Computational Photography

* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.

Georgia Tech College of Computing

Cameras, Optics, and Sensors

* Cameras: Pinhole Camera and Optics

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1. Rays to pixels
2. A camera without optics
3. Lens in the camera system
4. The Lens Equation

Recall: Context of Computational Photography

Rays

3D Scene

Illumination

Optics

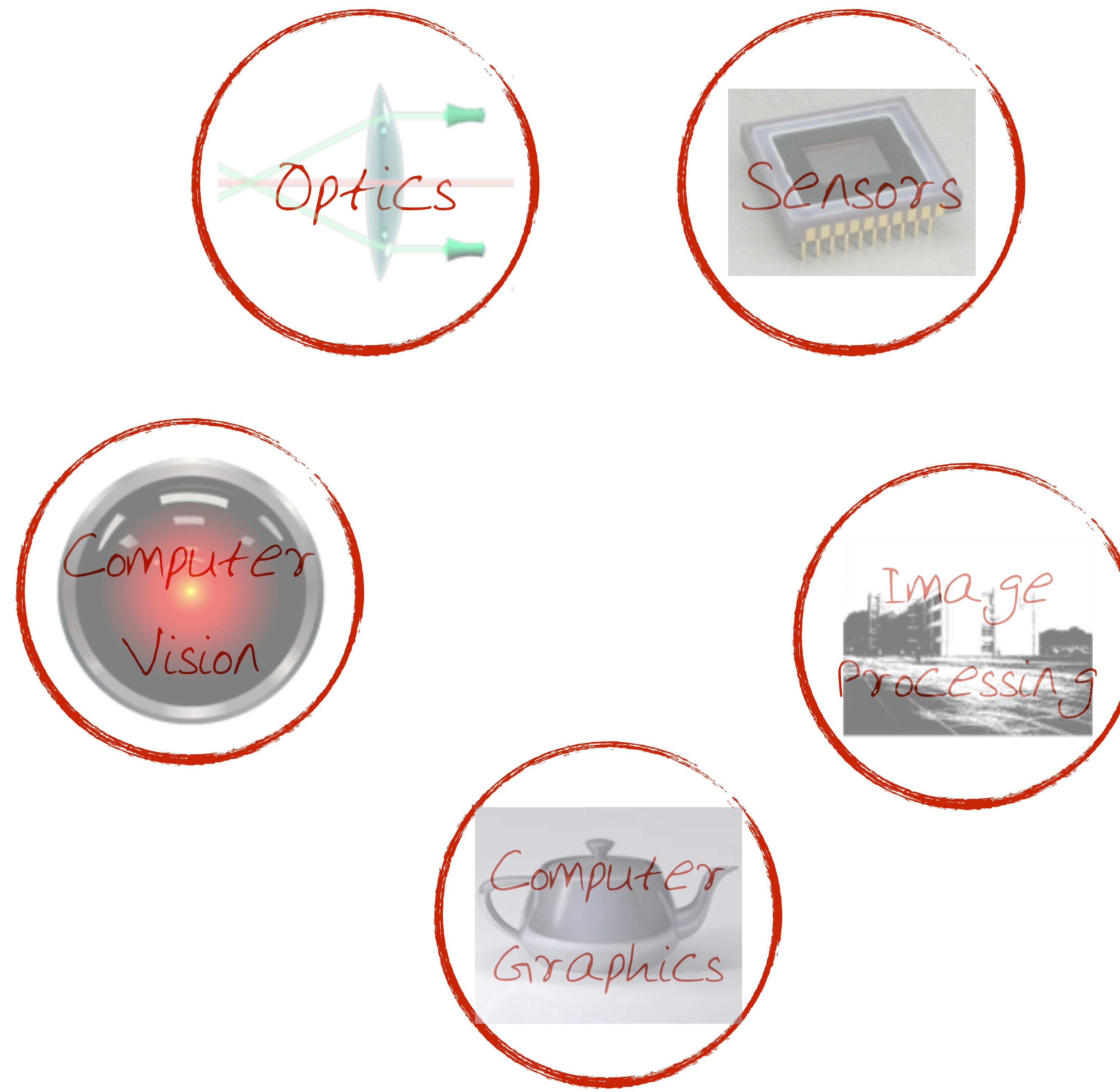
Sensor

Processing

Display

User

Pixels



Pixels vs. Rays

- 3D Scene
- Illumination
- Optics
- Sensor
- Processing
- Display
- User

http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg

- Scene via a 2D array of pixels
- Rays are fundamental primitives
- Illumination (Light Rays) follows a path from the source to the scene
- Computation can control the parameters of the optics, sensor and illumination

Evolution of the Camera


300 BC


1839

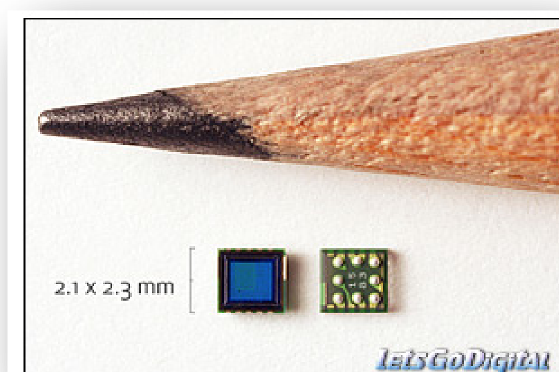

1907


1948

1986

1991

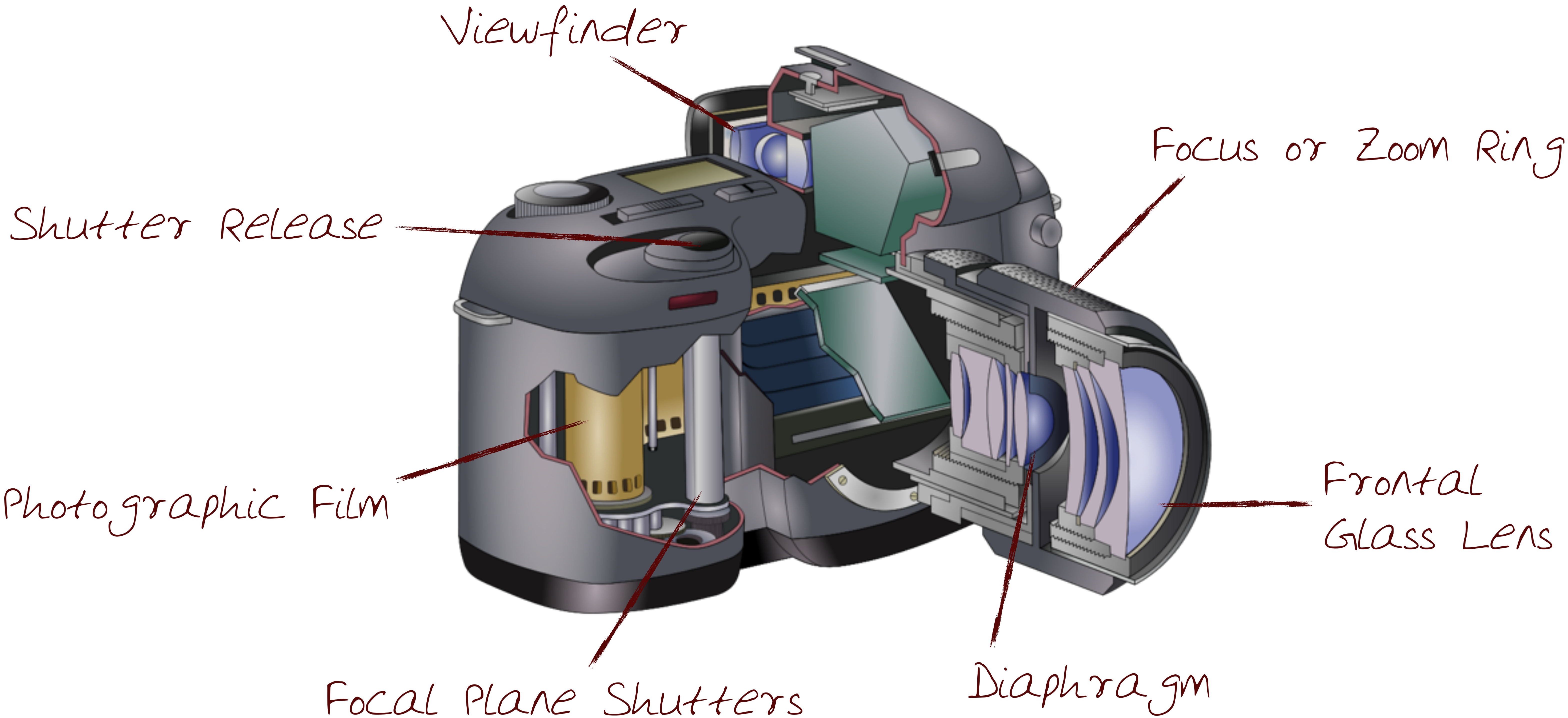

2000




Formal to Casual

http://ericwilliamcarroll.com/blog/?p=23
http://simplevideoproduction.blogspot.com/
http://webdesign.njit.edu/2012/248/evolution.html

Single-Lens Reflex Camera



When you take a picture

you try to capture

3D Scene

Illumination

Optics

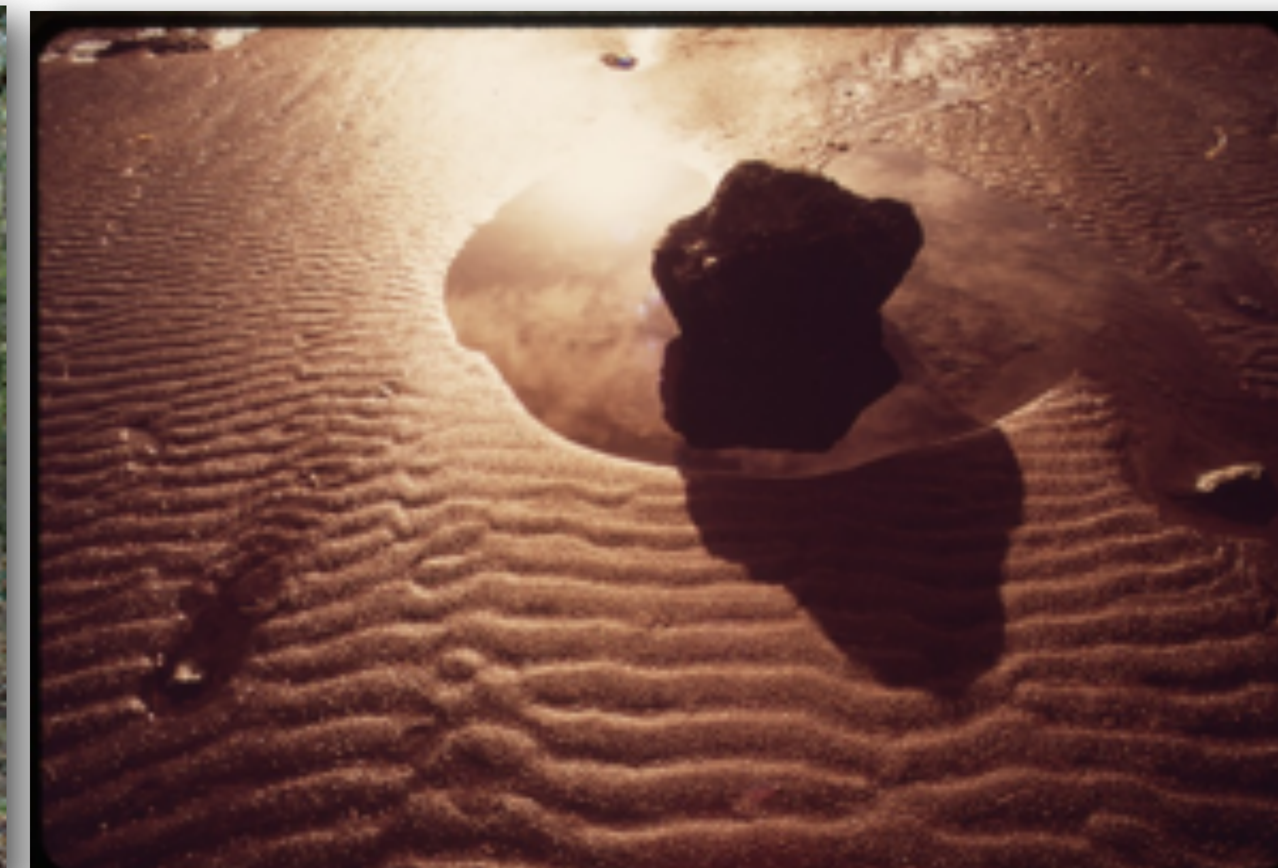
Sensor

Processing

Display

User

Geometry (Perspective)



Light Scattering

When you take a picture using

3D Scene

Illumination

Optics

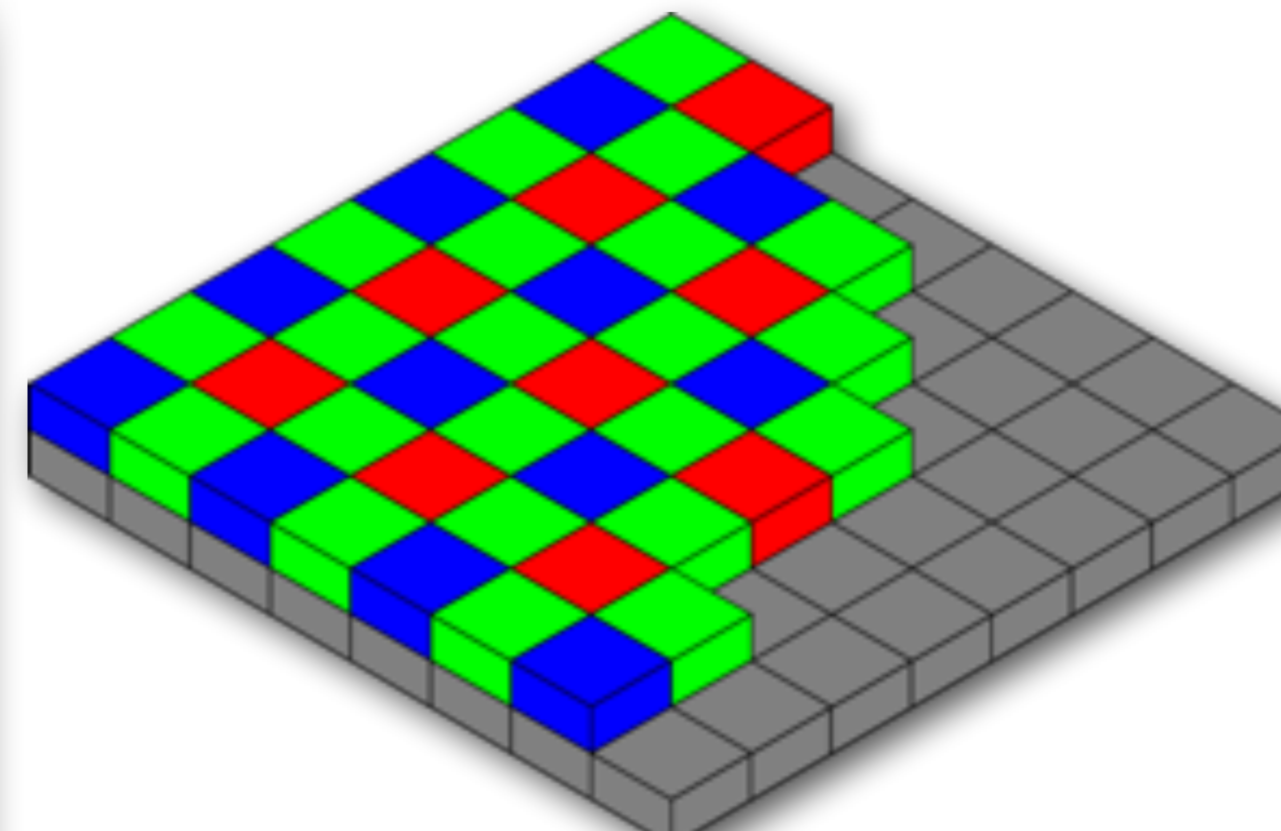
Sensor

Processing

Display

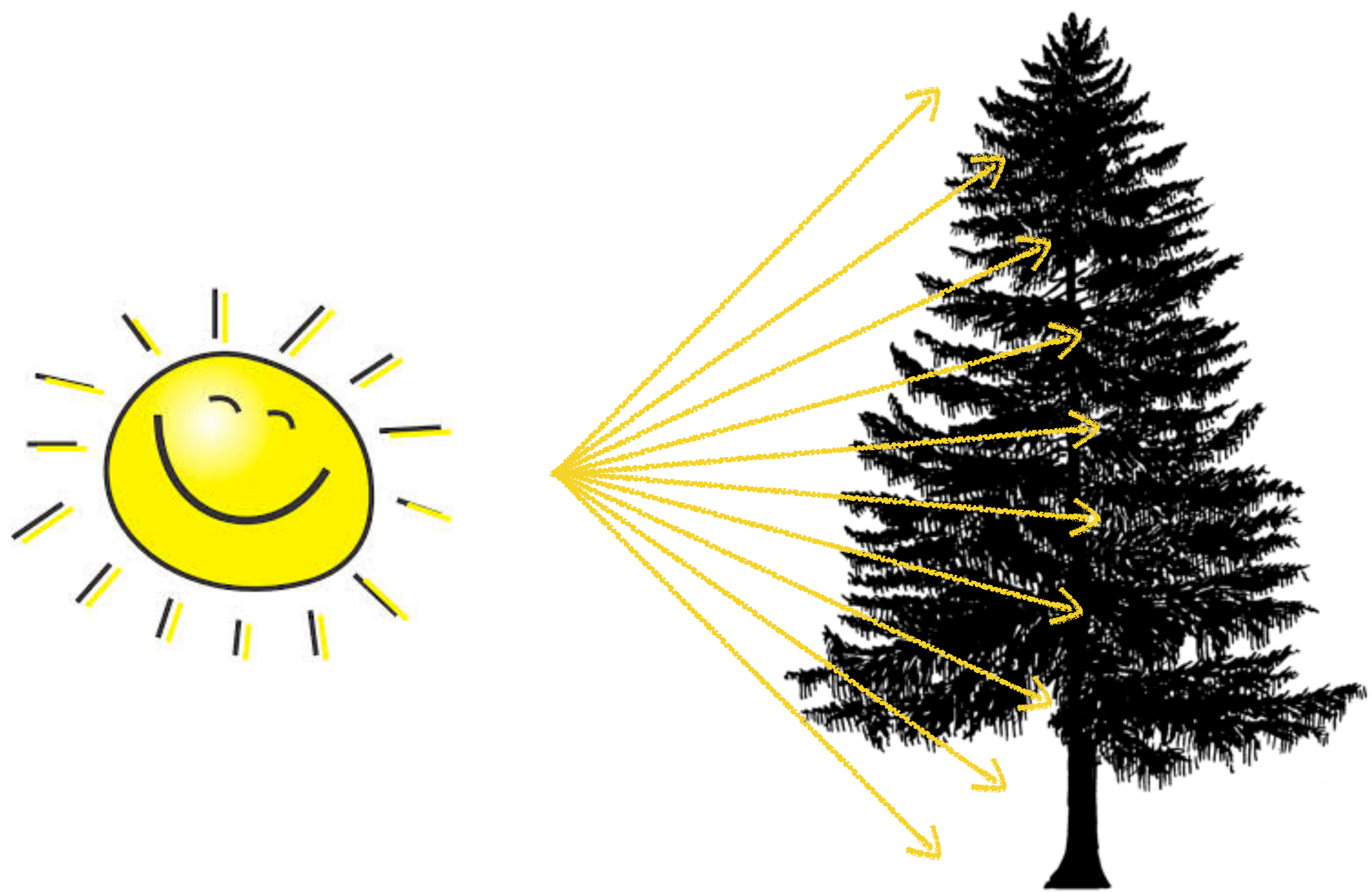
User

Optics / Lens

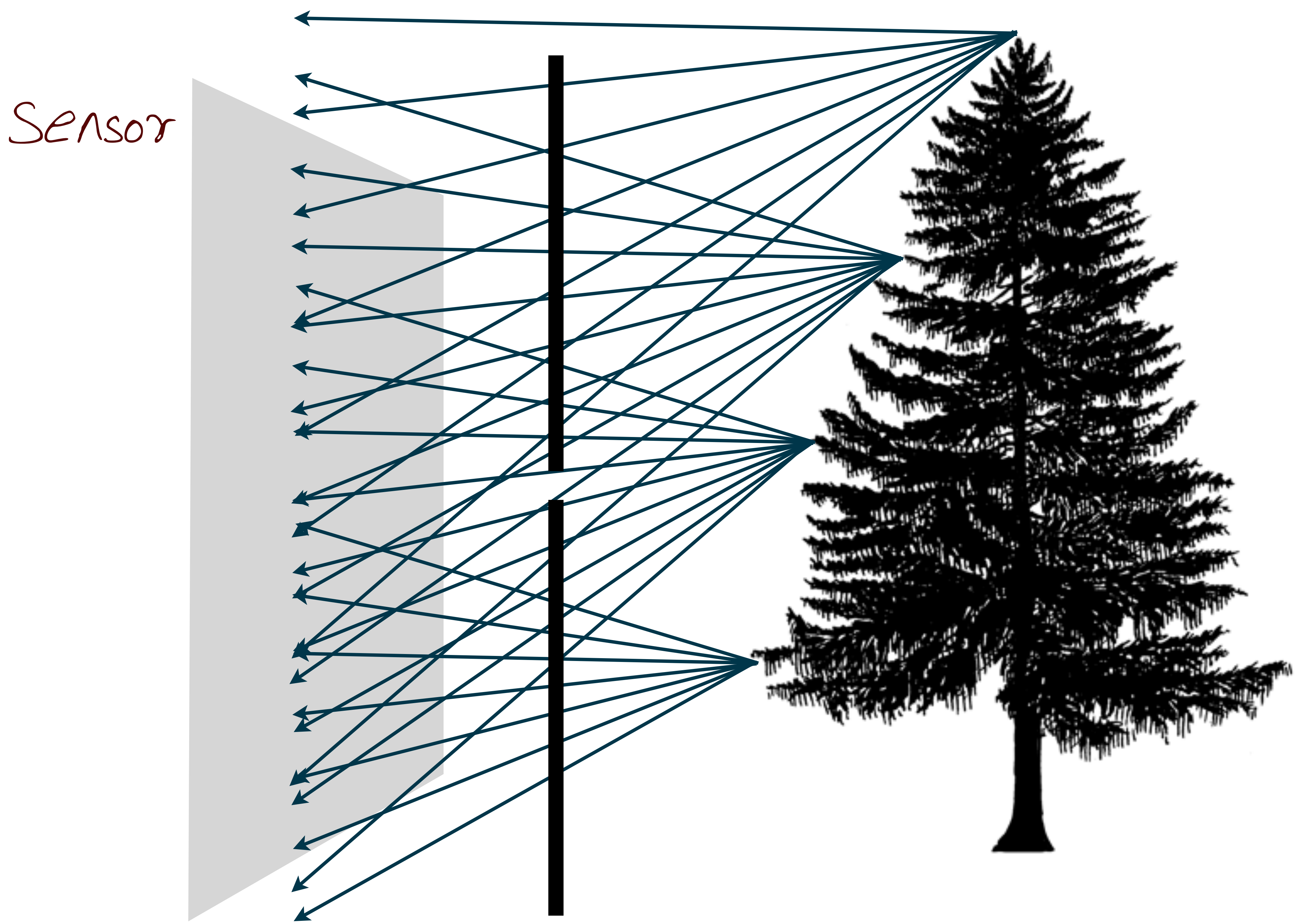


Sensor / Color Filter

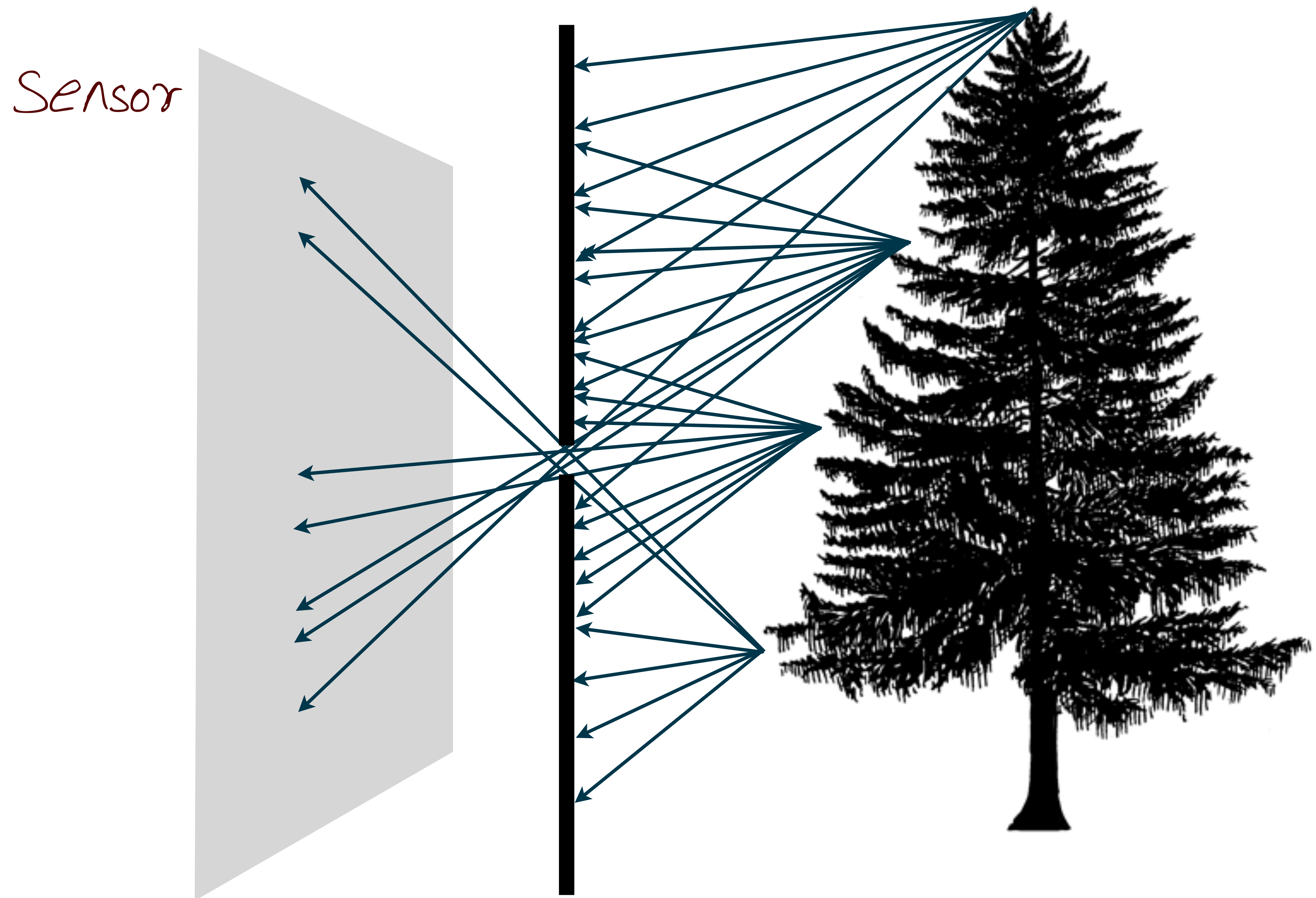
Cameras, without Optics



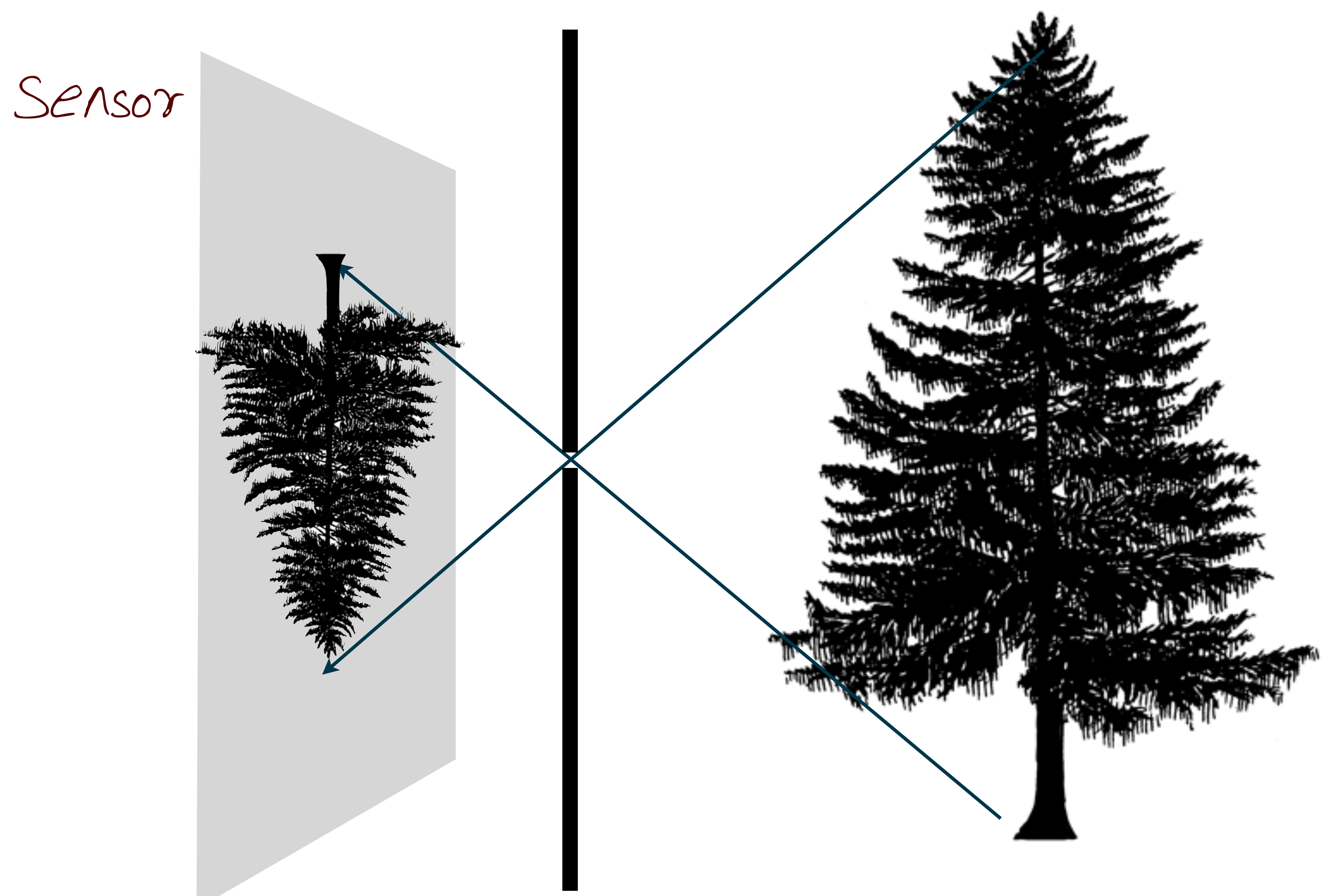
Cameras, without Optics



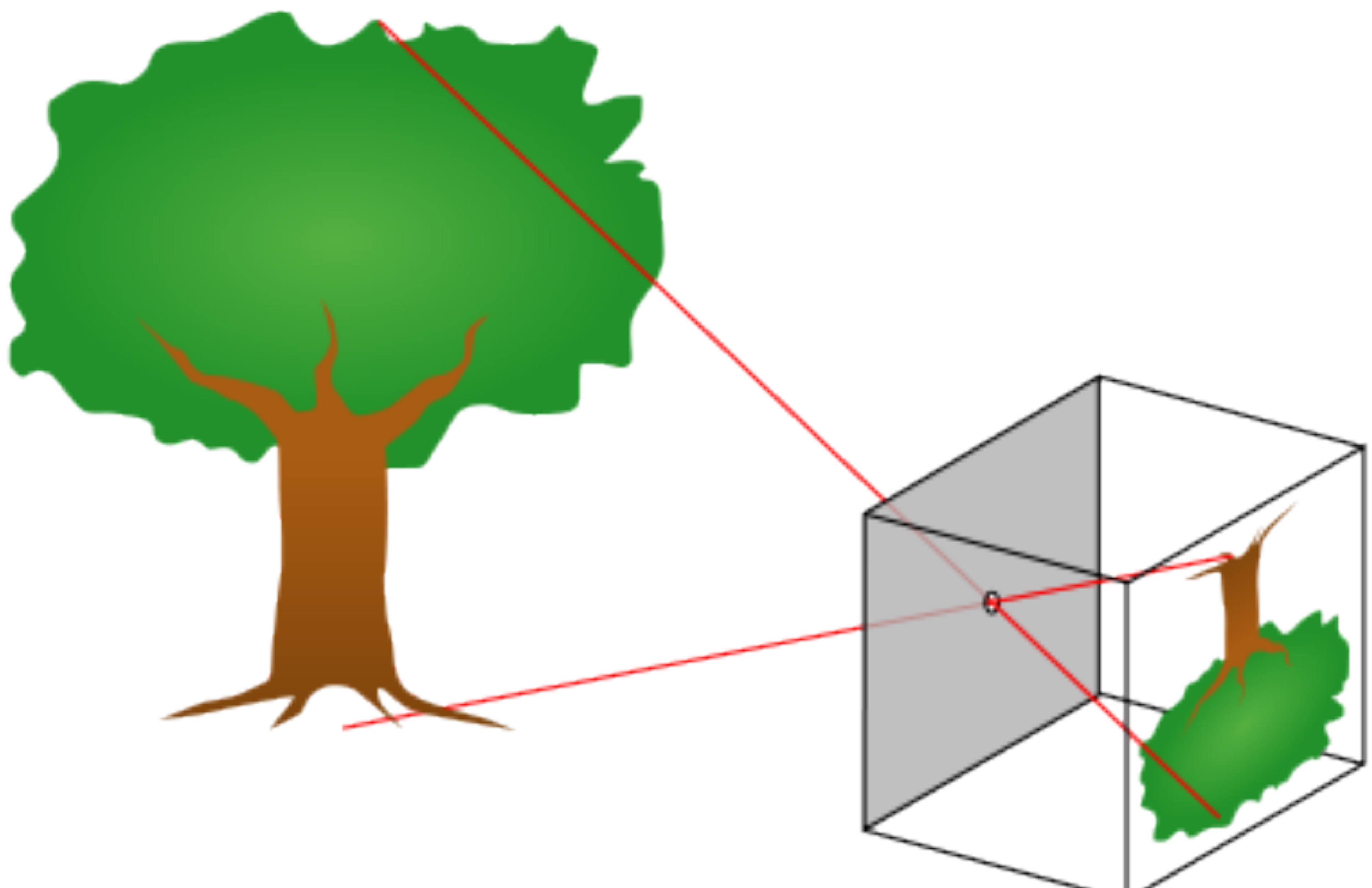
Cameras, without Optics



Cameras, without Optics



Camera Obscura
(Pinhole Camera)



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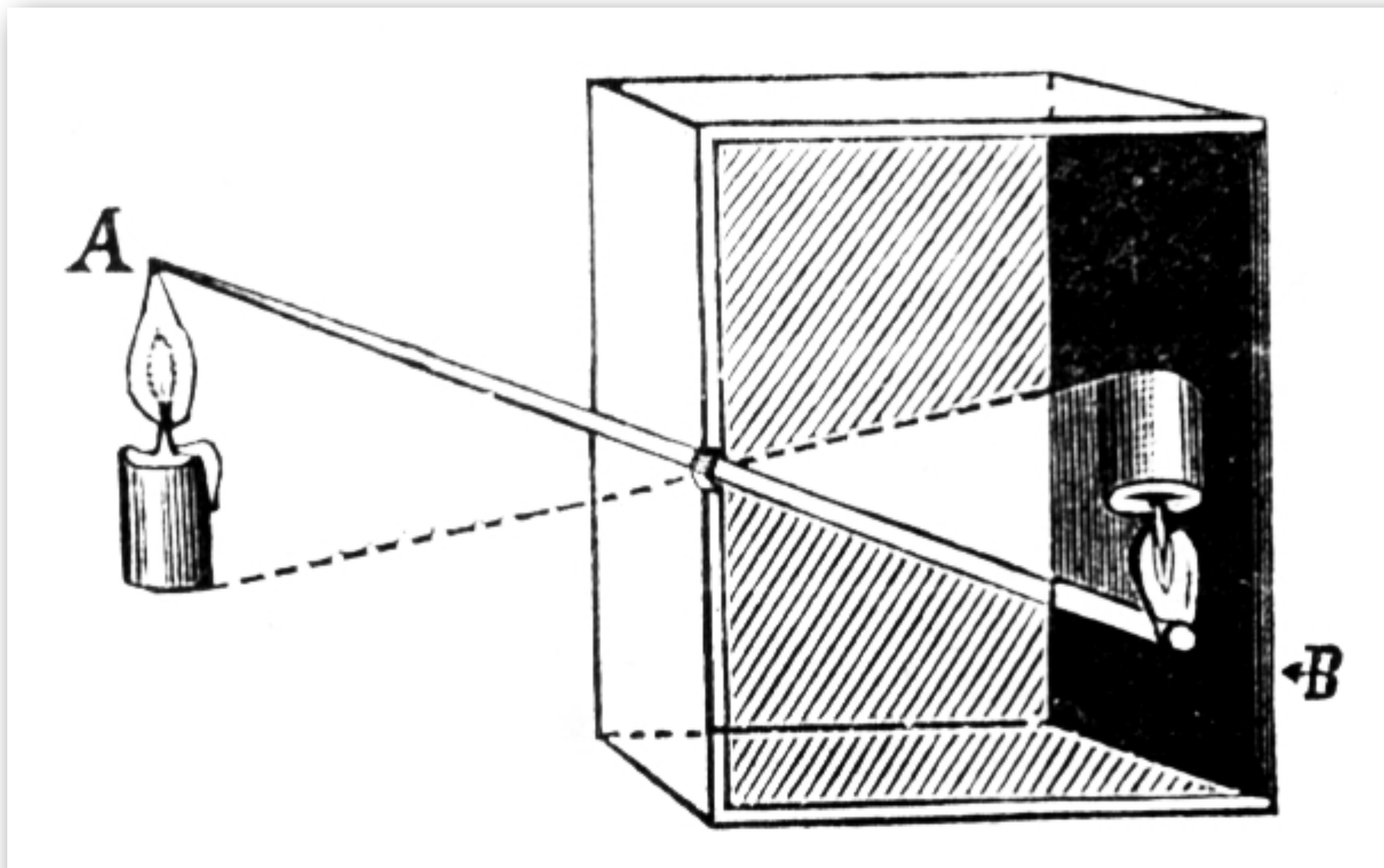


Illustration of camera obscura from "Sketchbook on military art, including geometry, fortifications, artillery, mechanics, and pyrotechnics"

Pinhole Photograph

Byelorussky Station: commons.wikimedia.org

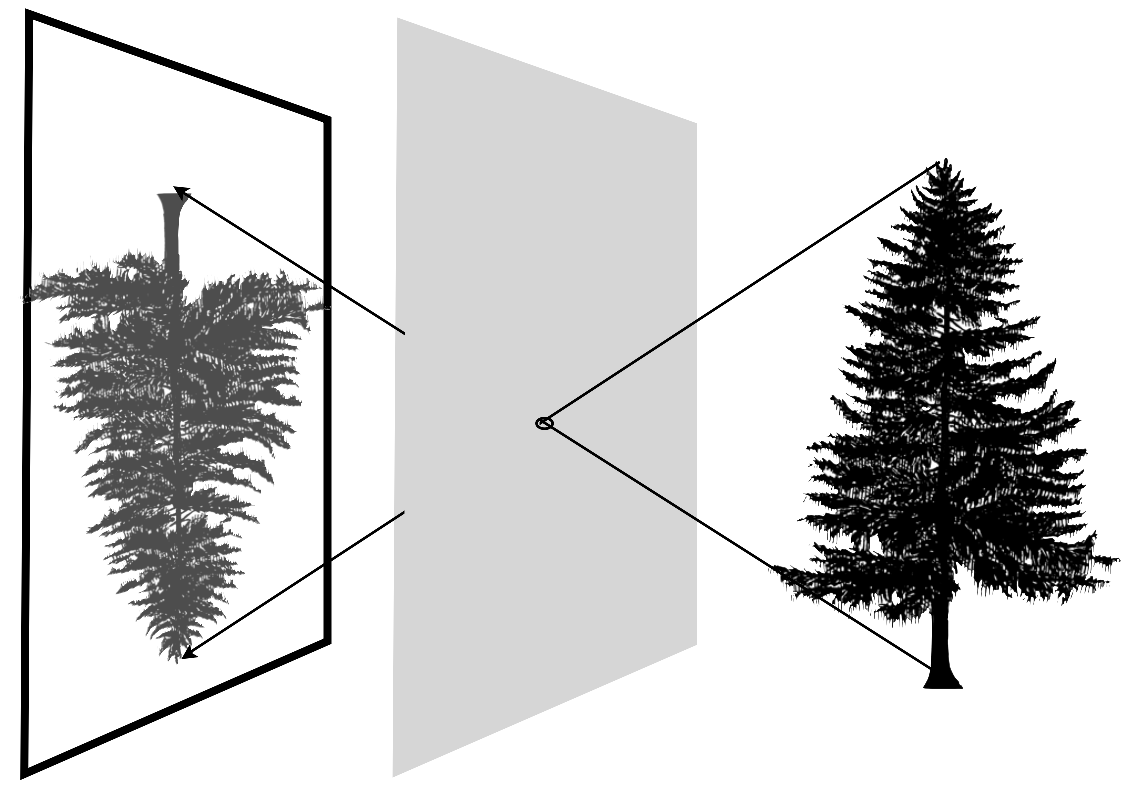
Theoretically,

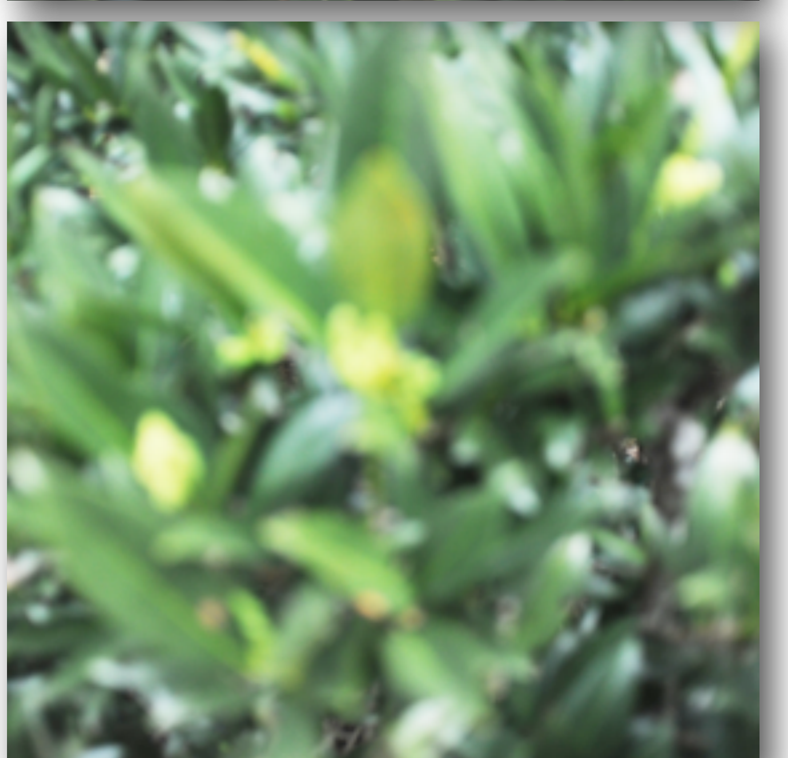
* No distortion: Straight Lines remain straight
* Infinite depth of field: Everything in focus (but there is optical blurring)

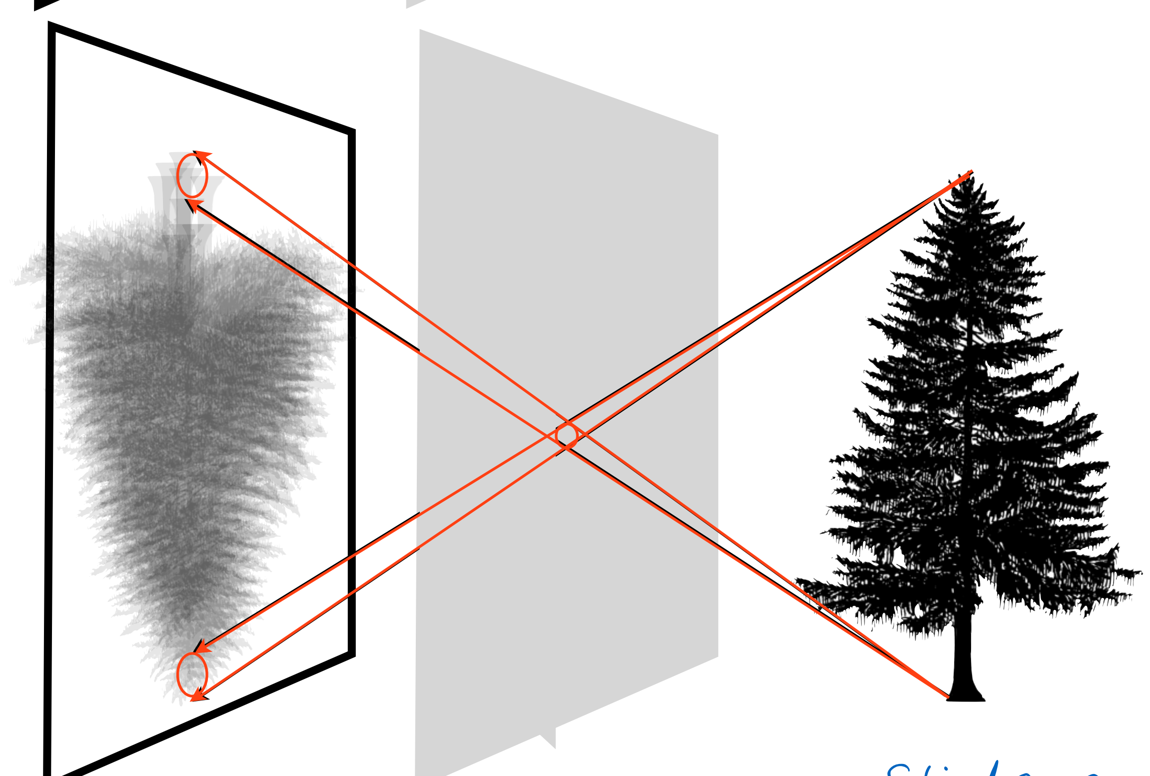
Slide adapted from marc Levoy

This could be done as an explorational exercise. “What would happen if we increased the pinhole size?”, followed by four images that simulate different changes (sharper, blurrier, double image, color change, etc.).

Pinhole Size and Image Quality







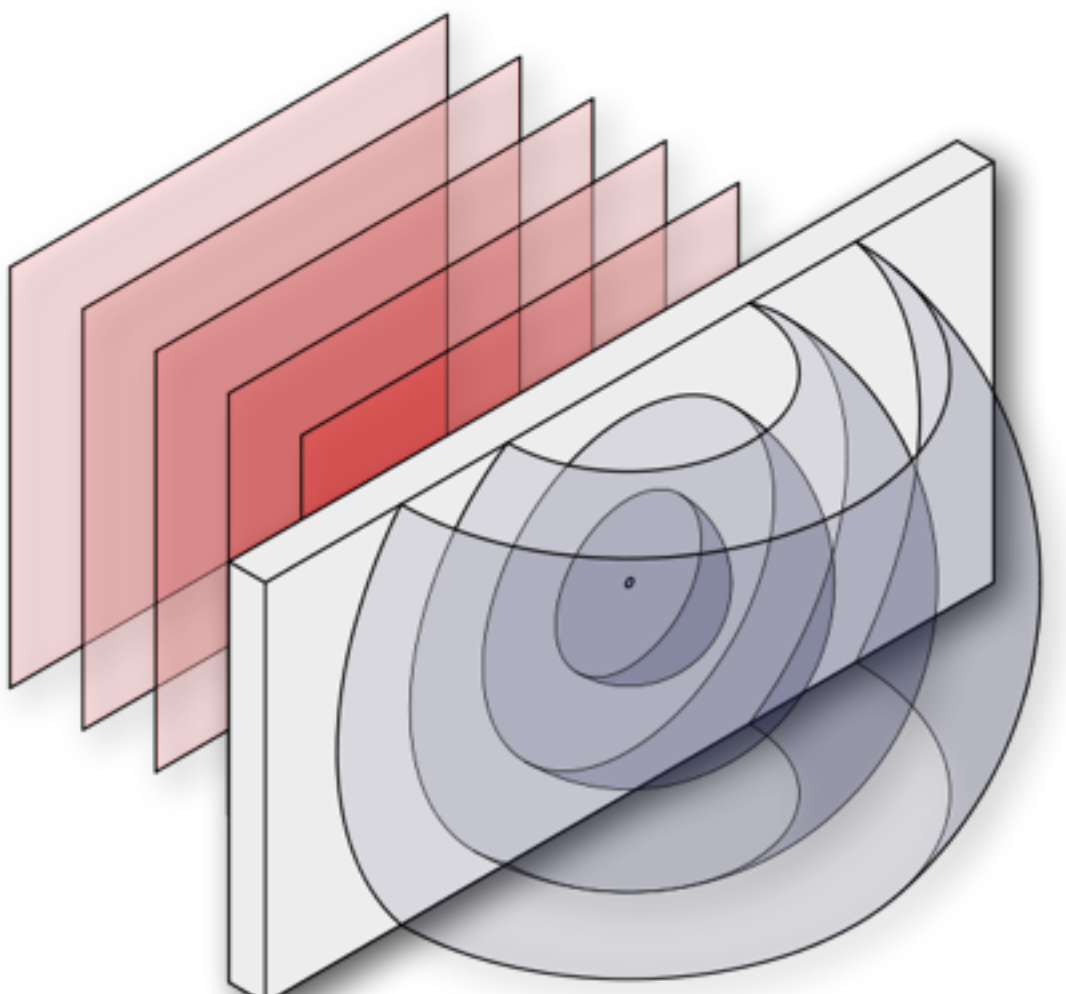
Pinhole “blur” simulated

Pinhole Size = Aperture!

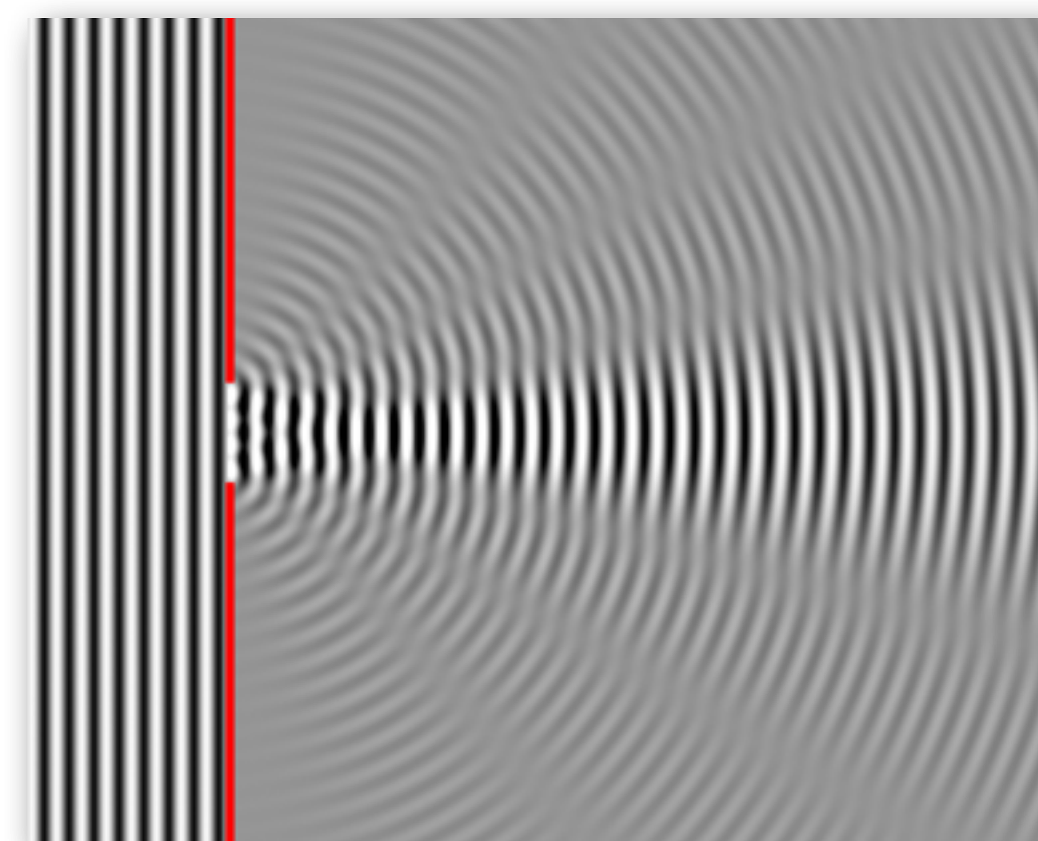
Slide adapted from Marc Levoy

Light Diffracts

* Wave Nature of Light
* Smaller Aperture means more Diffraction



3D Schematic



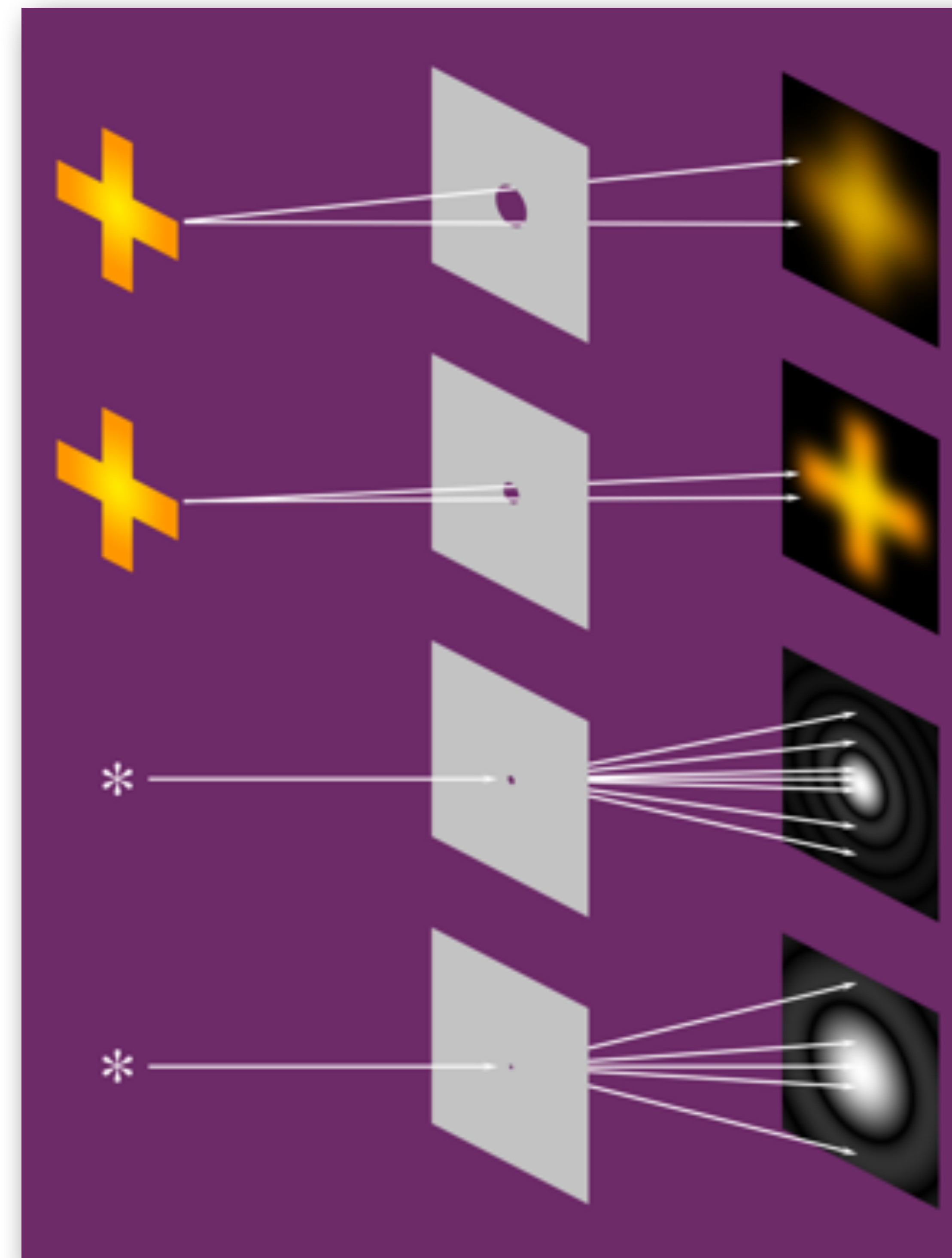
Actual Diffraction Pattern

Effect of Pinhole Size

Large Pinhole = Geometric Blur

Small Pinhole = Diffraction Blur

Best Pinhole = Very Little Light



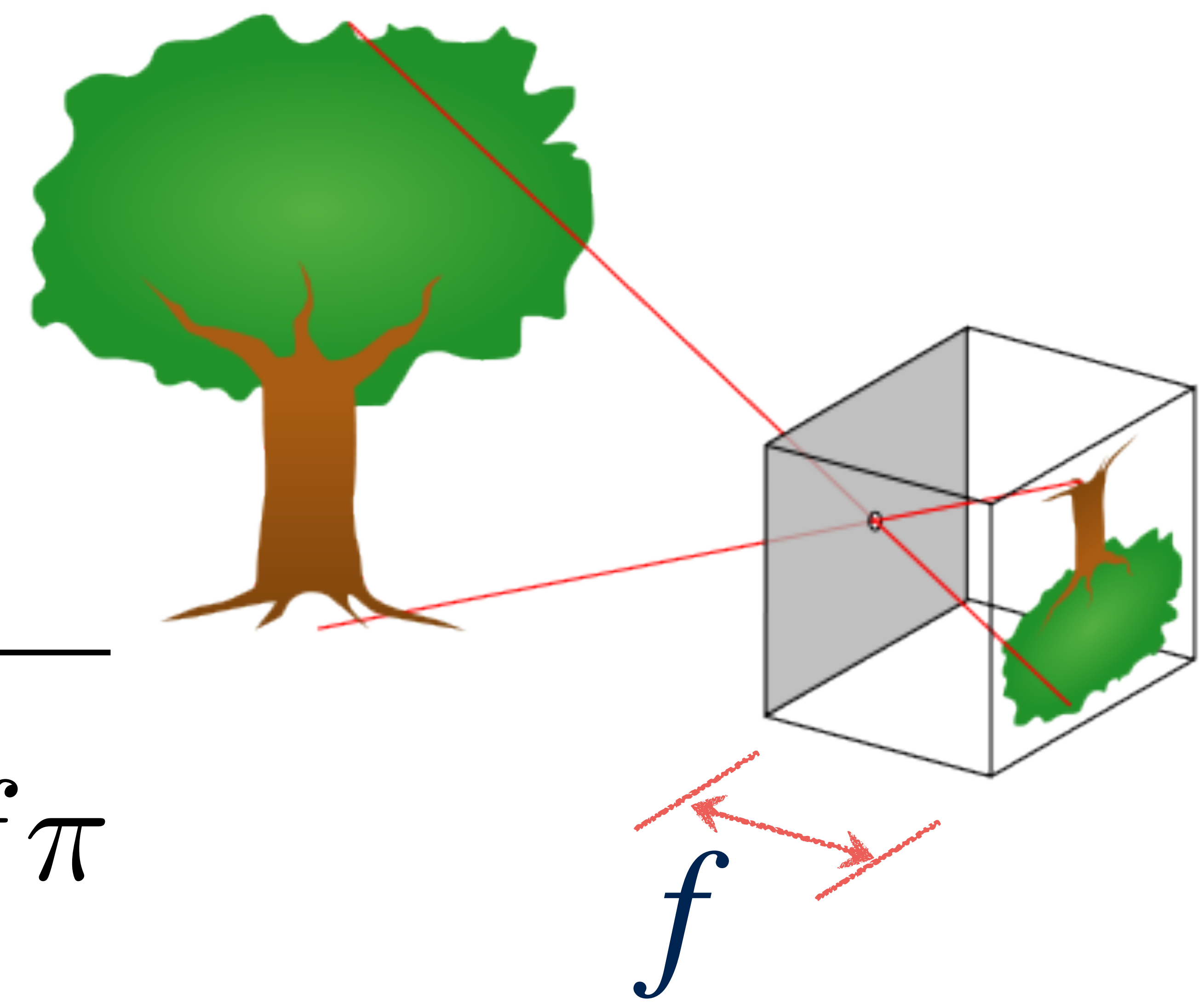
Slide adapted from Marc Levoy

Effect of Pinhole Size

For d (pinhole diameter),

f (distance from pinhole to sensor),

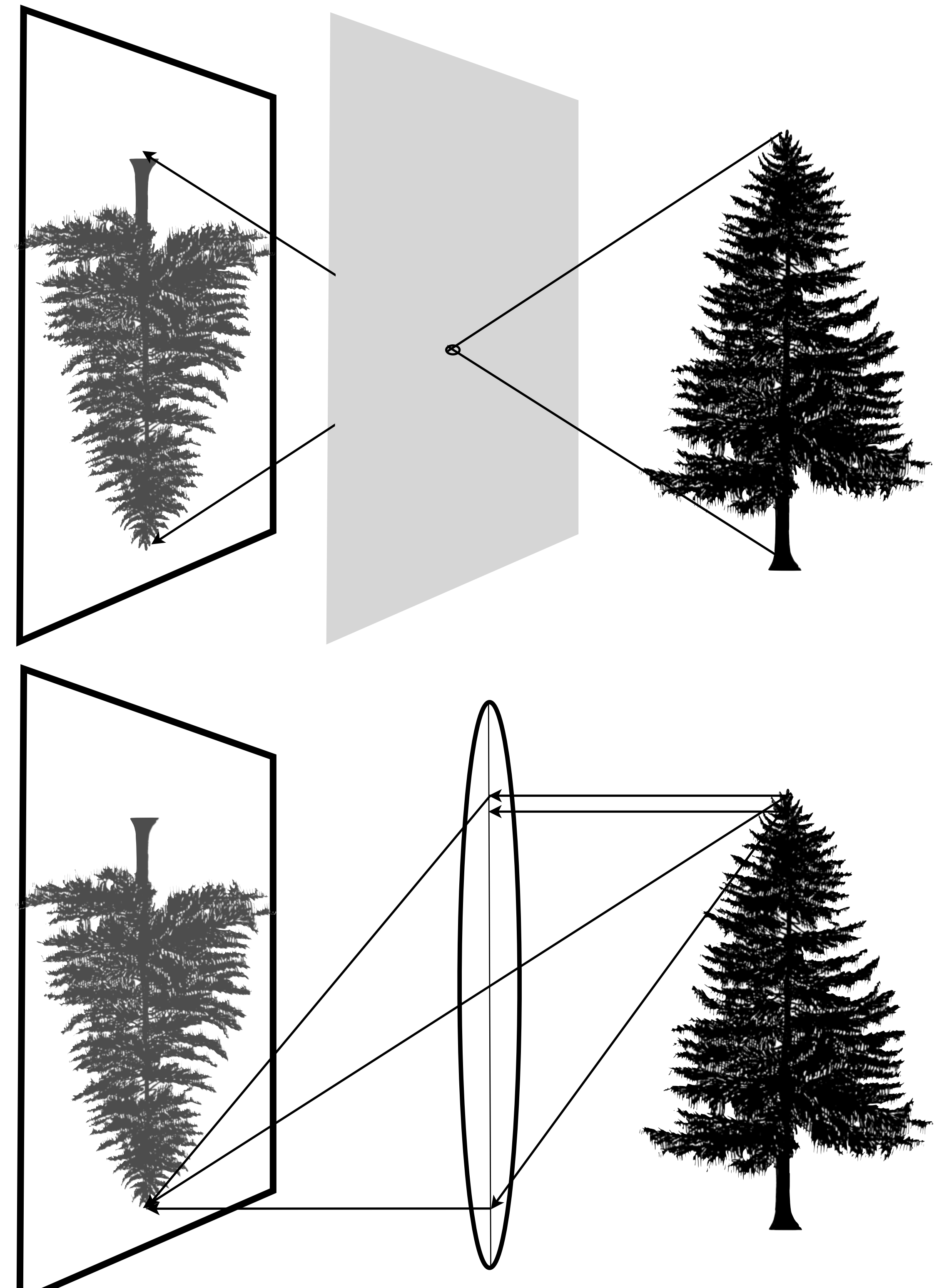
and π (wavelength of light):



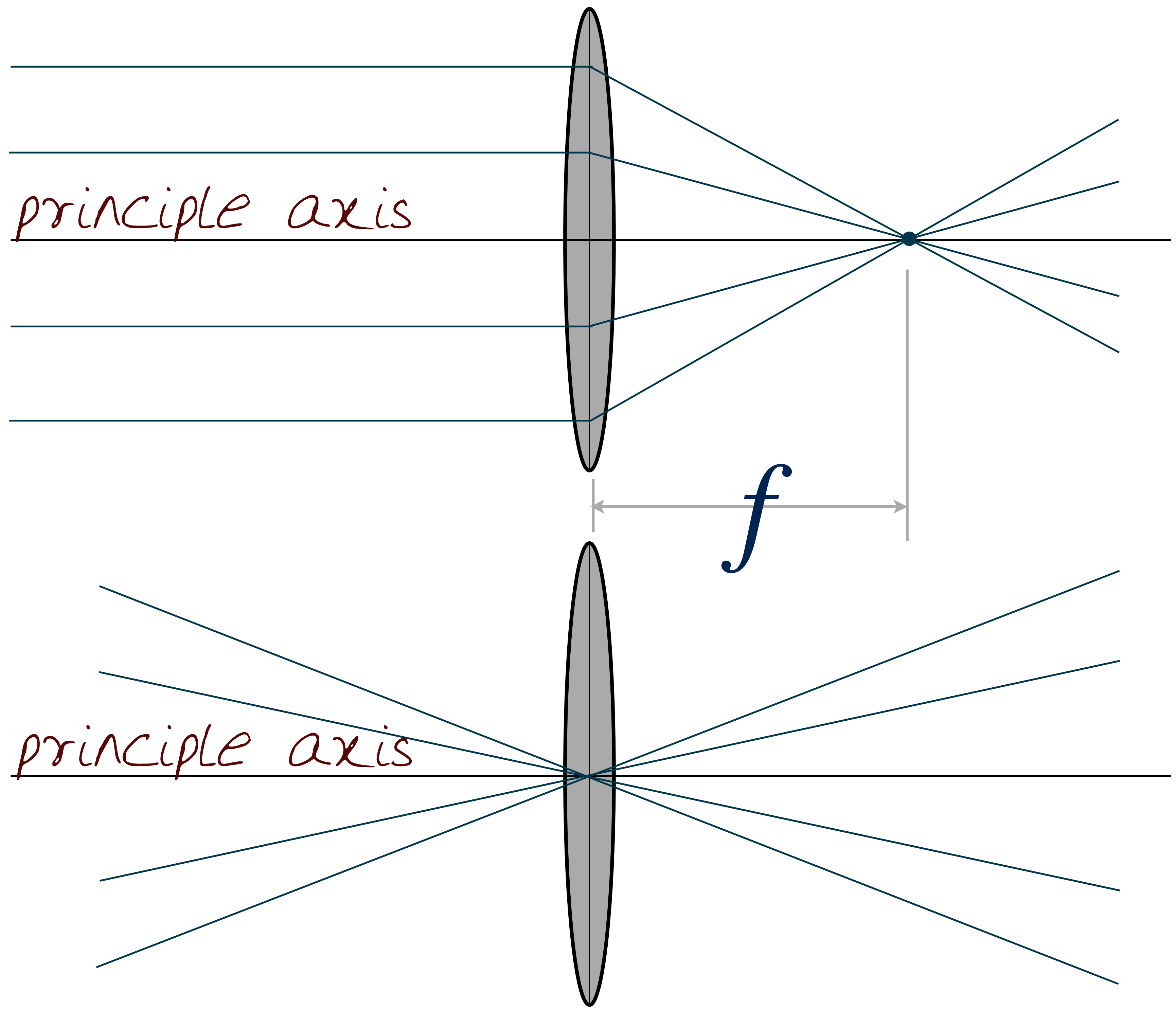
$$d = 2\sqrt{\frac{1}{2} f \pi}$$

Slide adapted from Marc Levoy

Replacing the Pinhole with a Lens

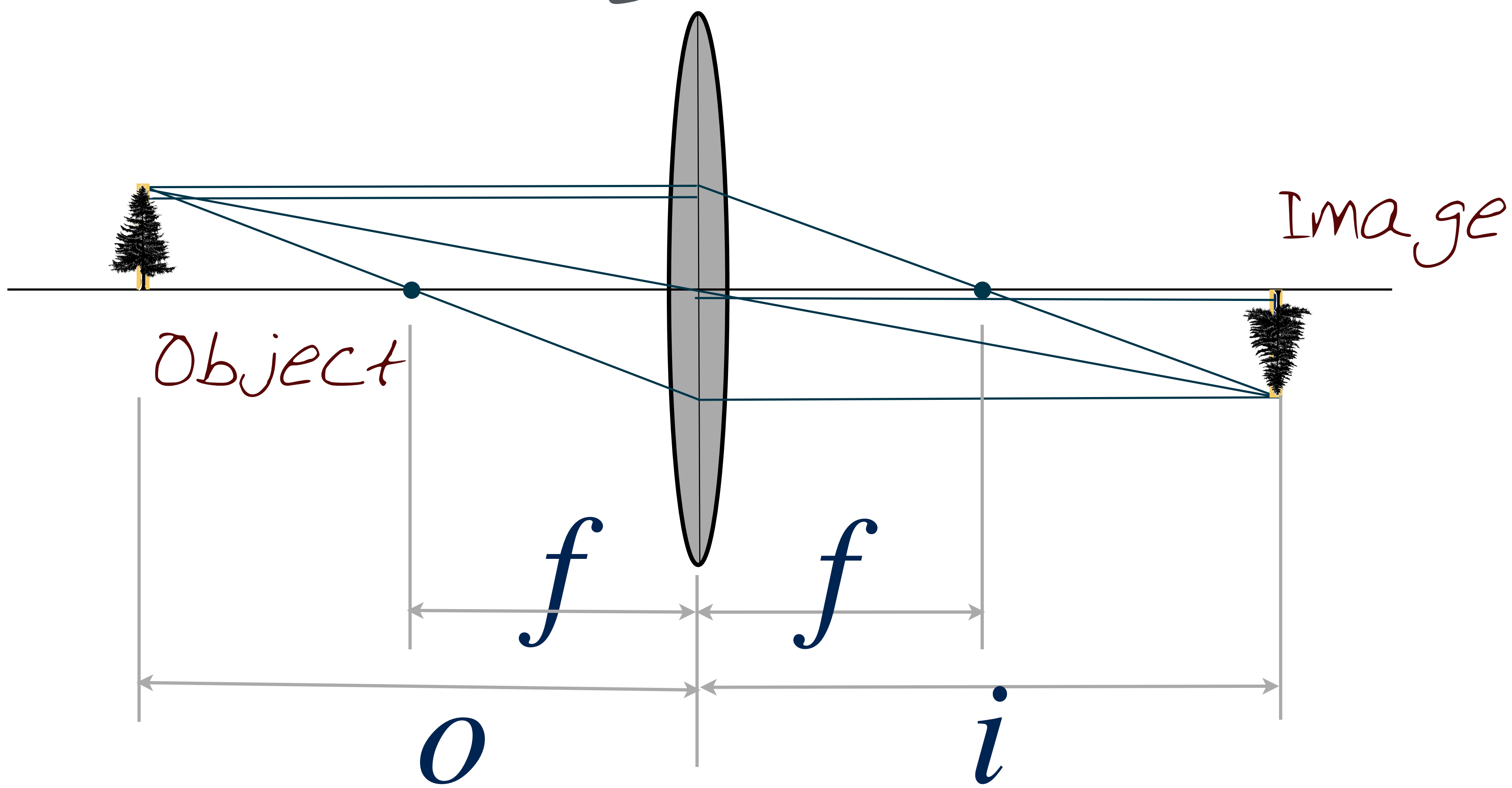


Geometrical Optics



- Parallel rays converge to a point located at focal length, f from lens
- Rays going through center of lens do not deviate (functions like a pinhole)

Ray Tracing with Lenses



$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

* Rays from points on a plane parallel to the lens, focus on a plane parallel to the lens on the other side (and upside down).
* Lens Equation

Summary

- Discussed the Foundations of How a Camera works
- Presented the Concept of a Pinhole Camera
- Introduced Optics and Lenses and the Role they play in a Camera

Next Class

* Cameras: Changes in Focal Length, Aperture, Shutter and Sensor

Credits

- For more information, see
  - Hecht, E. Optics, 4th ed. Reading, MA: Addison-Wesley and
  - London, B., Stone, J., & Upton, J., Photography, 10th ed. Upper Saddle River, NJ: Prentice Hall.
- Images retrieved from
  - http://commons.wikimedia.org/
    - http://commons.wikimedia.org/wiki/File:Sun_Rays.jpg
  - List will be available on website
- Some Slides adapted from Mark Levoy

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Cameras, Optics, and Sensors

- Cameras: Lenses and Impact of Focal Length on Photography

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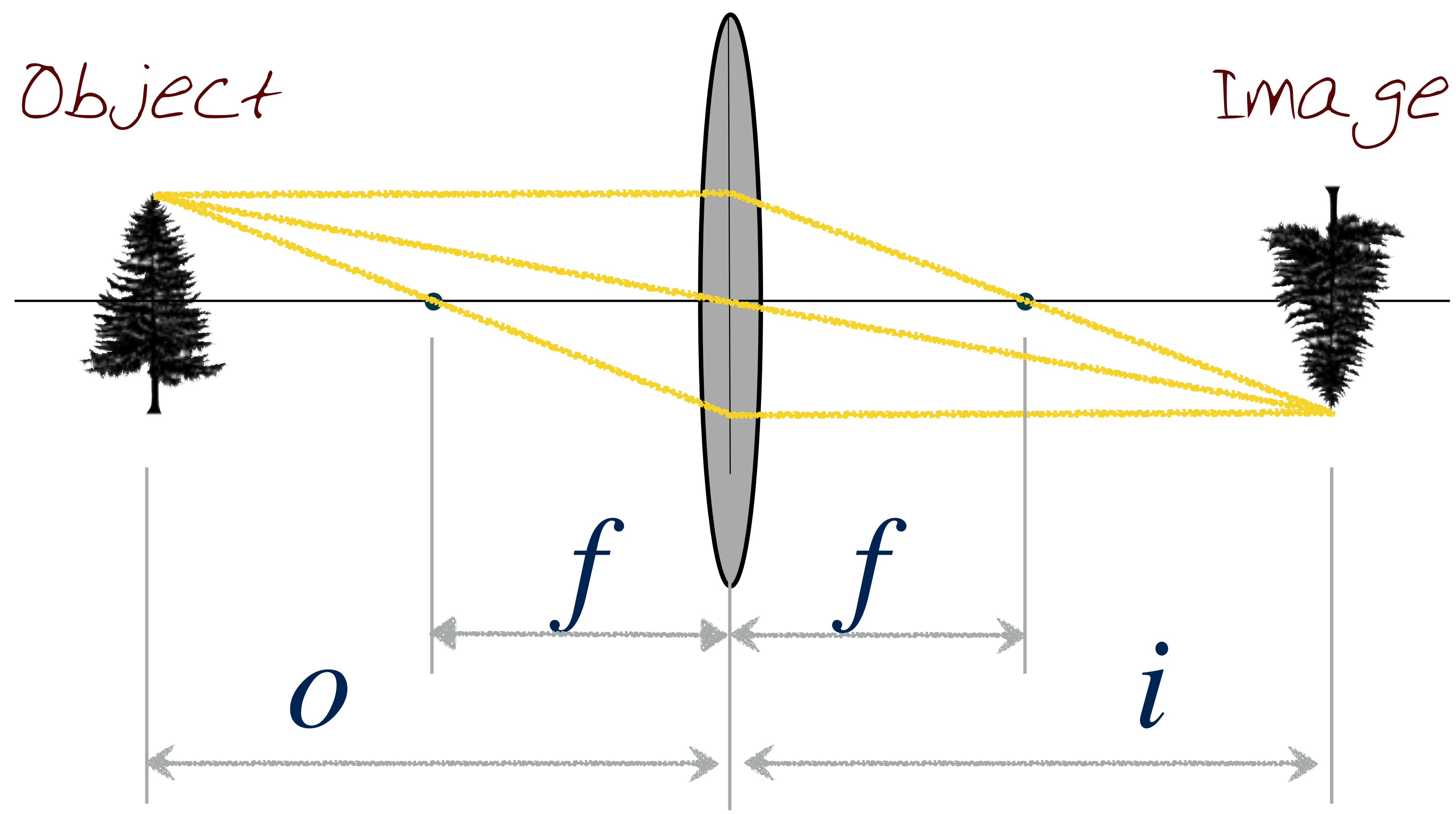
1. Focal Length
2. Field of View (FOV)
3. Sensor Size
4. Image Formation & Capture
5. Perspective Projection

Recall: Ray Tracing with Lenses



Thin lens equation

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

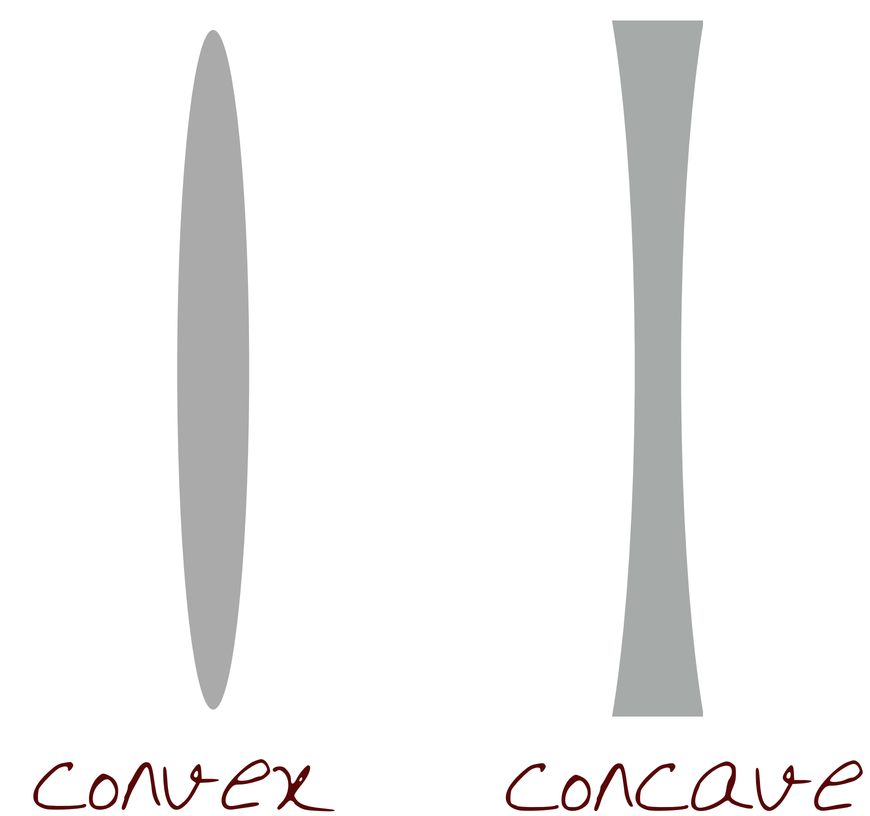
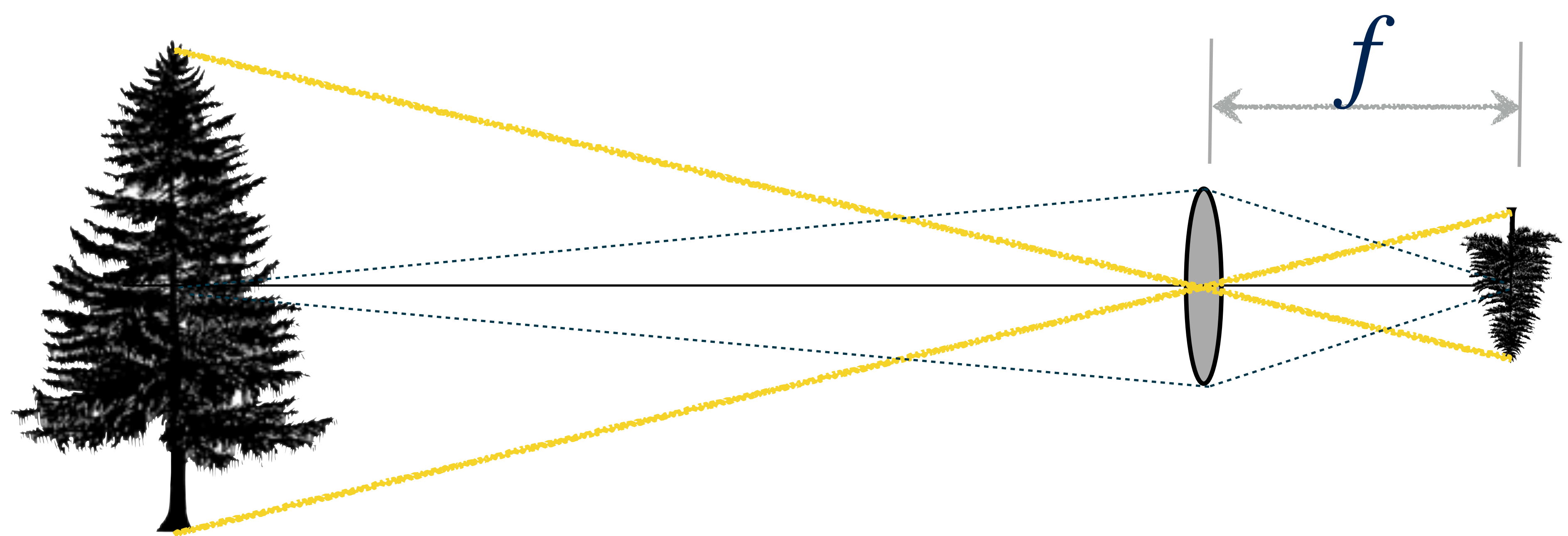
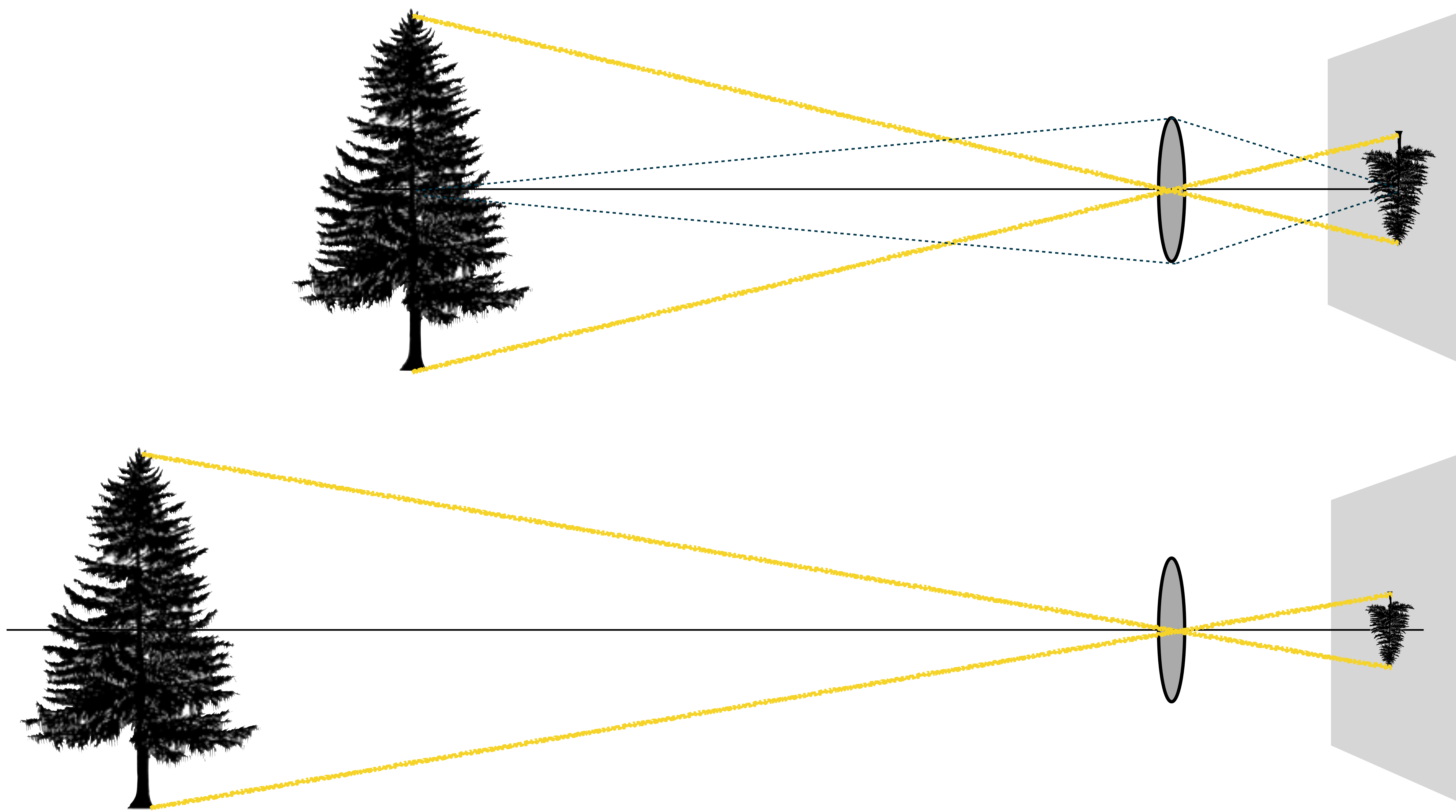


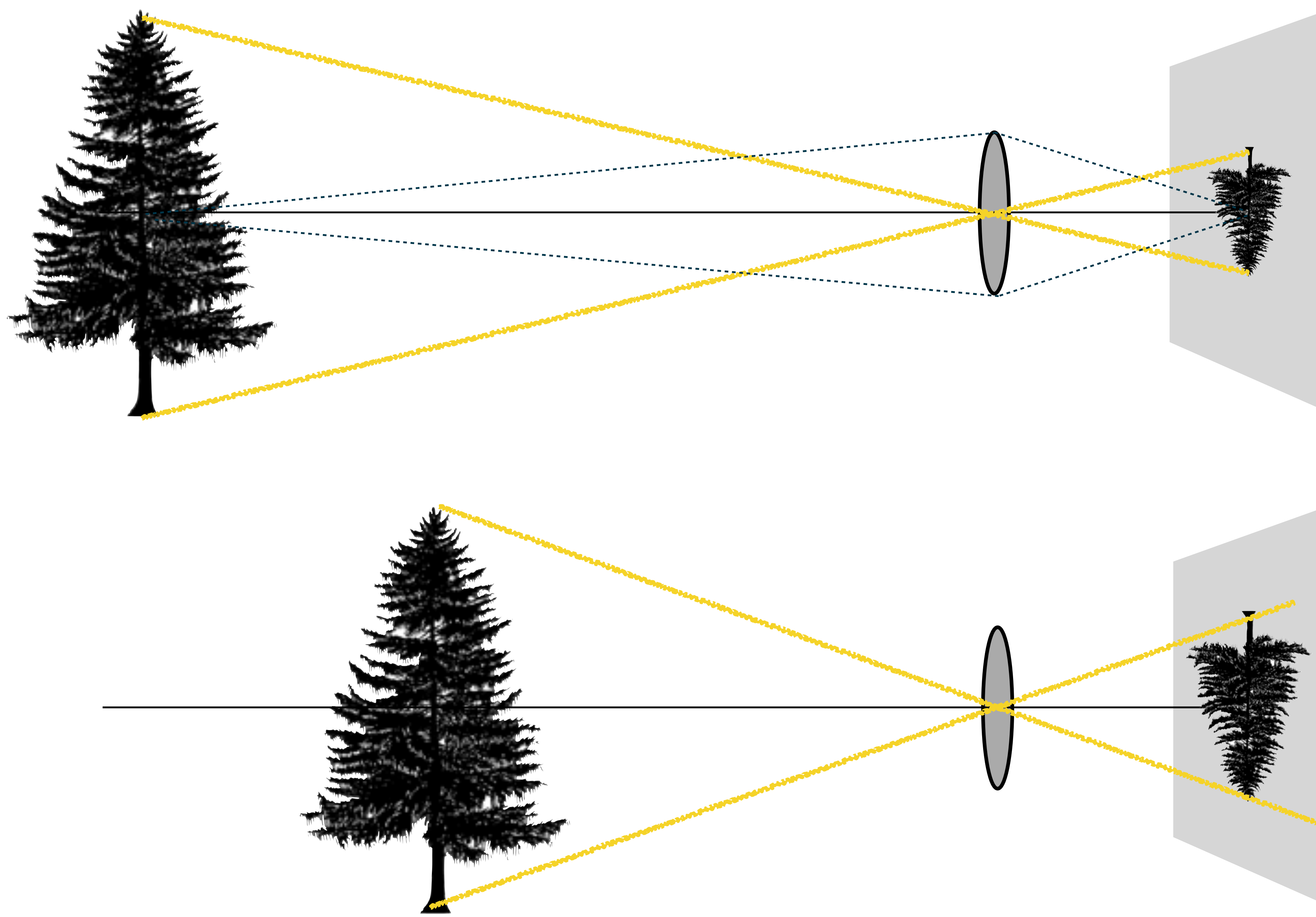
Image Formation



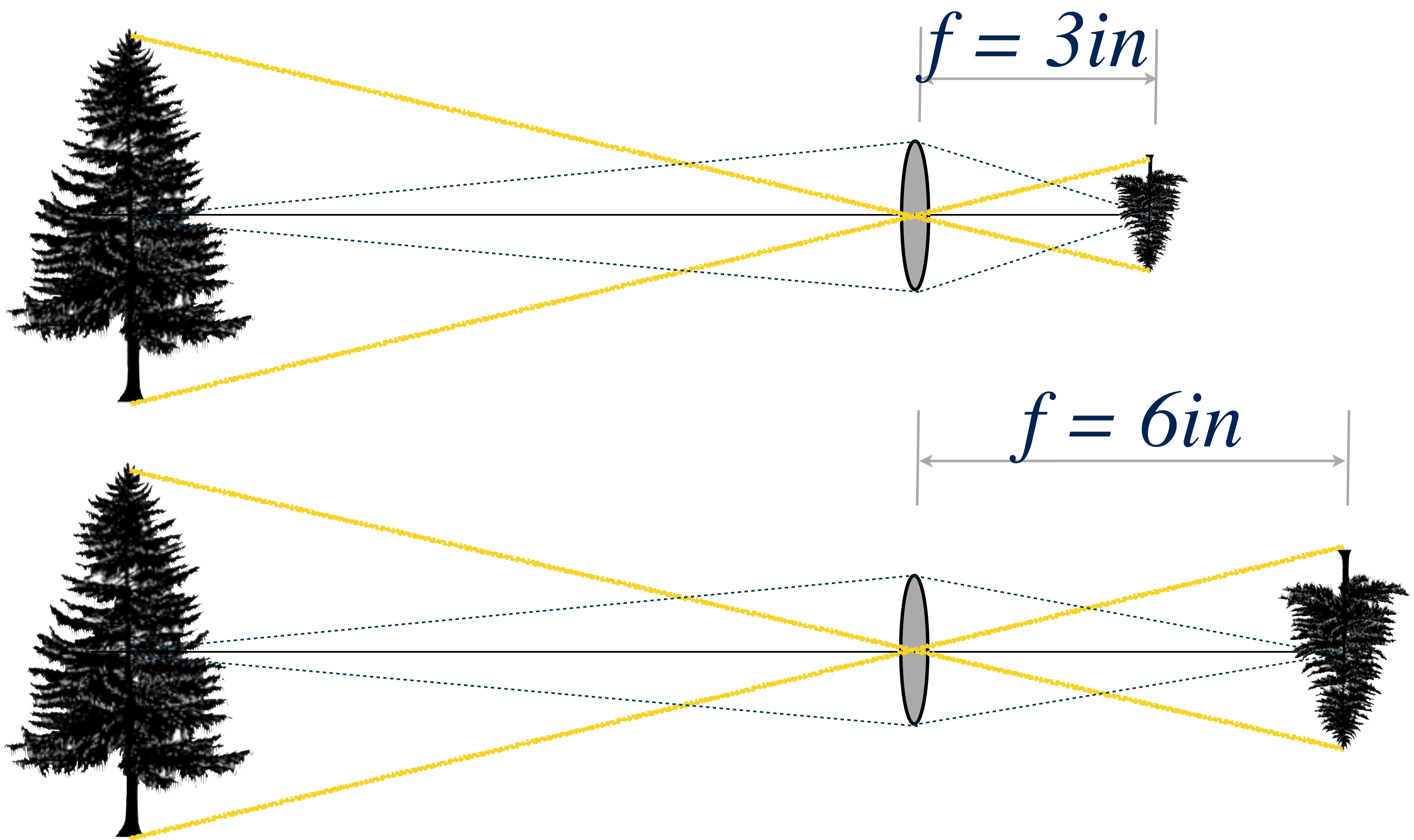
Changing object distance



Changing distances!

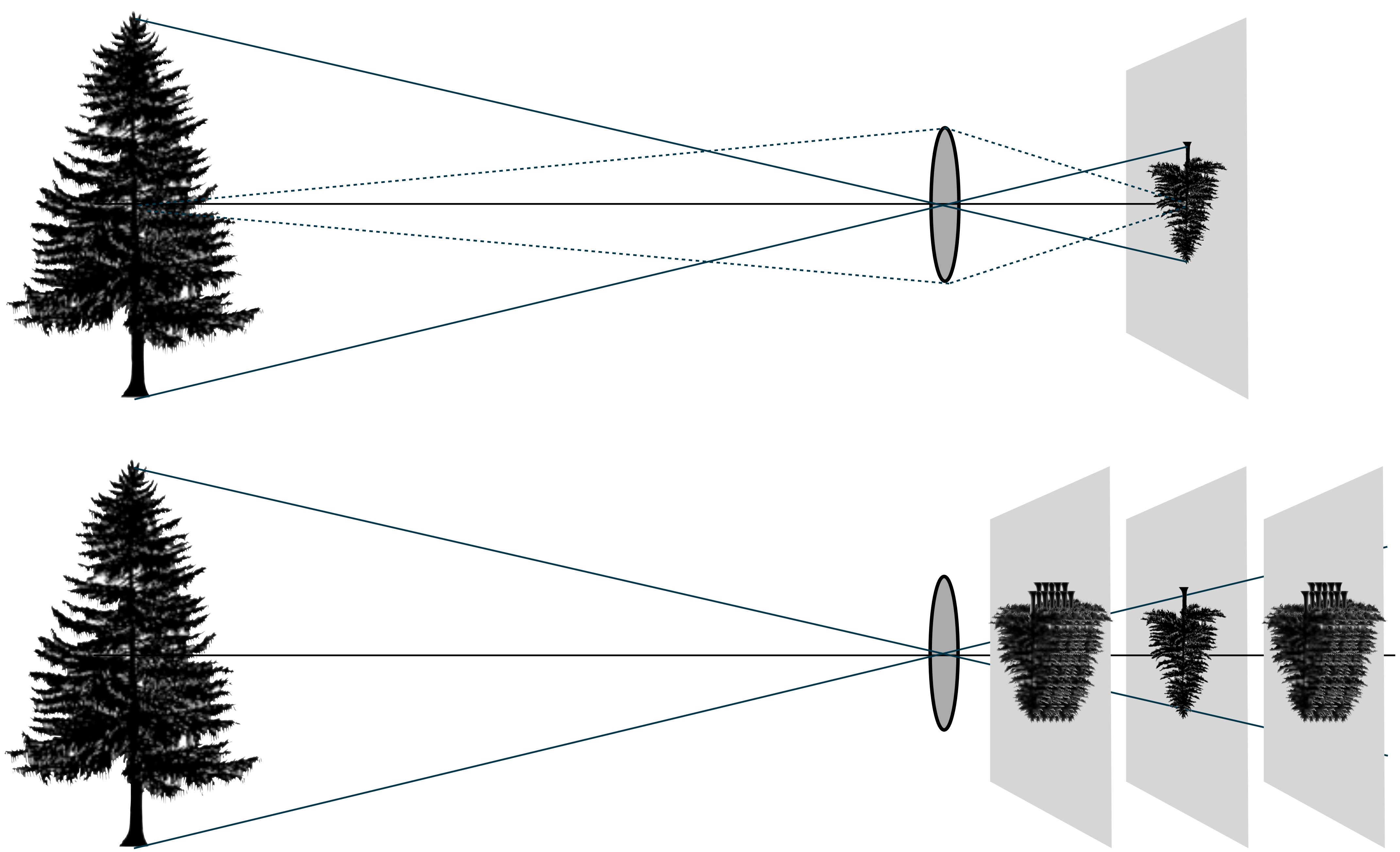


Changes in Focal Length



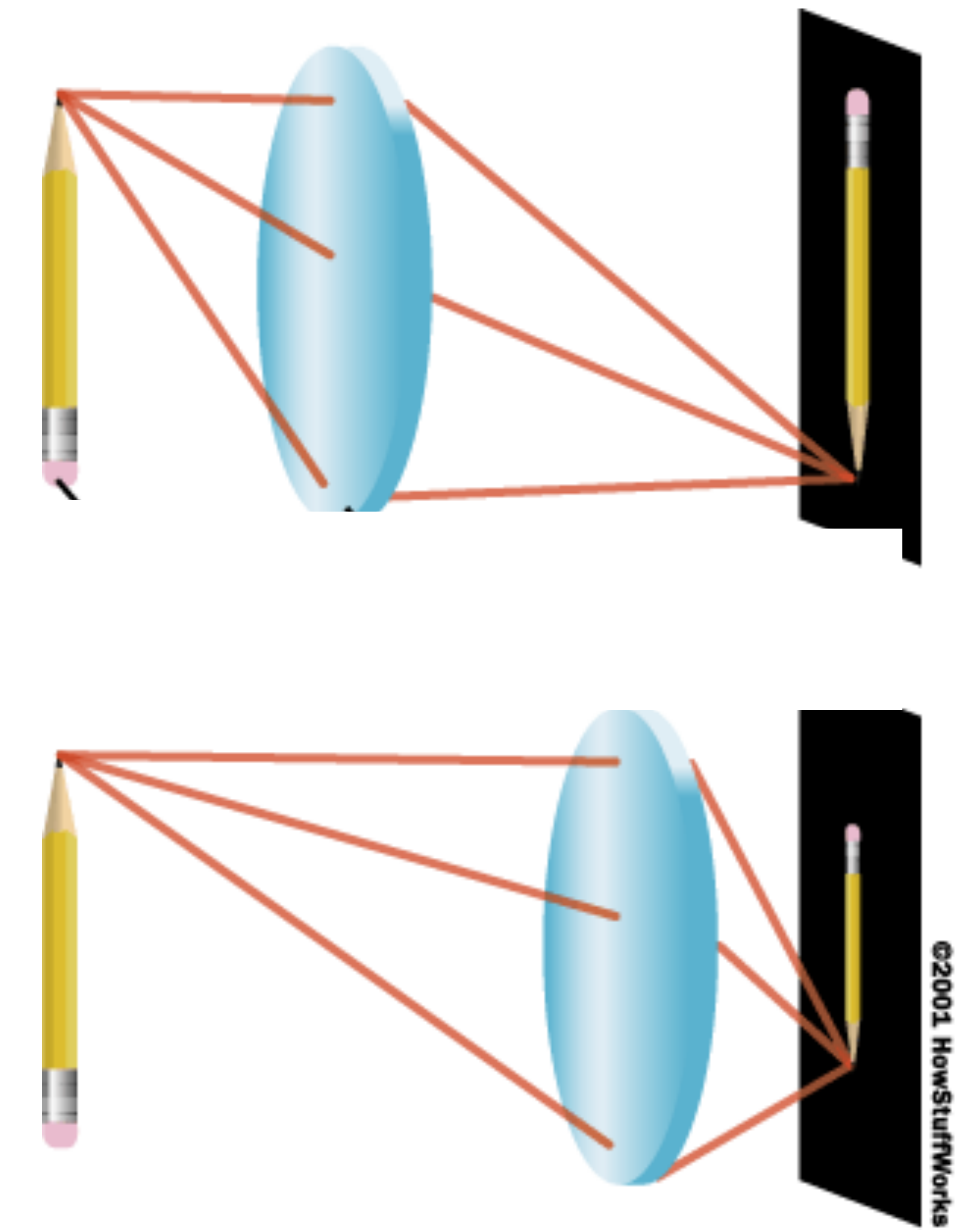
* longer or shorter f
* focal lengths are specific to lenses

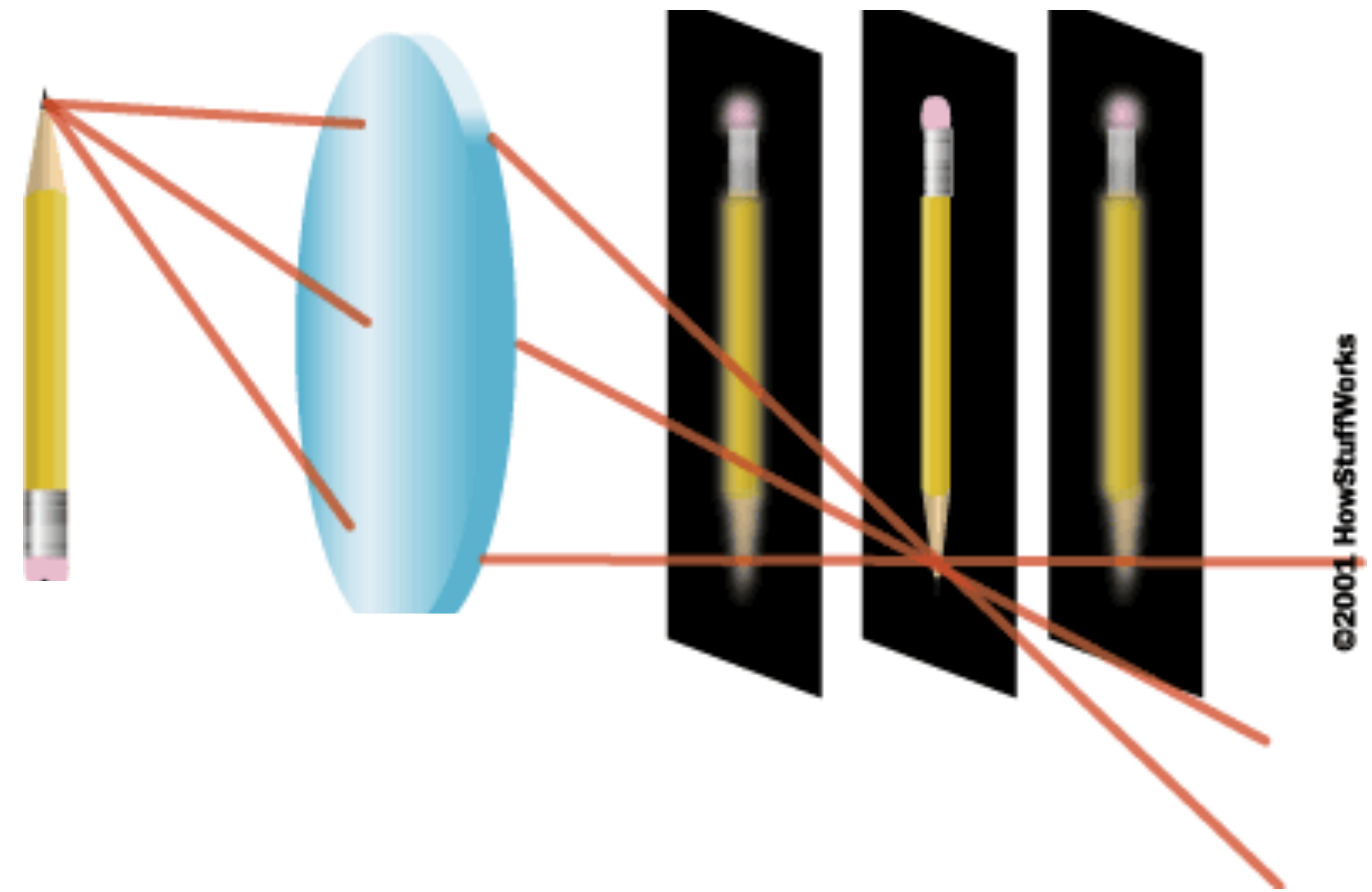
Focussing



* focusing: moving sensor back (or forward) wrt to lens

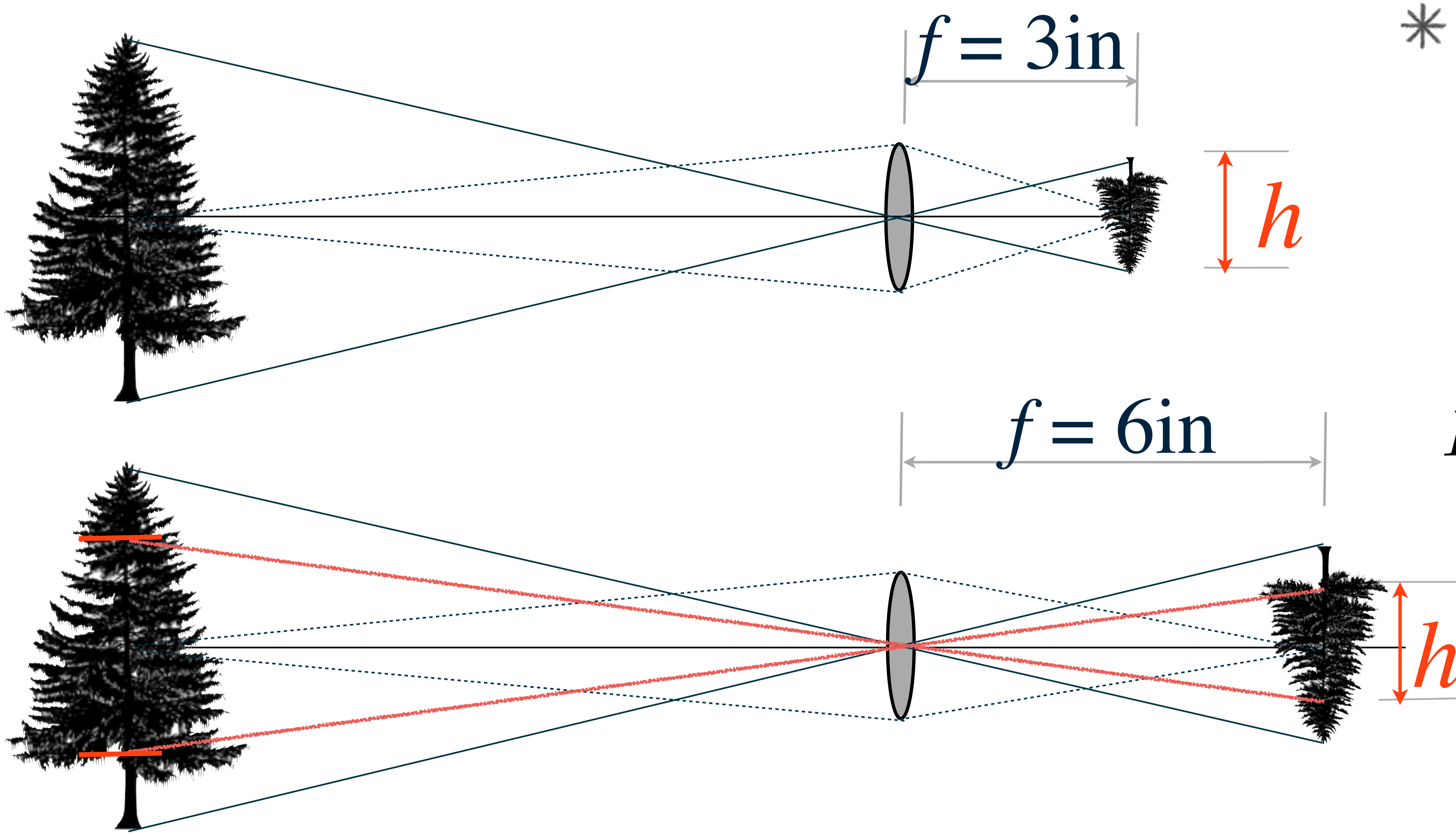
Focussing





from howstuffworks.com

Field of View (FOV)

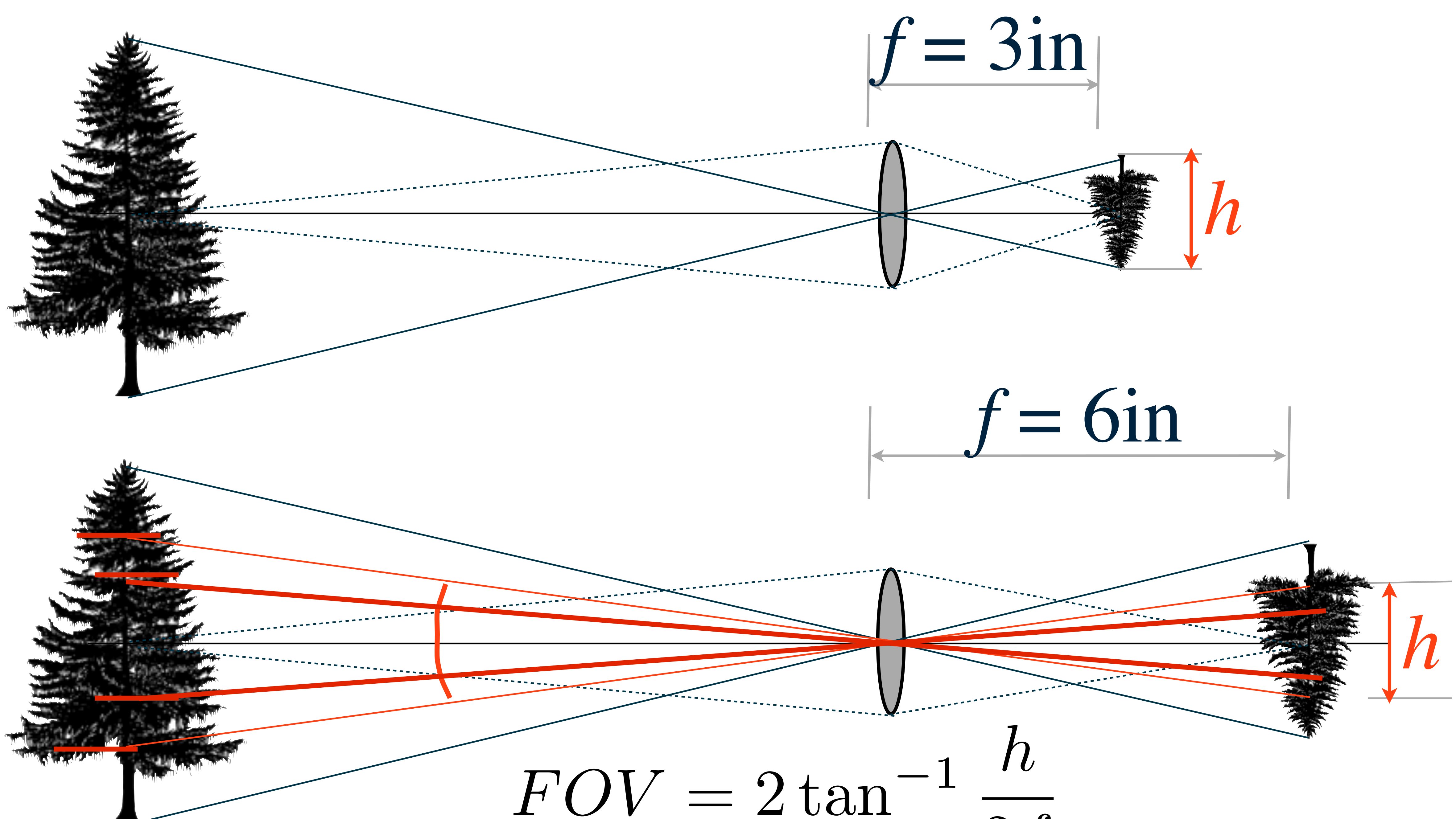


* Field of View (FOV) depends on sensor size, h

$$FOV = 2\tan^{-1}\frac{h}{2f}$$

Slide adapted from Mark Levoy

Field of View (FOV) Sensor Size



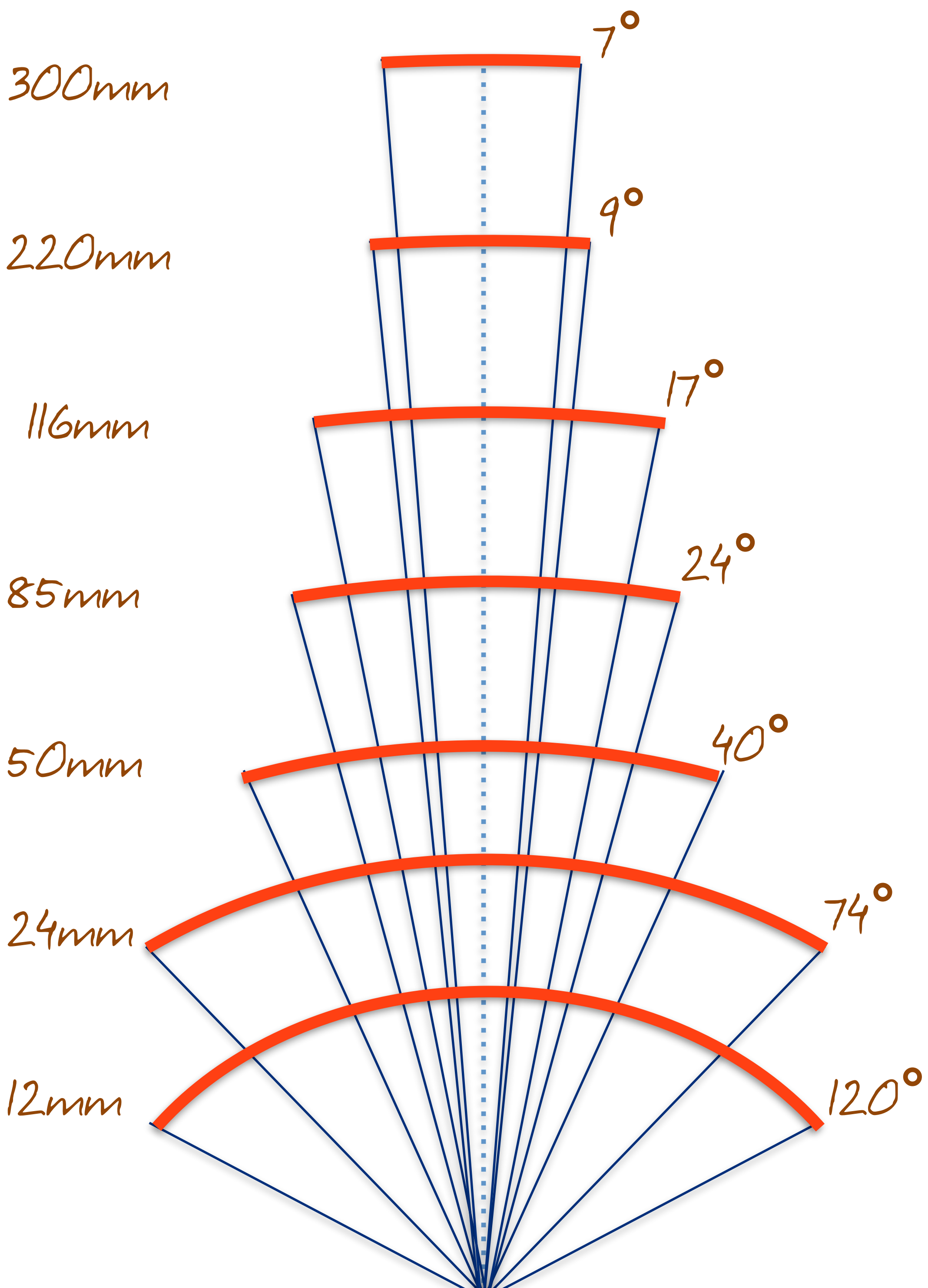
$$FOV = 2\tan^{-1}\frac{h}{2f}$$

* Sensor size small, FOV is small too
* Smaller sensors have fewer pixels, or noisier pixels

Slide adapted from mark Levoy

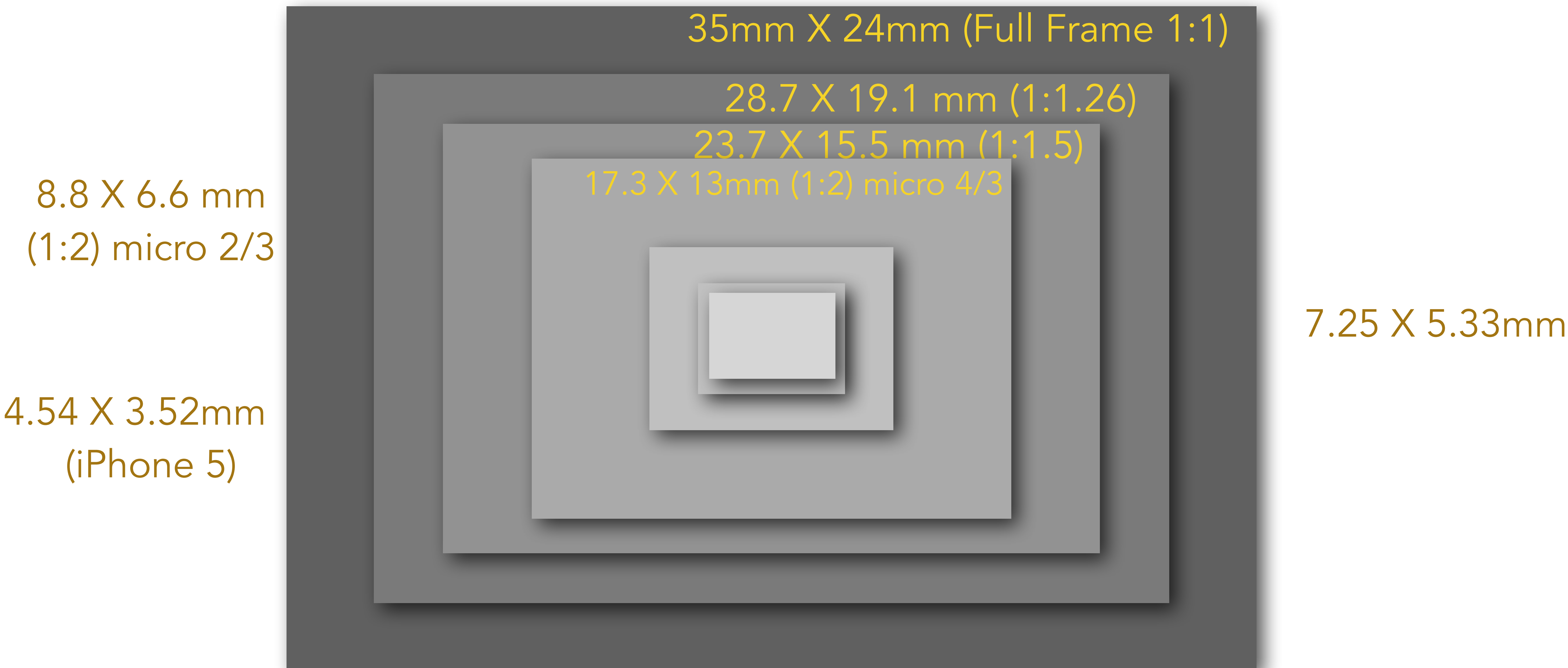

12 mm
24mm
50mm
85mm
116mm
220mm
300mm
TECH TECH

Focal Length and Field of View (FOV)



Photos by Henrik Christensen

Sensor Sizes



Focal Length vs. Viewpoint

f = 18mm, 35mm sensor

Distance to 1st Subject = 0.5m

Distance to 2nd Subject = 2.0m

f = 180mm, 35mm sensor

Distance to 1st Subject = 3.0m

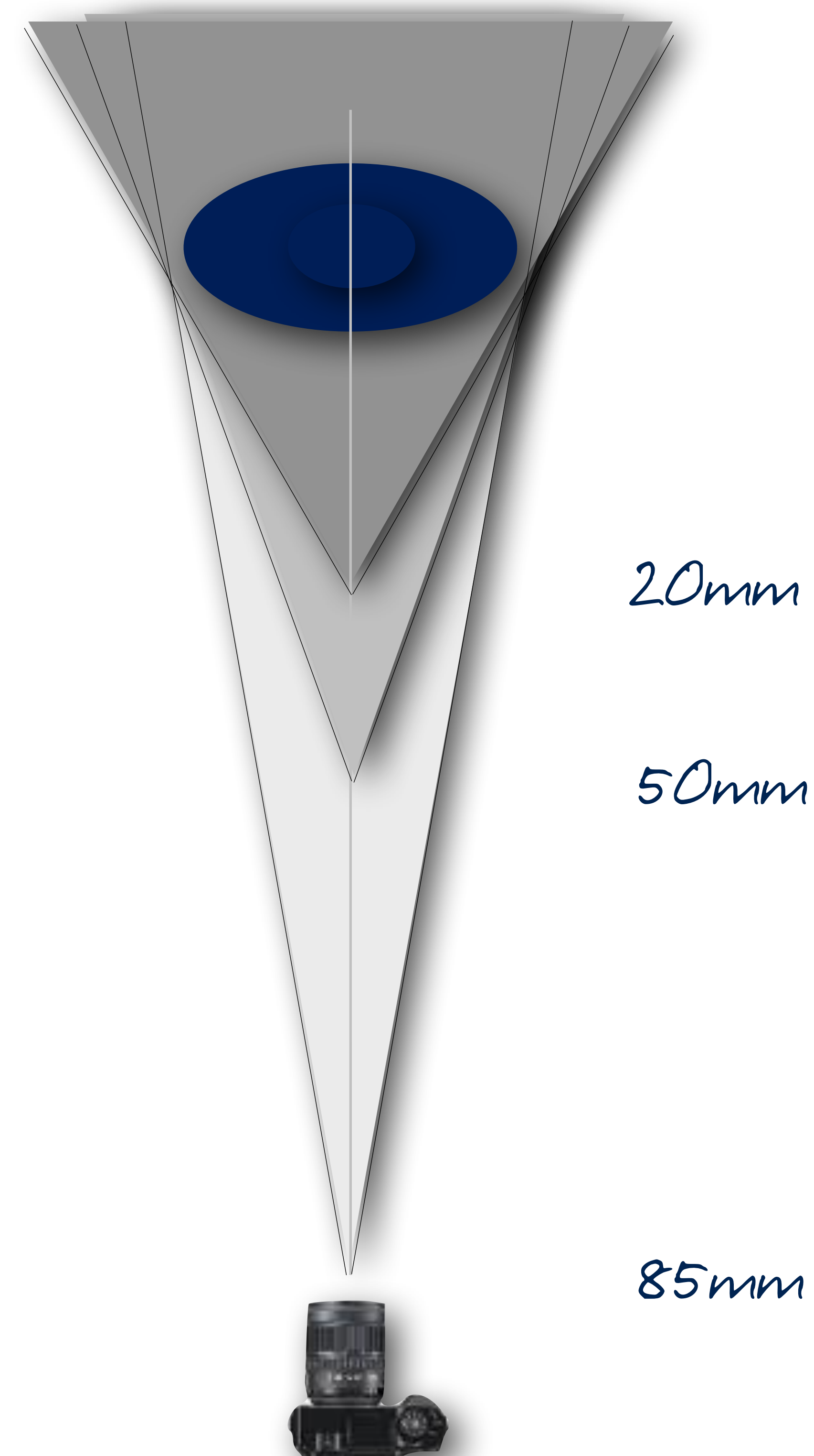
Distance to 2nd Subject = 4.5m

* Changing focal length allows us to move back, and still capture the scene
* Changing viewpoint causes perspective changes
* See the "vertigo" effect from Hitchcock movies

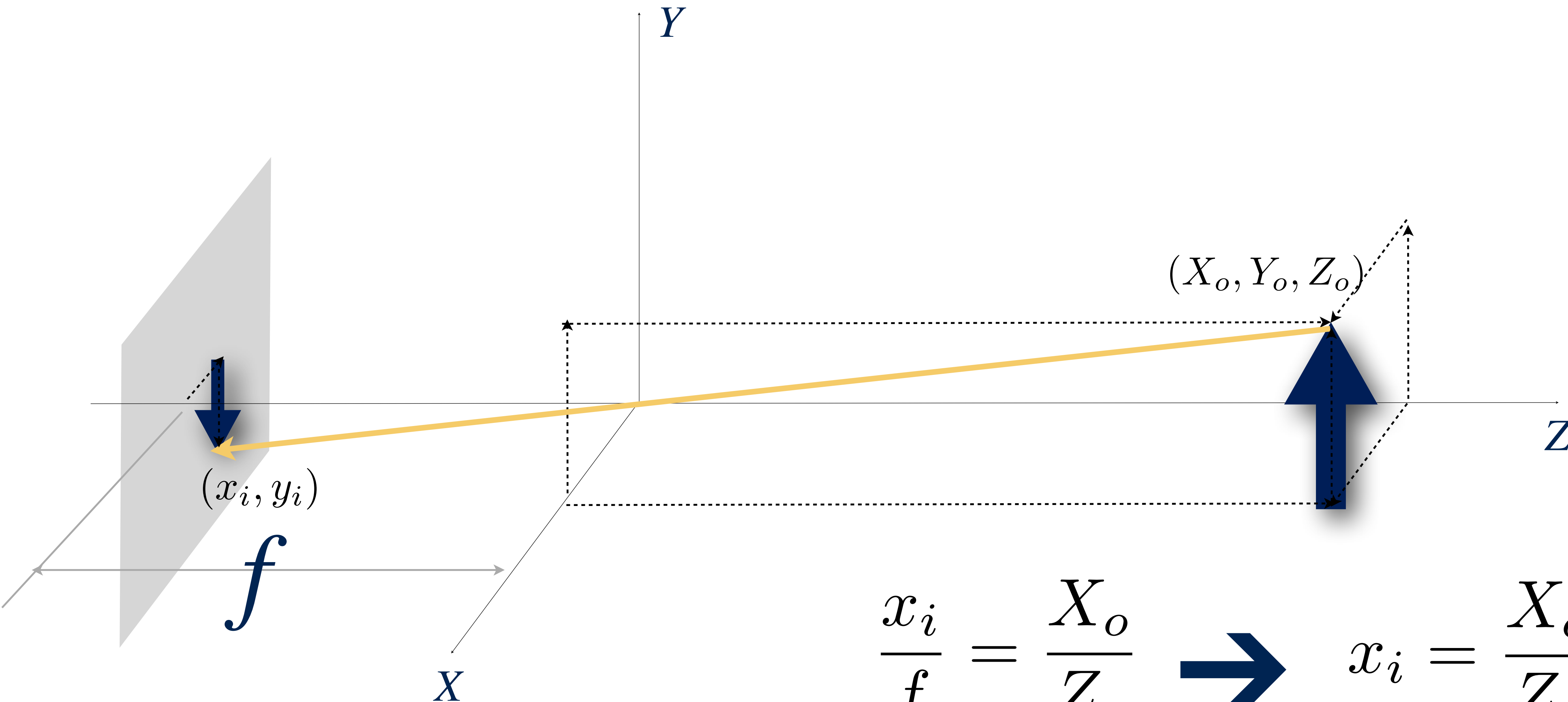
Camera as a Window in a 3D World

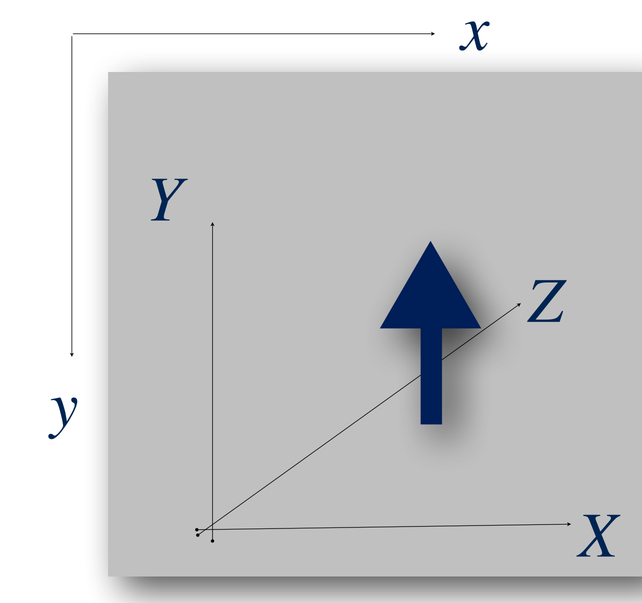
Geometry (Perspective)

Image: Wikimedia Commons



A Camera Model



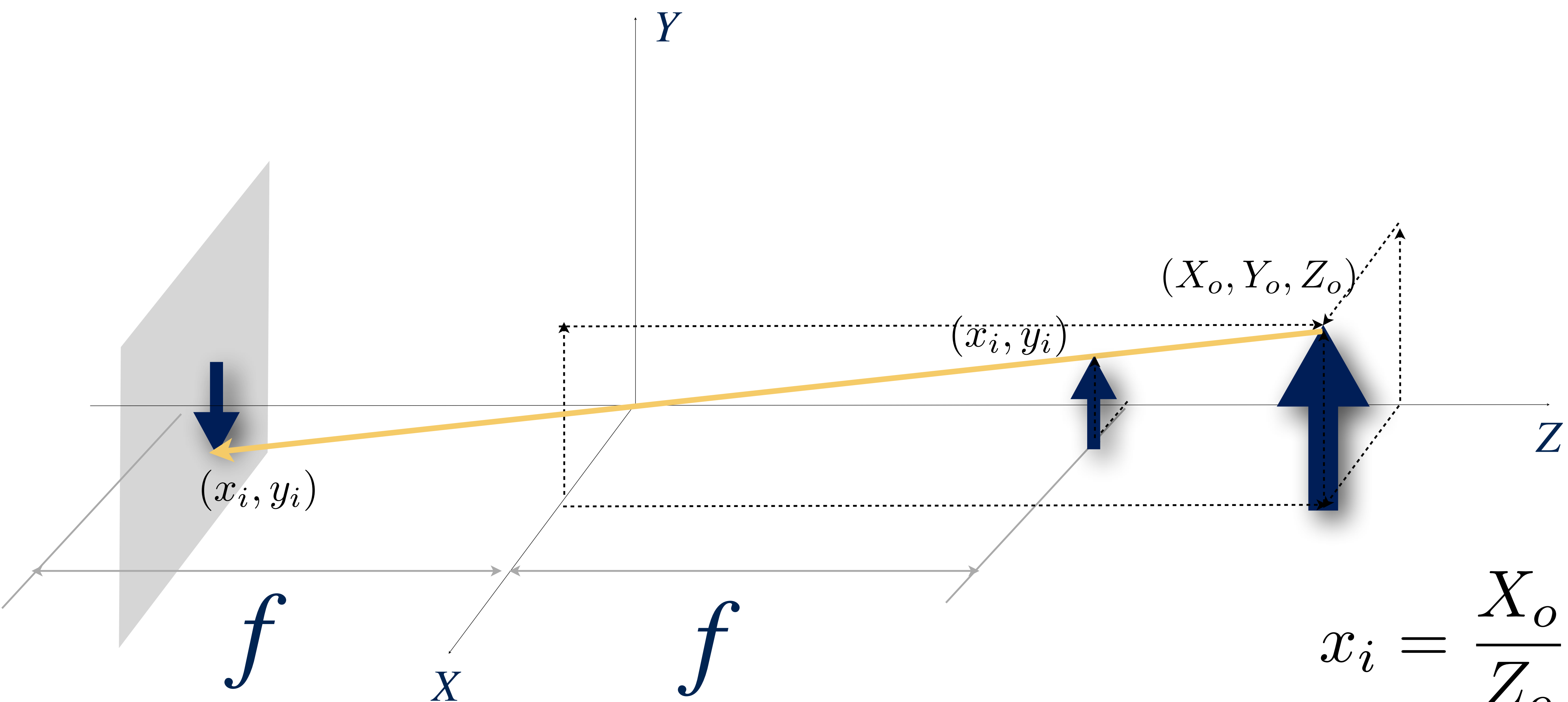


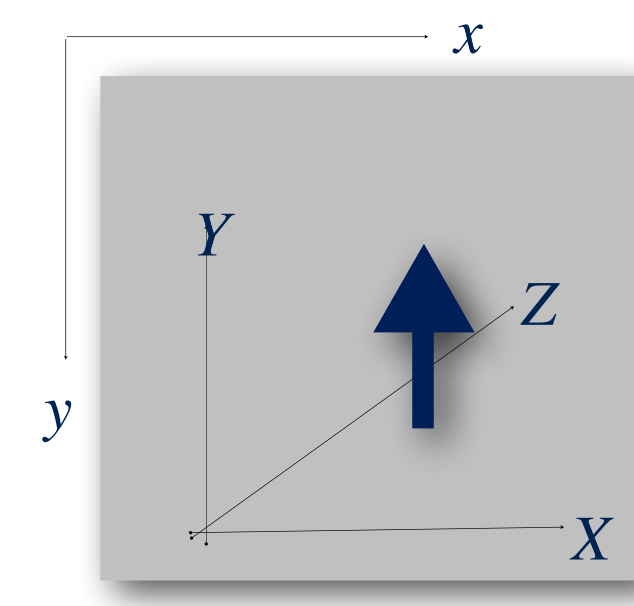
Using similar triangles

$$\frac{x_i}{f} = \frac{X_o}{Z_o} \rightarrow x_i = \frac{X_o}{Z_o} f$$

$$\frac{y_i}{f} = \frac{Y_o}{Z_o} \rightarrow y_i = \frac{Y_o}{Z_o} f$$

A Camera Model: Perspective

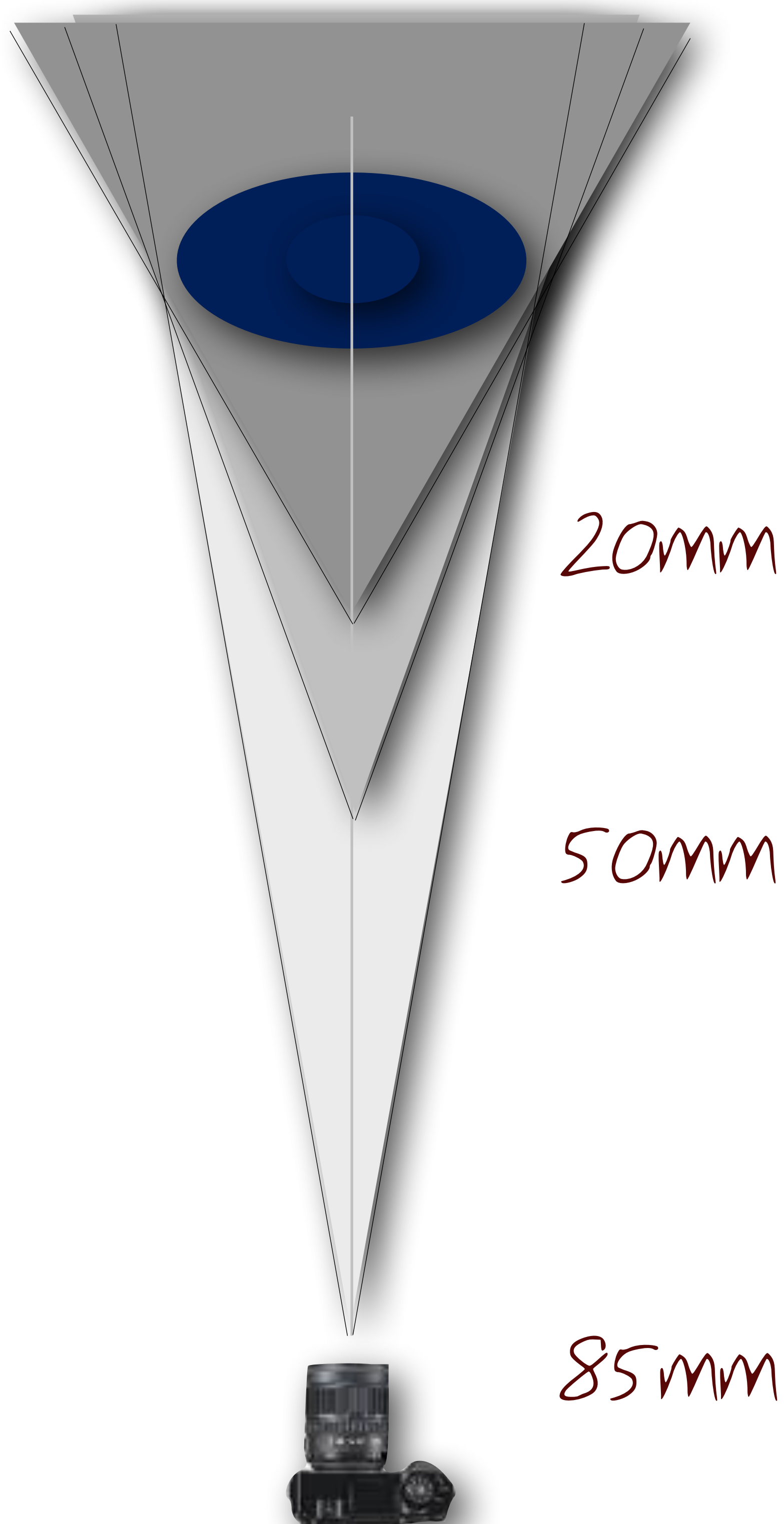


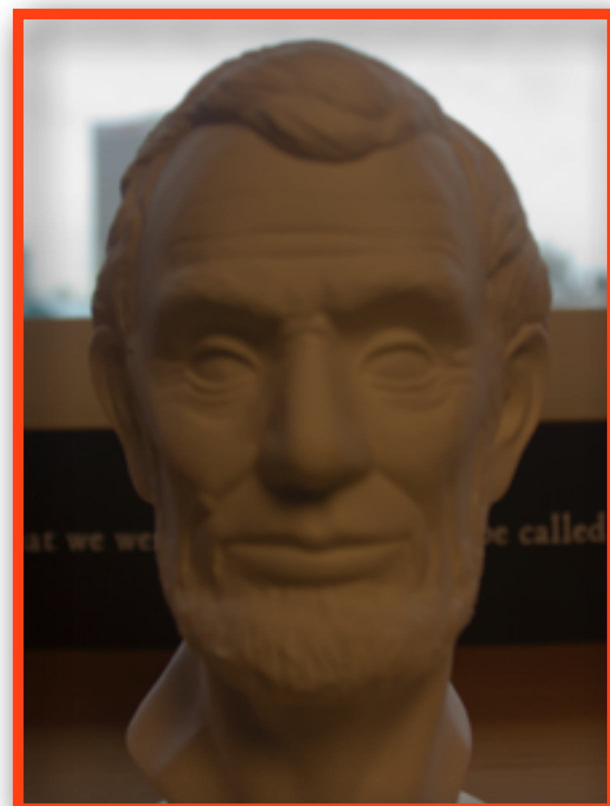


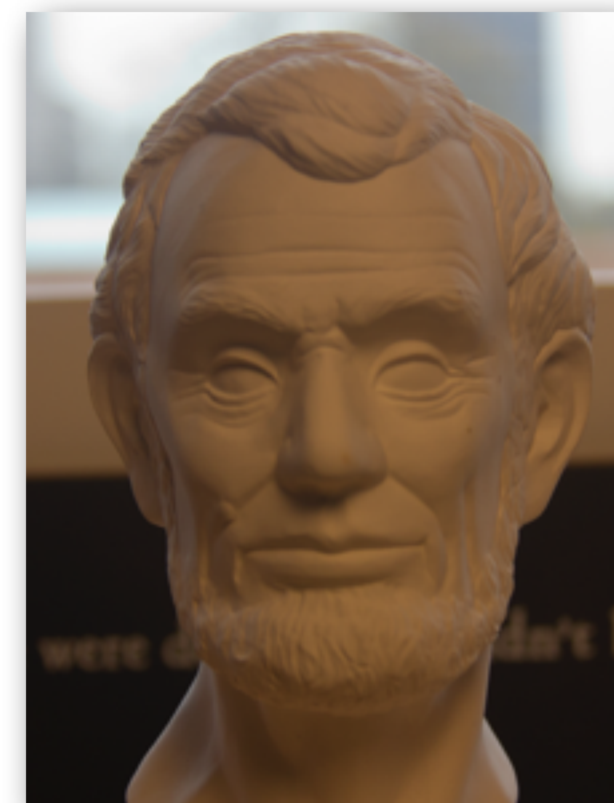
$$x_i = \frac{X_o}{Z_o} f$$

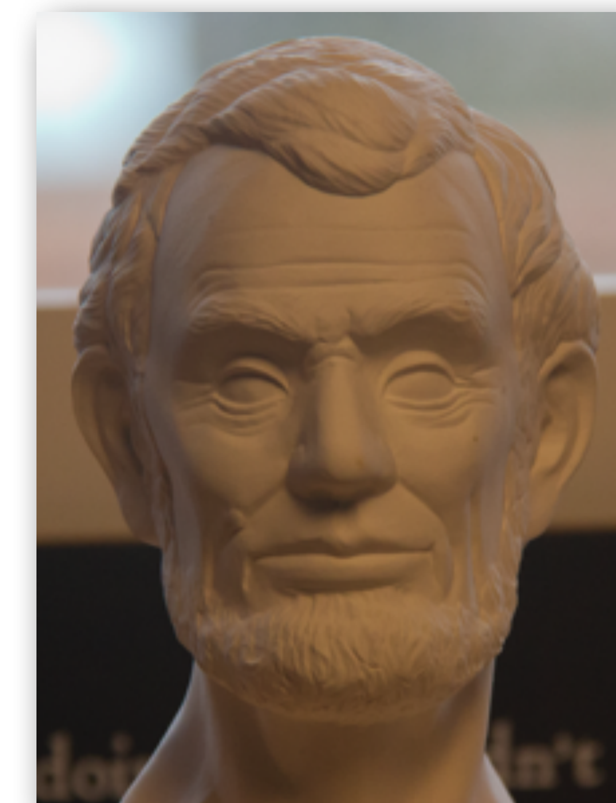
$$y_i = \frac{Y_o}{Z_o} f$$

Focal Length for Portraits









Traditionally, 75-135mm focal length (I prefer 85mm) are used for Portraits

Summary

* Brought together the concepts of Focal Length, FOV and Sensor Size
* Discussed the impact of Focal Length on Image Formation/ Capture
* Explained Perspective Projection for a camera with a Focal Length

Next Class

* Camera
  * Exposure Triangle
  * Aperture
  * Shutter Speed
  * ISO

Credits

* For more information, see
  * Hecht, E. (2002) Optics, 4th ed. Reading, MA: Addison-Wesley and
  * London, B., Stone, J., & Upton, J. (2011), Photography, 10th ed. Upper Saddle River, NJ: Prentice Hall.
* Some images retrieved from
  * http://commons.wikimedia.org/.
  * http://electronics.howstuffworks.com/camera1.htm
  * List available on website.
* Some Slides adapted from Mark Levoy.
* Photos by Henrik Christensen and Irfan Essa.

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Cameras, Optics, and Sensors

* Cameras: Aperture, Shutter speed Controls of a Camera.

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Exposure Triangle

* Aperture
* Shutter Speed
* ISO

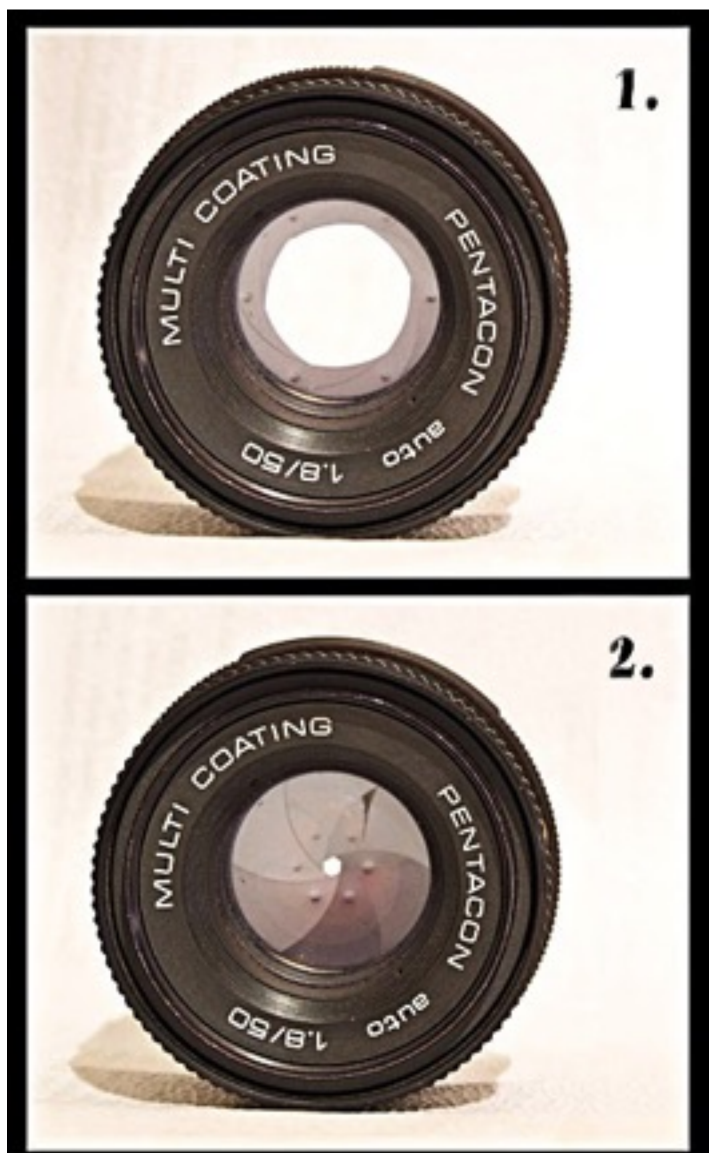
Recall: Focal Length vs. Viewpoint

f = 18mm, 35mm sensor
1st Subject: 0.5m away
2nd Subject: 2.0m away

f = 180mm, 35mm sensor
1st Subject: 3.0m away
2nd Subject: 4.5m away

* Changing focal length allows us to move back, and still capture the scene
* Changing viewpoint causes perspective changes

Exposure (H)



Exposure = Irradiance X Time

$$H = E * T$$

Irradiance (E)

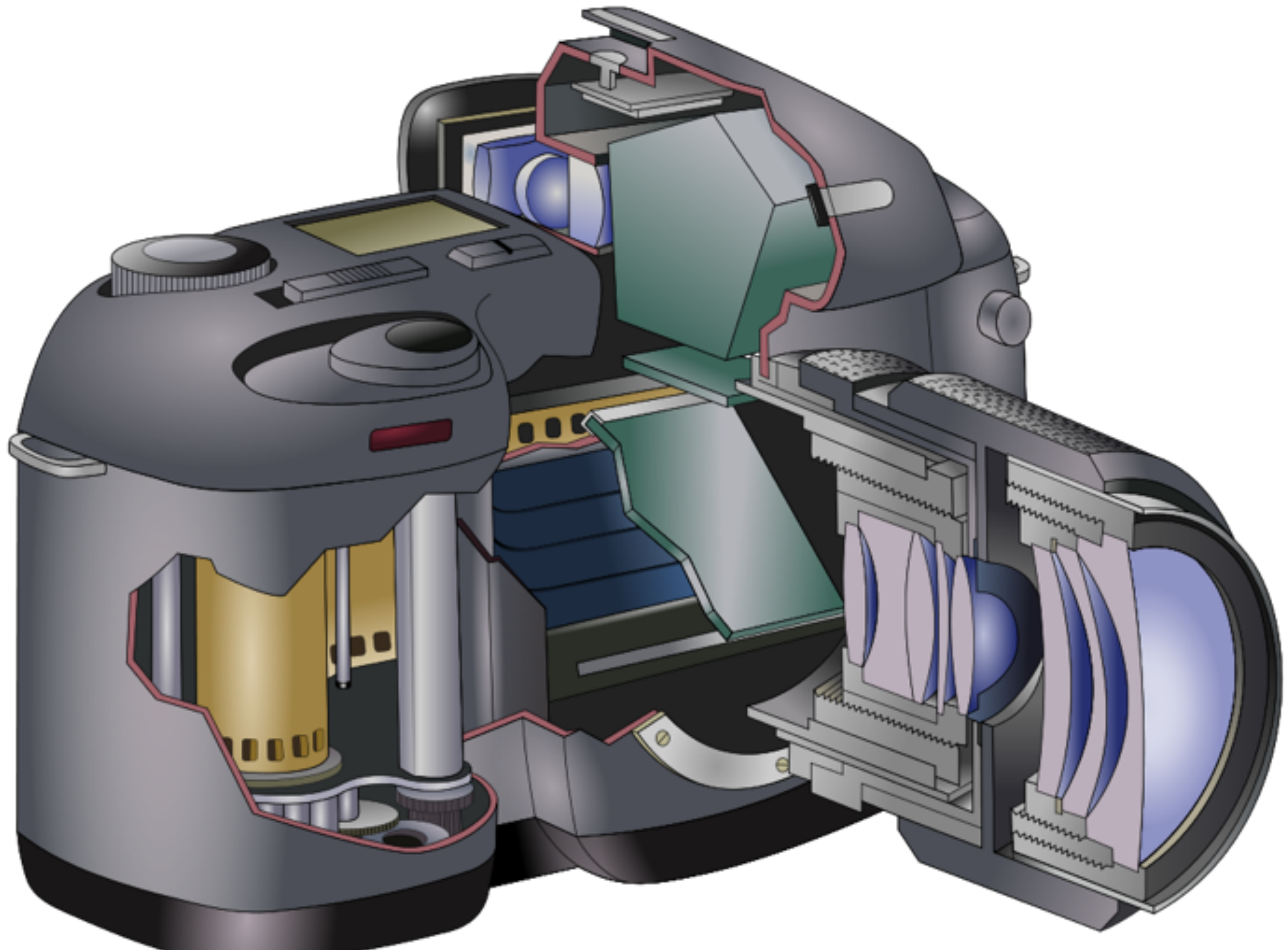
* Amount of light falling on a unit area of sensor per second
* Controlled by lens **aperture**

Exposure Time (T)

* How long the **shutter** is kept open

commons.wikimedia.org

Inside a Camera (an SLR)



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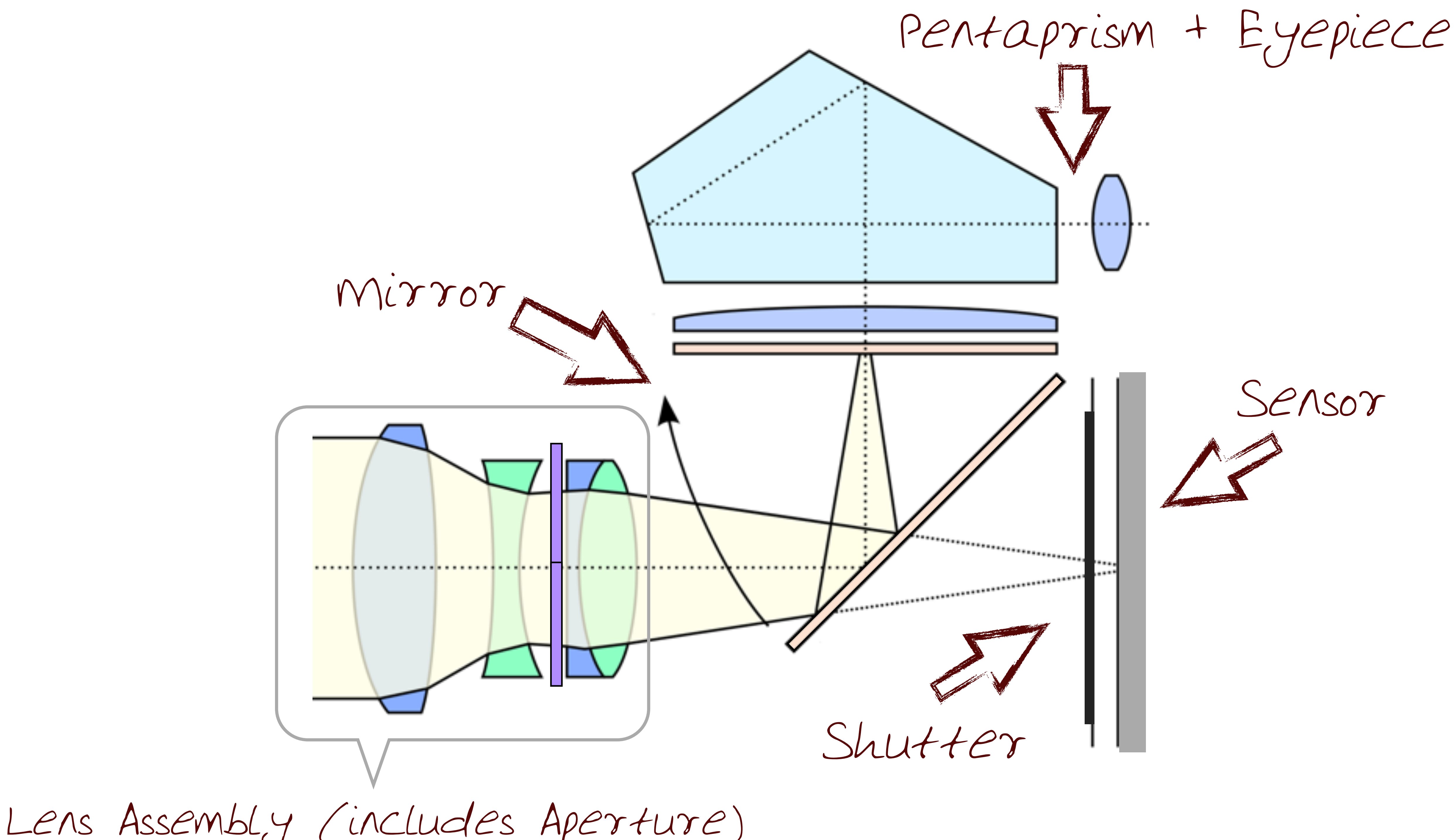


Adapted from commons.wikimedia.org/

Shutter Speed (1st Example)

http://commons.wikimedia.org/wiki/File:Shutter_speed_waterfall.gif

- Amount of time the sensor is exposed to light
- Usually denoted in fractions of a second (1/2000, 1/1000, ..., 1/250, ..., 1/60, ..., 1/15, ..., 15, 30, Bulb)
- Effects of motion Blur to Streaks

Shutter Speed (2nd example)

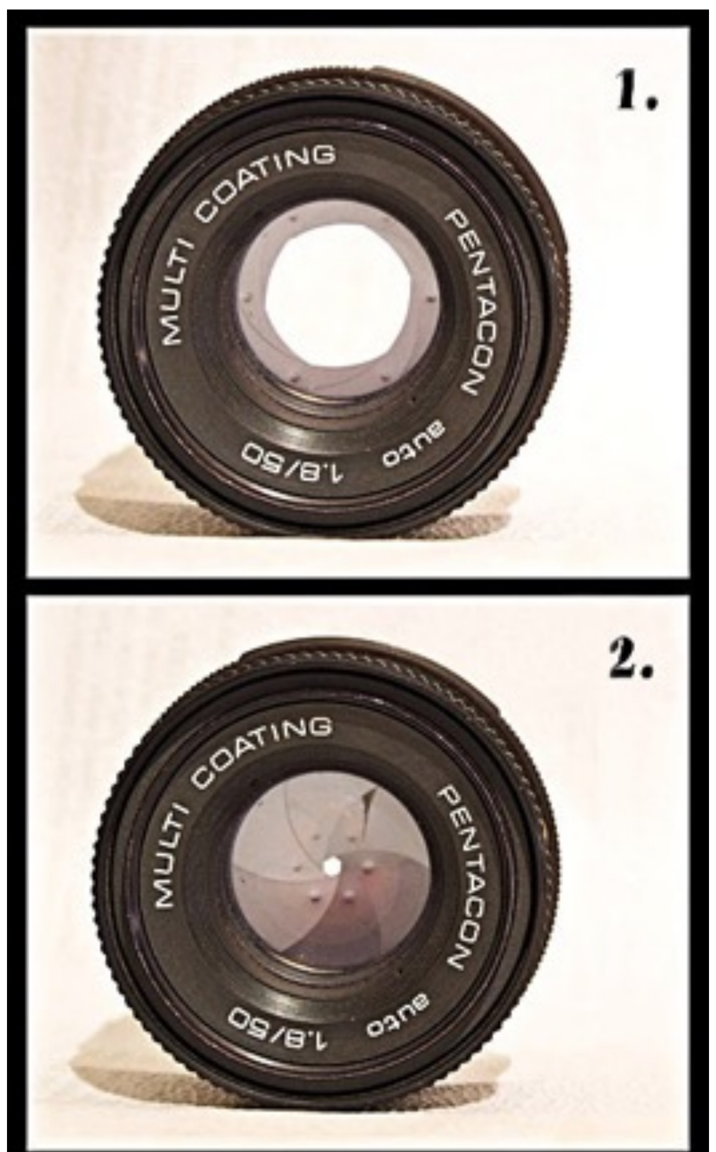
1/125 second

http://everydayhdr.com/wp-content/uploads/2012/09/Waterfall-Aperture-Compare.jpg

Shutter Speed (3rd Example)

http://commons.wikimedia.org/wiki/File:Windflower-05237-nevit.JPG

Aperture



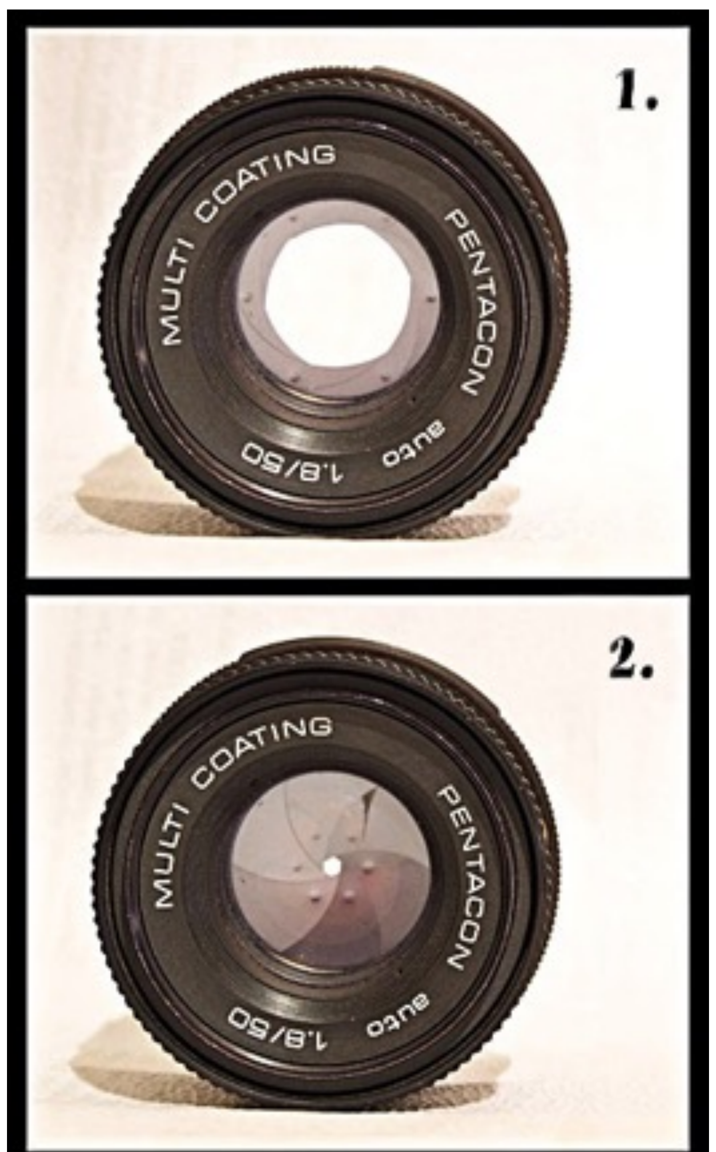
commons.wikimedia.org

Irradiance on Sensor → The amount of light captured is proportional to the Area of the Aperture (opening):

$$Area = \pi \left(\frac{f}{2N} \right)^2$$

* **f** is the the focal length. What is the diameter of the Aperture?
* Aperture Number **N** usually written as **f/N**

Aperture



commons.wikimedia.org

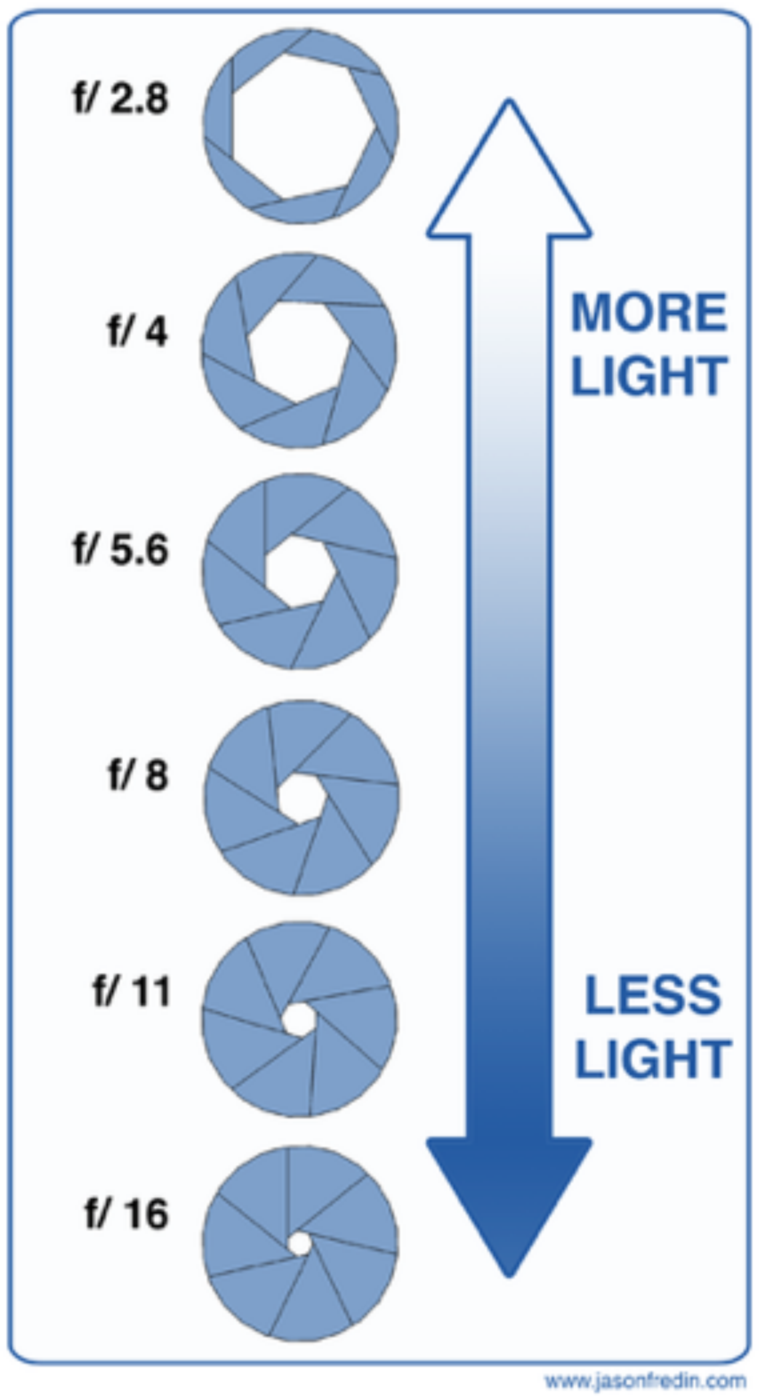
- Focal length: f
- Aperture Number: N (usually written f/N)
- Aperture Number gives irradiance irrespective of the lens in use

$$Area = \pi \left(\frac{f}{2N} \right)^2$$

  - f/2.0 on 50mm lens → aperture = 25mm
  - f/2.0 on 200mm lens → aperture = 100mm
- Low f-number (N) on telephoto lens means BIG lens

Aperture

$$Area = \pi \left(\frac{f}{2N}\right)^2$$



- Doubling N reduces A by $4X$, and therefore reduces light by $4X$
  - from $f/2.8$ to f/5.6 cuts light by $4X$
  - to cut light by $2X$, increase N by $\sqrt{2}$


f/22
f/18
f/14
f/11
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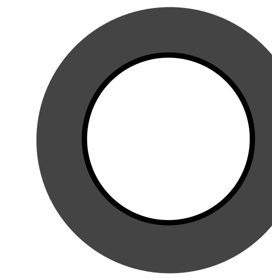
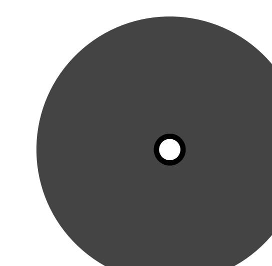
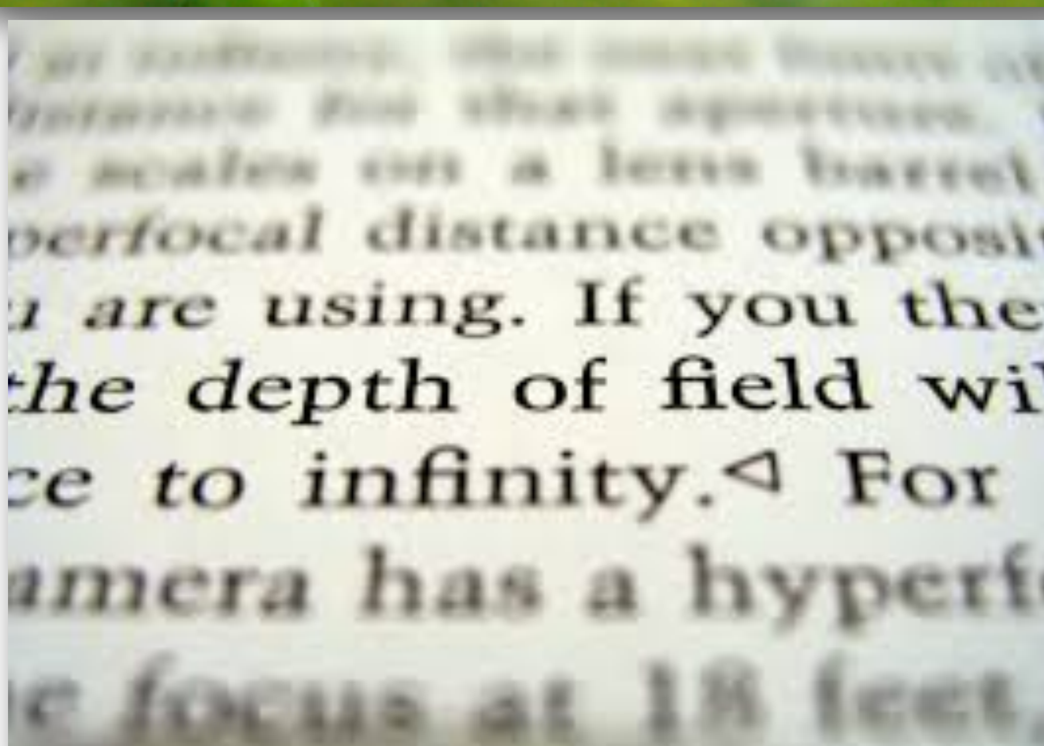


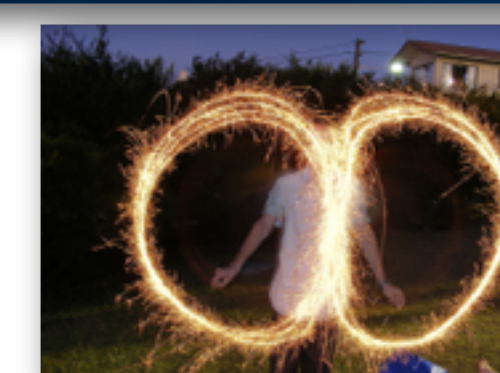
f/3.5



f/22

Photographic Values of Aperture/Shutter/Focal L.

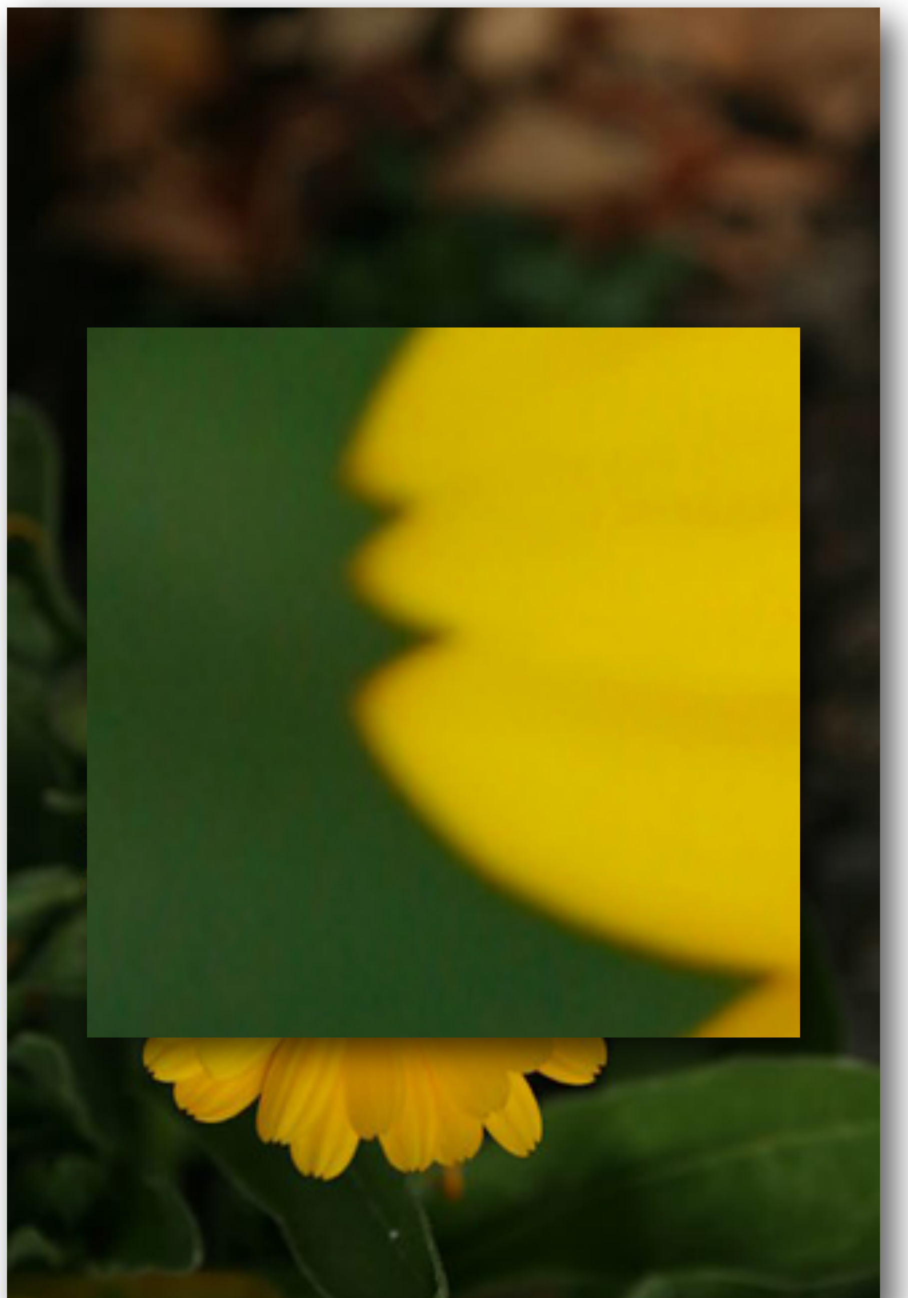




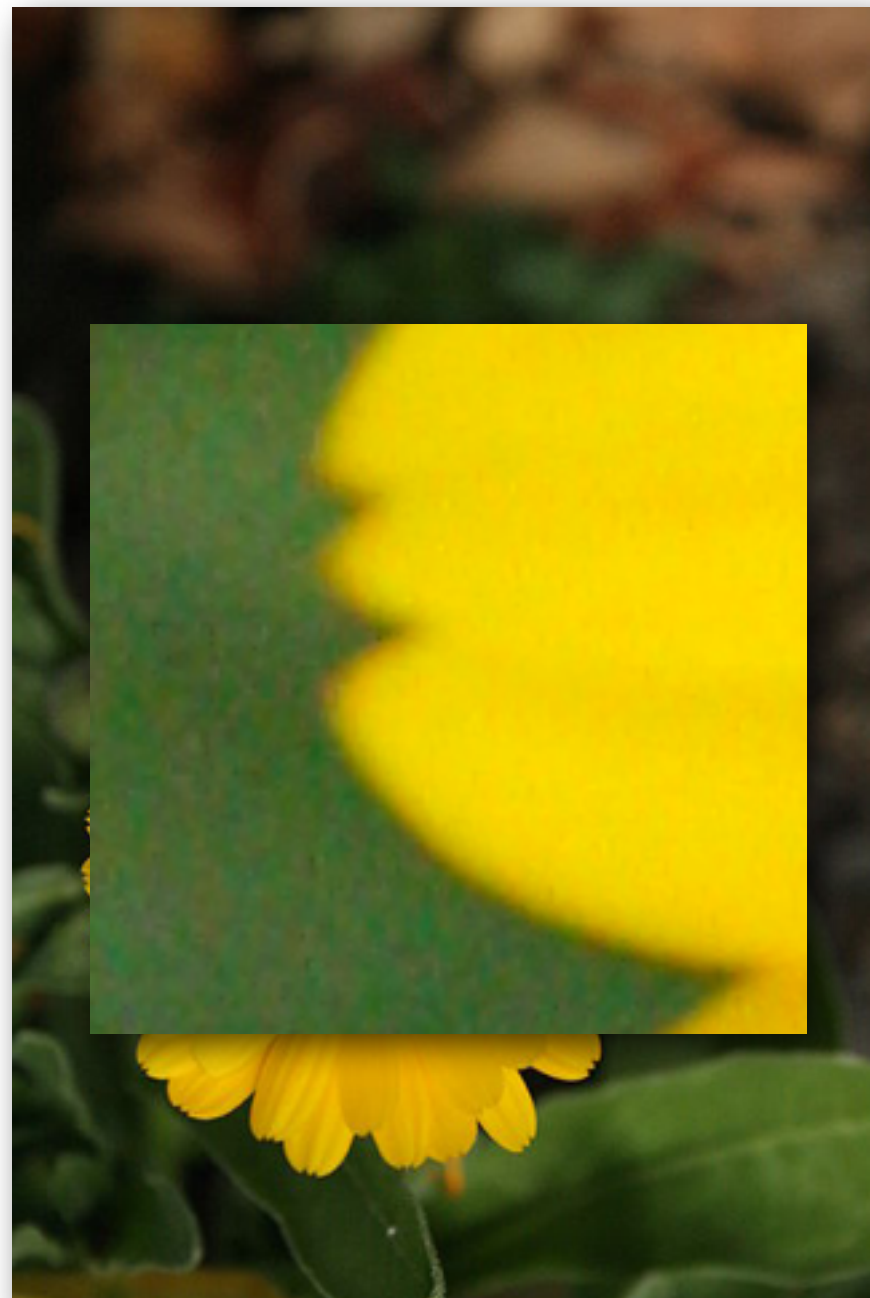
Images: commons.wikimedia.org

https://www.youtue.com/watch?v=RAe30VG5CI4

ISO (Sensitivity)



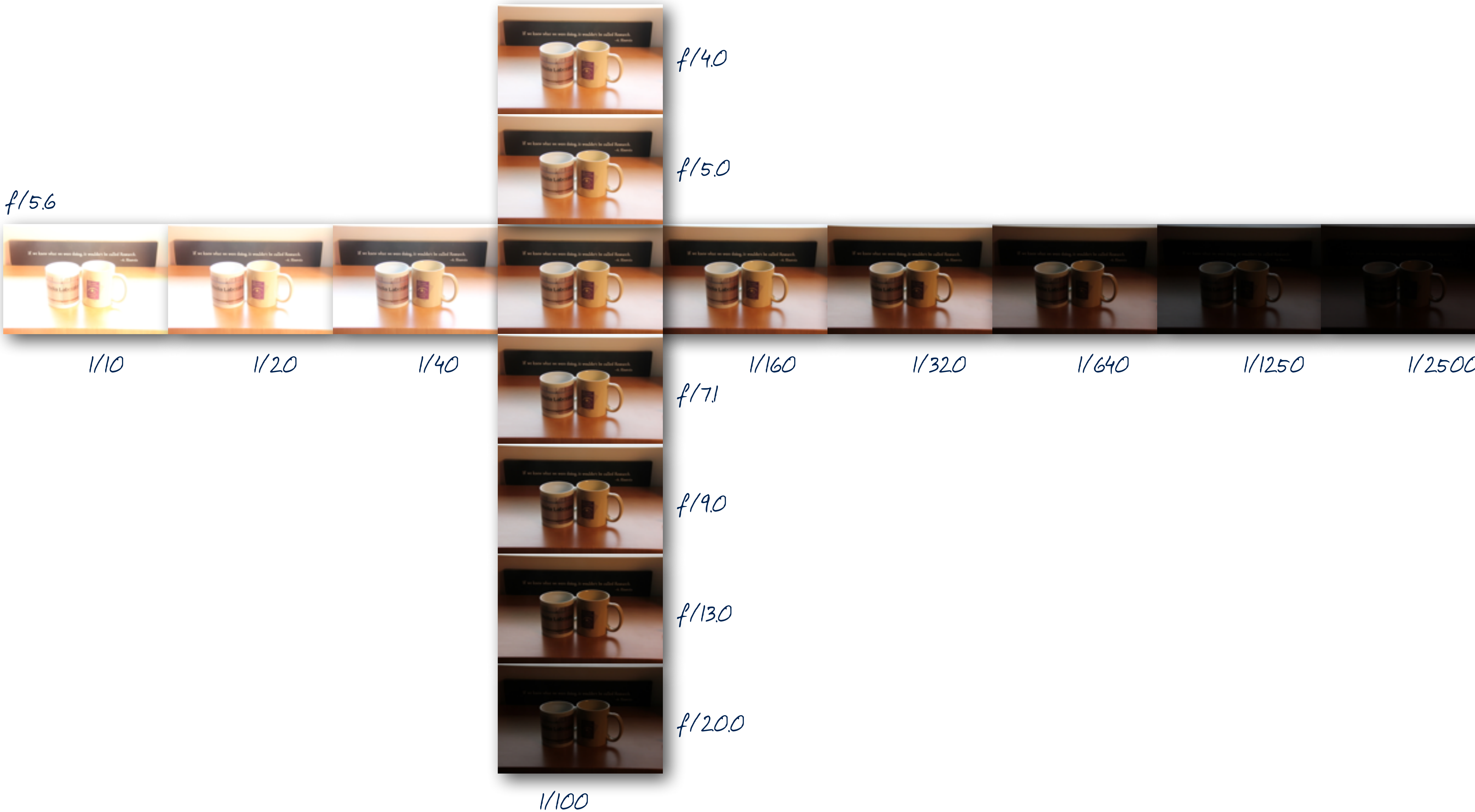
ISO 100



ISO 1600

- Third Variable in getting the right Exposure
- Film: Sensitivity vs. Grain (of film)
- Digital: Sensitivity vs. Noise (of sensor)
- Linear: 200 ISO needs half the light of 100 ISO

Images: commons.wikimedia.org


f/4.0
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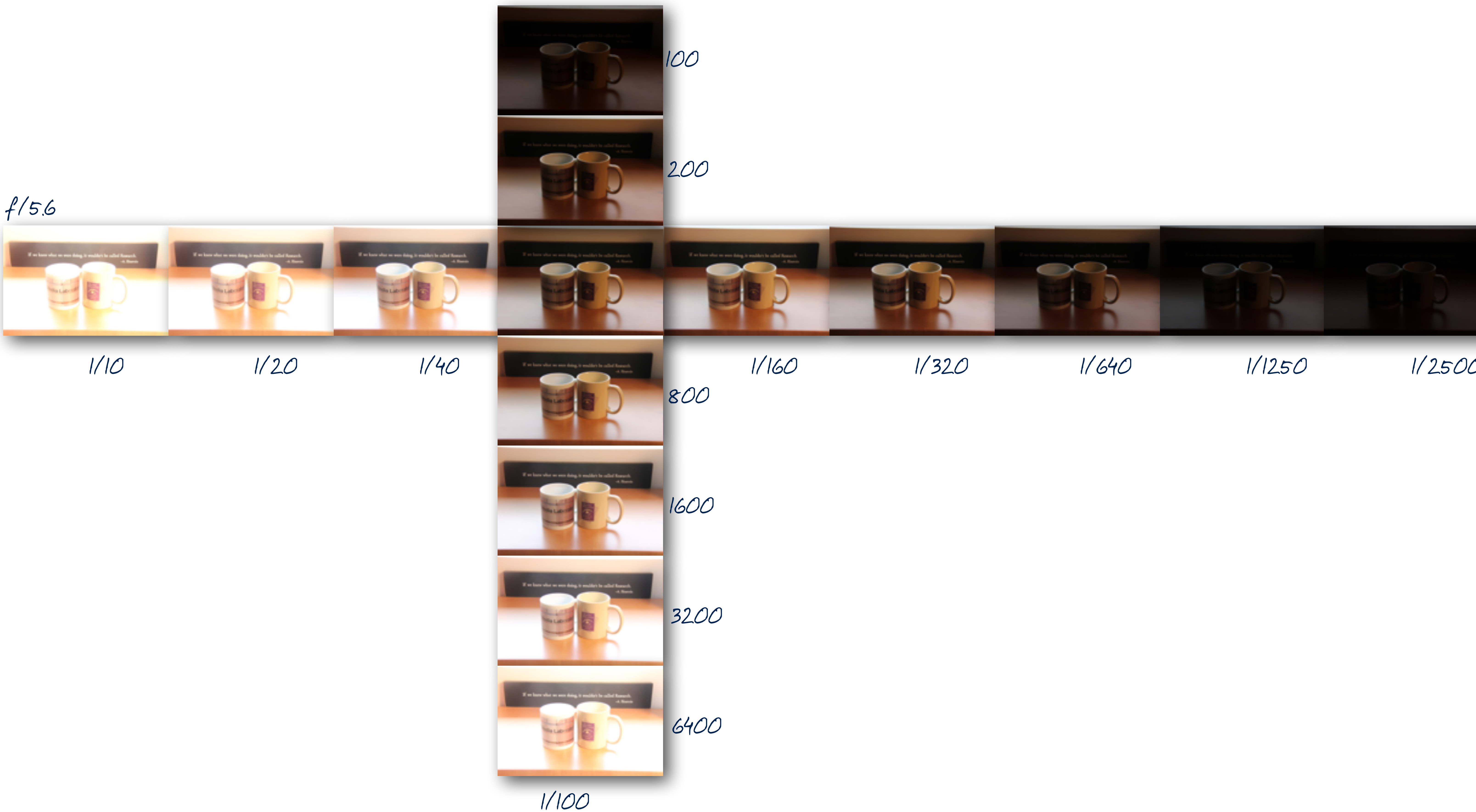
f/20.0
1/100


f/5.6
100
200
800
1600
3200
6400
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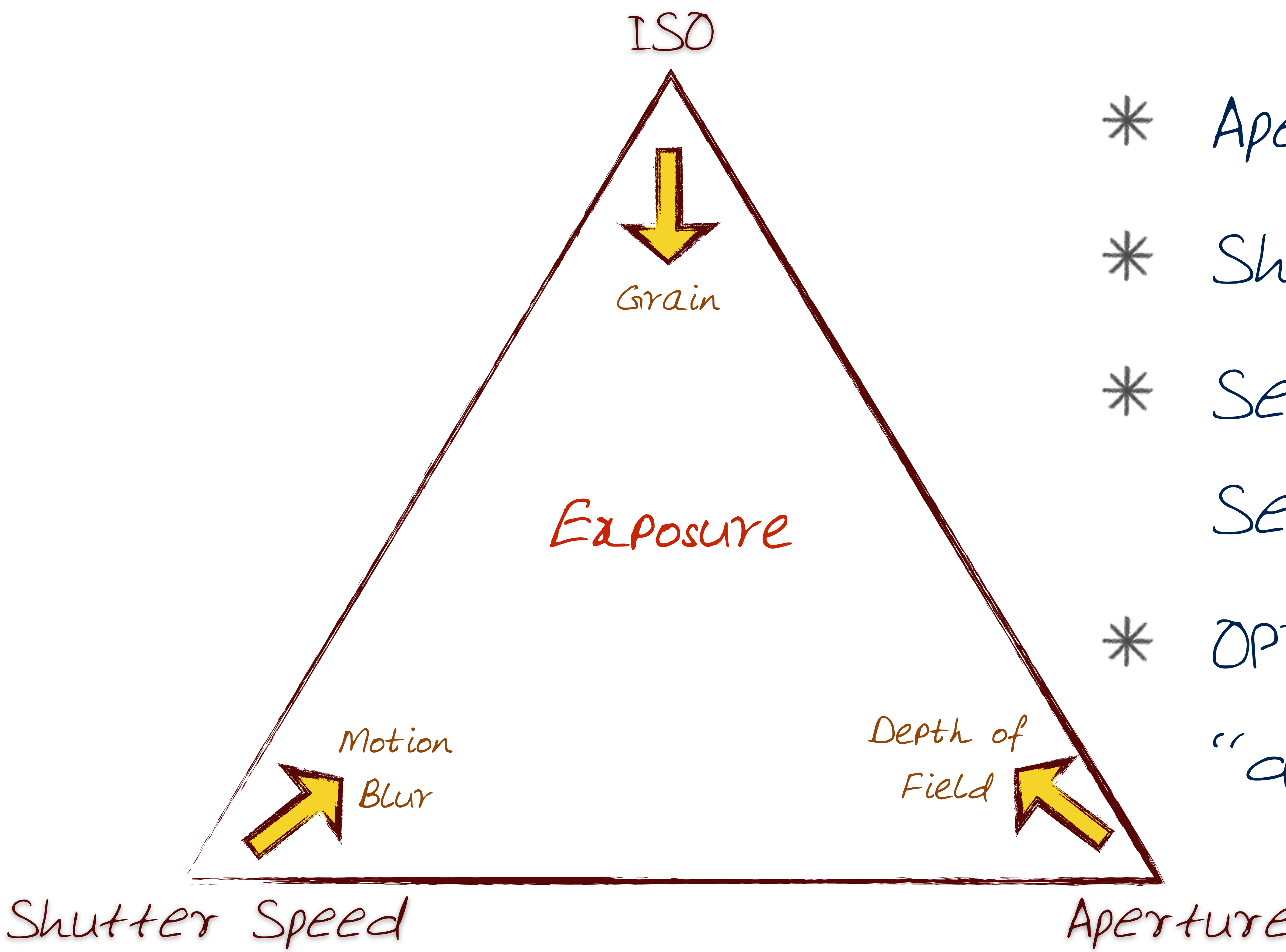
1/20
1/40
1/160
1/320
1/640
1/1250
1/2500
1/100

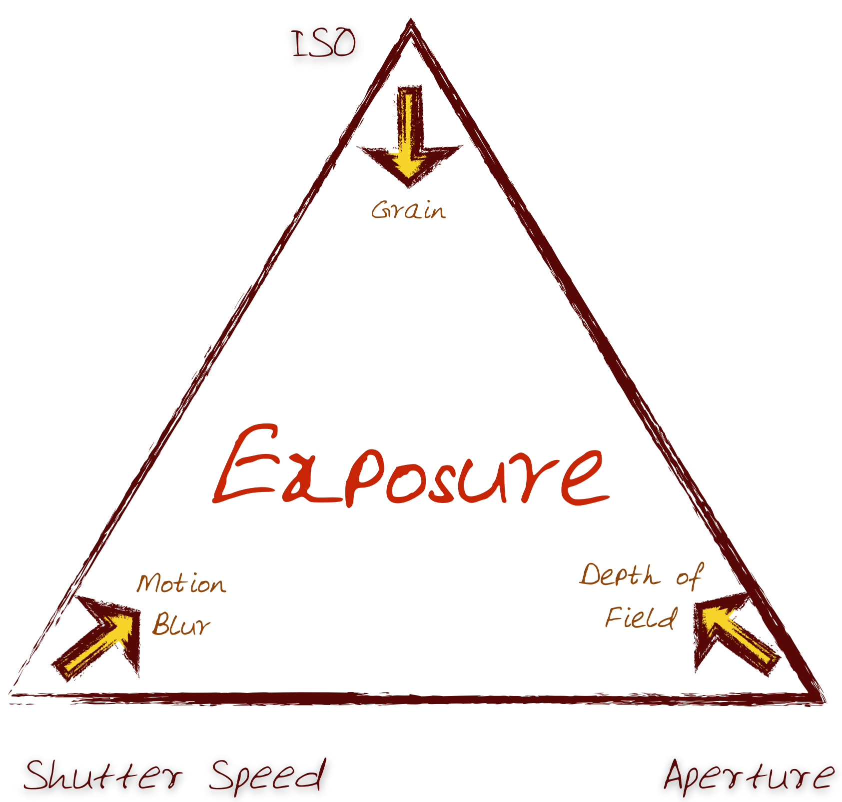
Exposure Triangle



* Aperture opening
* Shutter Speed
* Sensor/Film Sensitivity (ISO)
* OPTIMIZED to get a "desired" exposure

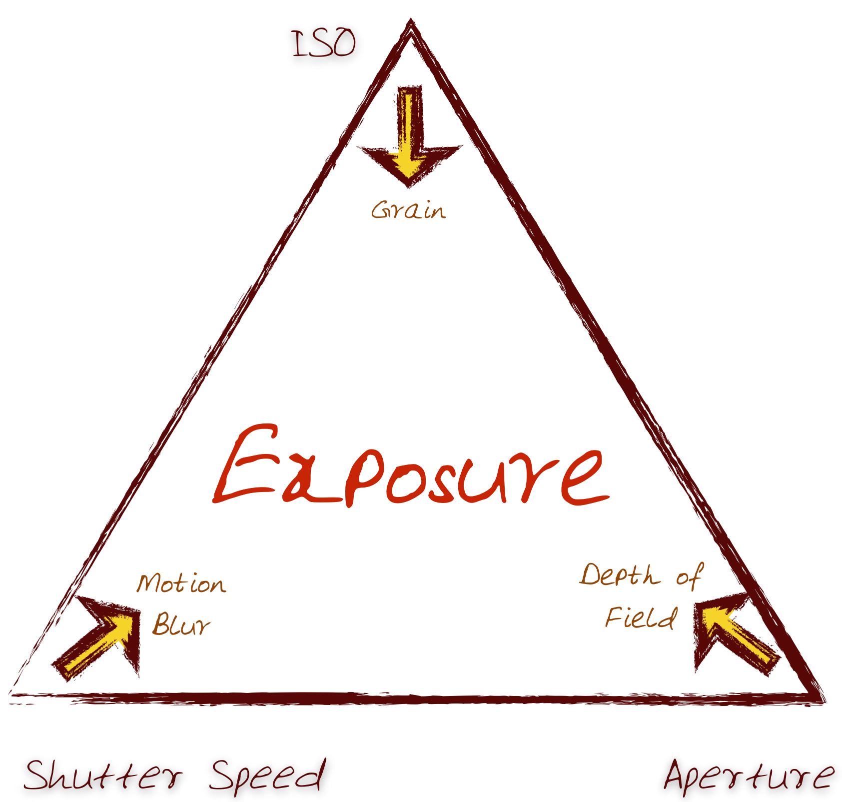
Recap: Exposure

* Exposure (**H**) = Irradiance (**E**) X Time (**T**)
* Irradiance (**E**): Controlled by Aperture opening
  * Lowering by 1/f stop doubles **H** (as Aperture opens more)
  * Lowering by 2/f stops doubles depth of field (DoF).



Recap: Exposure

- Exposure (H) = Irradiance (E) X Time (T)
- Exposure Time (T): Controlled by Shutter Speed
  - Doubling T doubles H
  - Doubling T doubles Motion Blur
- ISO: Doubling ISO needs half the light



Summary

- Presented how a camera operates
- Brought together the concepts Aperture Opening, Shutter Speed and Film Sensitivity (ISO) for optimizing Photographic Exposure
- Discussed the Exposure Triangle and how it combines various aspects of photography

Next Class

Cameras: Sensors

Credits

- For more information, see
  - Hecht, E. (2002), Optics, 4th ed. Reading, MA: Addison-Wesley and
  - London, B., Stone, J., & Upton, J. (2011), Photography, 10th ed. Upper Saddle River, NJ: Prentice Hall.
- Some images retrieved from
  - http://commons.wikimedia.org/.
  - List will be available on website.
- Some Slides adapted from Mark Levoy.

Computational Photography

* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.

Georgia Tech College of Computing

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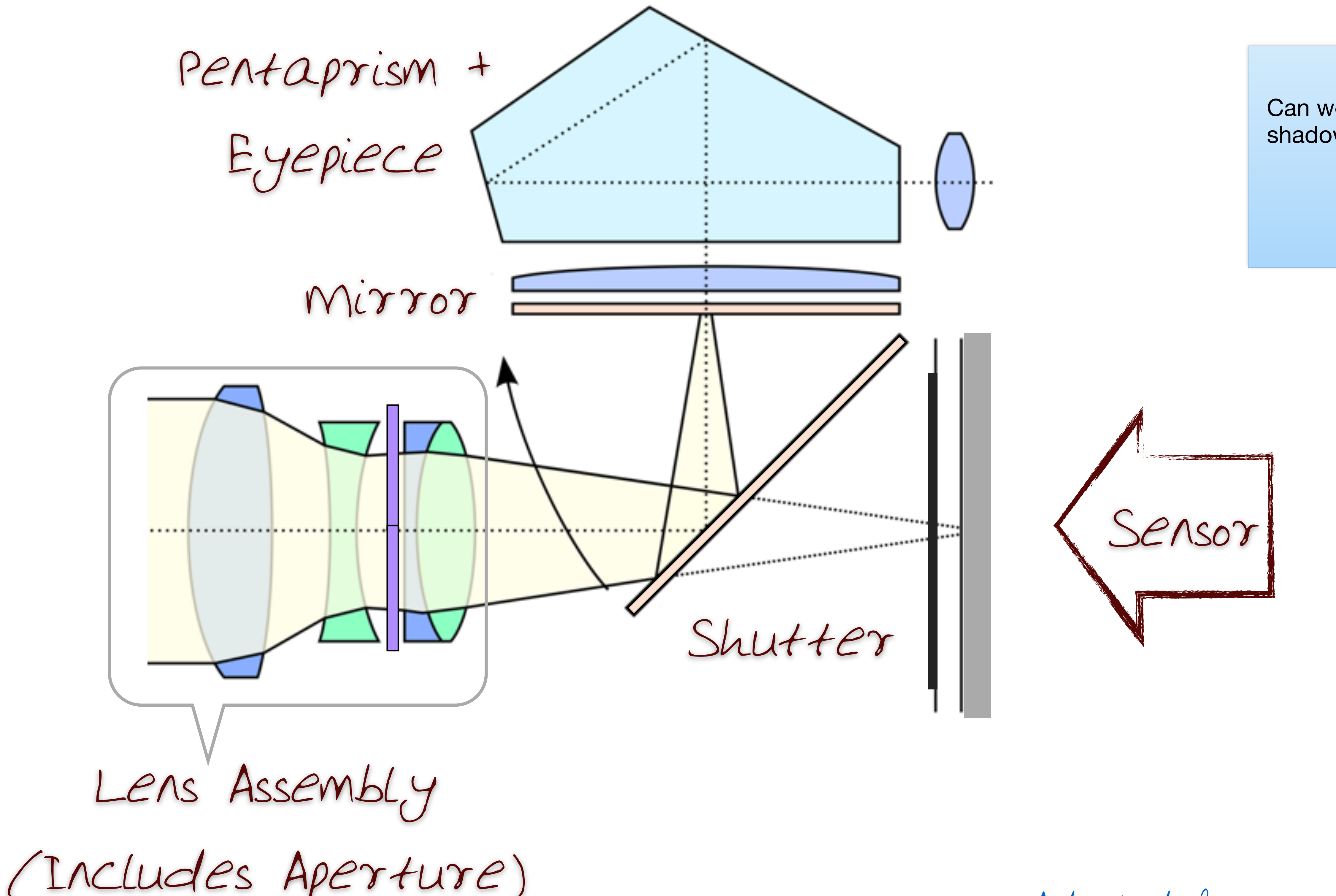
Cameras, Optics, Lenses, and Sensors

* Cameras: Sensors (and Film), where Rays of Light become Pixels

Georgia Tech College of Computing

1. Photographic Processes for Digital and Film Capture
2. Eight layers of Color Film
3. Five layers of a CCD
4. Differences between a CCD and CMOS Sensor
5. Two benefits of using the Camera Raw Format

Recall: Inside a Camera (an SLR)



Can we please remove the drop shadow on the text?

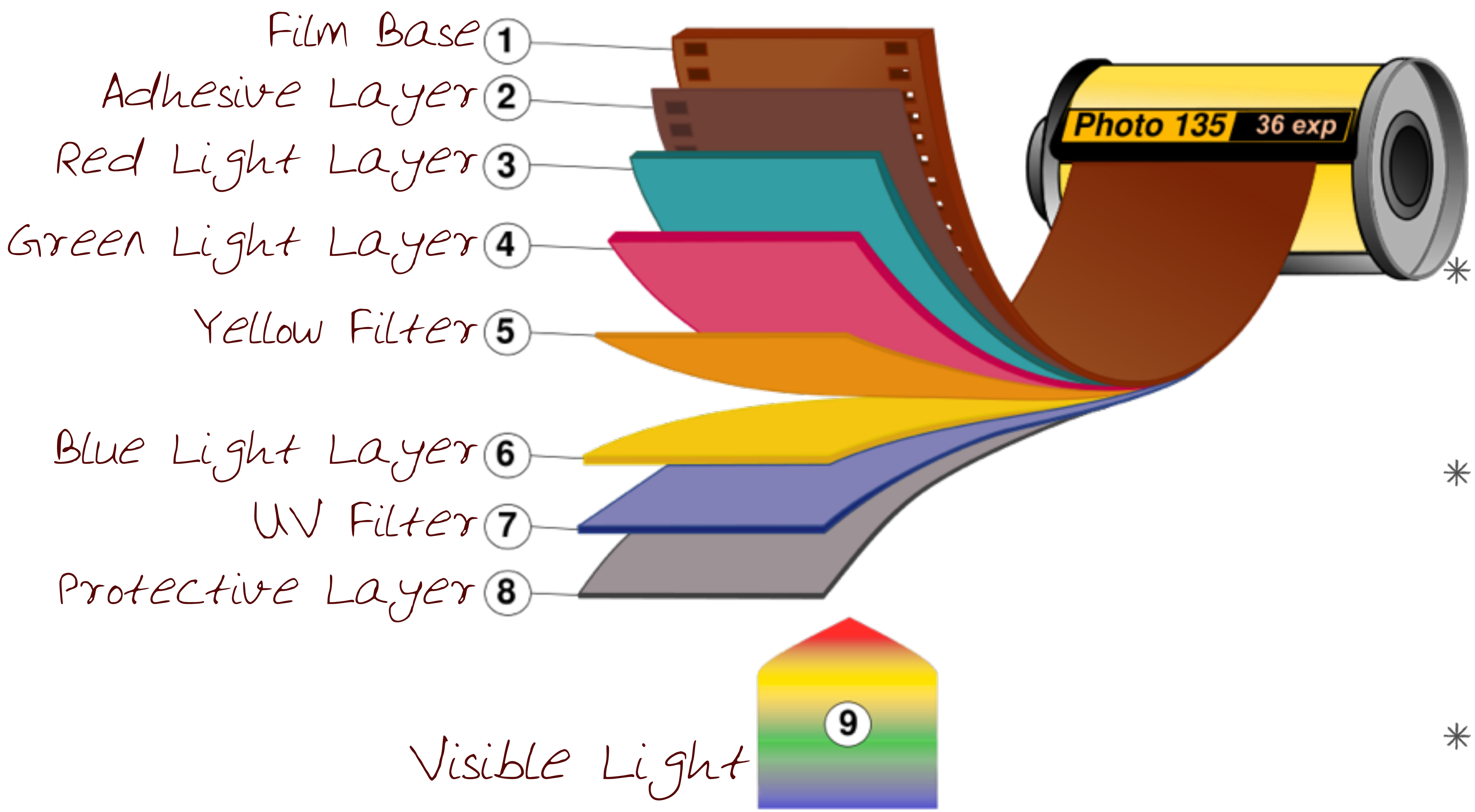
Adapted from commons.wikimedia.org/

Film vs. Digital

* Film and Digital Cameras are the same
  * There have been significant improvements in actuators, and lenses
* Difference is how light is **trapped and preserved**
* Chemical process for Film, and Electronic for Digital **capture the moment** in Time and Space

commons.wikimedia.org

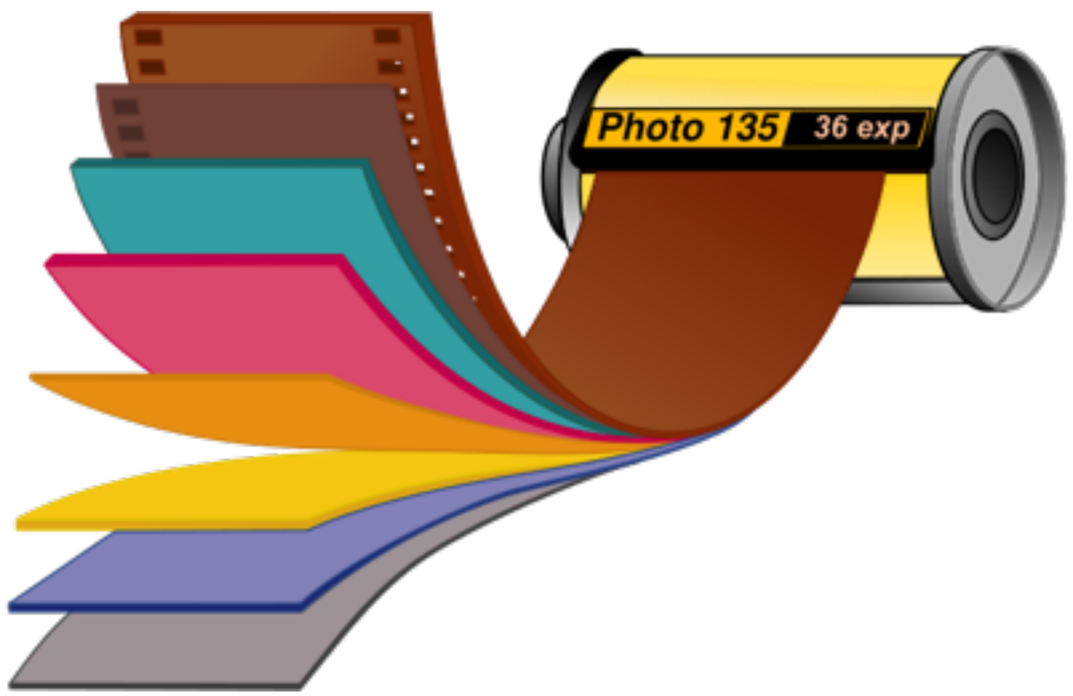
Film: Reaction between Light and Chemicals

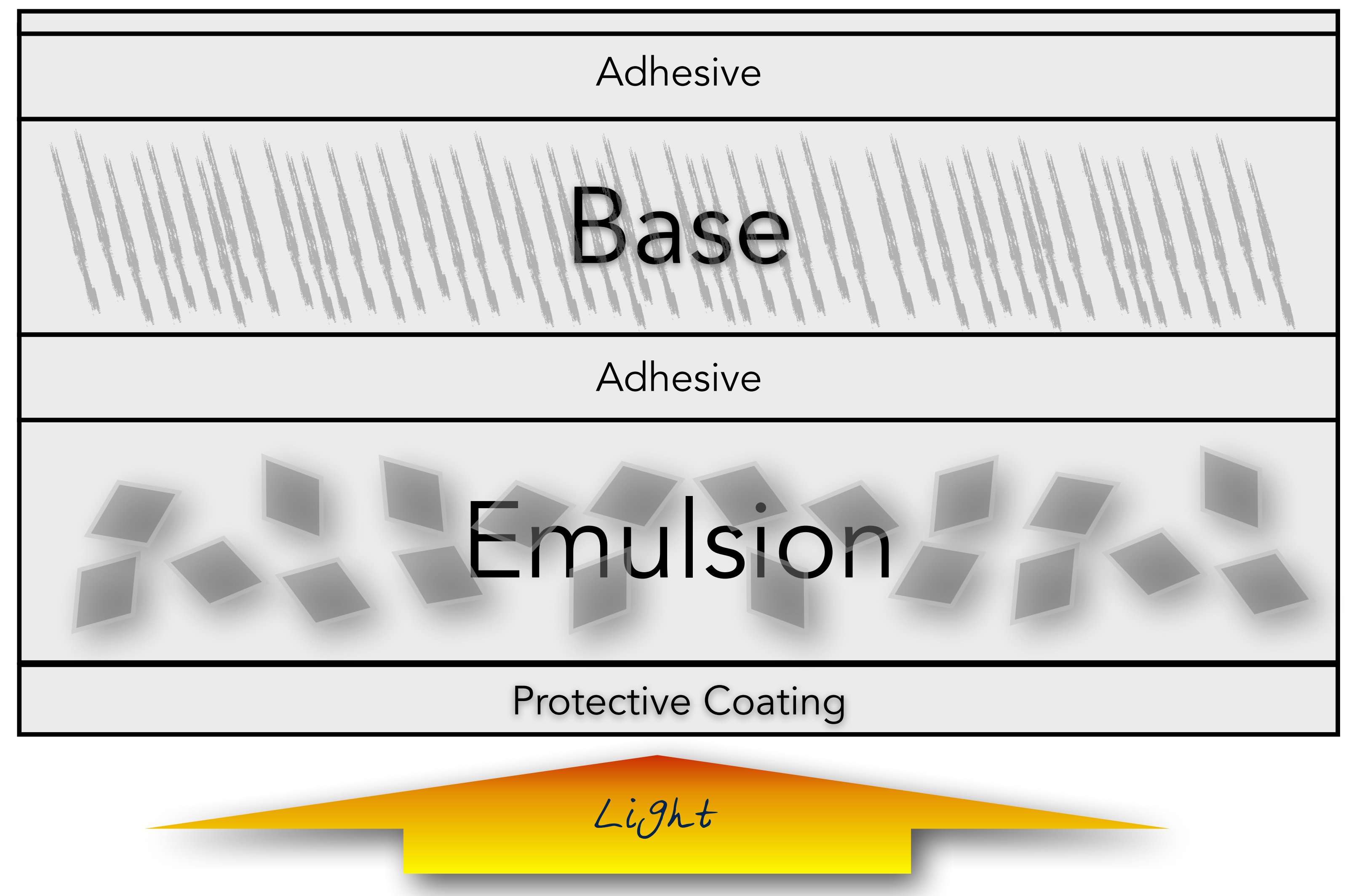


- A sheet of plastic (polyester, PET, nitrocellulose or cellulose acetate)
- Coated with an emulsion containing light-sensitive silver halide salts (bonded by gelatin)
- With variable crystal sizes that determine the sensitivity, contrast and resolution of the film.

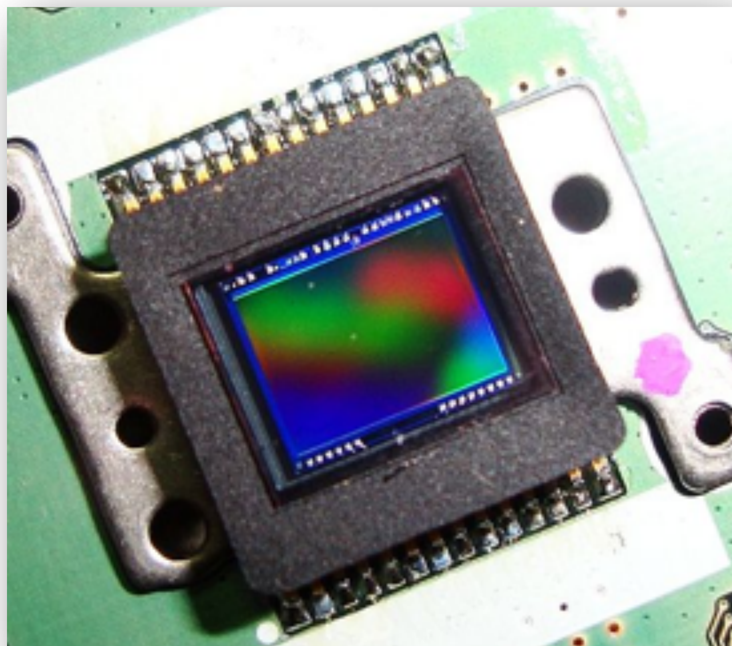
wikipedia.org/wiki/Photographic_film

Film: Reaction Between Light and Chemicals





Digital: Converting Light to Data

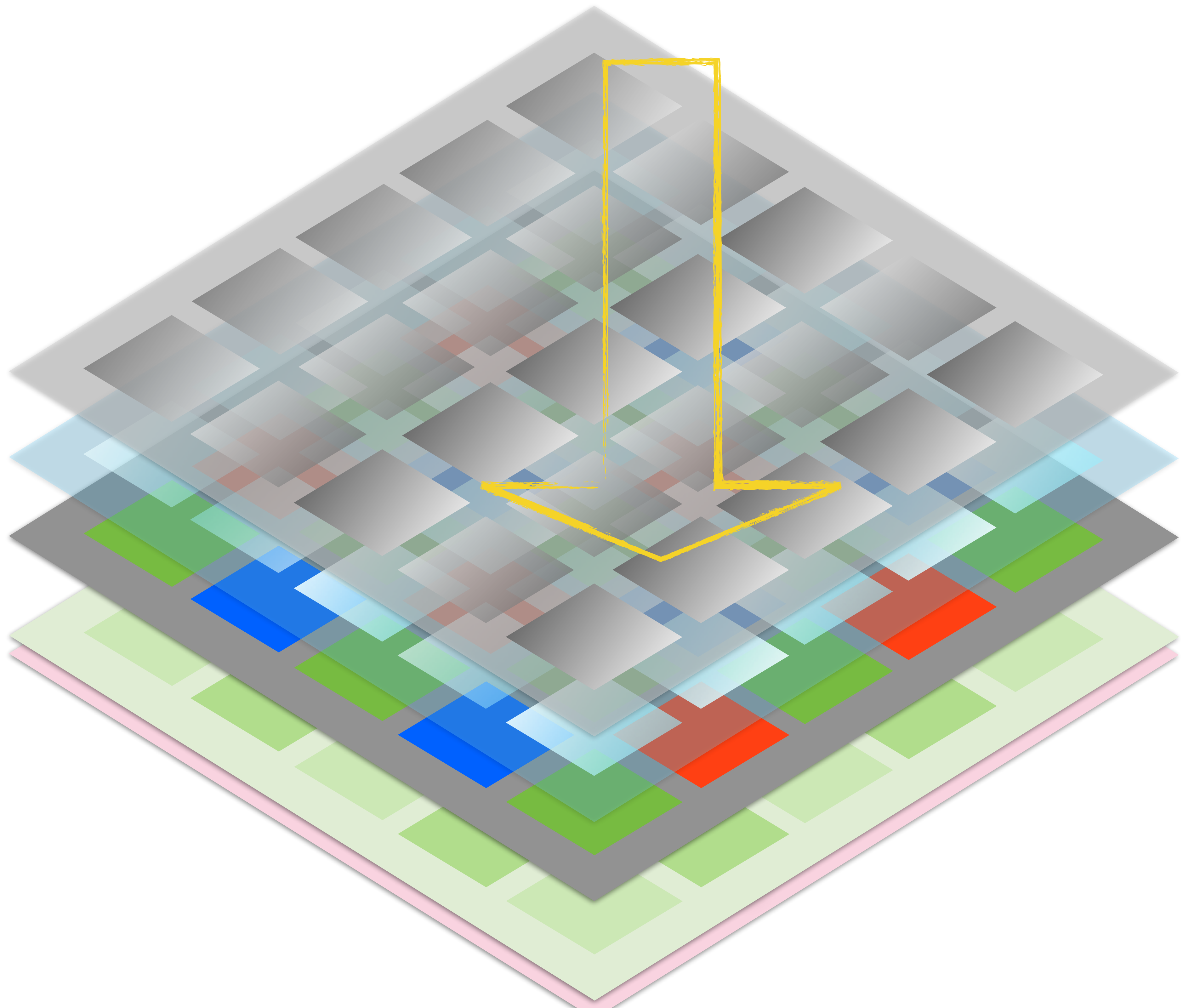


Smith and Boyle

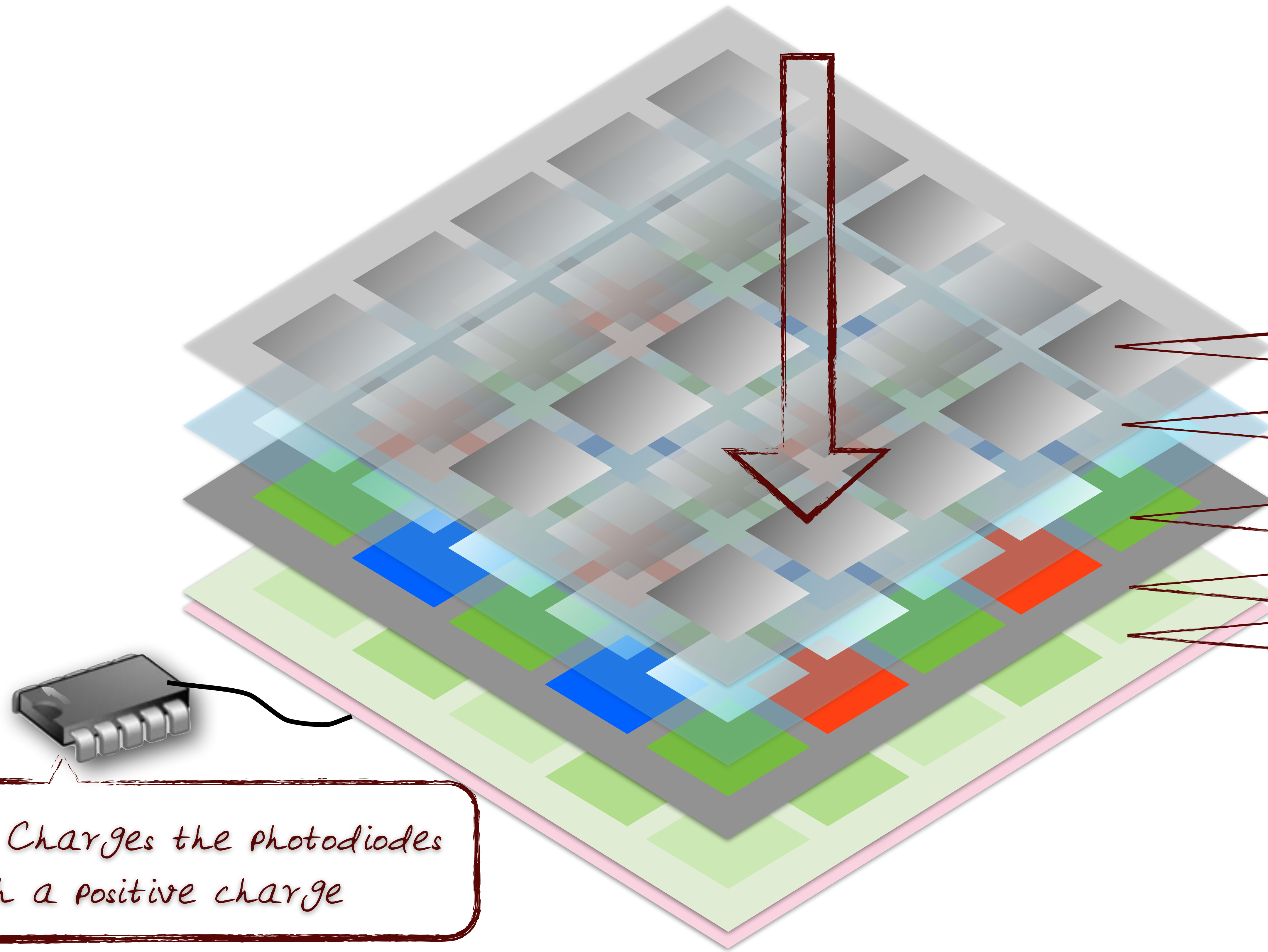
* CCD: Charge-Coupled Device, a device for converting electrical charge, into a digital value
* Pixels are represented by capacitors, which convert and store incoming photons as electron charges
* Willard Boyle and George E. Smith, 1969 (Won a Noble Prize in Physics in 2009).

commons.wikimedia.org

Digital: Converting Light to Data

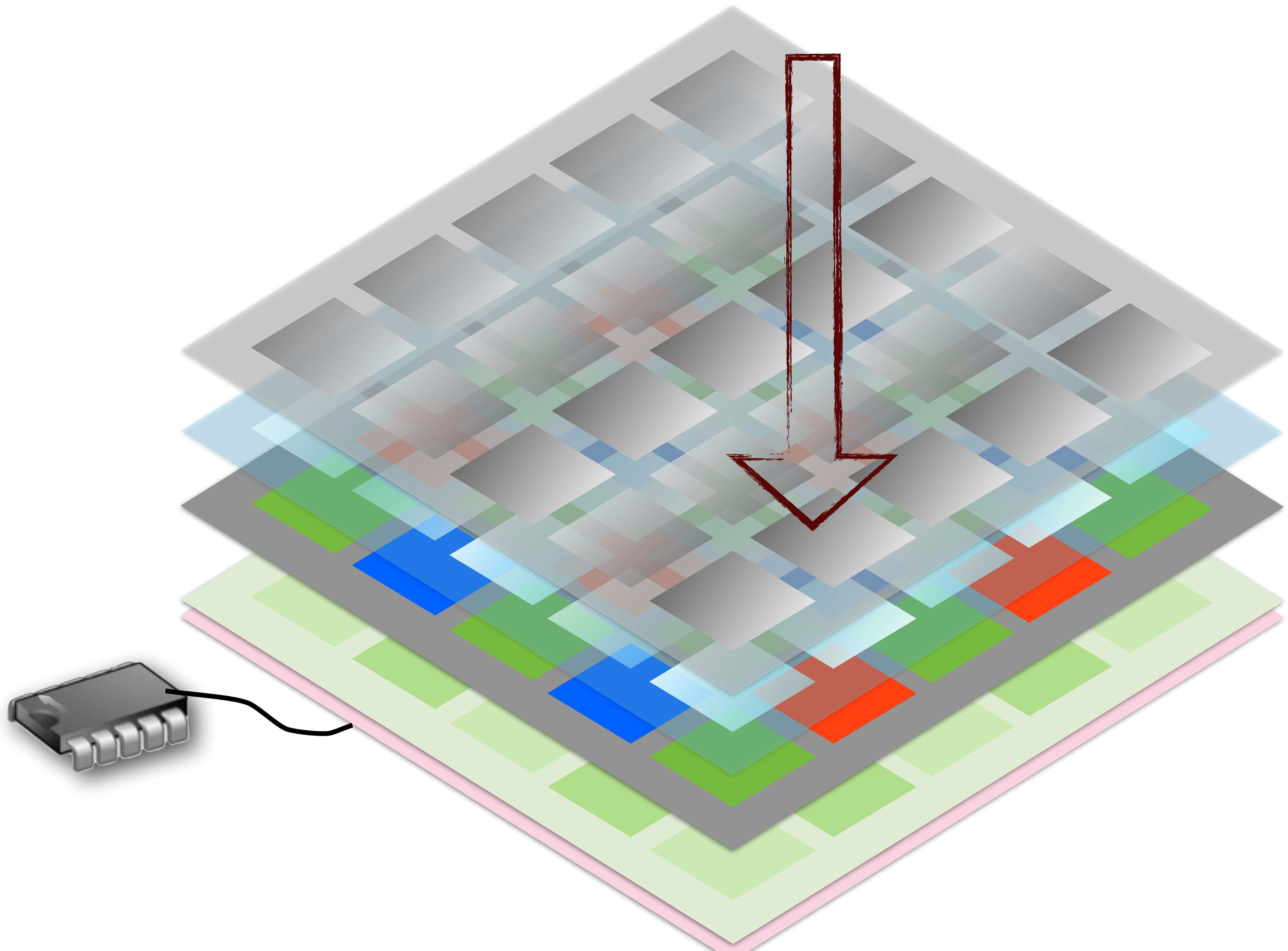


Digital: Converting Light to Data



Processor. Charges the photodiodes with a positive charge

Digital: Converting Light to Data



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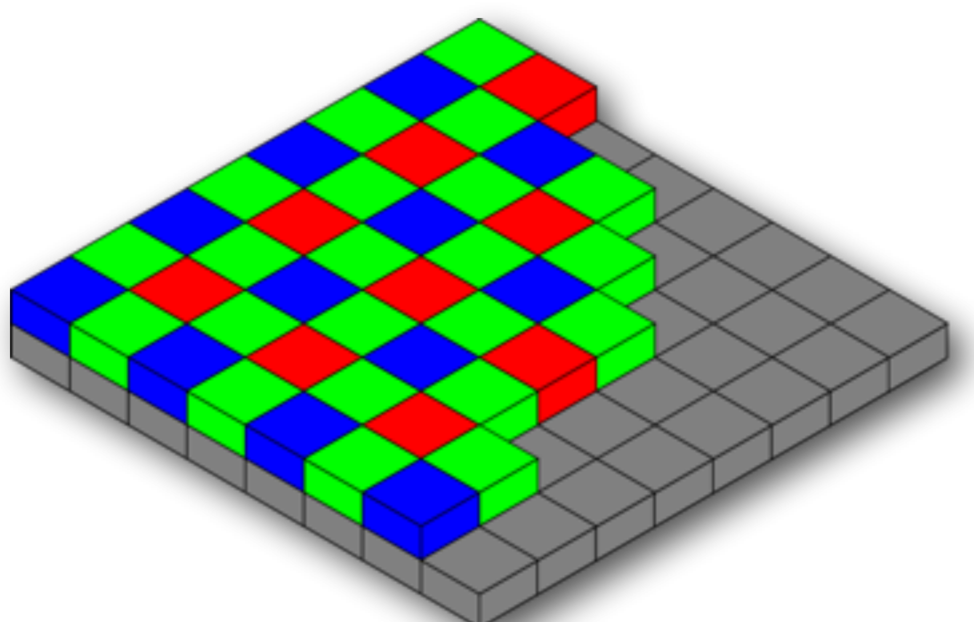
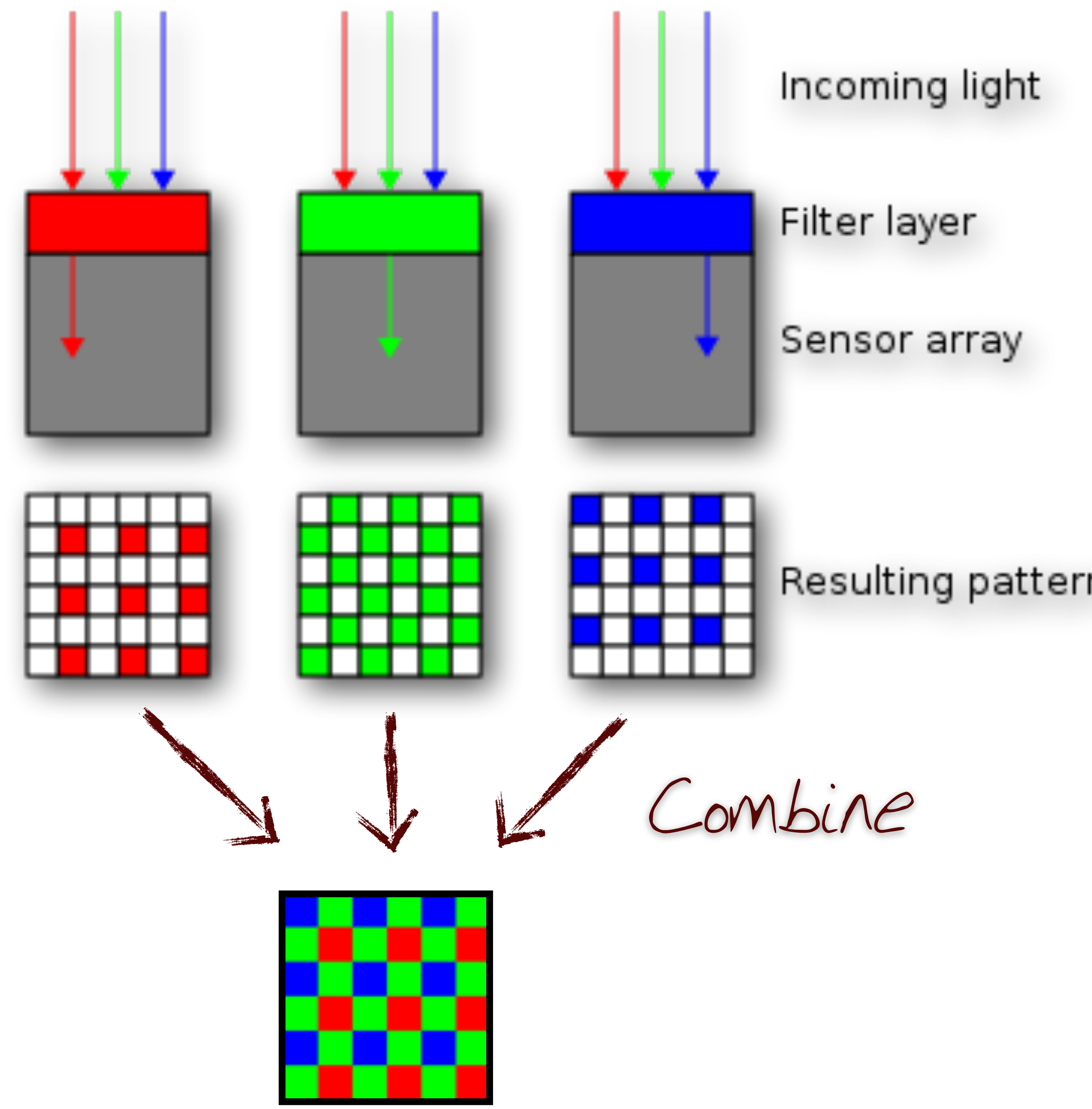
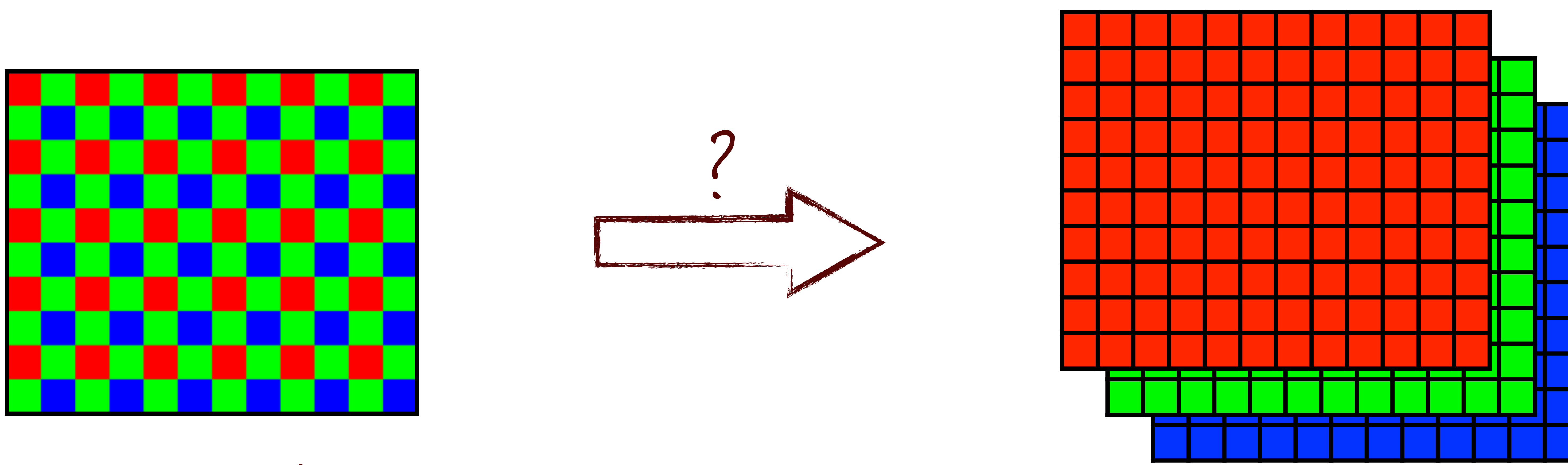


Bayer filter on a sensor



Images: Wikipedia

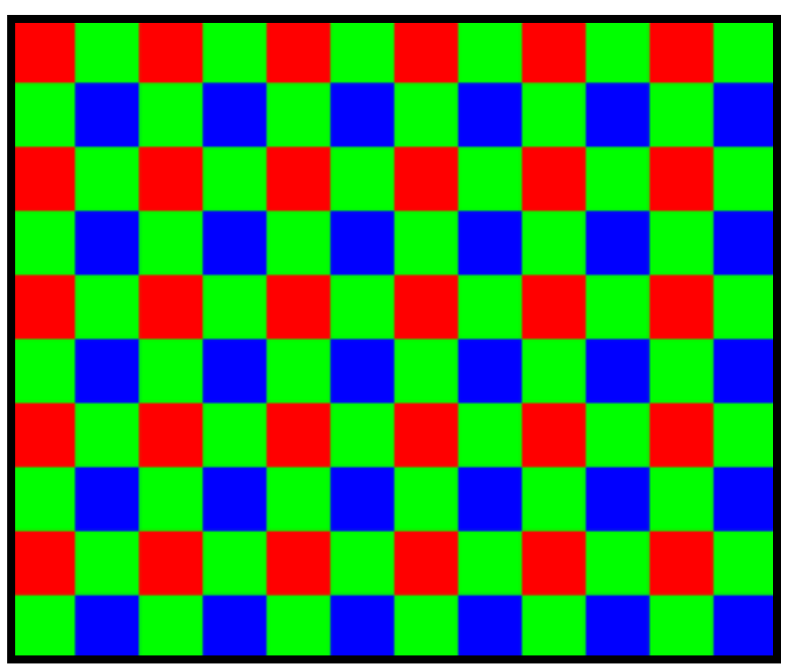
Digital: Converting Light to Data



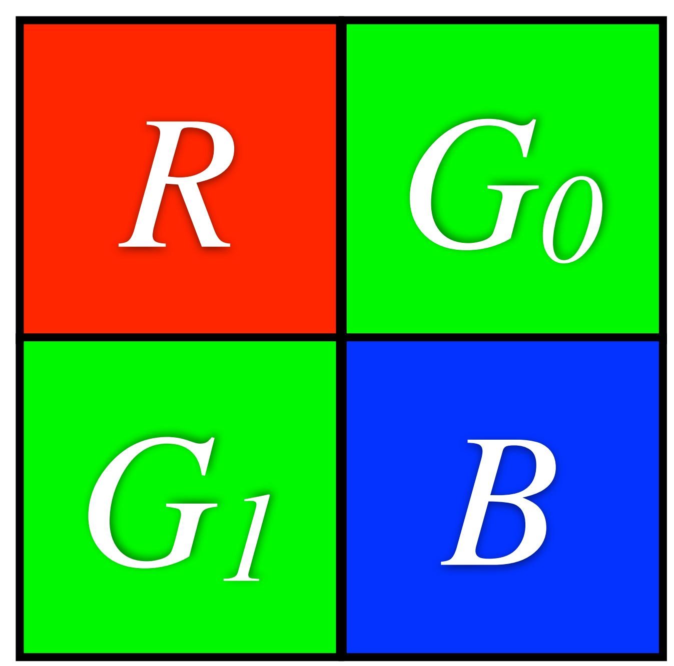
Raw input in Bayer mosaic format

RGB color planes

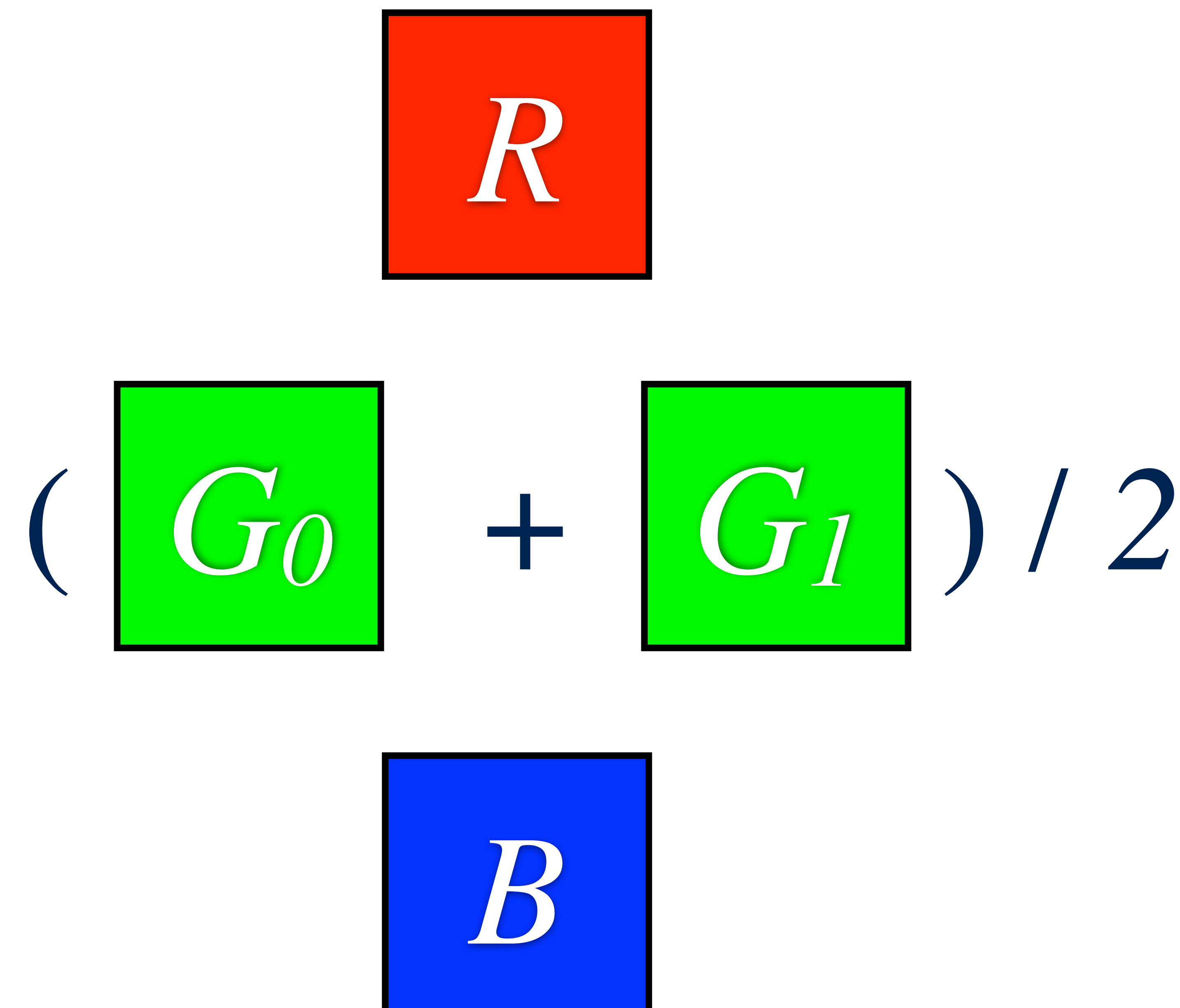
Bayer to RGB "Demosaicing"



Raw input in Bayer mosaic format

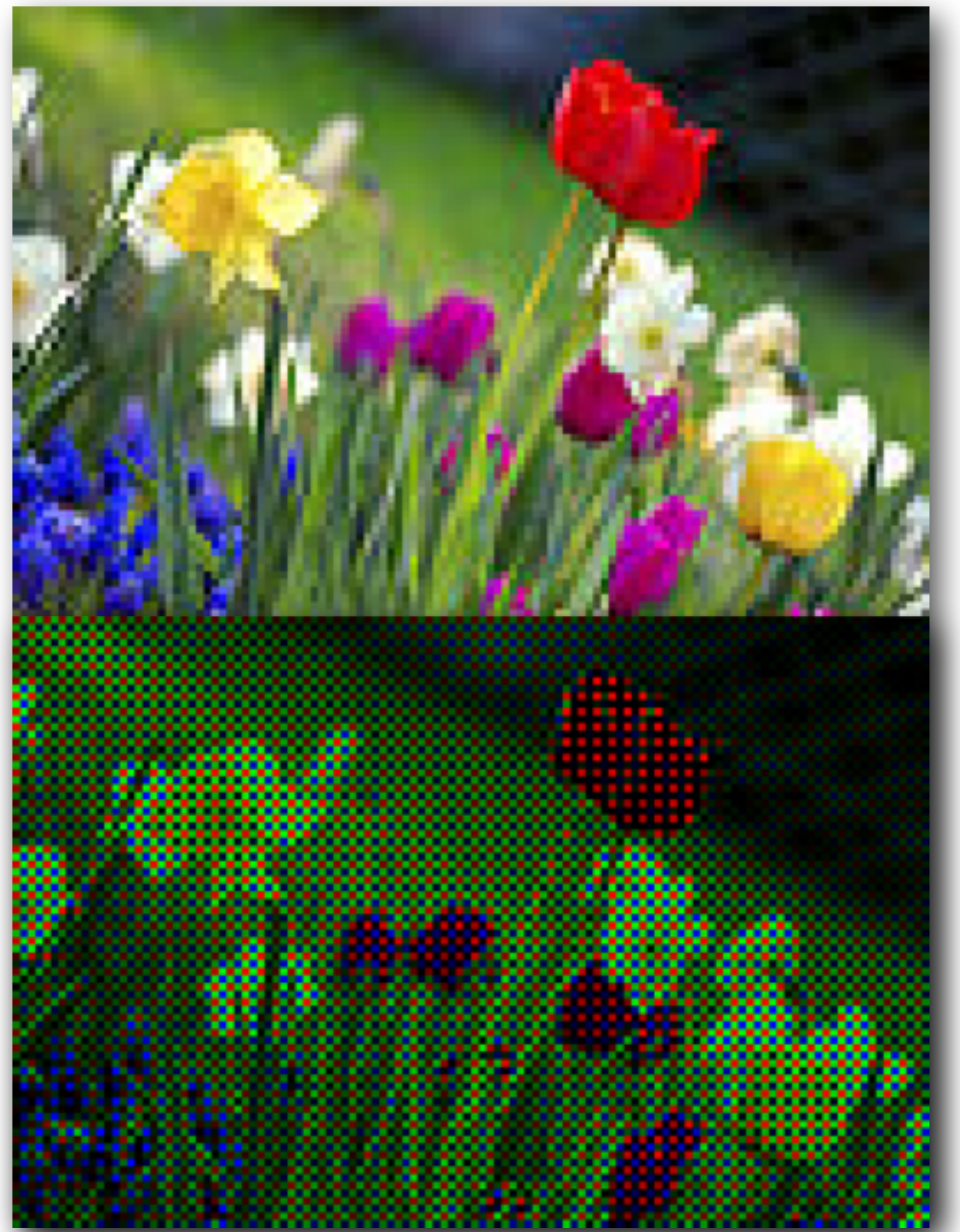


A 4x4 subset



Resulting RGB triple

Digital: Converting Light to Data

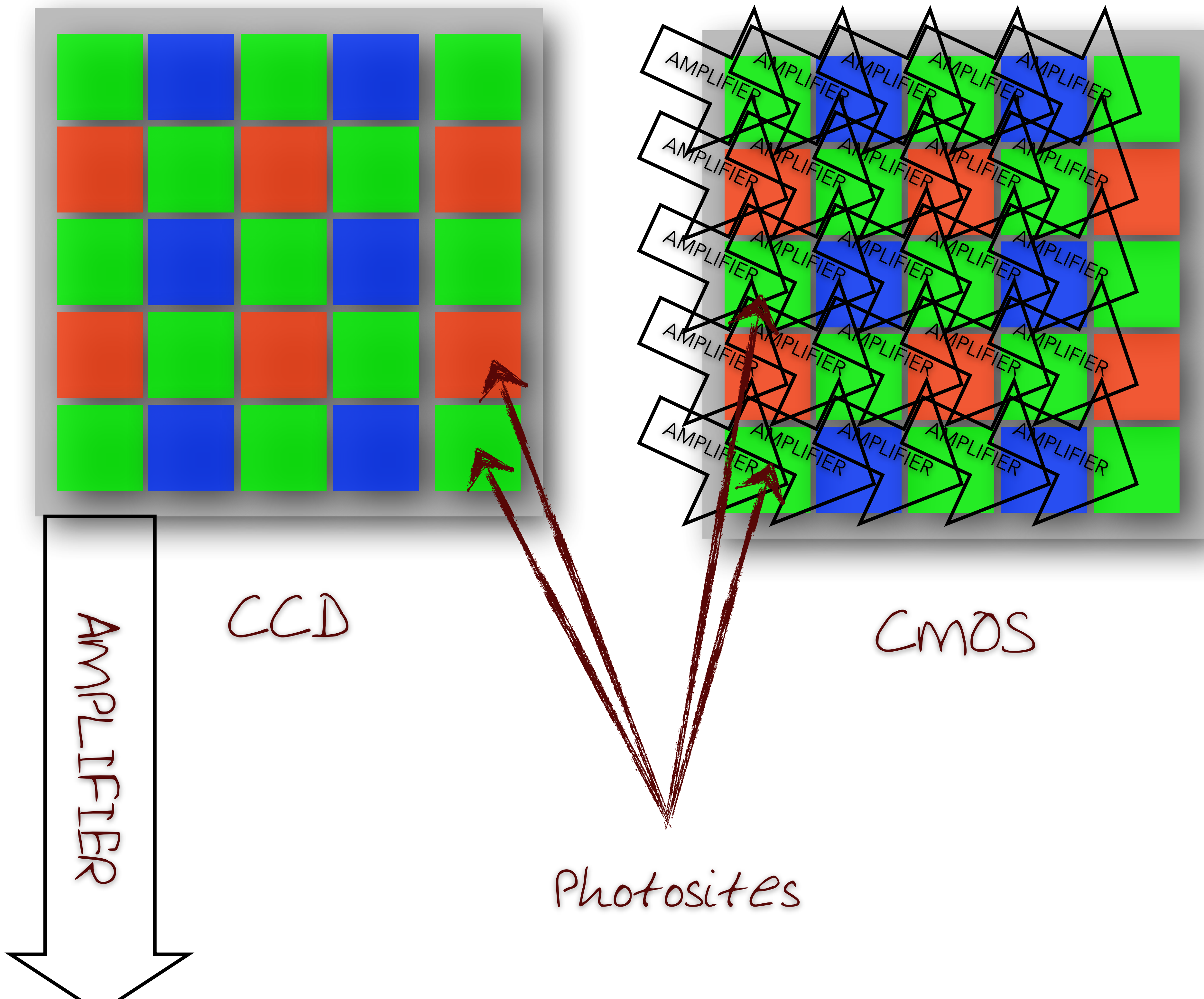


Reconstructed Image after Interpolation

Actual Sensor Information with Bayer Filter

Images: Wikipedia

CCD vs. CMOS Sensors



* CMOS: Complementary Metal Oxide Semiconductor
* Photosites in CCD are passive and do no "work"
* Photosites in CMOS are amplifiers and can do local processing

Camera RAW File Format

* Contains minimally processed data from the sensor
* Image encoded in a device-dependent colorspace
* Captures radiometric characteristics of the scene
* Viewable image from the camera's sensor data
* Like a photographic negative
    * has a wider dynamic range or color; preserves most of the information of the captured image

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- Viewable image from the camera's sensor data
- Like a photographic negative
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Summary

* Described the Photographic Processes for Digital and Film Capture
* Presented how sensors work in Cameras
* Discussed how a Color filter works in a sensor
* Presented CCD and CMOS sensors
* Discussed the benefits of the Camera Raw Format

Next Class

- Doing Computational Photography
  - Blending/Fading
  - Panoramas
  - High-Dynamic Range Imaging

Credits

* For more information, see
  * Hecht, E. (2002). Optics, 4th ed. Reading, MA: Addison-Wesley,
  * London, B., Stone, J., & Upton, J. (2011), Photography, 10th ed. Upper Saddle River, NJ: Prentice Hall, and
  * White, R. (2006), How DIgital Photography Works, Que Publishers
* Some images retrieved from
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