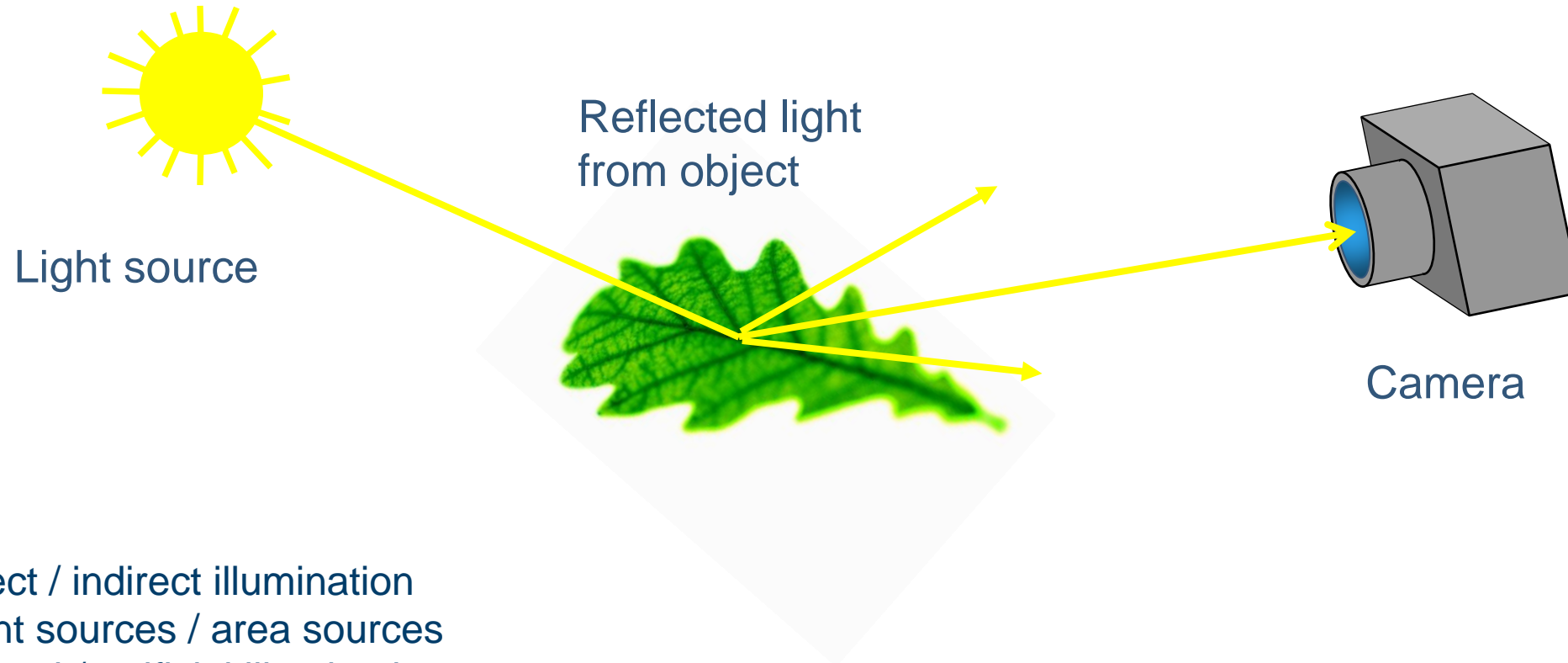


Image formation

Lecture 1.1 - Light, camera, optics and colour

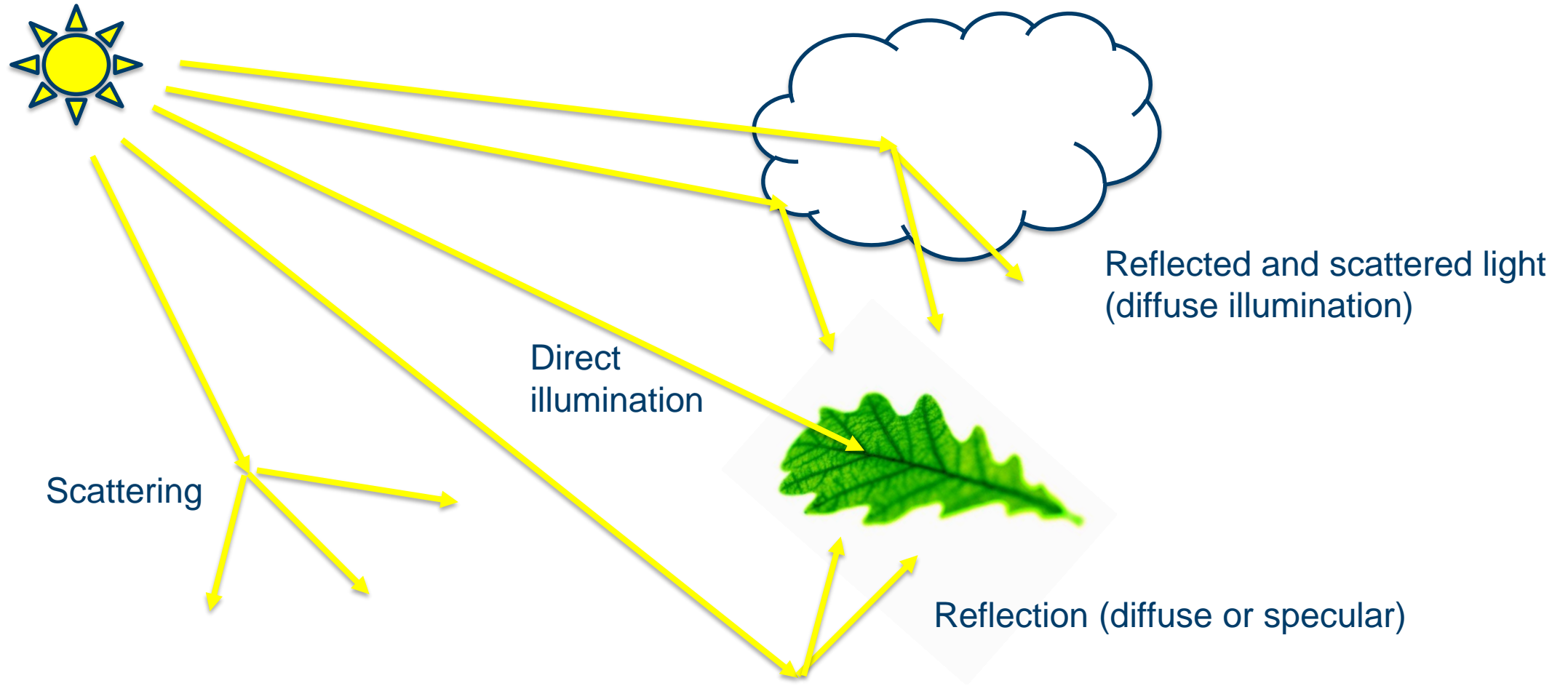
Idar Dyrdal

Imaging with visible light

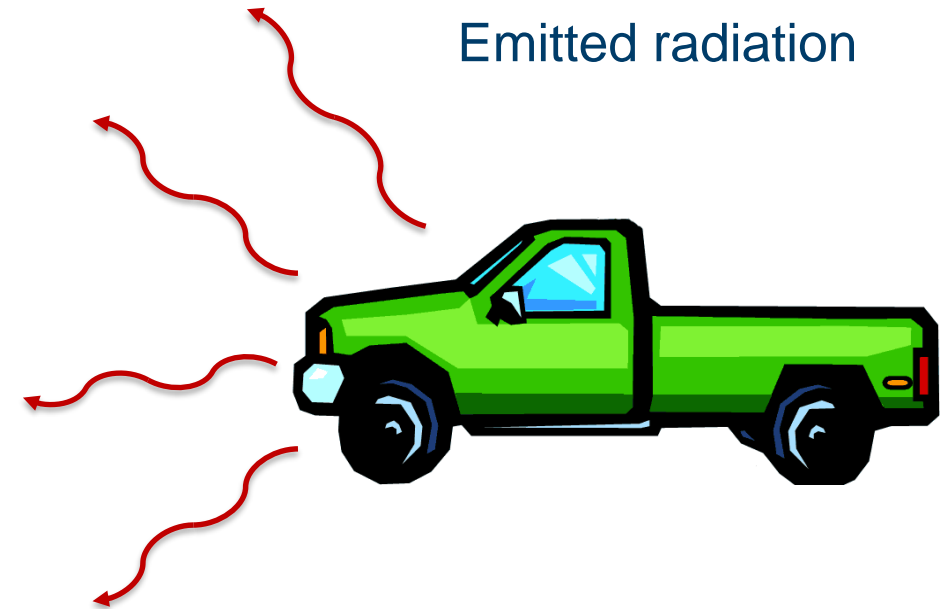
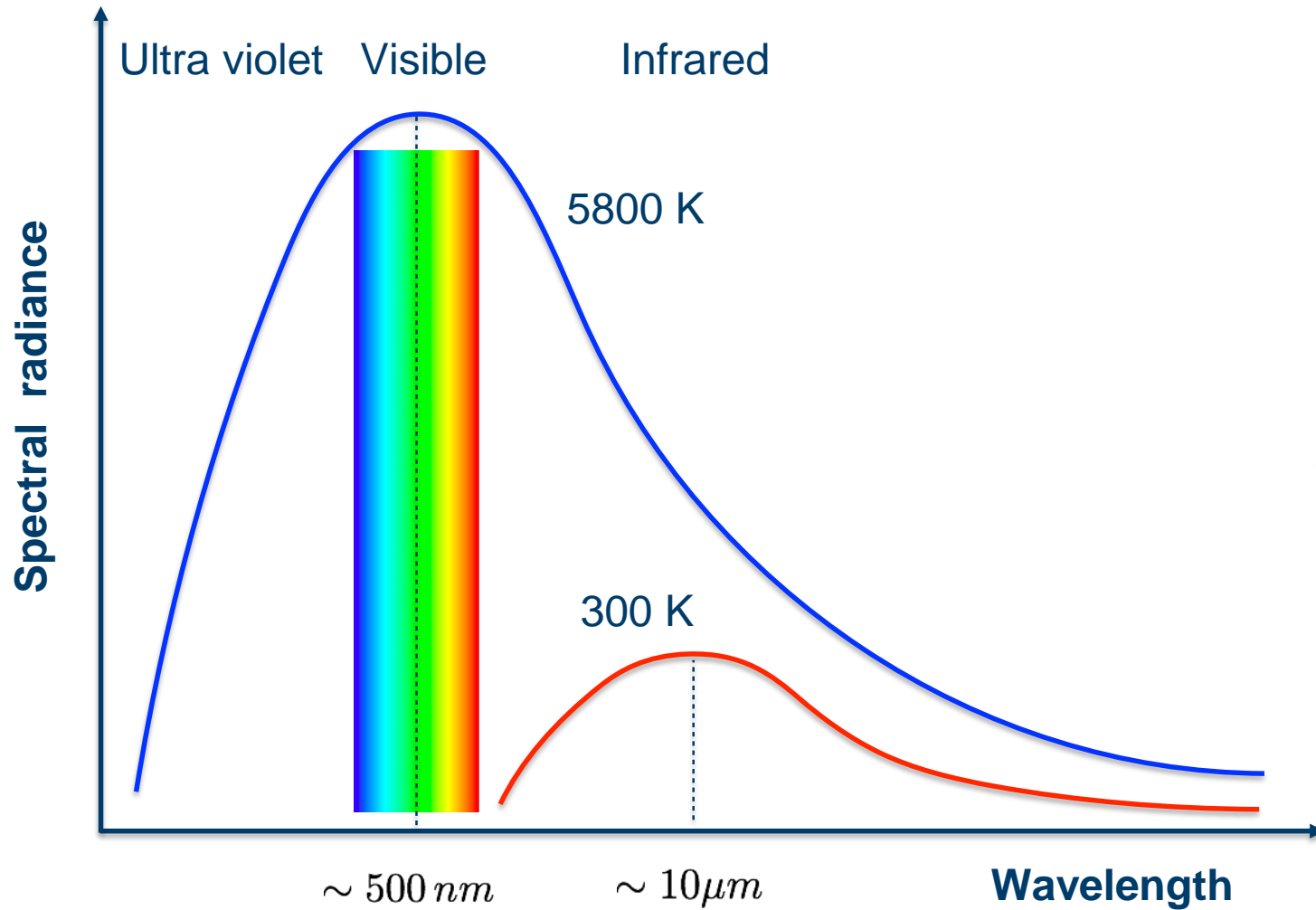


- Direct / indirect illumination
- Point sources / area sources
- Natural / artificial illumination

Direct and indirect illumination



Thermal radiation - Planck distribution

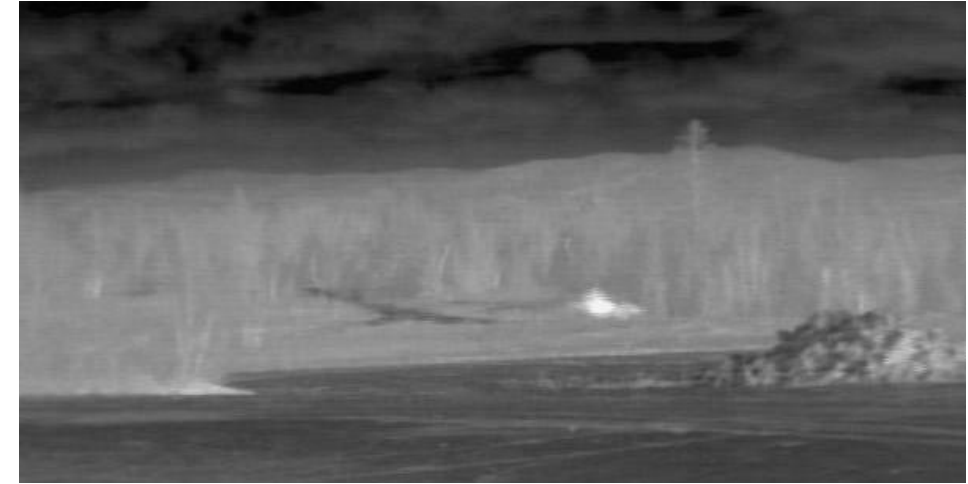


Reflected and emitted radiation



Image in visible light:

- Imaging with **reflected** (and scattered) radiation from the sun or other natural or artificial sources.



Infrared (thermal) image:

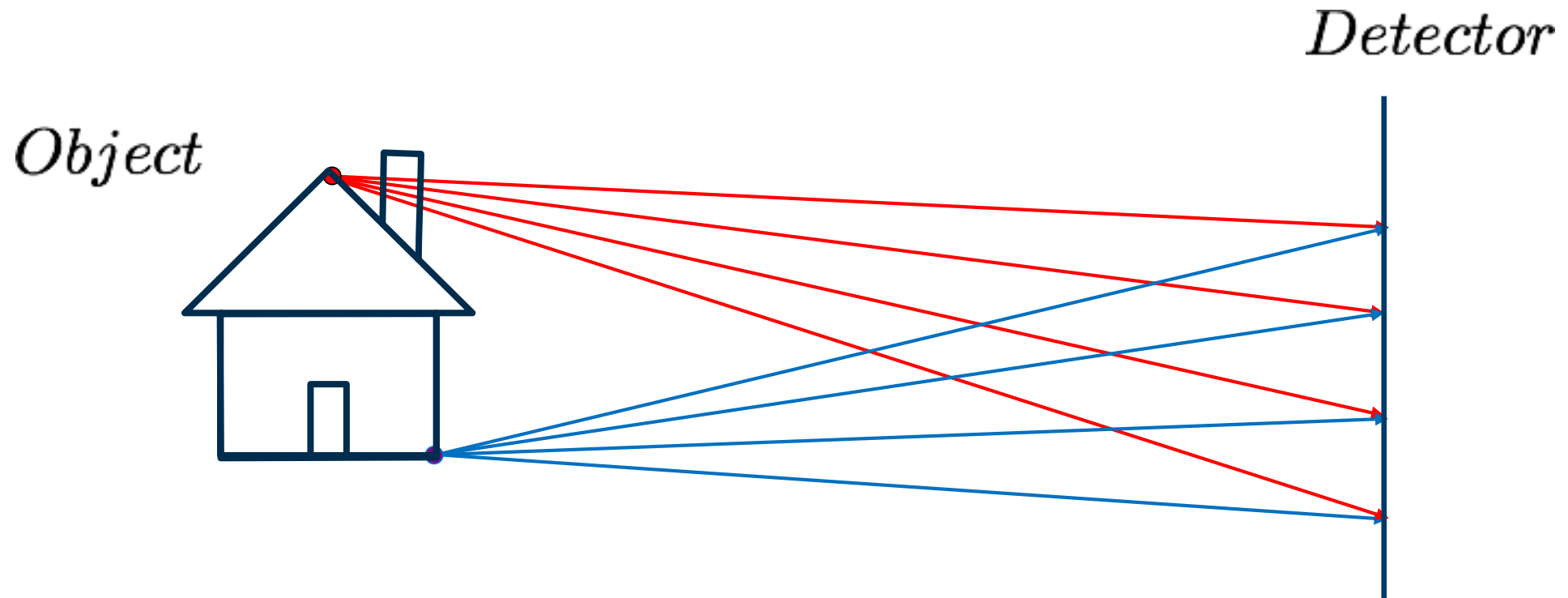
- Imaging with (mainly) the **emitted** thermal radiation from the scene.

Other frequency domains and wave types used for imaging:

- Millimeter waves, x-rays, ... (electromagnetic waves)
- Acoustic (sonar), seismic, ... (mechanical waves)

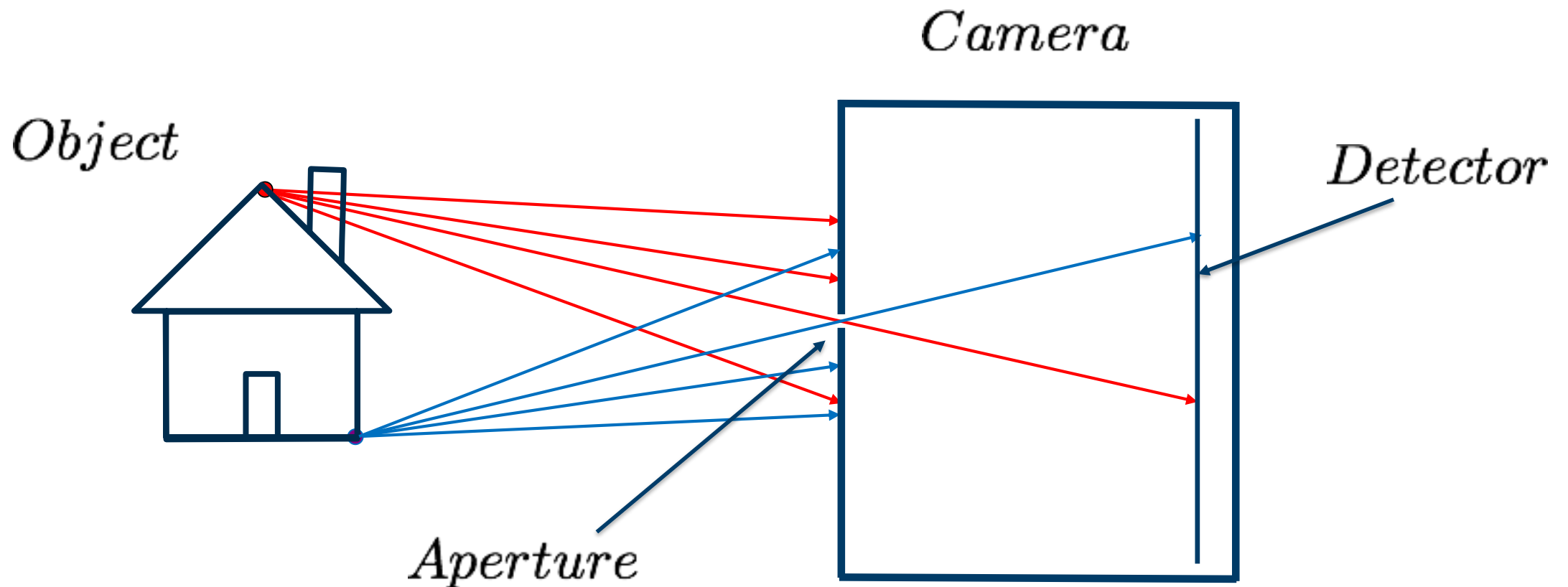


Image formation

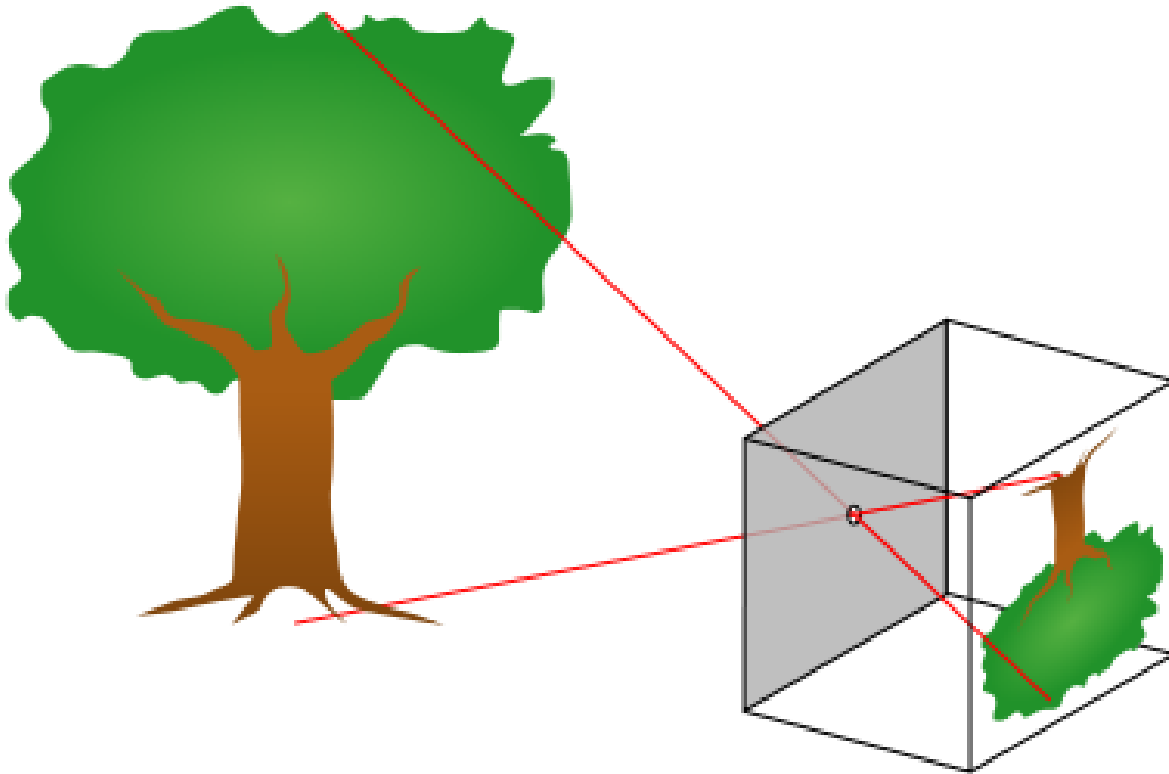


No image is formed!

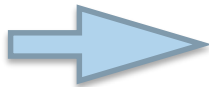
Simple camera - Pinhole camera



Pinhole camera



Small aperture



Dark image

Large aperture

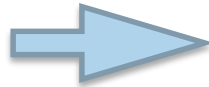
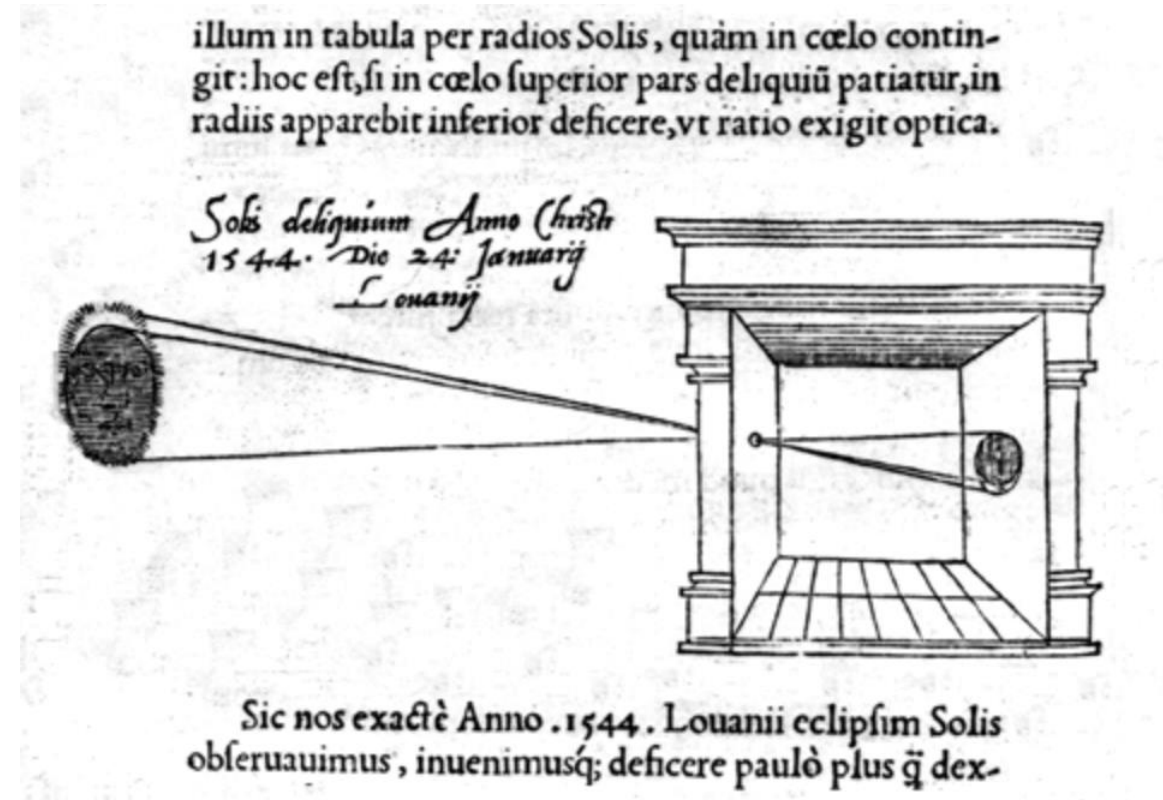
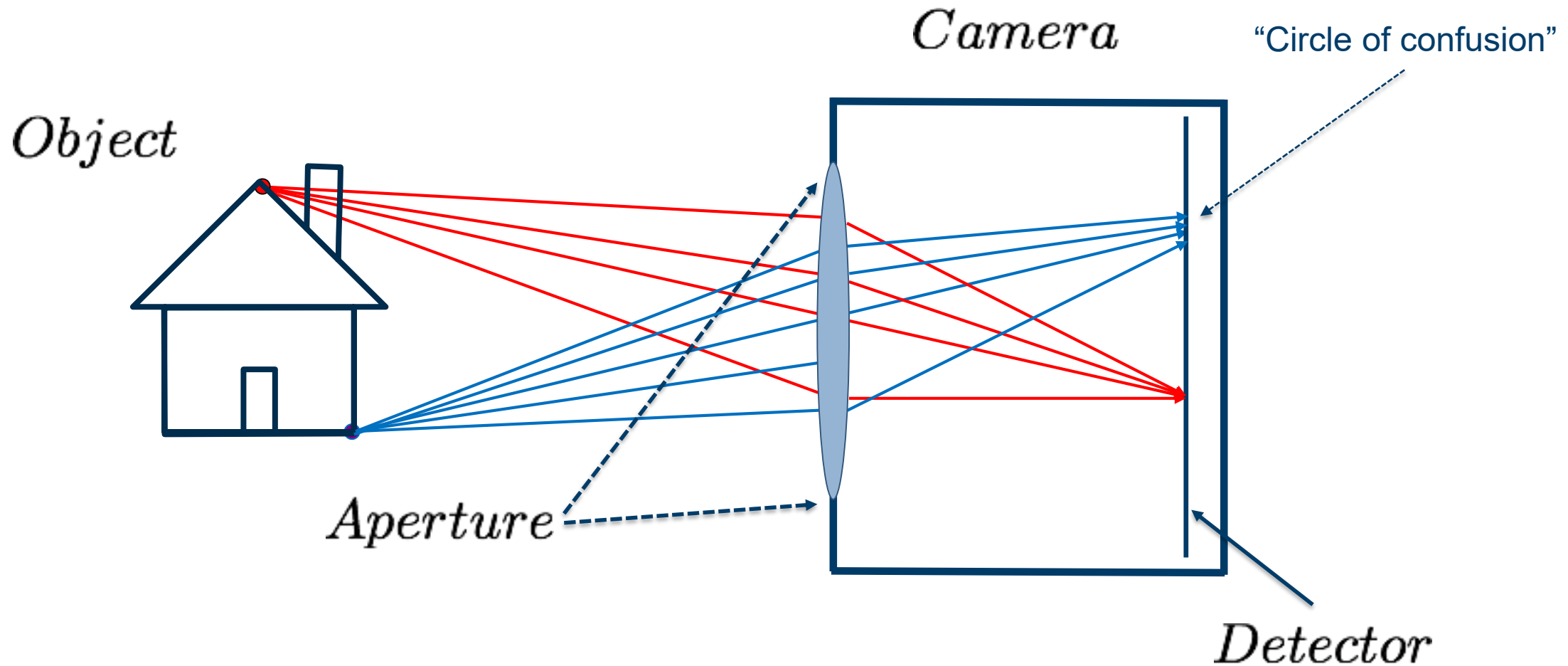


Image out of focus

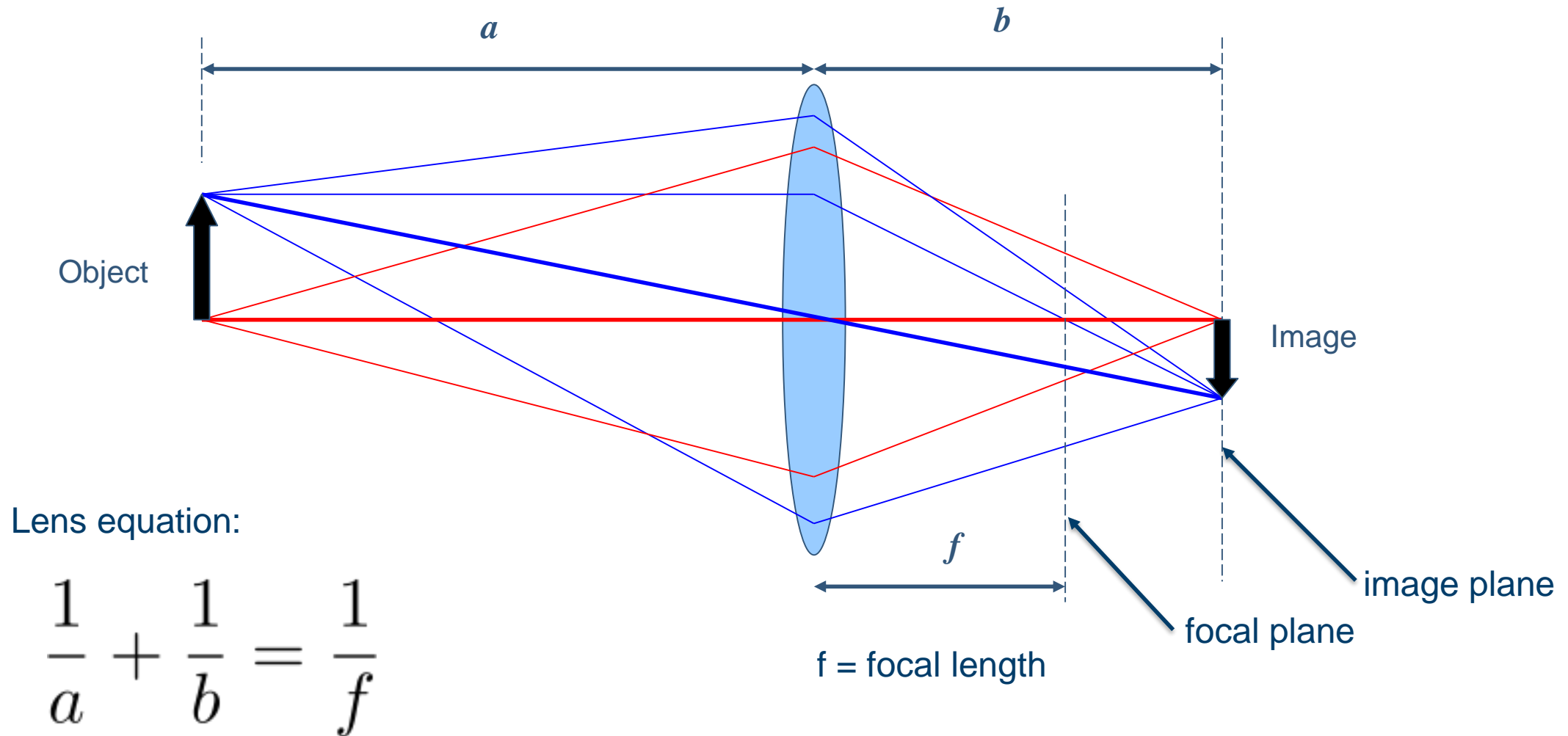
Camera obscura



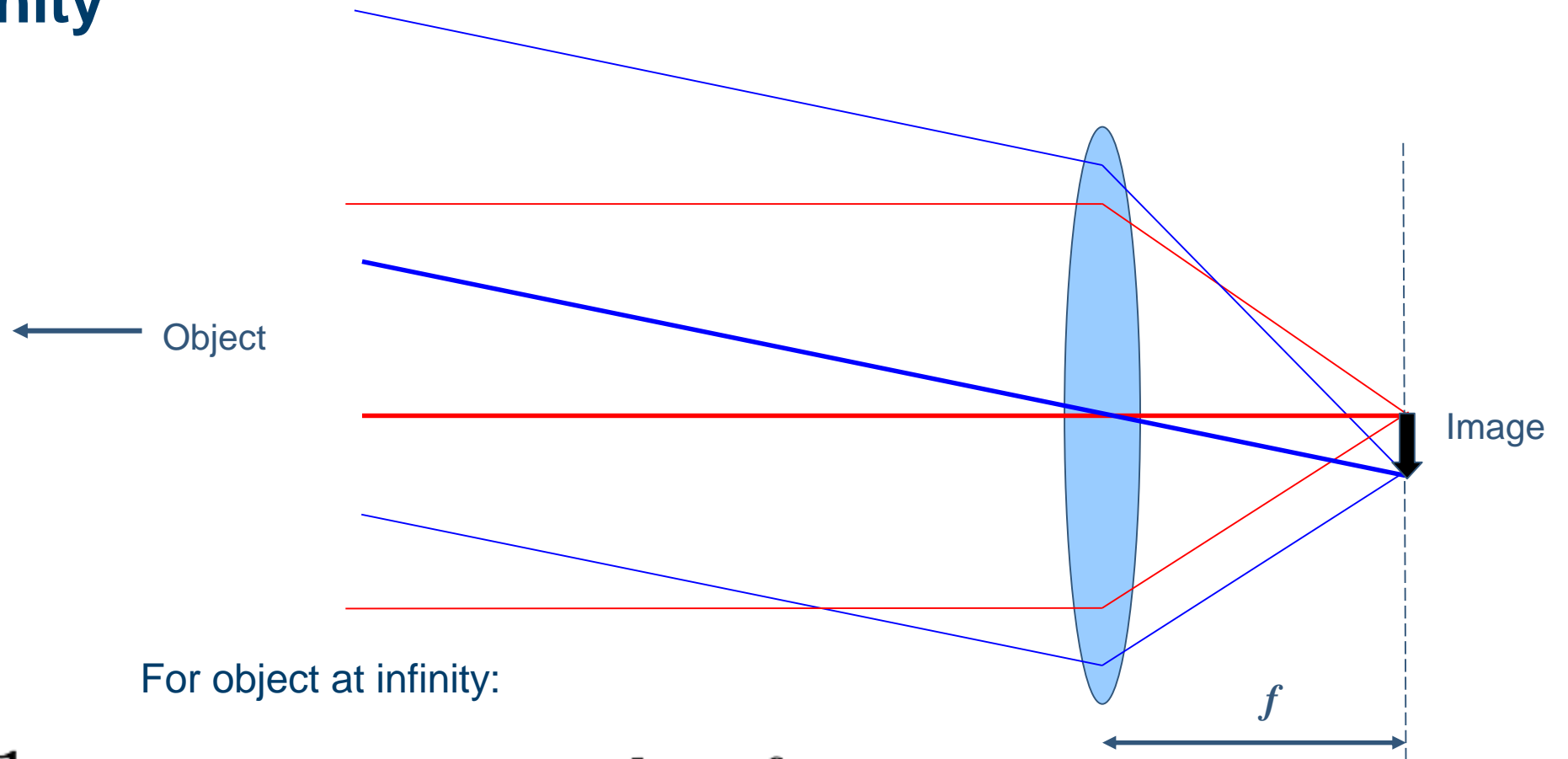
Camera with a lens



Imaging with a lens



Object at infinity



Lens equation:

$$\frac{1}{a} + \frac{1}{b} = \frac{1}{f}$$

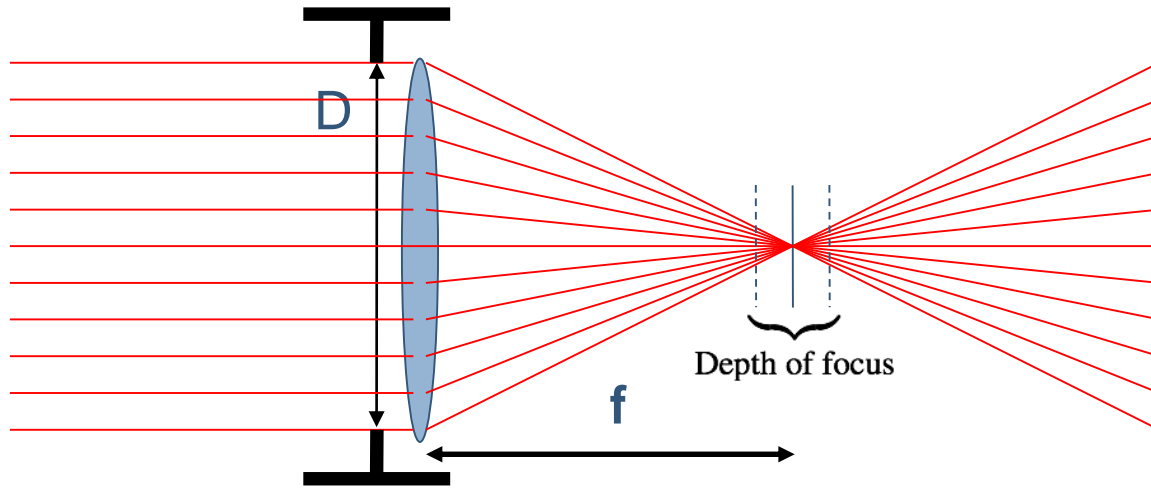
For object at infinity:

$$a = \infty \Rightarrow b = f$$

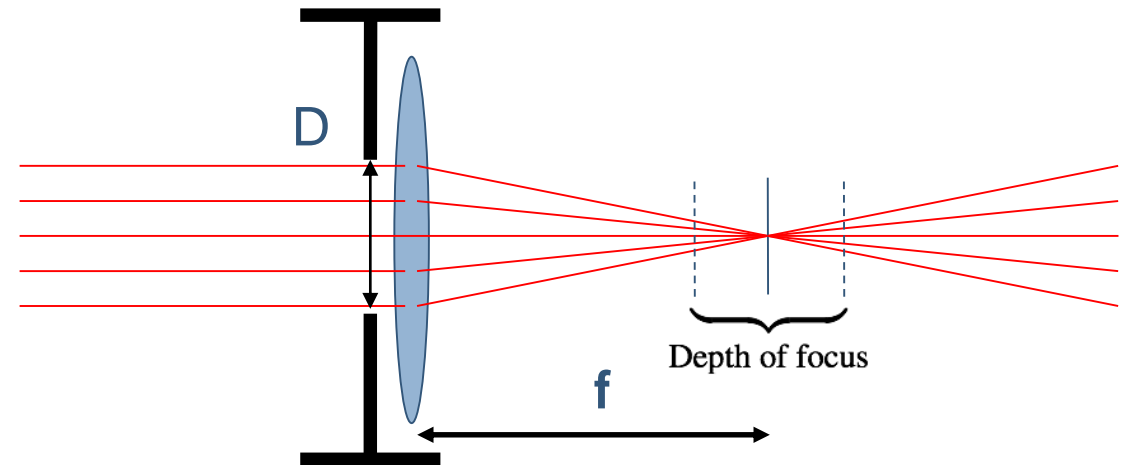
i.e. image is formed in focal plane.

Depth of focus

Large aperture

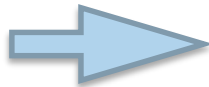


Small aperture



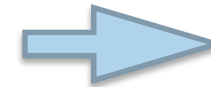
F-number: f/D (examples: $f/2.8$, $f/4$, $f/5.6$, $f/8$, $f/11$, $f/22$)

Small f-number



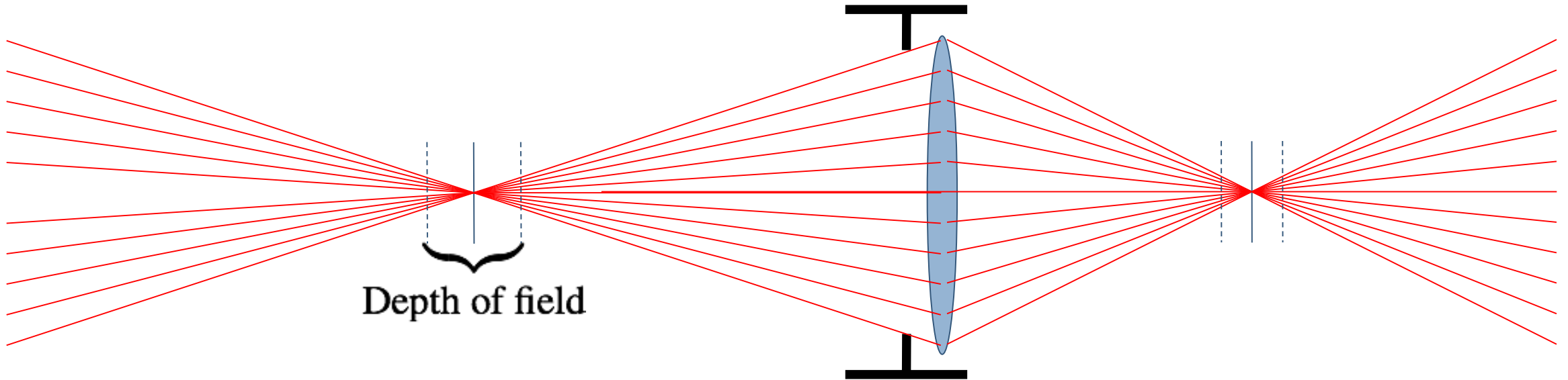
Narrow depth of focus

Large f-number



Large depth of focus

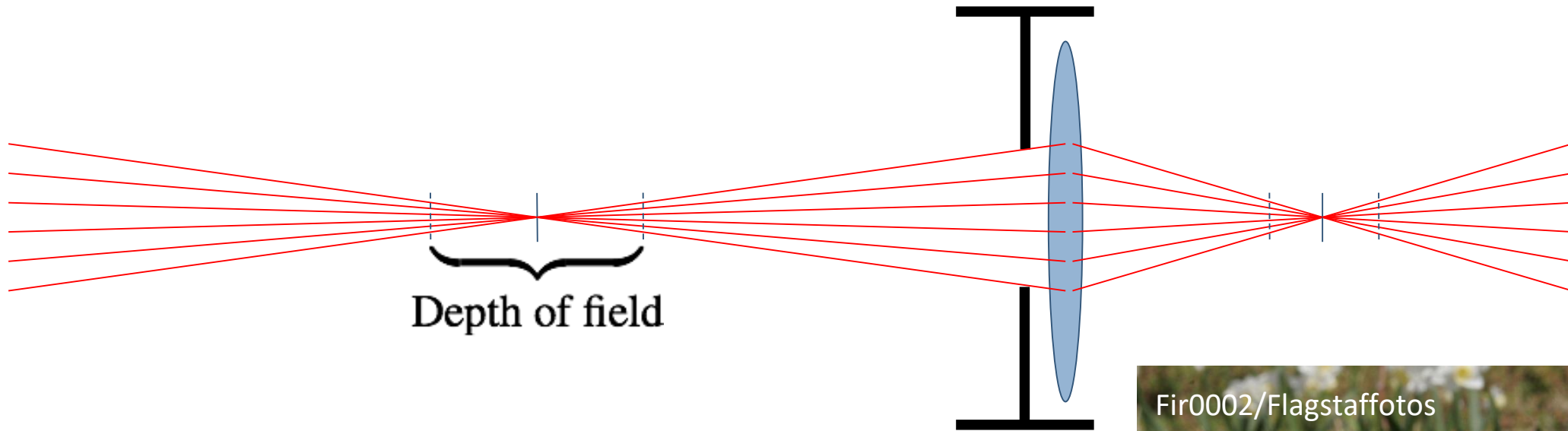
Depth of field – large aperture



Large aperture → Narrow depth of field



Depth of field – small aperture



Small aperture → Large depth of field

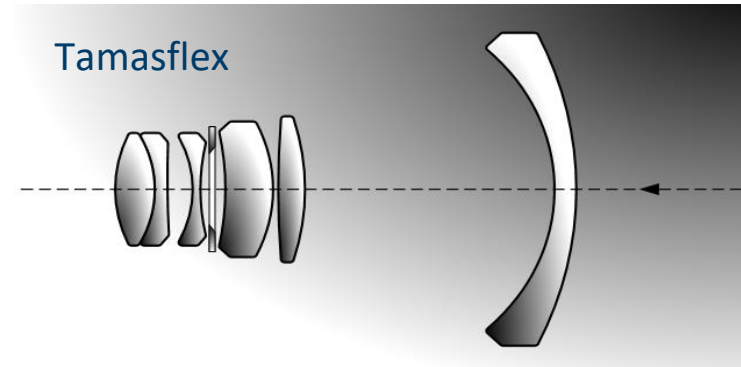
Too small aperture will lead to *diffraction* and loss of sharpness



Practical lenses

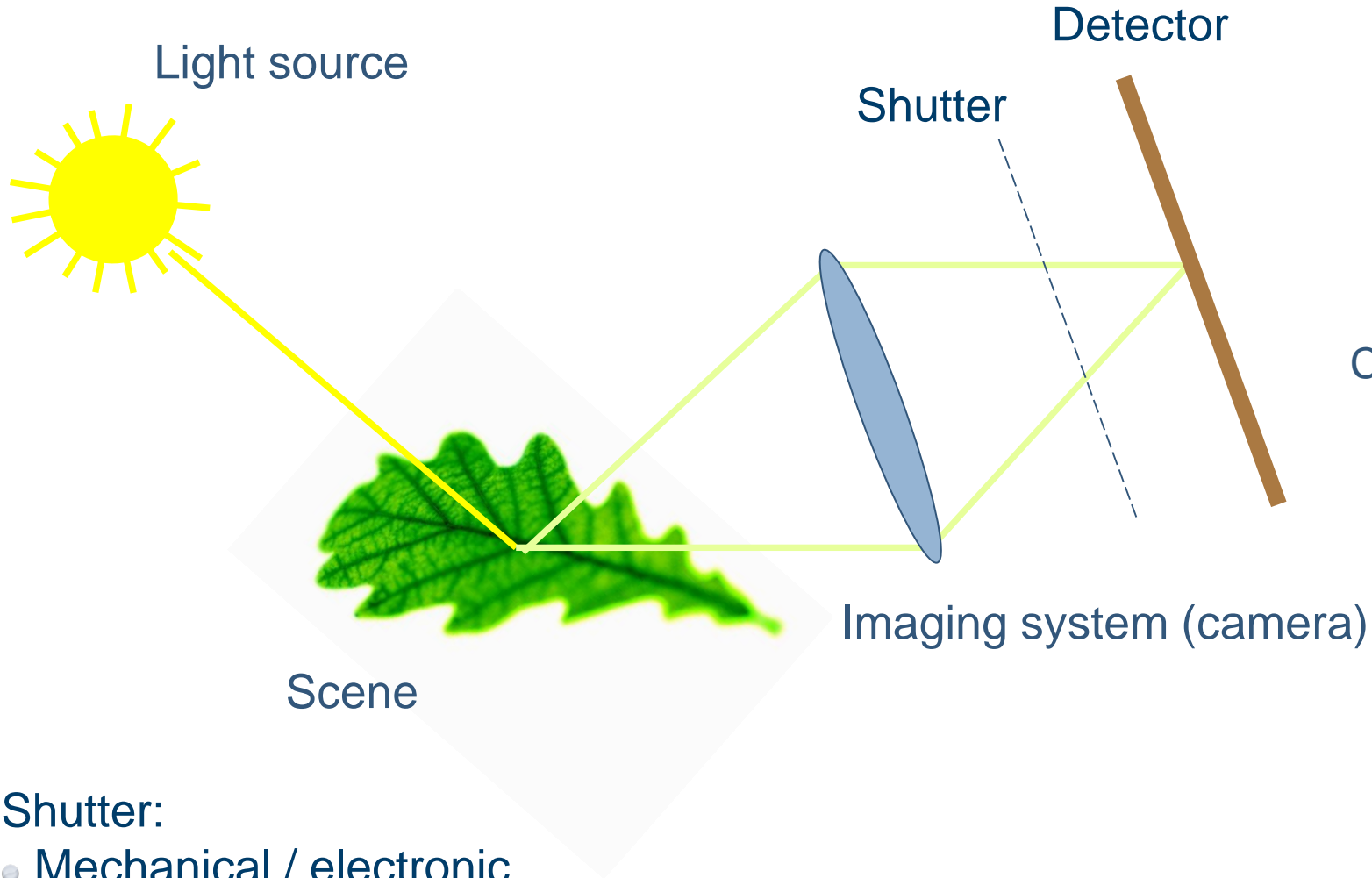


Fixed focal length lens



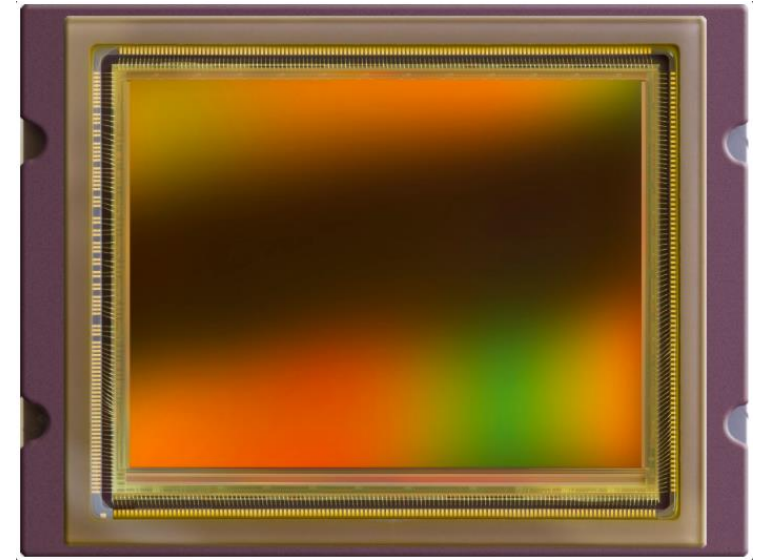
Zoom lens (variable focal length)

Image capture

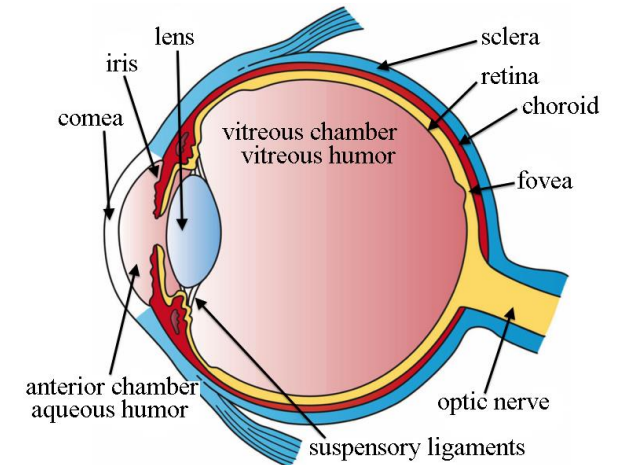


Shutter:

- Mechanical / electronic
- Global / rolling



CMOS image sensor (CMOSIS 48Mp)



Digital image



$j \rightarrow$

$i \downarrow$

| | | | | | | | | | |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 255 | 255 | 255 | 0 | 0 | 255 | 255 | 255 | 255 | 255 |
| 255 | 255 | 255 | 0 | 0 | 85 | 255 | 255 | 255 | 255 |
| 255 | 255 | 0 | 85 | 85 | 0 | 255 | 255 | 255 | 255 |
| 255 | 255 | 0 | 85 | 85 | 170 | 170 | 255 | 255 | 255 |
| 255 | 85 | 85 | 0 | 170 | 170 | 85 | 85 | 255 | 255 |
| 255 | 255 | 170 | 170 | 85 | 85 | 85 | 255 | 255 | 255 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |
| 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 | 255 |

$image(i, j)$

Colour images



RGB colour image

Red



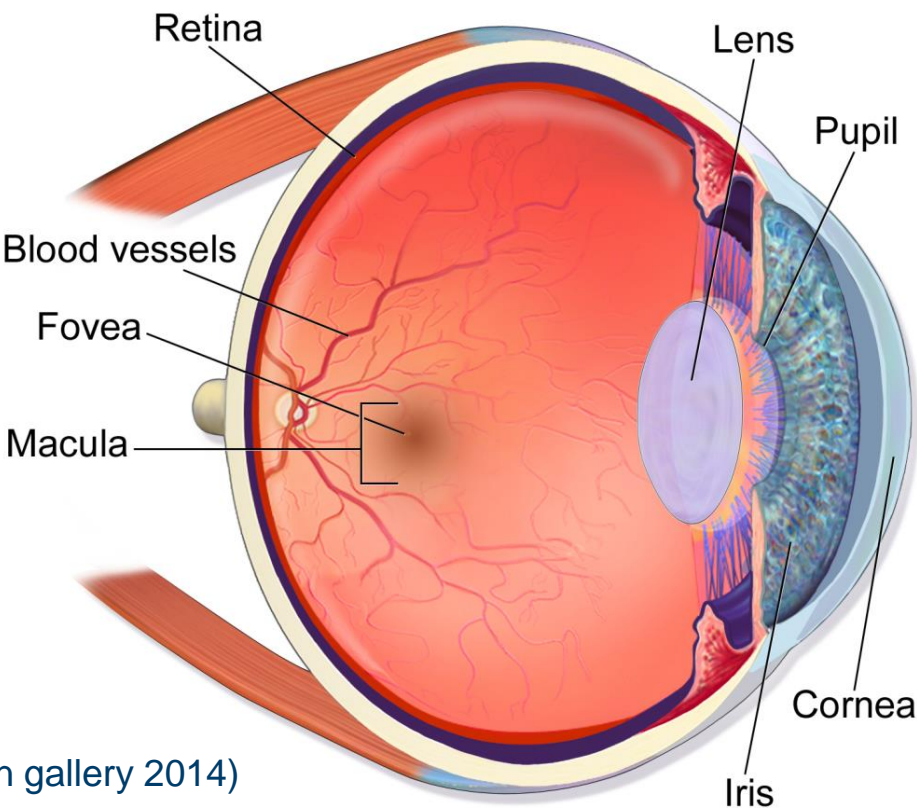
Green



Blue

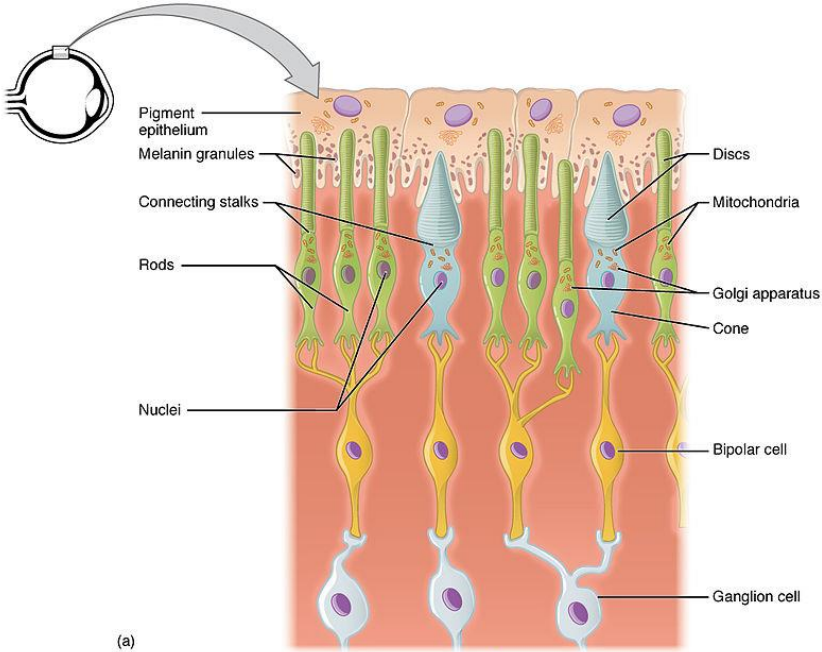


Human Vision

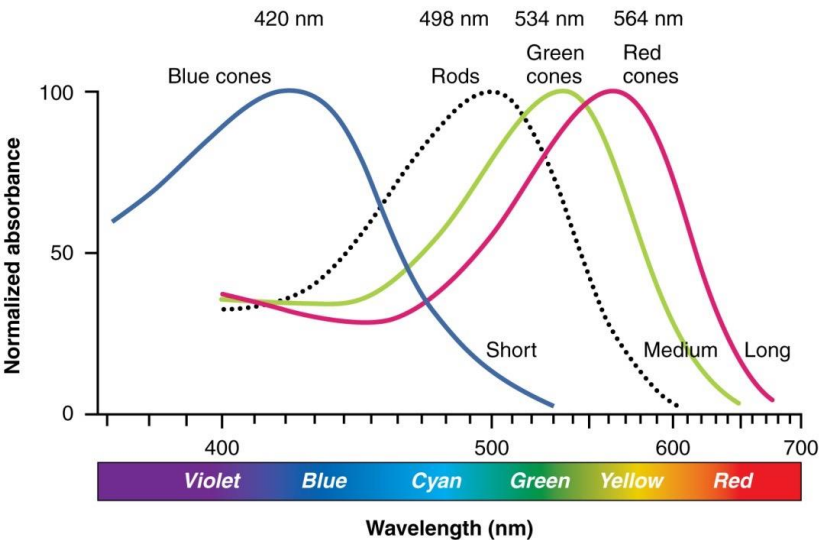


(Blausen gallery 2014)

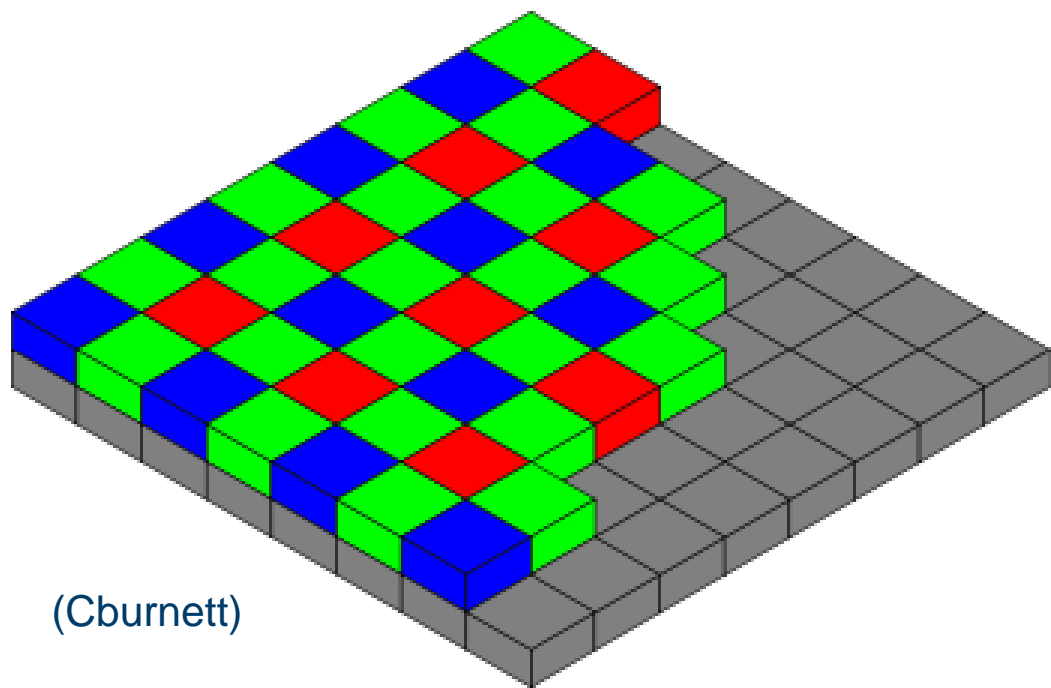
Eye Anatomy



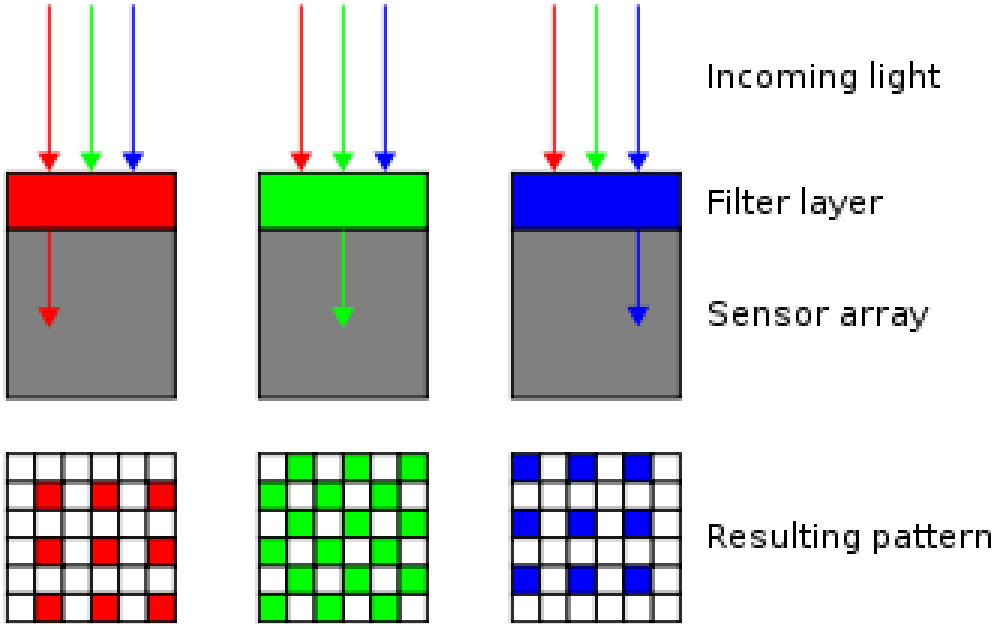
(OpenStax College - Anatomy & Physiology)



Colour Sensing in digital cameras - Bayer filter



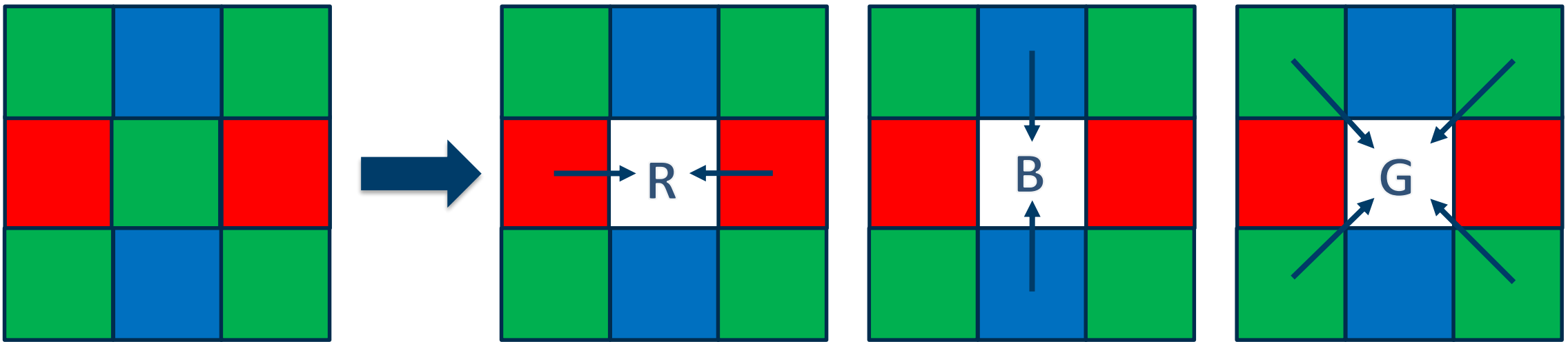
(Cburnett)



Undersampled (incomplete) colour information

Demosaicing (debayering)

Reconstruction of full colour image from incomplete colour information from the image sensor.



Algorithms:

- Nearest-neighbor interpolation
- Bilinear interpolation
- Bicubic interpolation

Other methods:

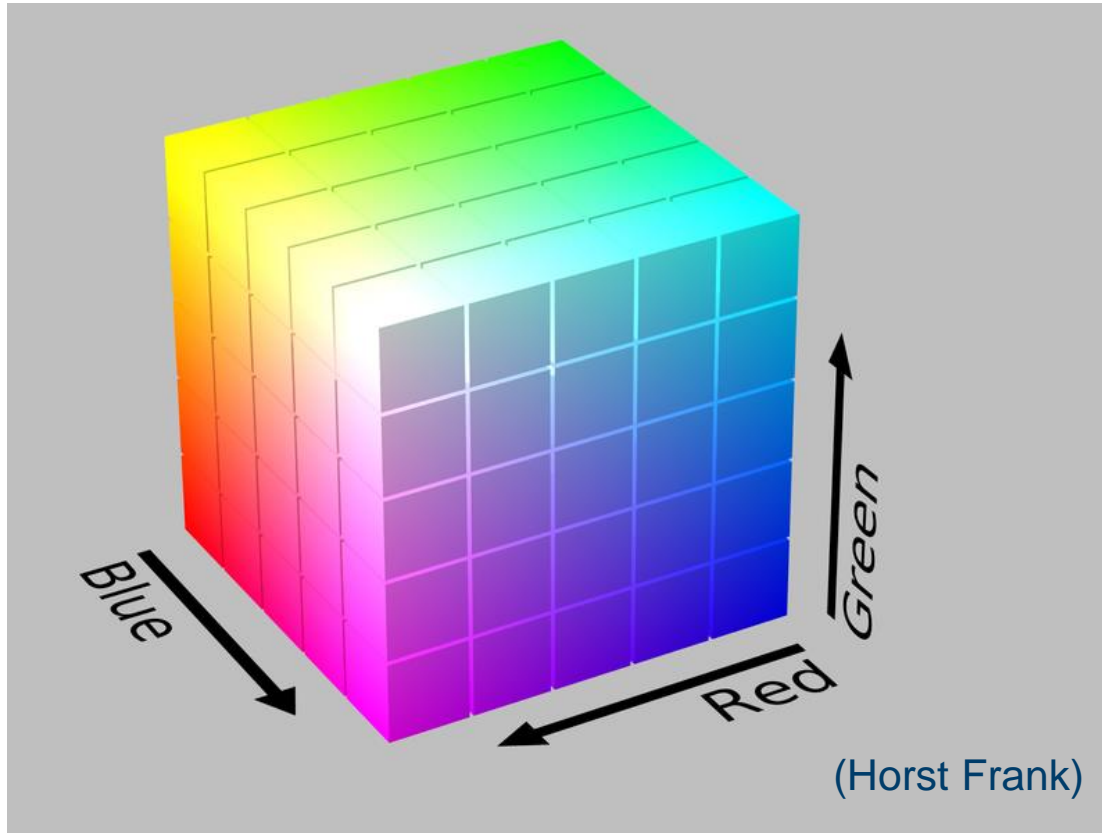
- Splines
- Lanczos resampling
- Methods utilizing pixel values

B

R

| R | | | | | | | | | | | | | | G | | | | | | | | | | | | | | B | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| | | | | | | | | | | | | | | 85 | 87 | 88 | 84 | 86 | 85 | 86 | 84 | 85 | 88 | 84 | 84 | 84 | 84 | 84 | 83 | 86 | 82 | 85 | 88 | 83 | 86 | 82 | 84 | 83 | 85 | 29 | 32 | 32 | 34 | 29 | 28 | 31 | 27 | 27 | 27 | 32 | 30 | 33 | 32 | 32 | 29 | 30 | |
| 140 | 141 | 145 | 141 | 144 | 142 | 143 | 141 | 143 | 146 | 142 | 142 | 142 | 144 | 143 | 145 | 144 | 144 | 141 | 143 | 84 | 86 | 84 | 86 | 88 | 86 | 86 | 86 | 85 | 83 | 85 | 82 | 88 | 83 | 84 | 82 | 86 | 83 | 88 | 83 | 86 | 82 | 84 | 83 | 85 | 32 | 33 | 30 | 29 | 29 | 28 | 28 | 29 | 28 | 31 | 31 | 28 | 29 |
| 142 | 144 | 139 | 144 | 143 | 141 | 141 | 141 | 144 | 142 | 144 | 146 | 144 | 144 | 143 | 145 | 141 | 144 | 146 | 143 | 86 | 88 | 85 | 86 | 86 | 85 | 83 | 85 | 82 | 86 | 83 | 88 | 83 | 88 | 83 | 86 | 83 | 84 | 83 | 32 | 33 | 30 | 30 | 29 | 29 | 28 | 28 | 29 | 28 | 31 | 31 | 28 | 31 | | | | | |
| 141 | 143 | 140 | 143 | 141 | 144 | 144 | 144 | 145 | 143 | 144 | 144 | 143 | 143 | 144 | 143 | 146 | 146 | 147 | 145 | 85 | 86 | 85 | 85 | 84 | 85 | 83 | 86 | 83 | 86 | 83 | 84 | 83 | 88 | 83 | 86 | 82 | 86 | 32 | 33 | 30 | 31 | 35 | 30 | 32 | 30 | 32 | 29 | 31 | 28 | 28 | | | | | | | |
| 141 | 142 | 142 | 142 | 143 | 143 | 145 | 143 | 144 | 143 | 143 | 141 | 143 | 144 | 144 | 142 | 144 | 143 | 147 | 147 | 84 | 86 | 82 | 84 | 88 | 85 | 83 | 86 | 83 | 86 | 83 | 88 | 83 | 88 | 83 | 86 | 32 | 33 | 30 | 32 | 30 | 29 | 32 | 33 | 30 | 32 | 32 | 30 | 32 | 30 | 35 | | | | | | | |
| 142 | 143 | 142 | 143 | 145 | 145 | 141 | 141 | 144 | 139 | 141 | 145 | 143 | 144 | 143 | 144 | 146 | 144 | 143 | 82 | 85 | 85 | 88 | 85 | 84 | 83 | 86 | 83 | 88 | 83 | 86 | 83 | 88 | 83 | 86 | 32 | 33 | 30 | 34 | 33 | 32 | 33 | 27 | 29 | 32 | 32 | 29 | 29 | 30 | | | | | | | | | |
| 141 | 140 | 140 | 145 | 143 | 143 | 142 | 139 | 142 | 142 | 145 | 143 | 141 | 144 | 145 | 143 | 144 | 144 | 143 | 150 | 86 | 84 | 86 | 88 | 86 | 88 | 84 | 82 | 84 | 83 | 86 | 83 | 84 | 83 | 86 | 34 | 31 | 30 | 30 | 35 | 34 | 30 | 32 | 32 | 29 | 33 | 28 | | | | | | | | | | | |
| 142 | 141 | 143 | 142 | 142 | 141 | 142 | 143 | 141 | 143 | 145 | 144 | 145 | 140 | 141 | 144 | 144 | 141 | 141 | 143 | 85 | 86 | 84 | 85 | 85 | 88 | 83 | 86 | 83 | 82 | 88 | 85 | 83 | 84 | 83 | 88 | 31 | 34 | 30 | 31 | 32 | 32 | 31 | 31 | 32 | 32 | 32 | 32 | 29 | | | | | | | | | |
| 143 | 144 | 143 | 139 | 140 | 140 | 142 | 142 | 143 | 141 | 143 | 143 | 145 | 143 | 139 | 142 | 142 | 141 | 145 | 143 | 84 | 82 | 86 | 85 | 84 | 85 | 84 | 82 | 85 | 83 | 84 | 83 | 84 | 83 | 85 | 32 | 30 | 31 | 32 | 31 | 34 | 32 | 28 | 30 | 32 | 32 | 32 | 32 | 32 | | | | | | | | | |
| 141 | 138 | 143 | 139 | 142 | 143 | 143 | 140 | 142 | 143 | 143 | 141 | 142 | 142 | 141 | 141 | 142 | 144 | 148 | 144 | 84 | 85 | 82 | 84 | 85 | 84 | 83 | 86 | 84 | 85 | 81 | 82 | 83 | 85 | 83 | 86 | 34 | 34 | 32 | 32 | 31 | 35 | 32 | 32 | 32 | 32 | 32 | 31 | 31 | | | | | | | | | |
| 138 | 138 | 138 | 142 | 143 | 142 | 139 | 140 | 142 | 139 | 141 | 142 | 141 | 143 | 142 | 138 | 139 | 142 | 144 | 144 | 89 | 86 | 86 | 85 | 85 | 84 | 83 | 86 | 83 | 85 | 83 | 88 | 83 | 86 | 39 | 37 | 36 | 34 | 31 | 32 | 35 | 32 | 34 | 34 | 32 | 34 | 32 | 31 | | | | | | | | | | |
| 141 | 142 | 141 | 144 | 143 | 138 | 139 | 143 | 143 | 143 | 142 | 142 | 141 | 145 | 144 | 142 | 142 | 142 | 141 | 141 | 89 | 89 | 88 | 86 | 86 | 84 | 83 | 86 | 83 | 85 | 83 | 88 | 83 | 86 | 40 | 37 | 37 | 35 | 31 | 32 | 34 | 34 | 35 | 34 | 32 | 31 | | | | | | | | | | | | |
| 139 | 141 | 140 | 137 | 142 | 139 | 140 | 143 | 146 | 144 | 143 | 143 | 141 | 142 | 145 | 142 | 143 | 142 | 141 | 141 | 85 | 88 | 85 | 88 | 85 | 84 | 83 | 86 | 83 | 85 | 83 | 88 | 83 | 86 | 40 | 38 | 33 | 35 | 40 | 37 | 33 | 33 | 35 | 35 | 35 | 35 | 35 | | | | | | | | | | | |
| 139 | 139 | 141 | 136 | 138 | 143 | 143 | 138 | 144 | 141 | 144 | 142 | 141 | 142 | 143 | 143 | 145 | 143 | 142 | 141 | 83 | 88 | 86 | 81 | 84 | 90 | 84 | 83 | 86 | 83 | 85 | 83 | 88 | 83 | 86 | 36 | 42 | 39 | 38 | 34 | 37 | 38 | 34 | 36 | 36 | 32 | 36 | | | | | | | | | | | |
| 139 | 139 | 138 | 138 | 139 | 141 | 137 | 136 | 141 | 143 | 137 | 140 | 147 | 144 | 140 | 140 | 142 | 142 | 142 | 145 | 85 | 84 | 89 | 85 | 84 | 82 | 84 | 83 | 86 | 83 | 85 | 83 | 88 | 83 | 86 | 41 | 38 | 39 | 38 | 40 | 34 | 37 | 38 | 36 | 36 | 33 | 33 | | | | | | | | | | | |
| 139 | 141 | 139 | 138 | 139 | 141 | 139 | 138 | 137 | 143 | 141 | 139 | 139 | 141 | 143 | 139 | 143 | 143 | 139 | 143 | 88 | 87 | 85 | 87 | 84 | 86 | 83 | 86 | 83 | 85 | 83 | 88 | 83 | 86 | 44 | 43 | 39 | 39 | 38 | 39 | 37 | 40 | 33 | 36 | 37 | 35 | | | | | | | | | | | | |
| 136 | 140 | 140 | 141 | 141 | 139 | 139 | 141 | 139 | 138 | 140 | 139 | 142 | 139 | 141 | 143 | 142 | 143 | 140 | 140 | 91 | 89 | 88 | 87 | 87 | 84 | 83 | 86 | 83 | 85 | 83 | 88 | 83 | 86 | 45 | 41 | 45 | 43 | 42 | 40 | 38 | 39 | 35 | 34 | 35 | 37 | | | | | | | | | | | | |
| 138 | 136 | 140 | 142 | 139 | 141 | 142 | 143 | 142 | 141 | 140 | 140 | 139 | 141 | 141 | 143 | 139 | 142 | 144 | 142 | 87 | 91 | 87 | 91 | 88 | 89 | 84 | 83 | 86 | 83 | 85 | 83 | 88 | 43 | 43 | 43 | 44 | 43 | 43 | 41 | 40 | 38 | 40 | 36 | 35 | | | | | | | | | | | | | |
| 143 | 139 | 136 | 140 | 140 | 139 | 138 | 139 | 143 | 139 | 143 | 141 | 143 | 141 | 138 | 140 | 139 | 139 | 142 | 144 | 85 | 86 | 85 | 85 | 89 | 91 | 84 | 83 | 86 | 83 | 85 | 83 | 88 | 49 | 46 | 43 | 41 | 43 | 41 | 40 | 41 | 43 | 39 | 37 | 37 | | | | | | | | | | | | | |
| 141 | 139 | 139 | 140 | 143 | 140 | 139 | 138 | 142 | 140 | 140 | 142 | 144 | 141 | 139 | 138 | 139 | 144 | 143 | 141 | 89 | 90 | 88 | 85 | 85 | 88 | 87 | 85 | 87 | 88 | 87 | 87 | 87 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 139 | 143 | 143 | 137 | 139 | 141 | 140 | 142 | 145 | 143 | 140 | 140 | 141 | 139 | 138 | 139 | 141 | 140 | 140 | 140 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

RGB colour space



Normalized RGB values:

$$r = \frac{R}{R + G + B}$$

$$g = \frac{G}{R + G + B}$$

$$b = \frac{B}{R + G + B}$$

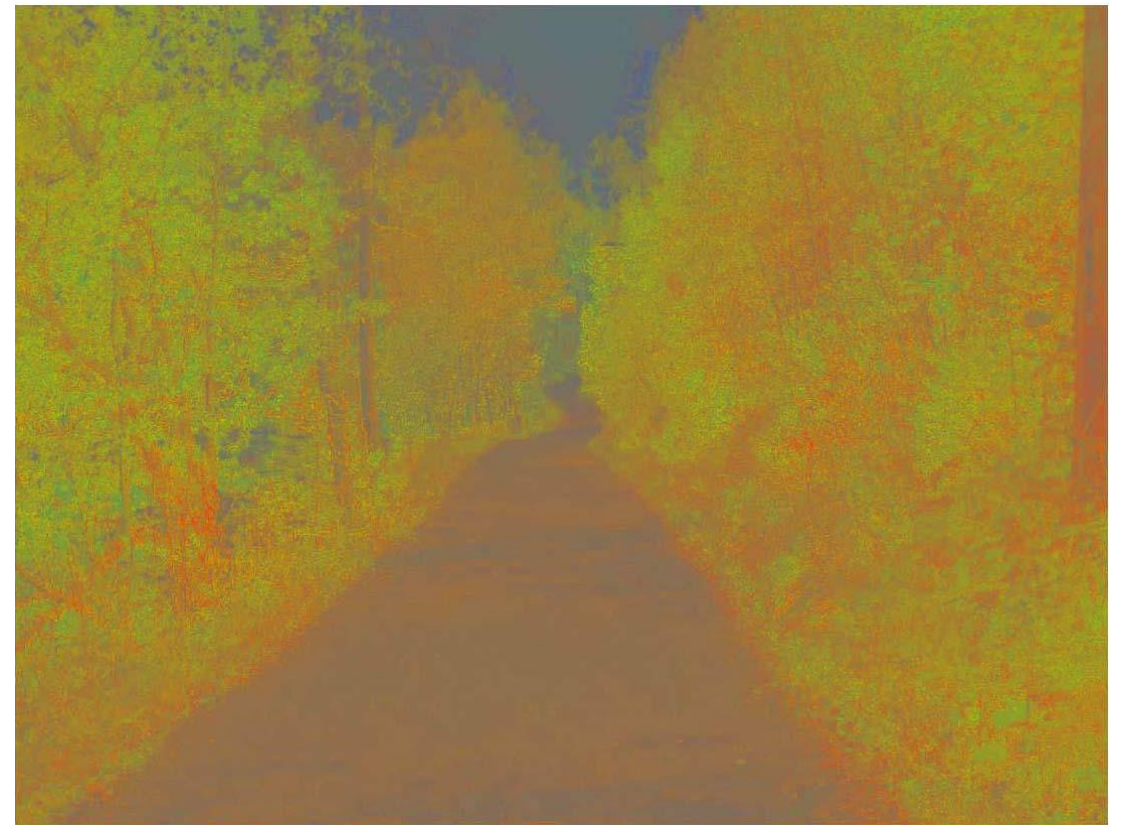
(Illumination invariance)

Colour coordinate systems: $RGB \Rightarrow XYZ \Rightarrow LAB$

RGB normalization (example)

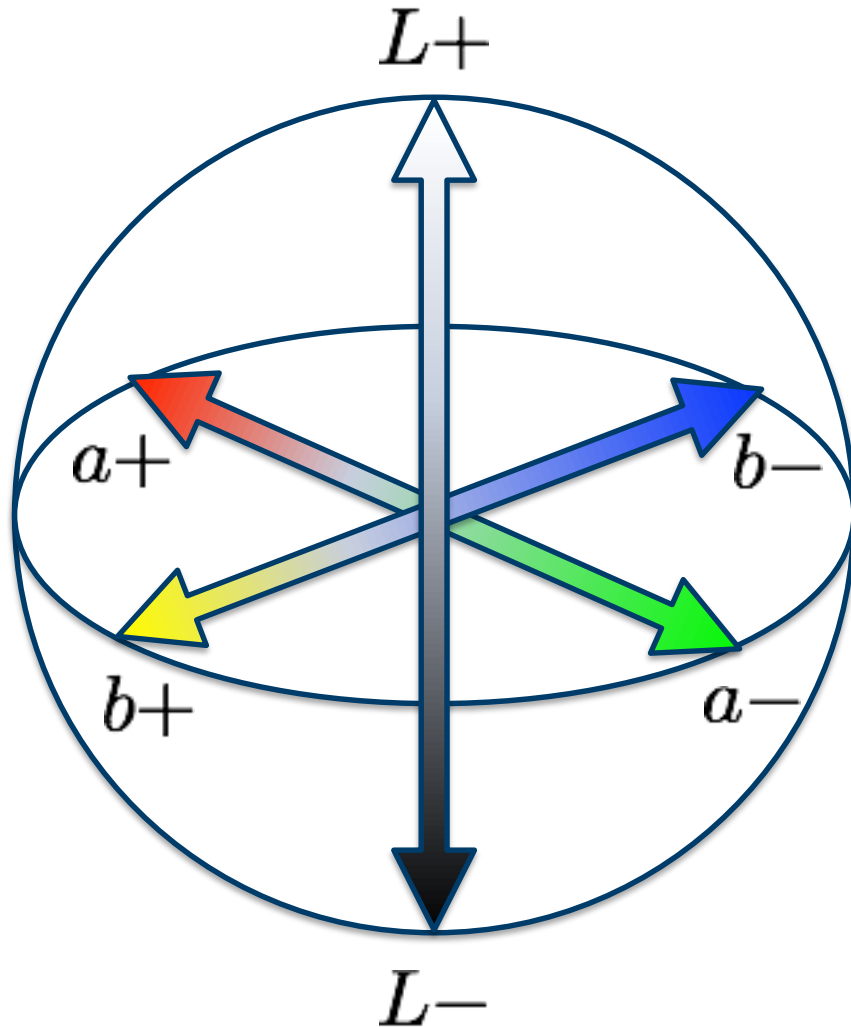


RGB original



Normalized RGB

Lab colour space (CIE 1976 L^* a^* b^*)



«Perceptually uniform» colour space:

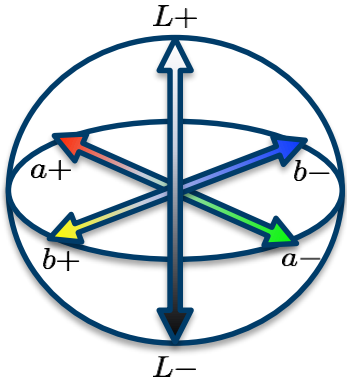
- Approximation to human vision
- L^* = Lightness
- a^* , b^* = Colour opponent dimensions
- L^* = darkest black to brightest white (0 - 100)
- a^* = green to red (-100 to +100)
- b^* = blue to yellow (-100 to +100)

Lab - example

L



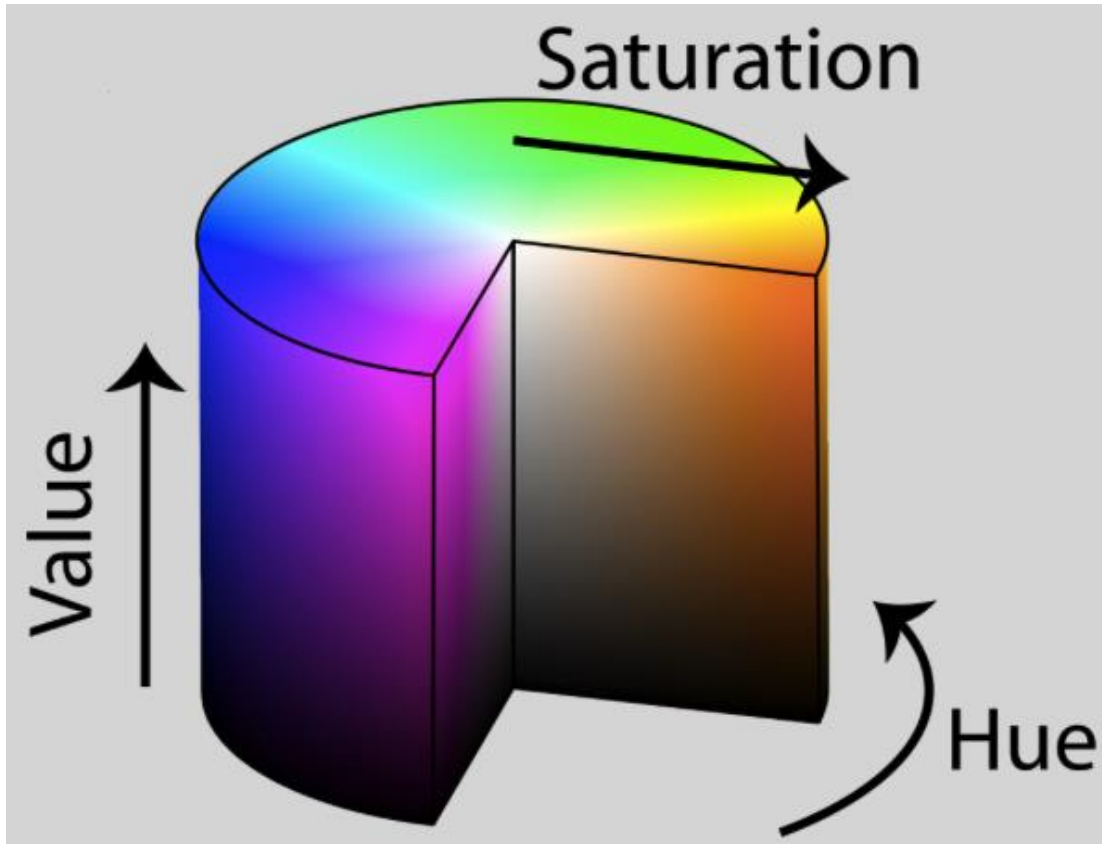
a



b



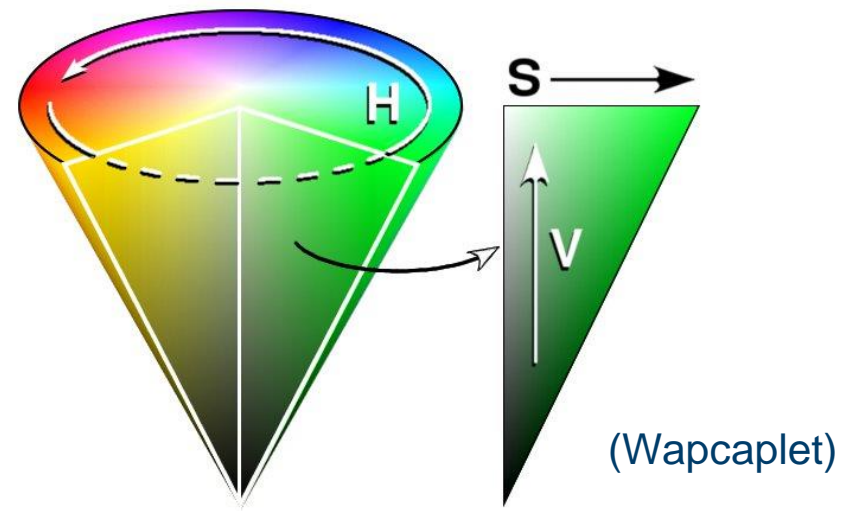
HSV colour space (Hue, Saturation, Value)



(Jacob Rus, 2010)

Intuitive colour space:

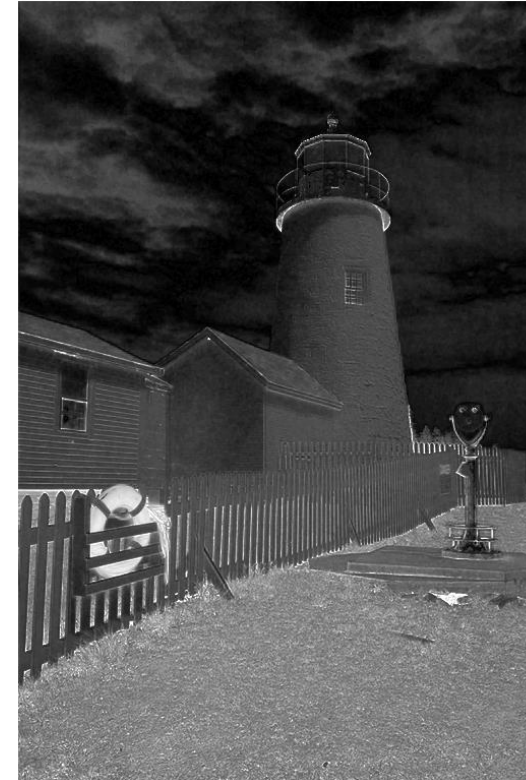
- Cylindrical representation of RGB values
- Hue = angle from 0° to 360°
- Saturation = 0 - 100% (gray to primary colour)
- Value = 0 - 100% (totally black to bright colours)



HSV



Hue



Saturation



Value

Summary

Image formation:

- Illumination
- Cameras
- Optics
- Image Capture
- Colour Sensing.

More information: Szeliski 2.2 and 2.3

