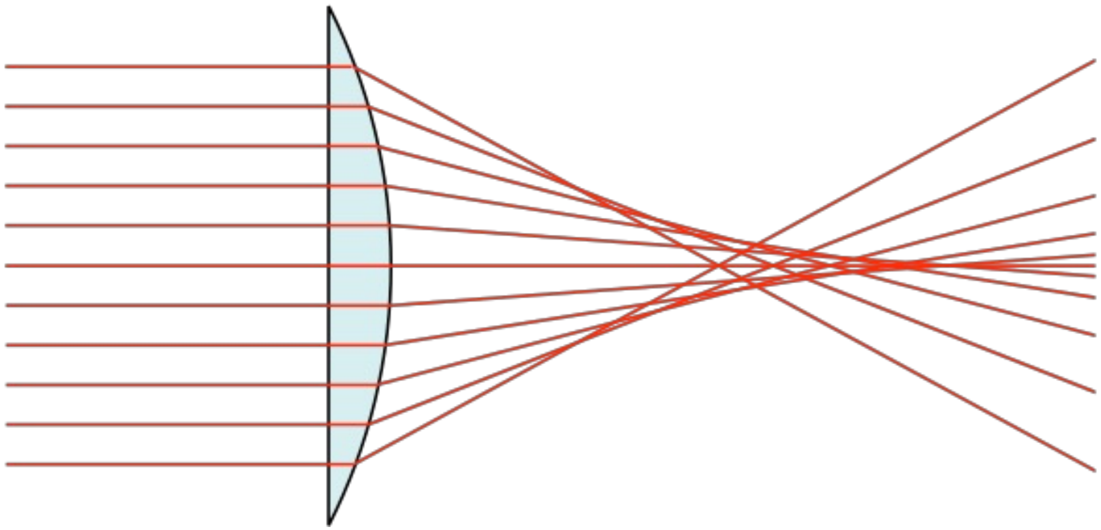


mustache distortion

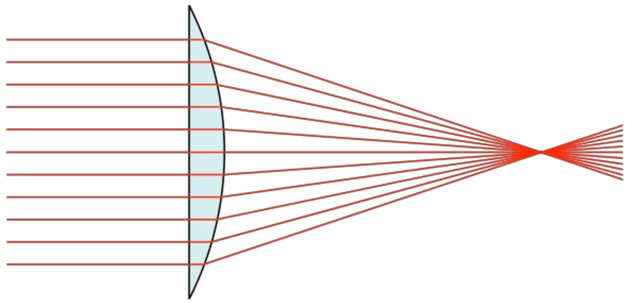
Image courtesy: Wikipedia

Spherical Aberration

Effect in a lens due to the increased refraction of light rays when they strike a lens



spherical aberration
(DE: Sphärische Aberration)

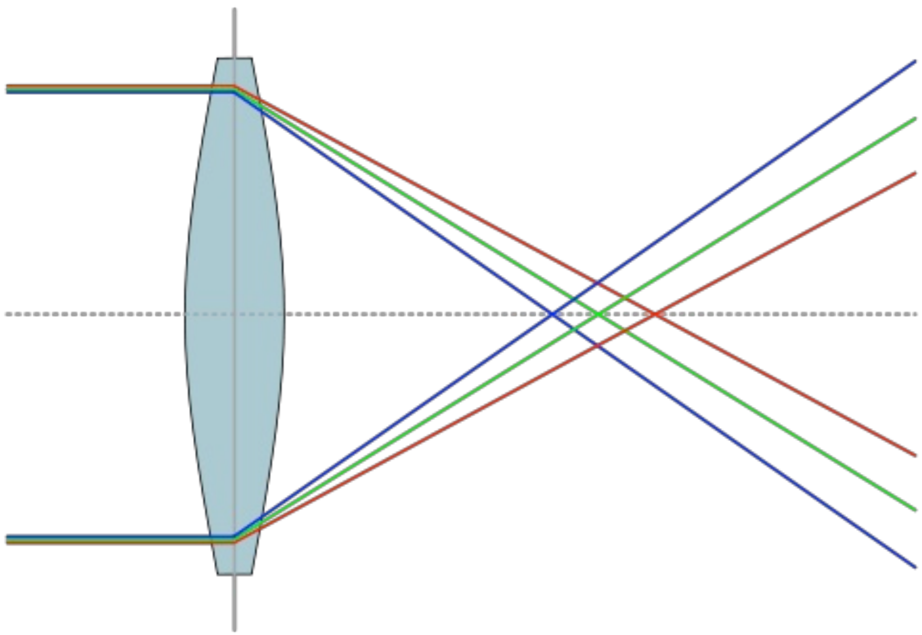


ideal

Image courtesy: Wikipedia

Chromatic Aberration

- Index of refraction for glass varies slightly as a function of wavelength
- Light at different wave length are not projected to the same point (are focused with a different focal length)



chromatic aberration
(DE: Chromatische Aberration)

Image courtesy: Wikipedia

Astigmatism

A different focus point in vertical and horizontal direction

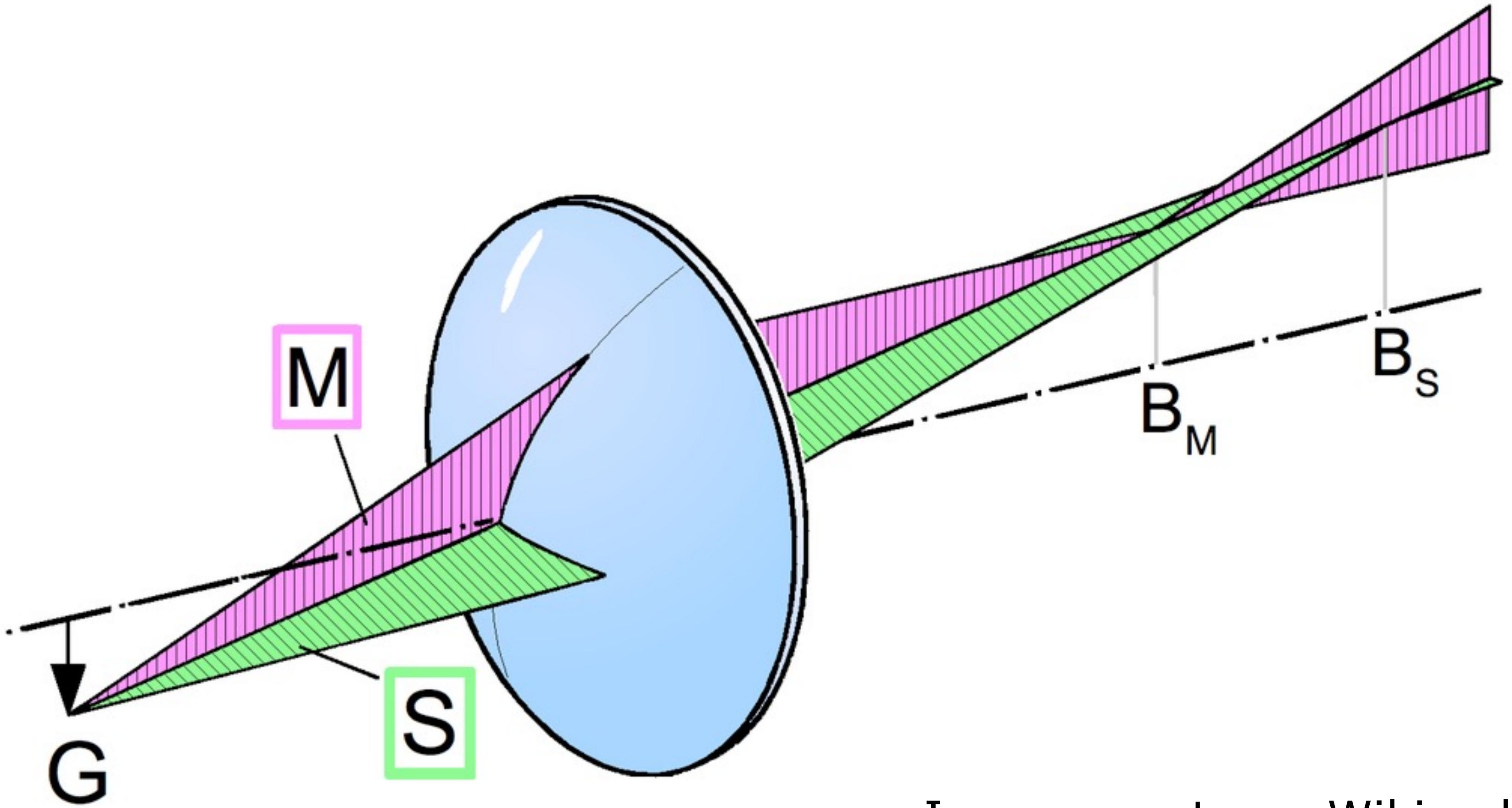


Image courtesy: Wikipedia

Comatic Aberration / Coma

Combination of spherical aberration and astigmatism in case of incoming rays striking the lens at an angle to the optical axis

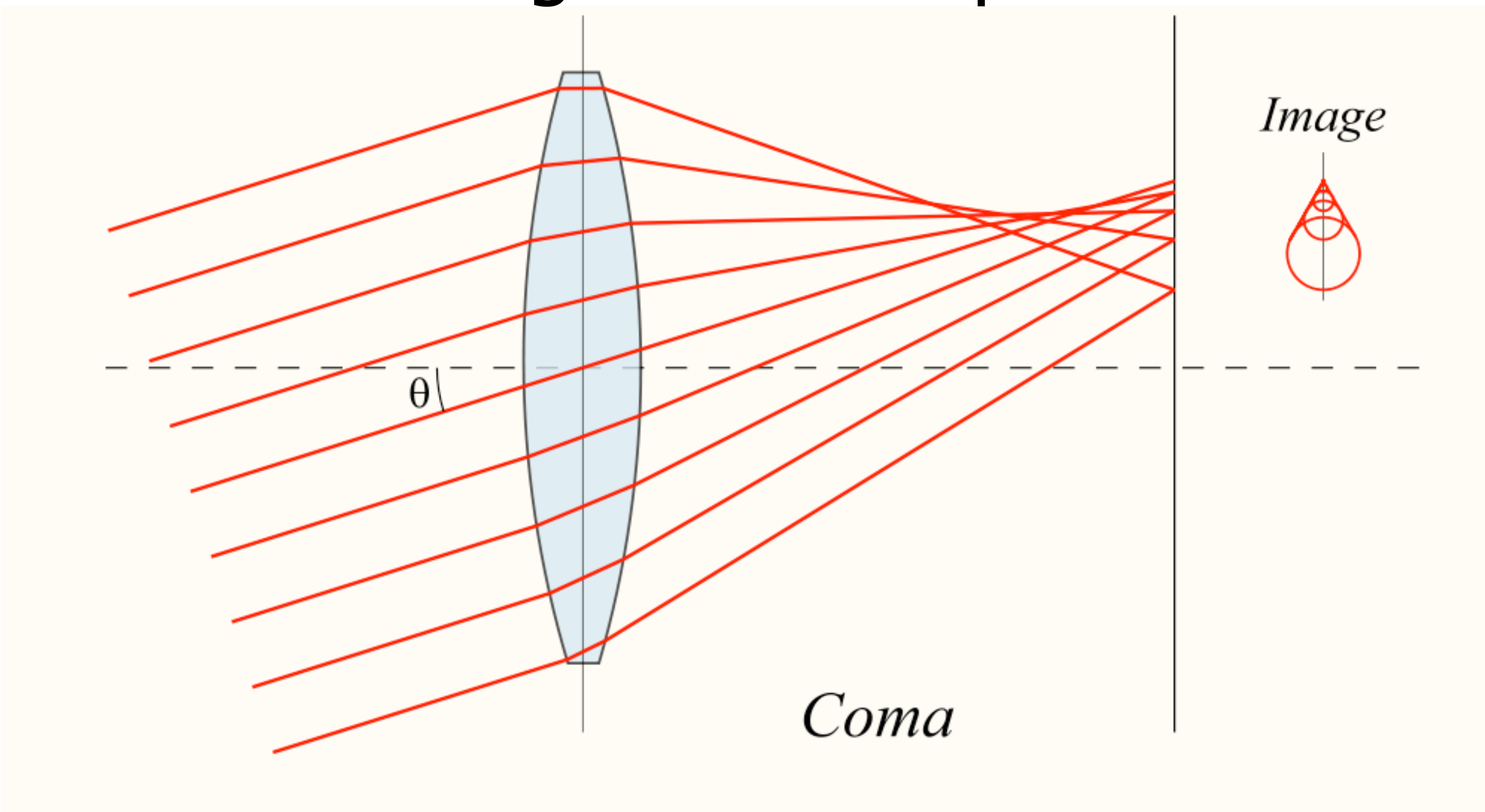


Image courtesy: Wikipedia

Vignetting

- The brightness of the image falls off towards the edge of the image
- Often compensated by the camera

Image courtesy: Wikipedia

Wave Optics

Wave Optics

- Considers light as an electro-magnetic wave described by the Maxwell equations
- Describes interference und diffraction
  (DE: Interferenz und Beugung)
- Visible light from 400nm to 700nm
- Electro-magnetic waves cover a large spectrum of wave lengths

Spectrum

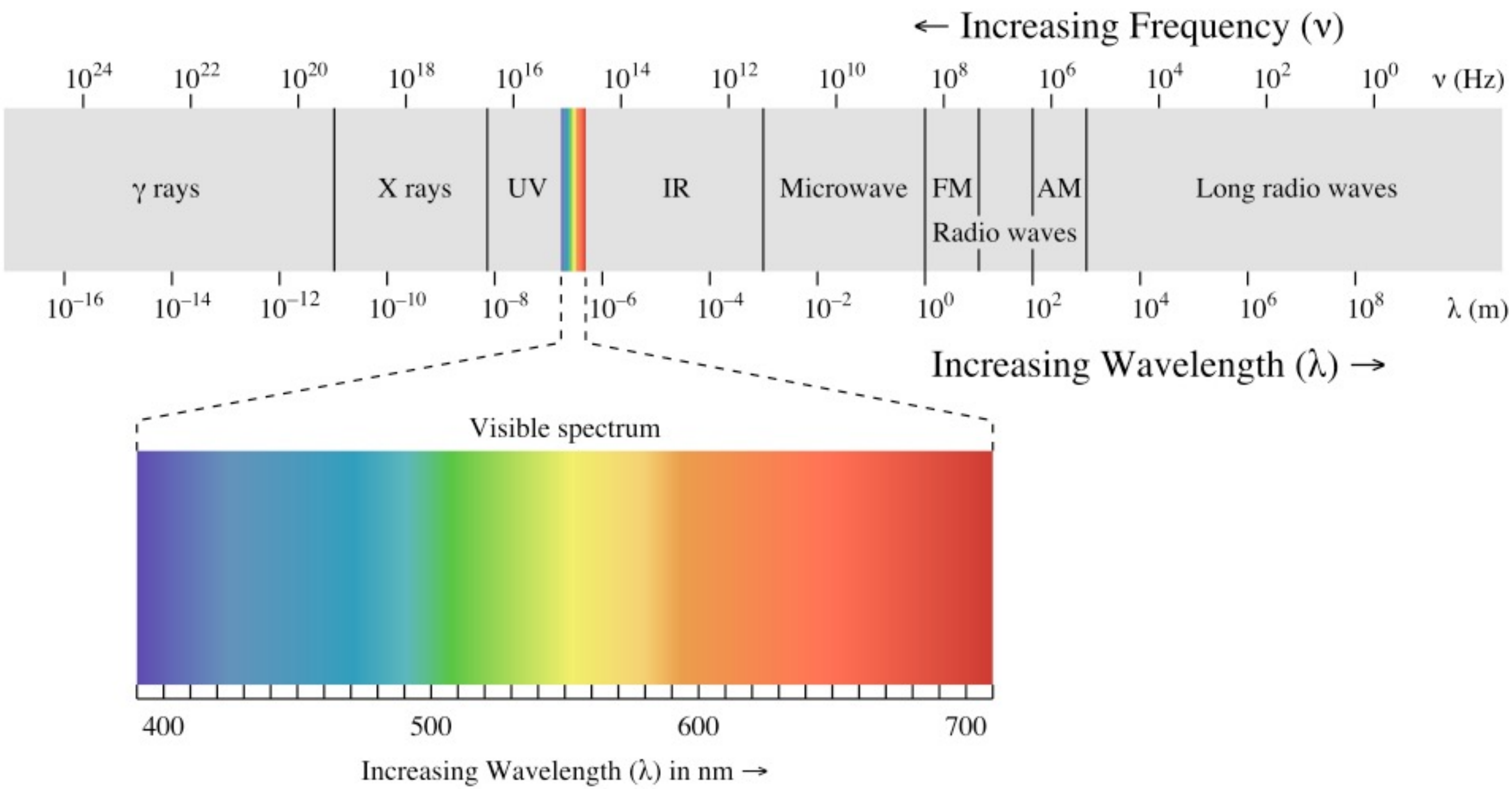


Image courtesy: Wikipedia

Frequency

- The frequency ν is defined as

$$\nu = \frac{c}{\lambda}$$

speed of light (vacuum)

$c \approx 2.998 \times 10^8 \frac{m}{s}$

wave length

Frequency

- The frequency ν is defined as

speed of light (vacuum)

$c \approx 2.998 \times 10^8 \frac{m}{s}$

$$\nu = \frac{c}{\lambda}$$

wave length

- and depends on the material

$$\nu = \frac{c}{\lambda n}$$

refraction index

We Are Mainly Using 3 Bands

red $\lambda \approx 650\,nm$

green $\lambda \approx 550\,nm$

blue $\lambda \approx 450\,nm$

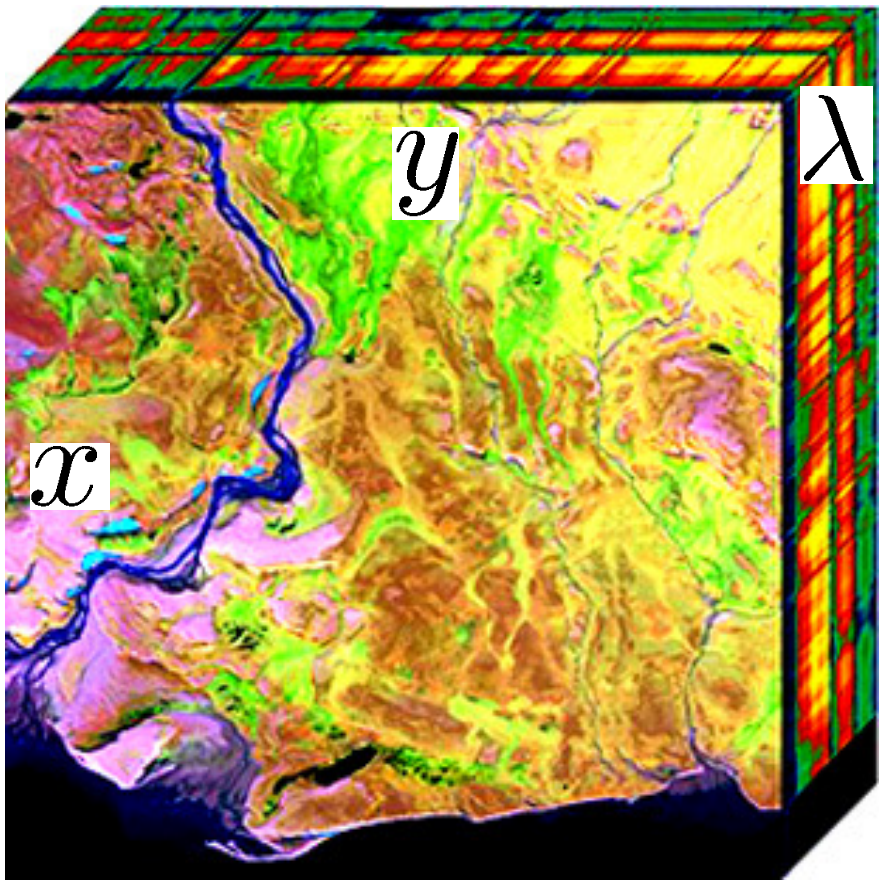
Near the Visible Spectrum

Infrared light (λ≈1mm) is strongly reflected by chlorophyll and thus often used for monitoring vegetation

Image courtesy: Wikipedia (left), Förstner (right)

Hyperspectral Images

Hyperspectral images are three-dimensional data cubes $[x, y, \lambda]$



Particle/Quantum Optics

Light as Particles

- Quantum mechanics/optics introduces the wave-particle duality
- Certain properties of light can be described by particles
- Alternative description that tries to explain phenomena that cannot be explained using wave optics
- Useful for describing the interactions between light and matter

Photon

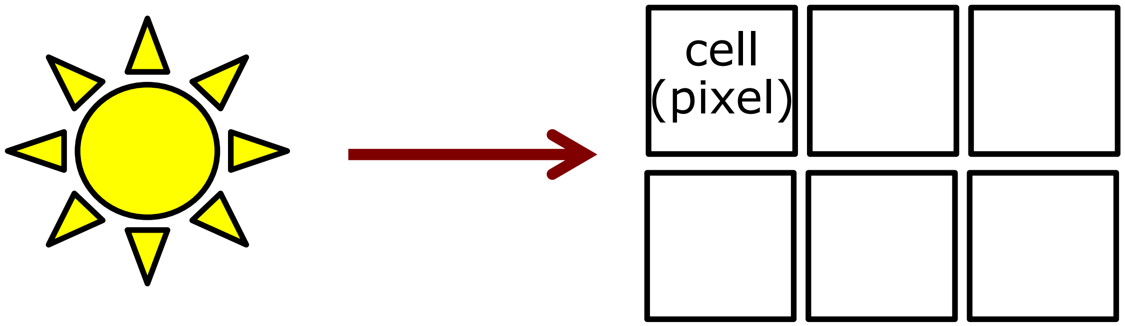
- A photon is an elementary particle
- It is the “quantum of light”
- Energy of a photon is

$$Q = h\,\nu$$

- where h is the Planck constant

$$h = 6.625 \times 10^{-34}\ W s^2$$

Photons and Intensity



- Quantum optics can model the interaction of light and matter
- Every sensor element of a camera chip turns photons into electric charge
- Intensity is proportional to the number of photons reaching the sensor (pixel)

Pixels are Photon Counters

- Each pixel is a photon counter
- How many quanta of light reach the pixel through the pinhole within the exposure time
- Larger values = more photons

Intensity Values

External

- Amount of light reflected from a scene to the camera

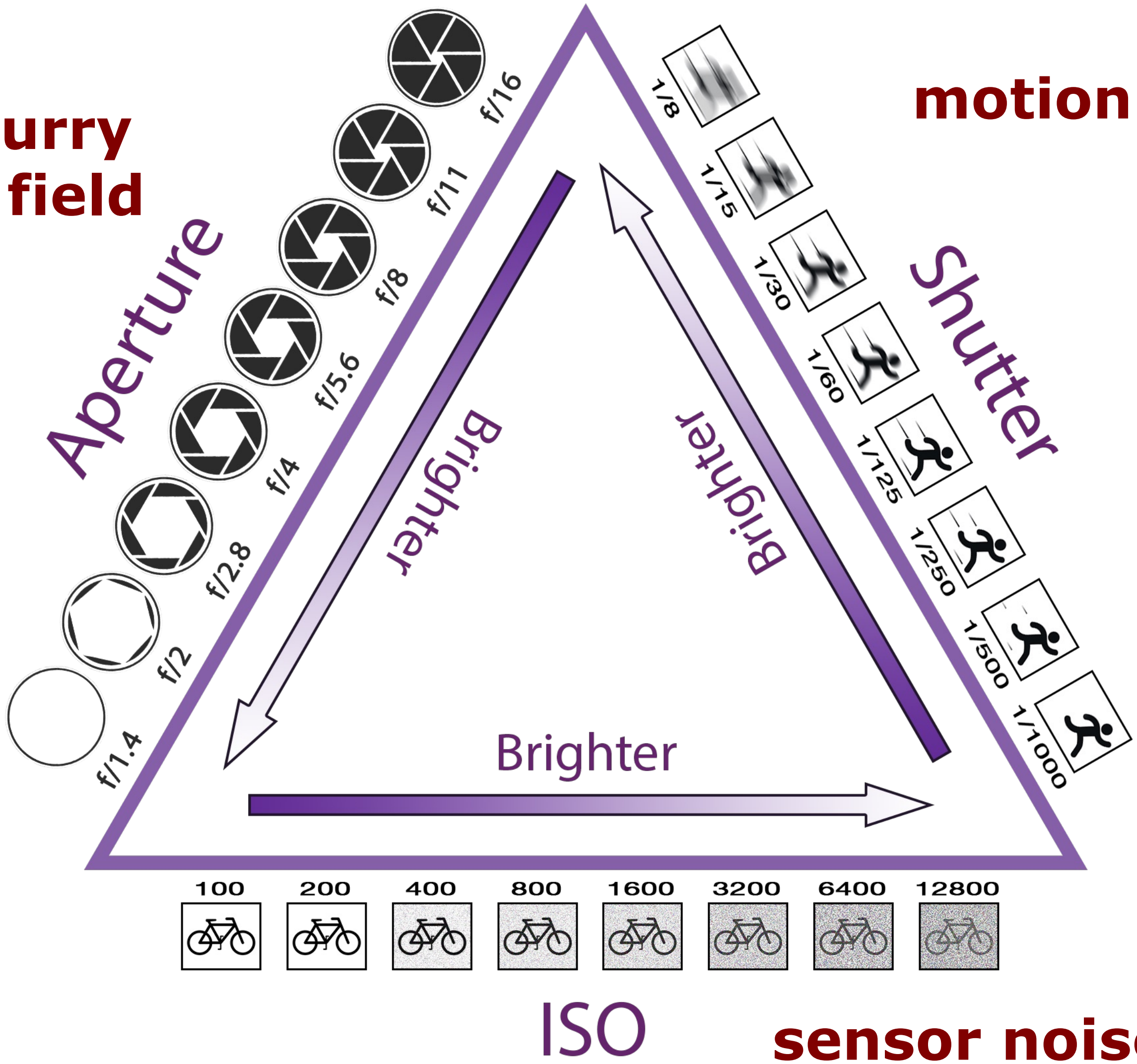
Camera

- Exposure time (“Tv”)
- Aperture/pinhole size (“Av”)
- Sensitivity of the chip (“ISO”)

Exposure Triangle

sharp/blurry
depth of field

motion blur



sensor noise

See:
https://actioncamera.blog/2017/02/2

Image courtesy: M. Walsh

Lighting and Reflectivity

Lighting and Reflectivity

- Lighting is essential
- Light intensity depends on the light source, the reflection properties of the material, and relative locations

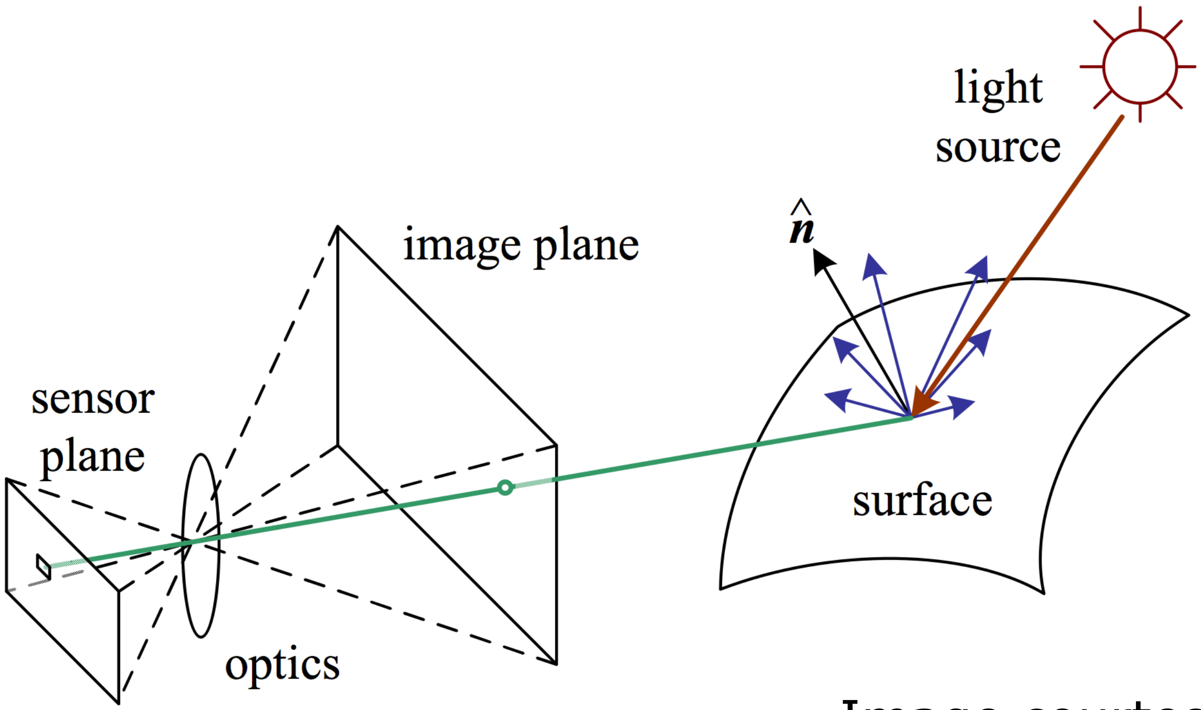


Image courtesy: Szeliski

Albedo

- Measure of the diffuse reflection of solar radiation
- Value in [0,1]
- 1 = material reflects all radiation
- 0 = black body

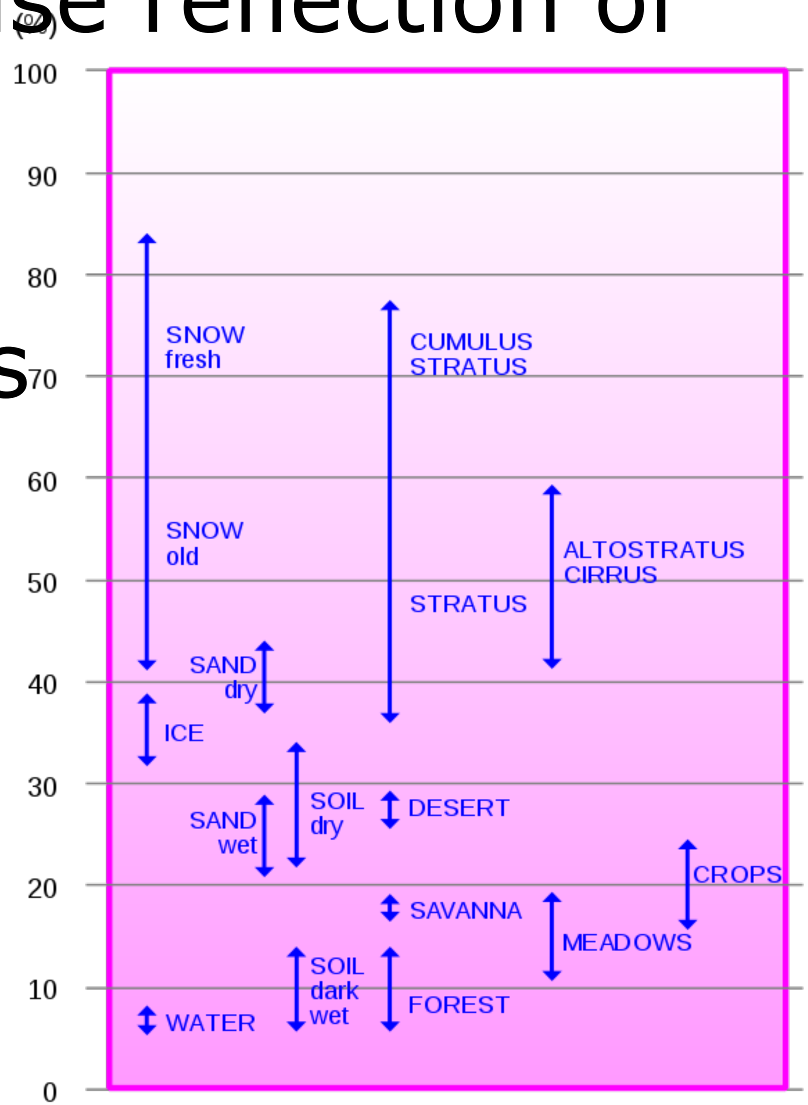


Image courtesy: Wereon

Reflectivity

- BRDF: Bidirectional Reflectance Distribution Function
- **General model of light scattering**

$$f_r(\underbrace{\theta_i, \phi_i, \theta_r, \phi_r}_{\text{geometry}}, \underbrace{\lambda}_{\text{wavelength}})$$

- Describes how much light of each wavelength arriving at an incident direction is emitted in a direction

BRDF

Describes how much of each wavelength arriving at an incident direction $\hat{v}_i$ is emitted in a reflected direction $\hat{v}_r$

$$f_r(\theta_i, \phi_i, \theta_r, \phi_r, \lambda)$$

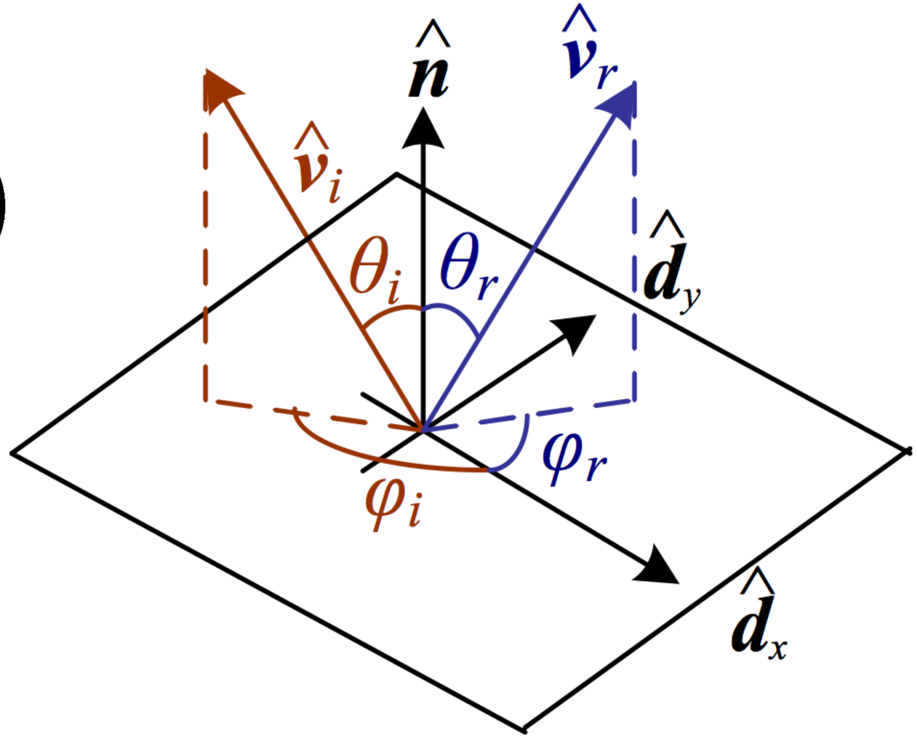


Image courtesy: Szeliski

Reflected Light

Amount of light exiting a surface point in a direction $\hat{v}_r$ is

$$\underbrace{L_r(\hat{v}_r, \lambda)}_{\text{reflected}} = \int \underbrace{L_i(\hat{v}_i, \lambda)}_{\text{incoming}} f_r(\hat{v}_i, \hat{v}_r, \hat{n}, \lambda) \cos^+ \theta_i \, d\hat{v}_i$$

with $\cos^+ \theta_i = \max(0, \cos \theta_i)$

Example: BRDF Estimation

Video courtesy: Proesmans and Van Gool

Example: Rendering with BRDFs

Video courtesy:
Proesmans and Van Gool

Summary

- Basic elements of a camera
- What a camera measures
- What impacts the measurements
- Different physical models to describe light (ray, wave, particle)
- Pinhole camera model
- Aberrations
- Reflectivity of objects

Literature

- Förstner, Scriptum Photogrammetrie I, Chapters 2 & 3
- Szeliski, Computer Vision: Algorithms and Applications, Chapters 2.2 & 2.3

Slide Information

- The slides have been created by Cyrill Stachniss as part of the photogrammetry and robotics courses.
- **I tried to acknowledge all people from whom I used images or videos. In case I made a mistake or missed someone, please let me know.**
- The photogrammetry material heavily relies on the very well written lecture notes by Wolfgang Förstner and the Photogrammetric Computer Vision book by Förstner & Wrobel.
- Parts of the robotics material stems from the great Probabilistic Robotics book by Thrun, Burgard and Fox.
- If you are a university lecturer, feel free to use the course material. If you adapt the course material, please make sure that you keep the acknowledgements to others and please acknowledge me as well. To satisfy my own curiosity, please send me email notice if you use my slides.

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