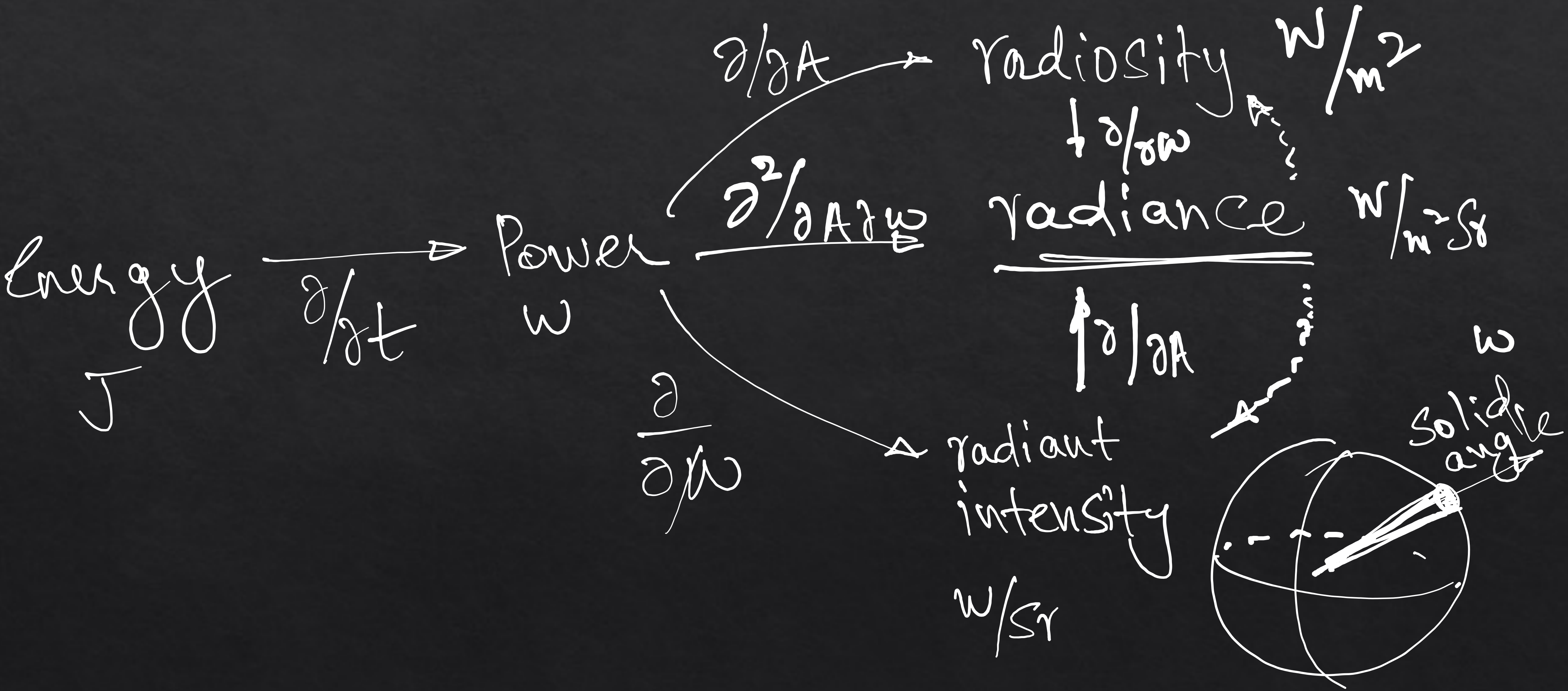
Computer Graphics

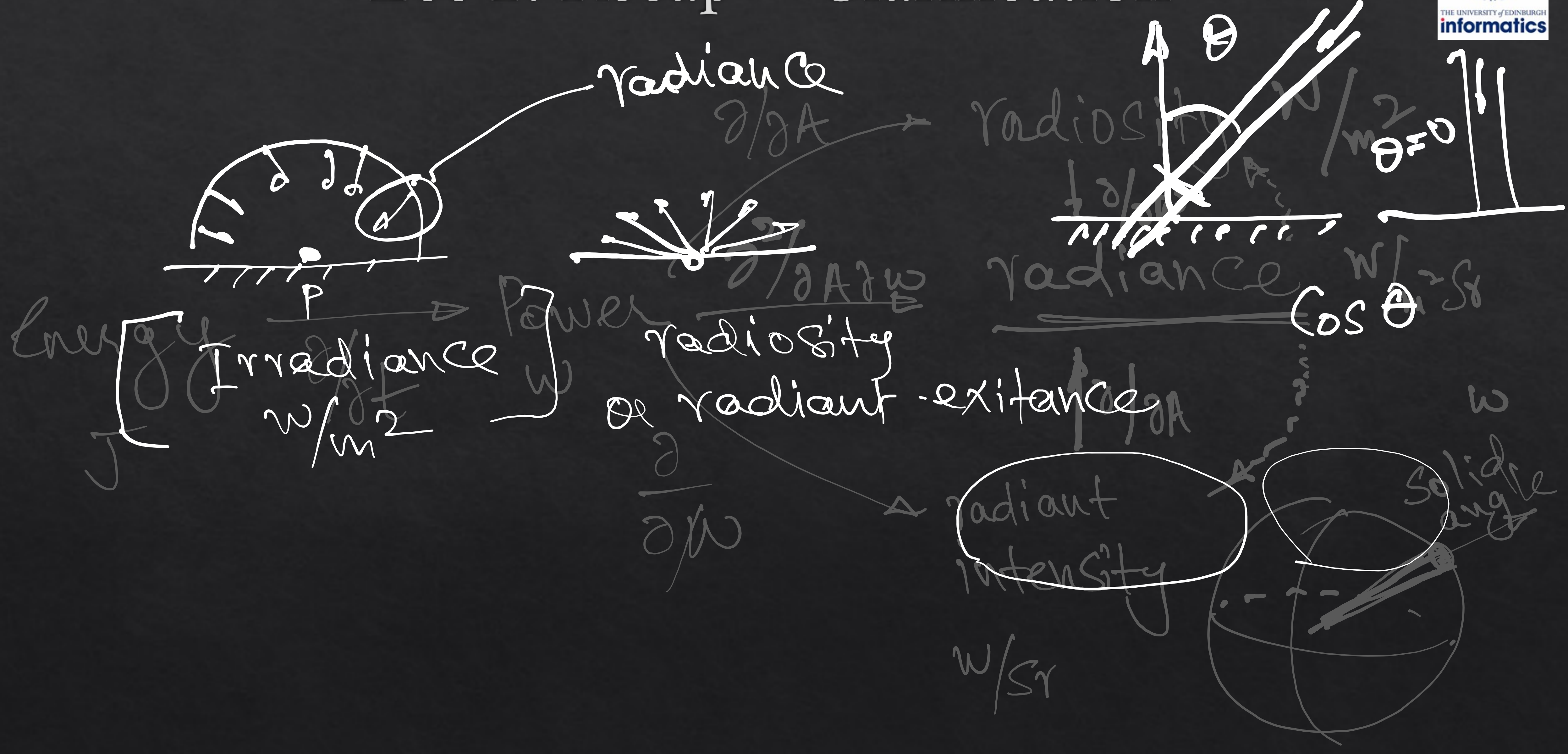
Lecture 3: Cameras

Kartic Subr

Lec 2: Recap + Clarification



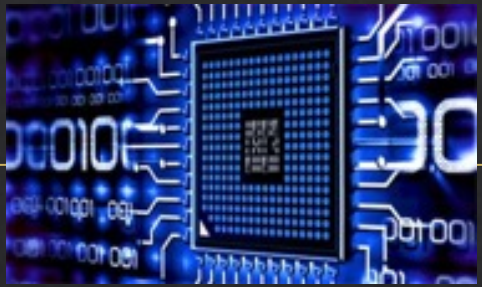
Lec 2: Recap + Clarification



photography

rendering

Virtual



Cameras

iPhone 16 Pro Max

48MP Fusion: 24mm, ƒ/1.78 aperture, second-generation sensor-shift optical image stabilisation, 100% Focus Pixels, support for super-high-resolution photos (24MP and 48MP)

Also enables 12MP 2x Telephoto: 48mm, ƒ/1.78 aperture, second-generation sensor-shift optical image stabilisation, 100% Focus Pixels

48MP Ultra Wide: 13mm, ƒ/2.2 aperture and 120° field of view, Hybrid Focus Pixels, super-high-resolution photos (48MP)

12MP 5x Telephoto: 120mm, ƒ/2.8 aperture and 20° field of view, 100% Focus Pixels, seven-element lens, 3D sensor-shift optical image stabilisation and autofocus, tetraprism design

5x optical zoom in, 2x optical zoom out; 10x optical zoom range

Digital zoom up to 25x

48MP macro photography

Apple ProRAW

Wide colour capture for photos and Live Photos

Lens correction (Ultra Wide)

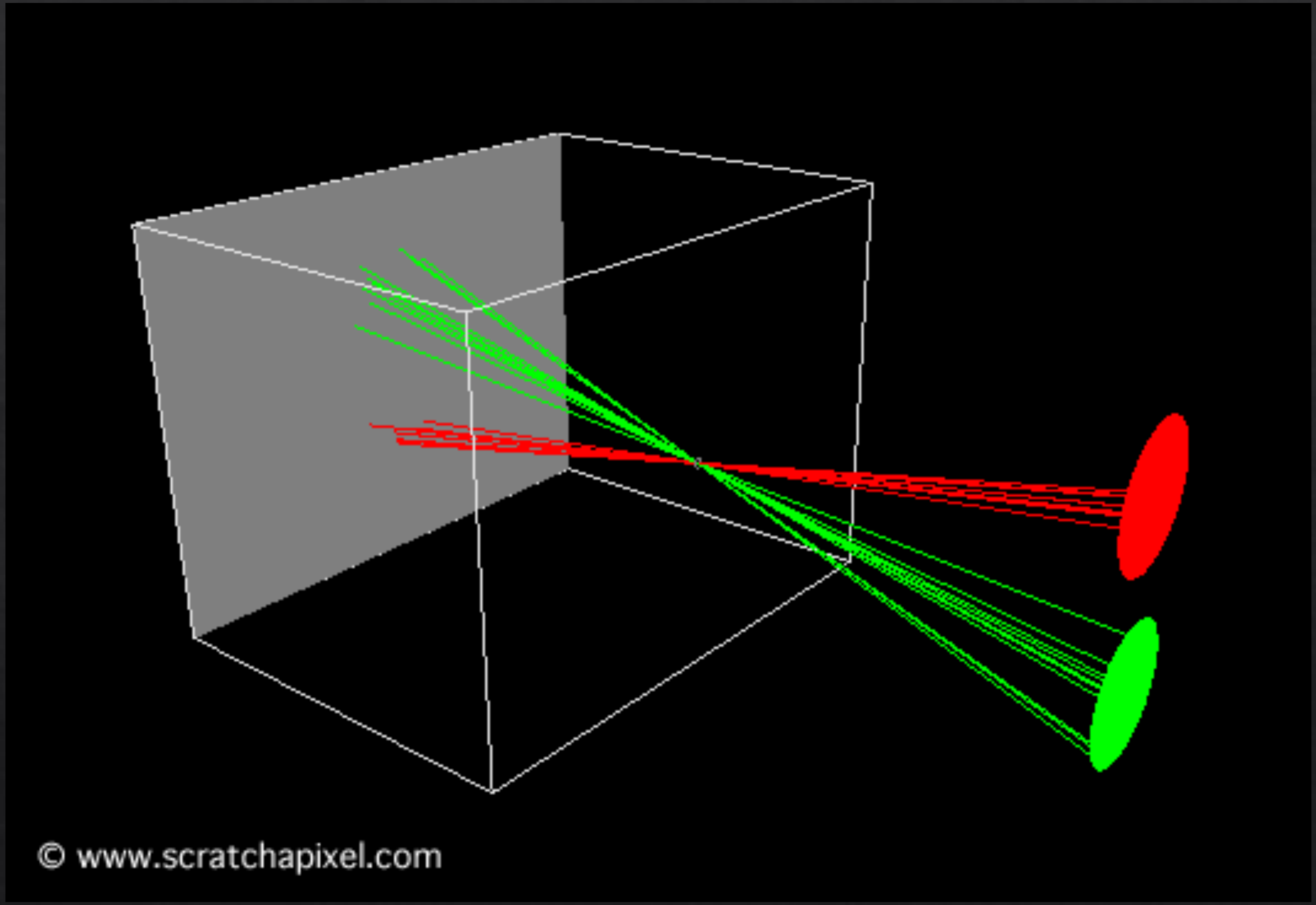
Advanced red-eye correction

Auto image stabilisation

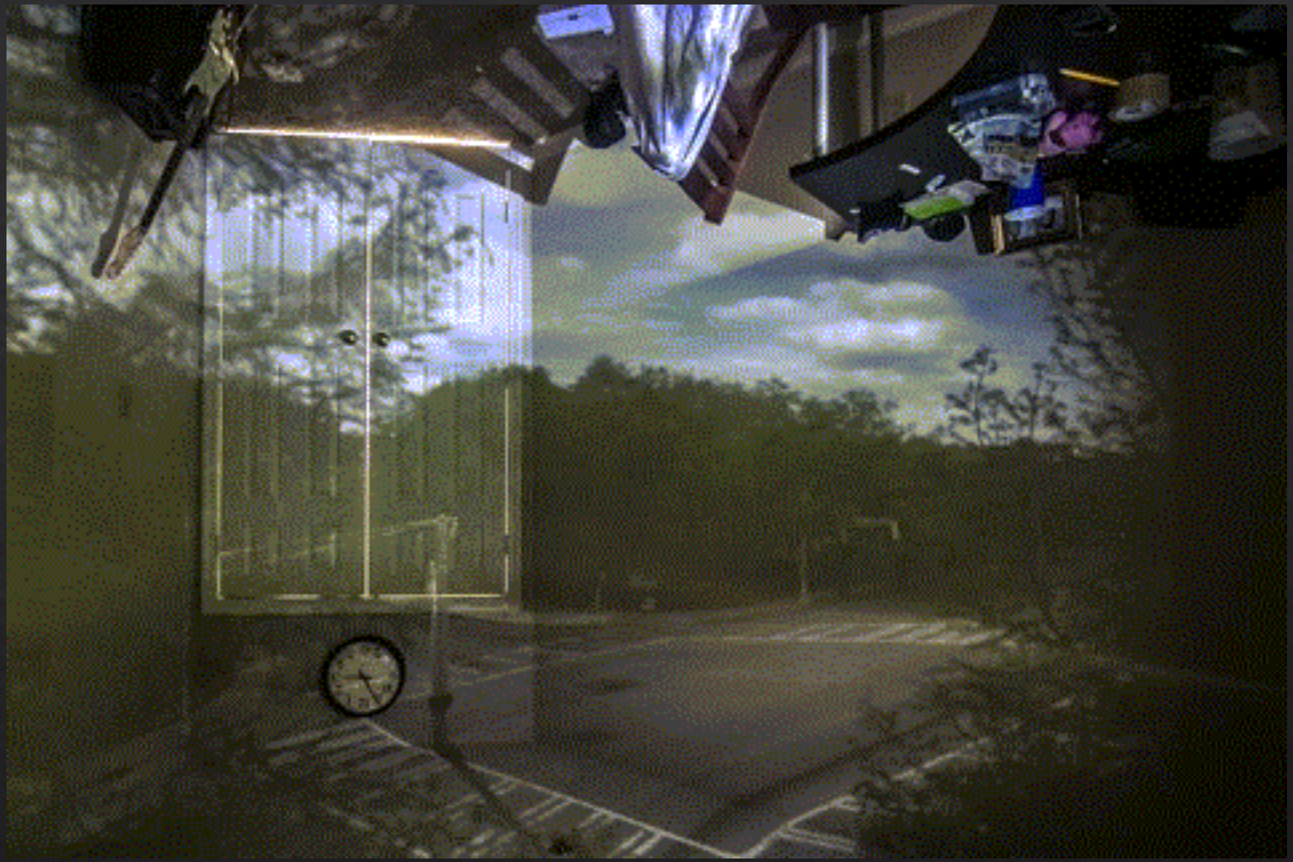
The pinhole camera

Pinhole camera

Ibn al-Haytham (965-1040 AD)



Camera Obscura

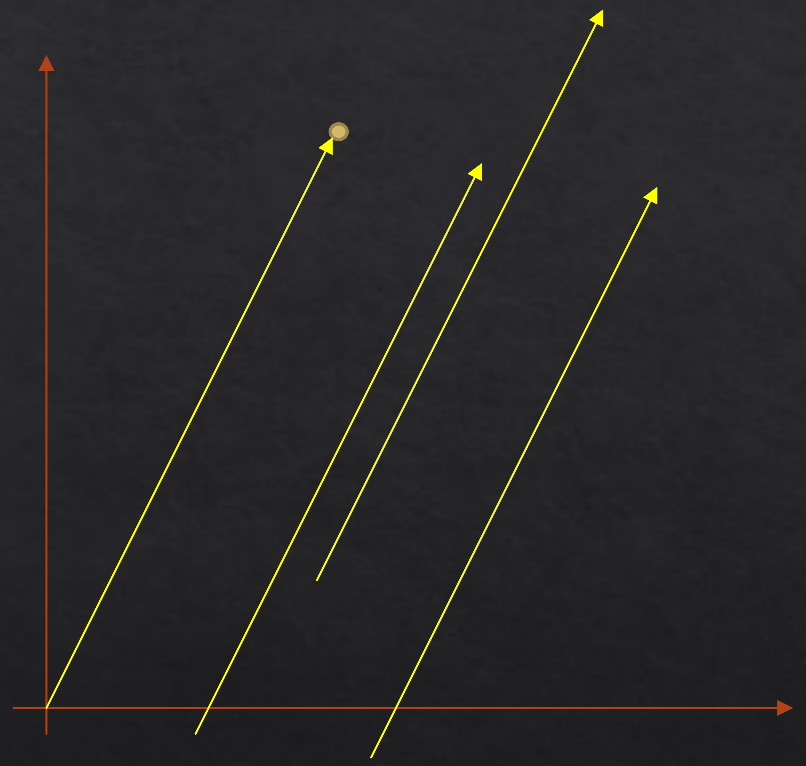


The making of …

Projection

What is a vector? e.g. 2D

$$\begin{bmatrix} u \\ v \end{bmatrix}$$



What is a matrix? e.g. 2x2

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

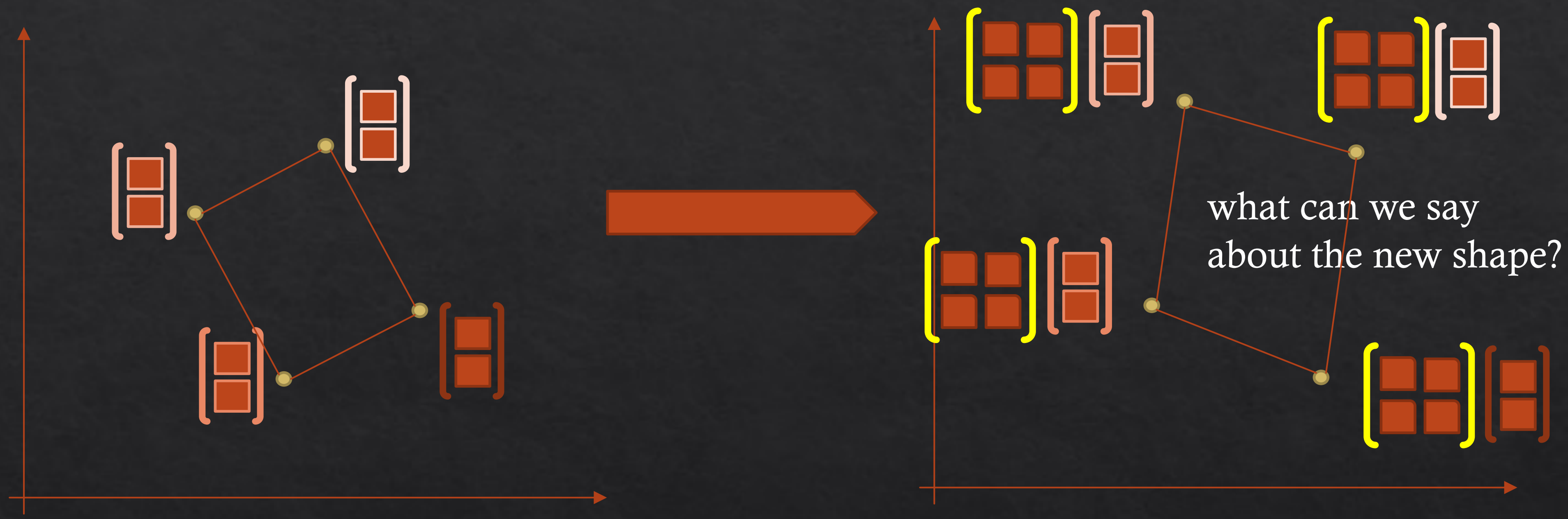
Can we 'operate on' a vector?

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} au + bv \\ cu + dv \end{pmatrix}$$

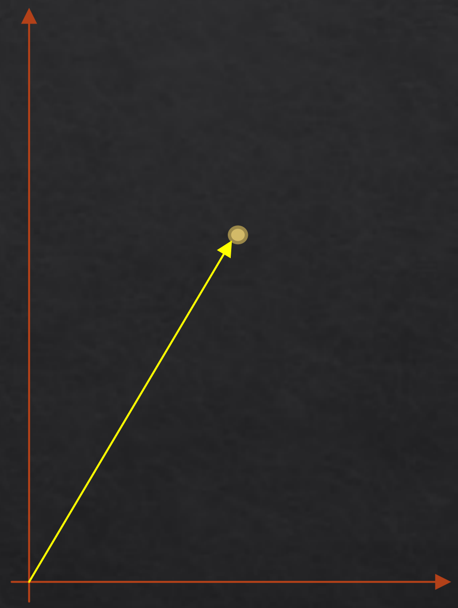
Can we ‘operate on’ a vector?

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} au + bv \\ cu + dv \end{pmatrix}$$

What operations can it achieve?



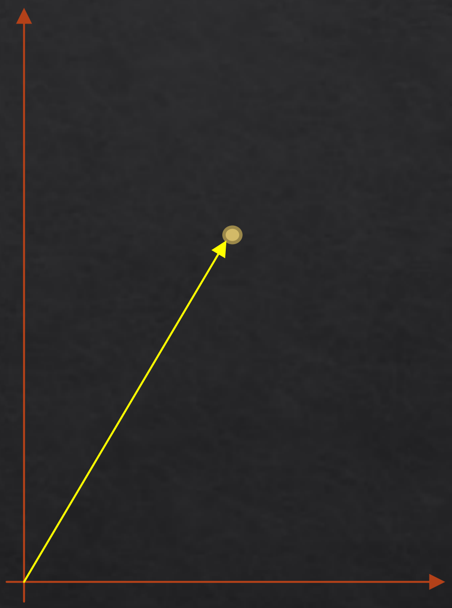
What operation achieves translation?



$$\begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} c_x \\ 0 \end{bmatrix}$$

Can we achieve this with a matrix?

Can we achieve this with a matrix?



Ans: Not with a 2x2 matrix

What if we add a dimension?

$$\begin{pmatrix} a & b & c \\ d & e & f \\ g & h & i \end{pmatrix} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix}$$

matrix
is 3x3

still 2D
vectors

Now, translation is possible as an operation

$$\begin{pmatrix} 1 & 0 & c_x \\ 0 & 1 & c_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} u + c_x \\ v + c_y \\ 1 \end{pmatrix}$$

Homogeneous coordinates are useful!

$$\begin{bmatrix} u' \\ v' \\ s \end{bmatrix} \quad \text{equivalent to} \quad \begin{bmatrix} u'/s \\ v'/s \\ 1 \end{bmatrix}$$

point in 3D homogenous space

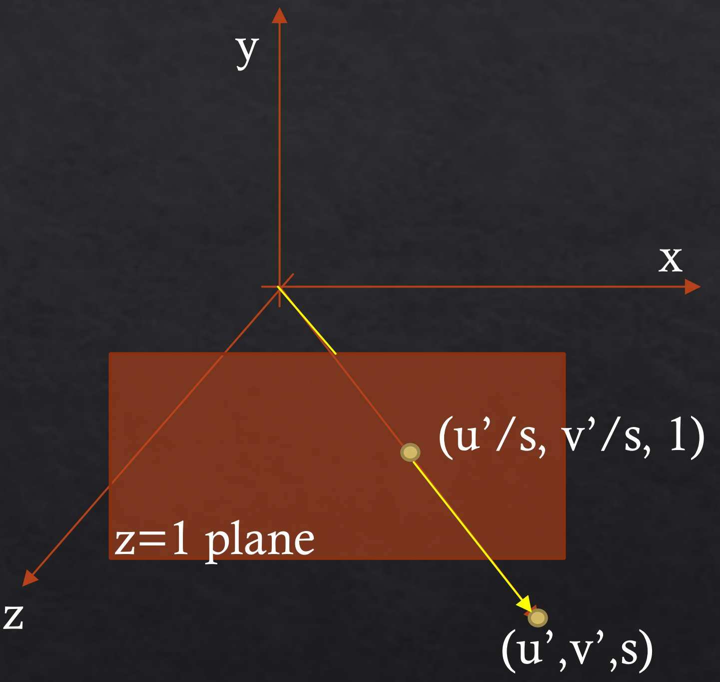
point in 2D space

Homogeneous coordinates are useful!

$$\begin{bmatrix} u' \\ v' \\ s \end{bmatrix} \quad \text{equivalent to} \quad \begin{bmatrix} u'/s \\ v'/s \\ 1 \end{bmatrix}$$

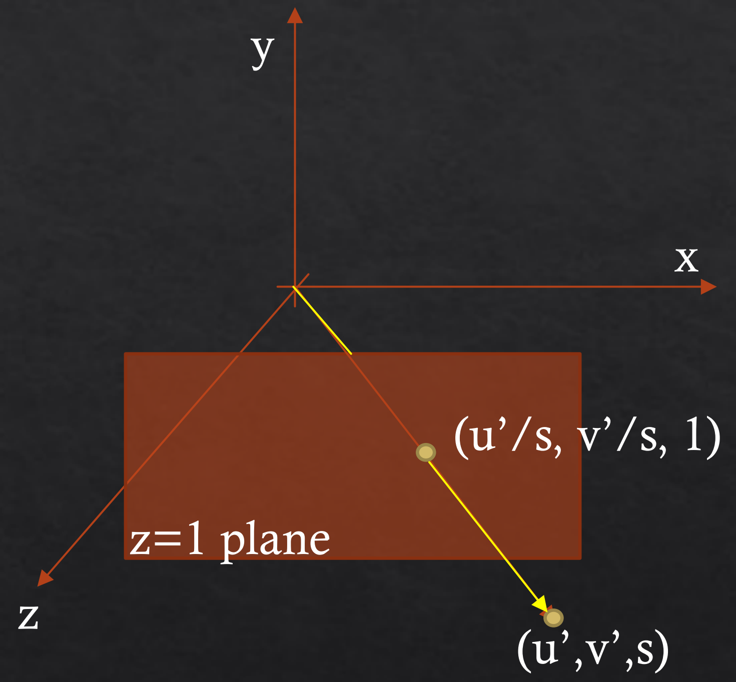
point in 3D homogenous space

point in 2D space



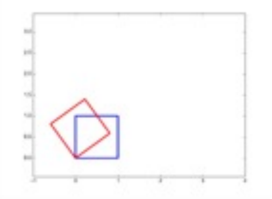
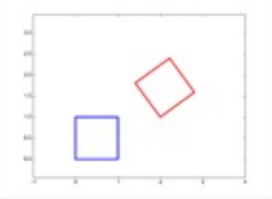
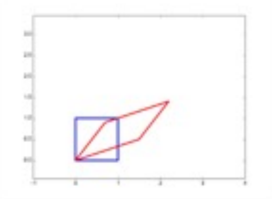
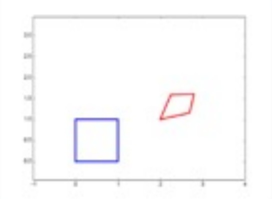
Homogeneous coordinates are useful!

$$\begin{bmatrix} u' \\ v' \\ s \end{bmatrix} \quad \text{equivalent to} \quad \begin{bmatrix} u'/s \\ v'/s \\ 1 \end{bmatrix}$$



$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} 2x \\ 2y \\ 2 \end{bmatrix} = \begin{bmatrix} 3x \\ 3y \\ 3 \end{bmatrix} = \begin{bmatrix} 4x \\ 4y \\ 4 \end{bmatrix} \ldots$$

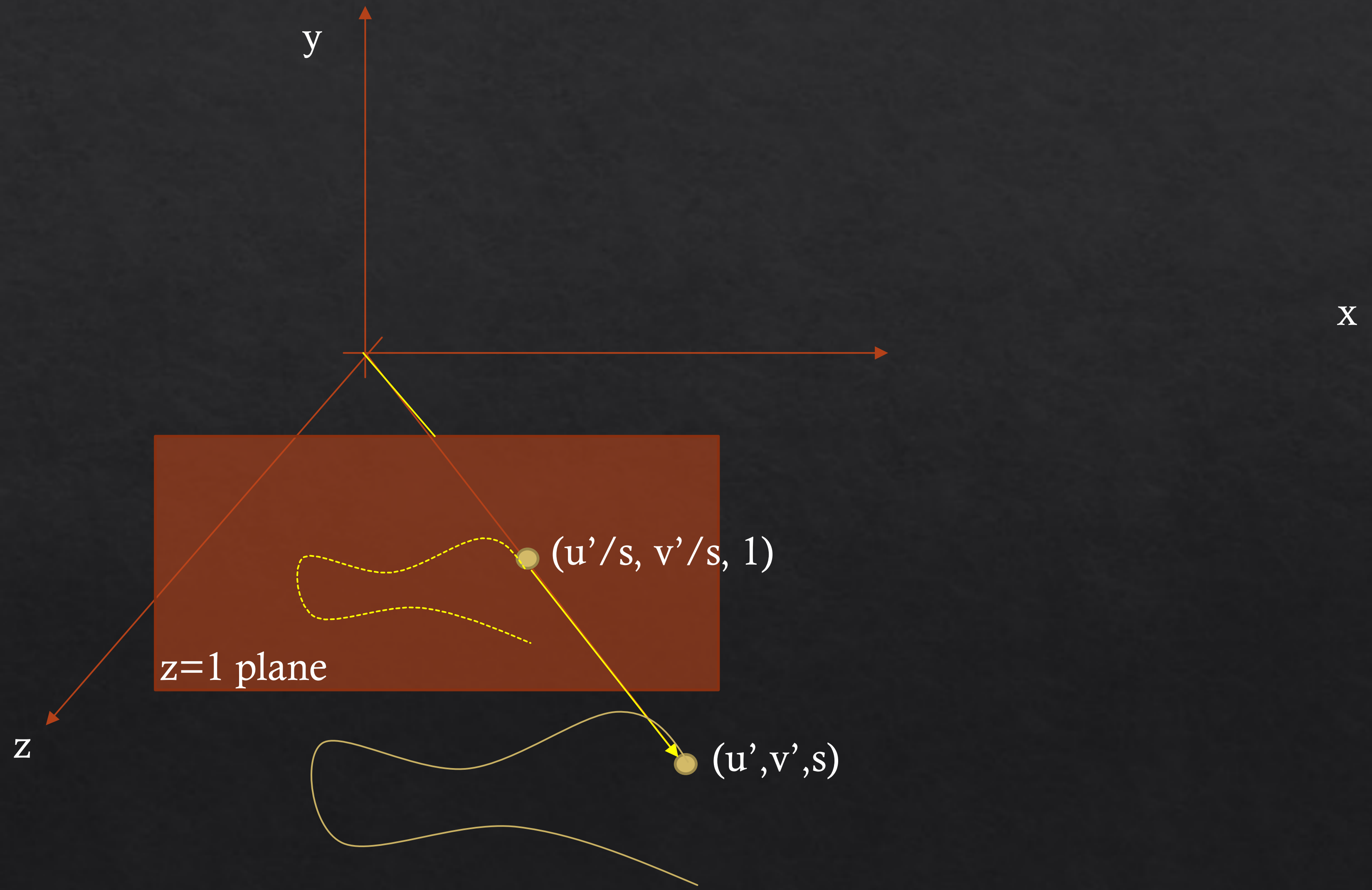
What operations are possible now?

	Translation	$\begin{pmatrix} 1 & 0 & t_1 \\ 0 & 1 & t_2 \\ 0 & 0 & 1 \end{pmatrix}$
	Rotation	$\begin{pmatrix} \cos(\phi) & -\sin(\phi) & 0 \\ \sin(\phi) & \cos(\phi) & 0 \\ 0 & 0 & 1 \end{pmatrix}$
	Rigid Body	$\begin{pmatrix} \cos(\phi) & -\sin(\phi) & t_x \\ \sin(\phi) & \cos(\phi) & t_y \\ 0 & 0 & 1 \end{pmatrix}$
	Affine	$\begin{pmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{pmatrix}$
	Projective Transform	$\begin{pmatrix} a & b & c \\ d & e & f \\ g & h & 1 \end{pmatrix}$

https://staff.fnwi.uva.nl/r.vandenboomgaard/IPCV20162017/LectureNotes/MATH/homogenous.html#sec-homogeneous

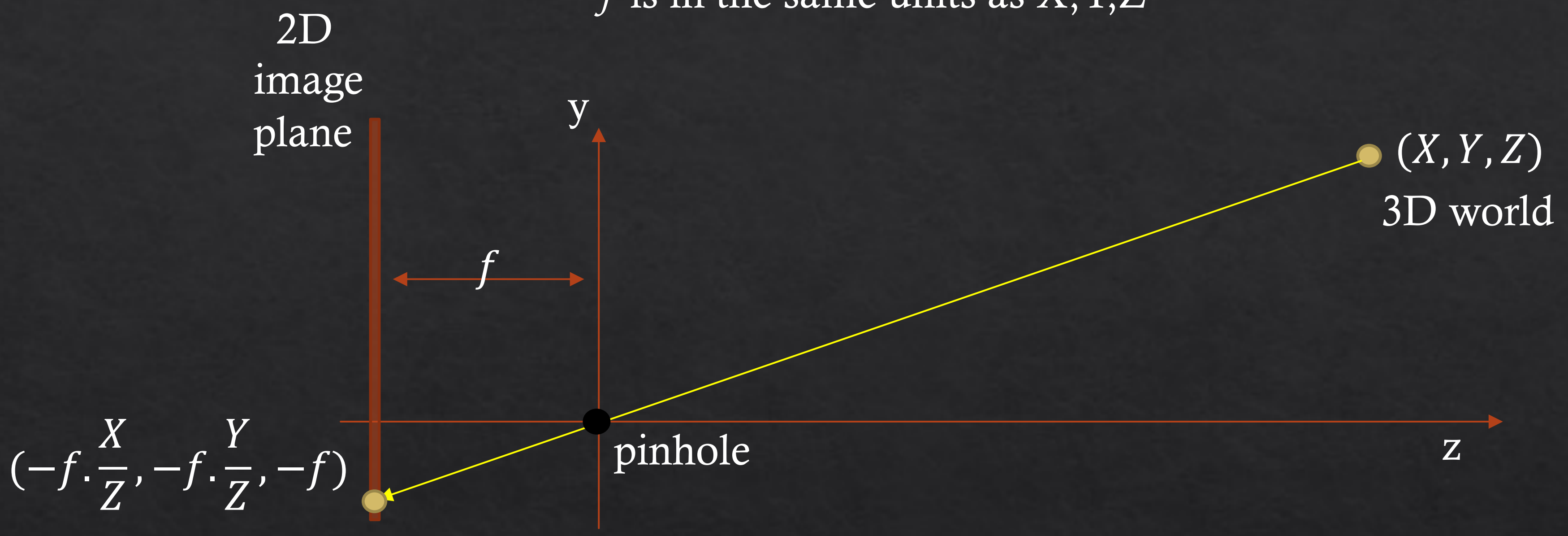
Remind you of a camera sensor plane?

Yes, if the camera is at the origin looking down the Z-axis

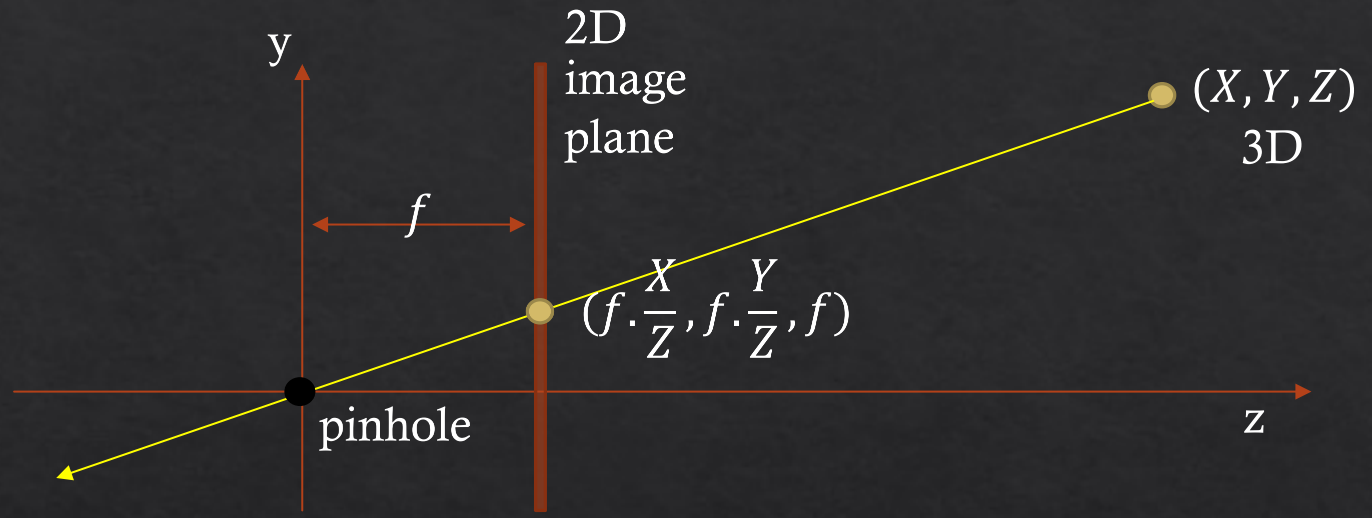


Ideal pinhole camera 3D

f is in the same units as X,Y,Z



Ideal vs virtual pinhole model



$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} \qquad \begin{pmatrix} fX \\ fY \\ Z \end{pmatrix} = \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

Pixel coordinates
(u,v)
on z=1 plane

Pixel coordinates from 3D point

1. Projection from 3D to 2D

$$\begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

2. Scaling pixels by pixel resoln.

$$\begin{pmatrix} s_x f & 0 & 0 & 0 \\ 0 & s_y f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

3. Translation to positive quadrant

$$\begin{pmatrix} f_x & 0 & u & 0 \\ 0 & f_y & v & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

4. Skew, if sensor not perpendicular to optic axis

$$\begin{pmatrix} f_x & \alpha & u & 0 \\ 0 & f_y & v & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

More details here

Pixel coordinates from 3D point

When the camera is at the origin looking towards Z

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \longleftarrow \begin{bmatrix} f_x & \alpha & u & 0 \\ 0 & f_y & v & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

2D pixel coordinates

3D world coordinates

Pinhole camera matrix

When the camera is at an arbitrary location

$$
\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}
\leftarrow
\begin{bmatrix} f_x & \alpha & u \\ 0 & f_y & v \\ 0 & 0 & 1 \end{bmatrix}
\begin{bmatrix} r11 & r12 & r13 & t1 \\ r21 & r22 & r23 & t2 \\ r31 & r32 & r33 & t3 \end{bmatrix}
\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}
$$

2D pixel coordinates

intrinsic

extrinsic

3D world coordinates

Problems with pinhole camera?

image flipped

not bright

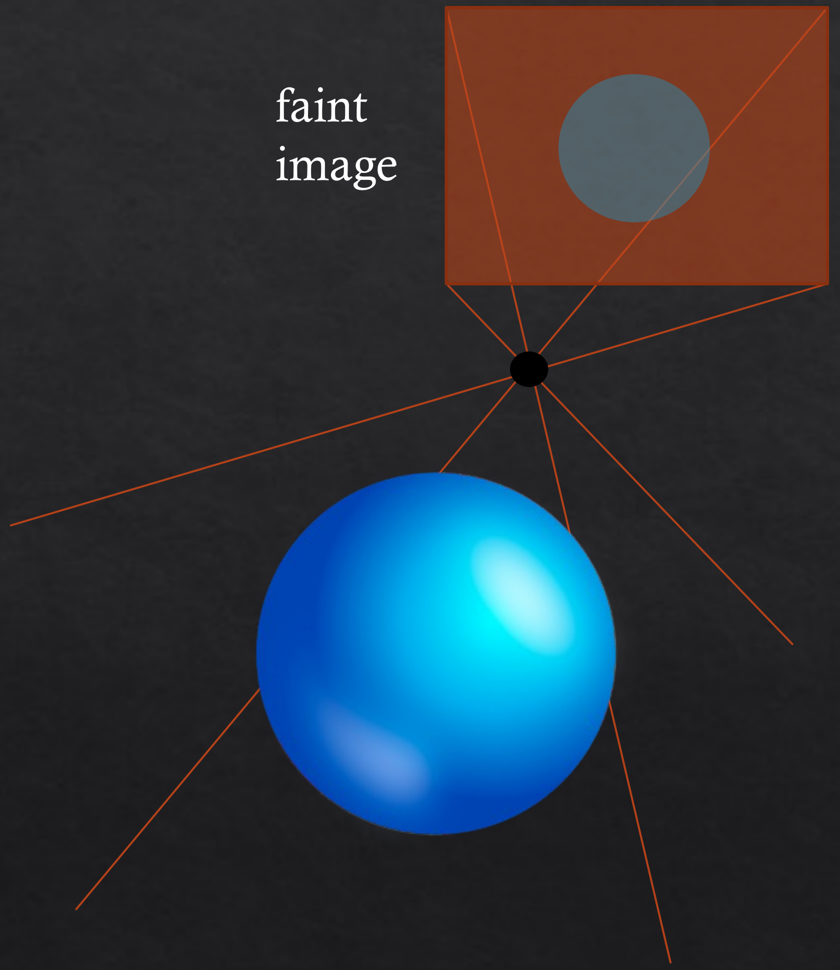
not similar to eye

no lens

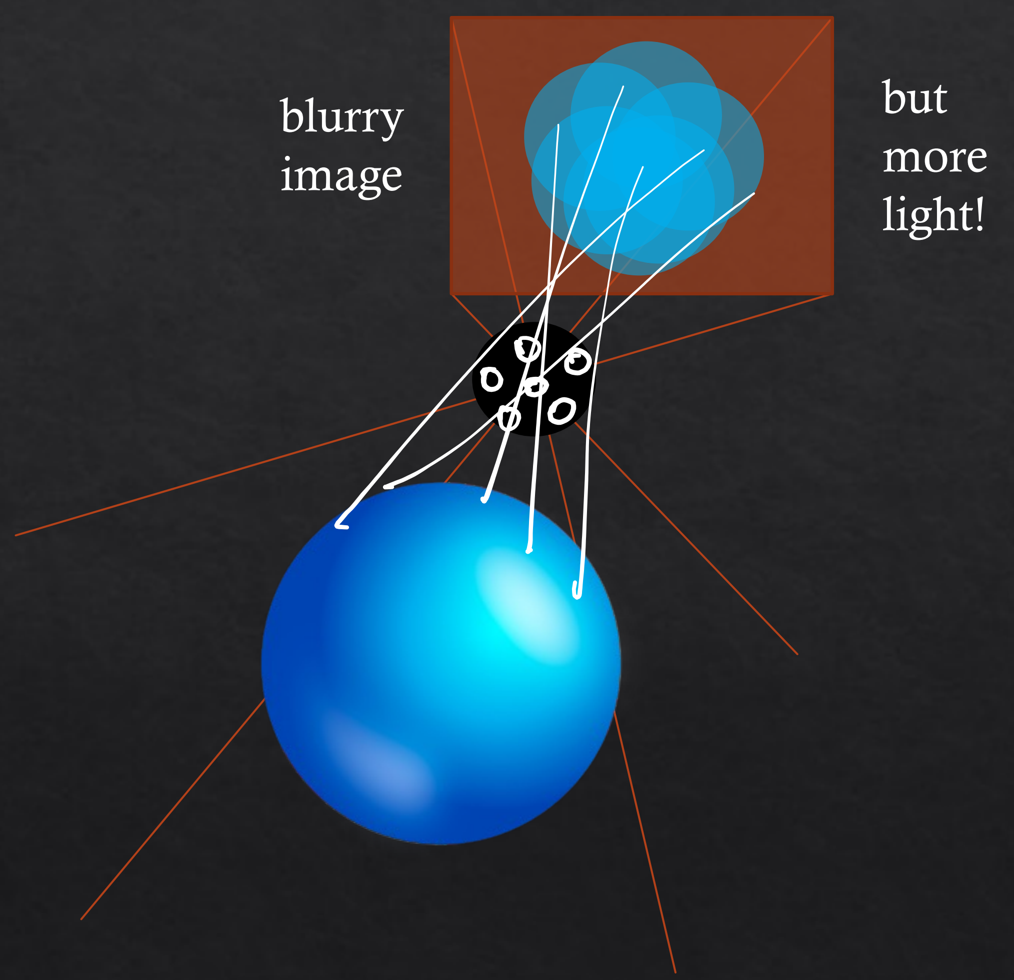
field of view

need a small hole

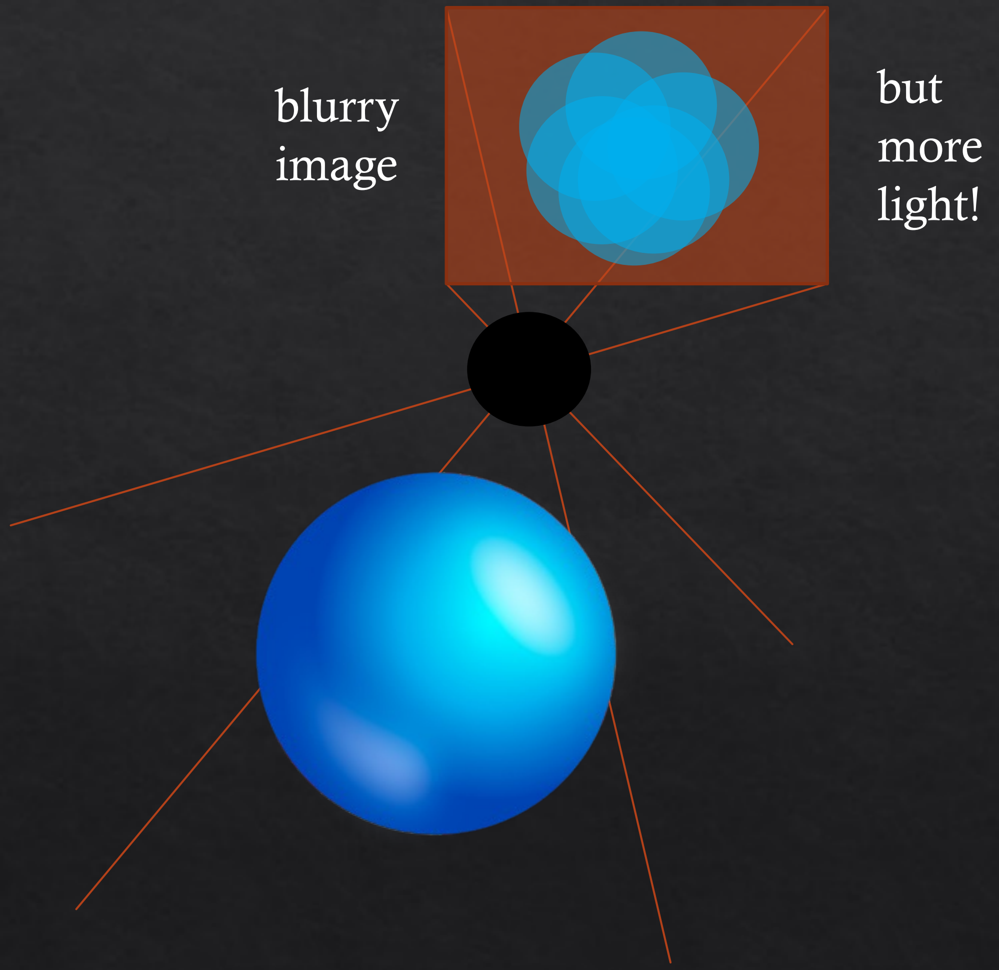
Pinhole only allows little light through



Large hole: many superposed images

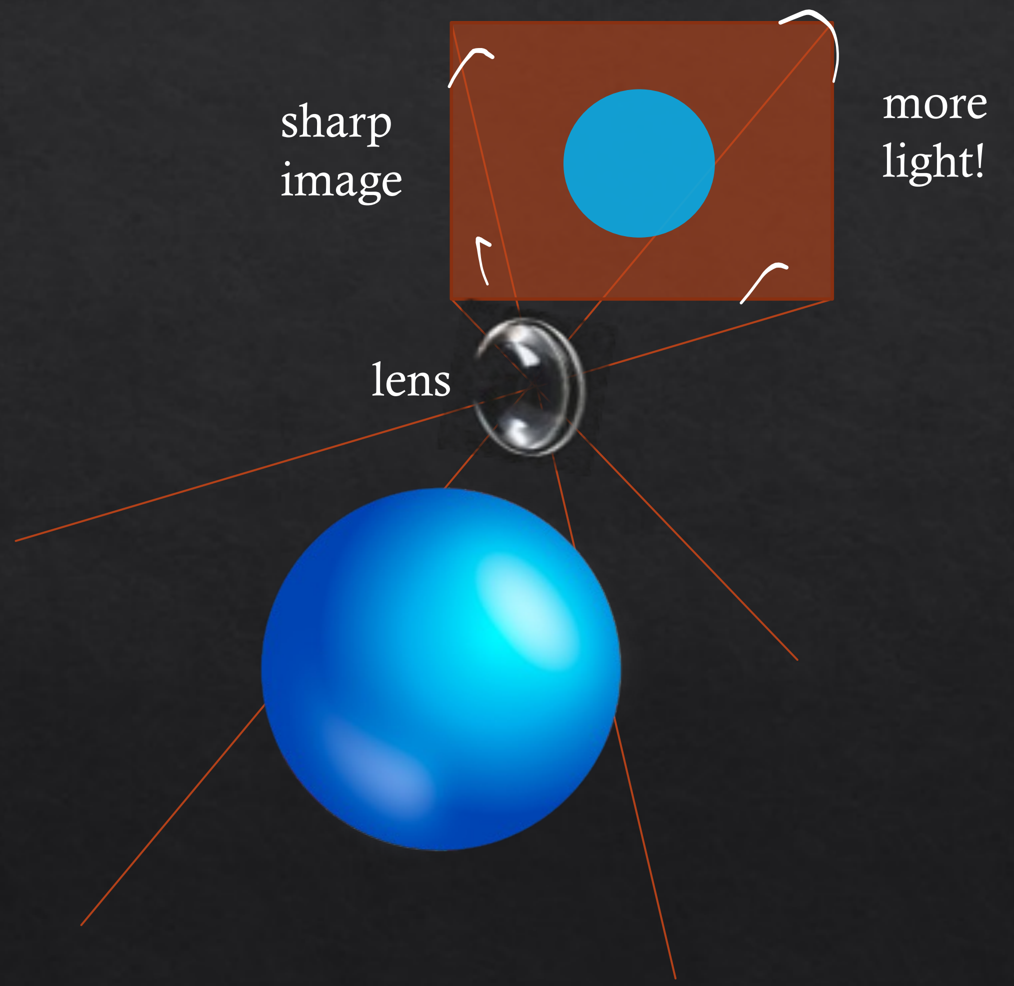


Can we improve light and avoid blur?

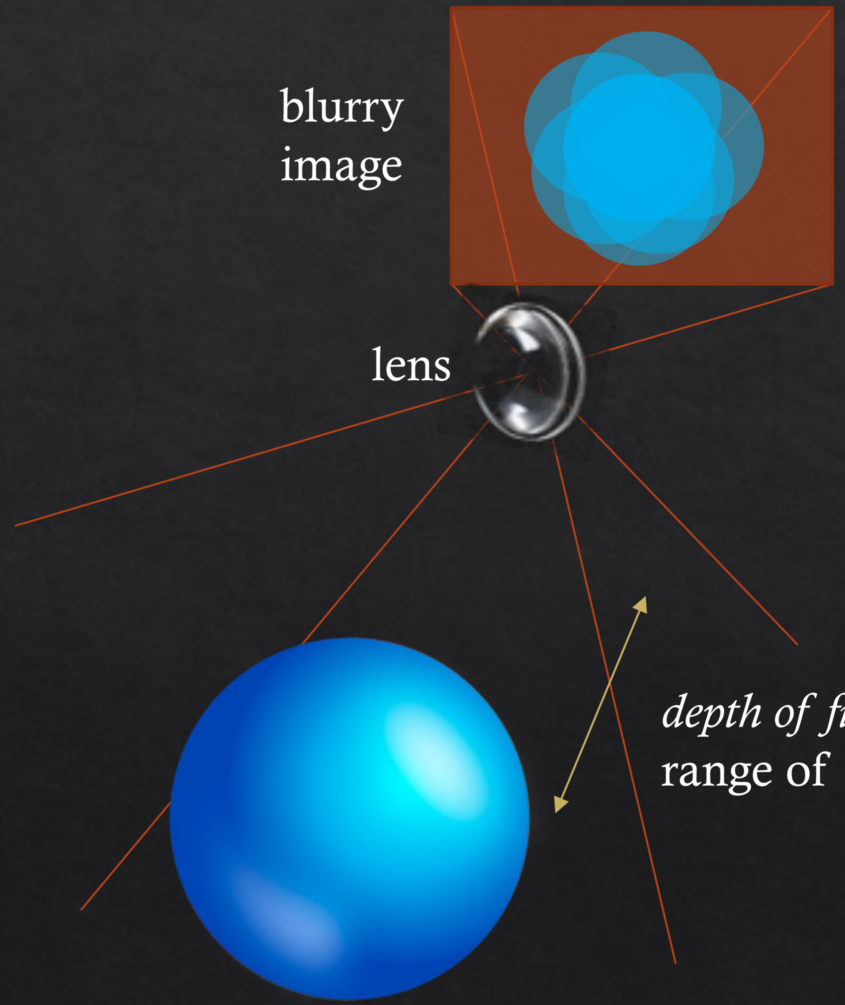


Lens improves light efficiency, but …

distortion



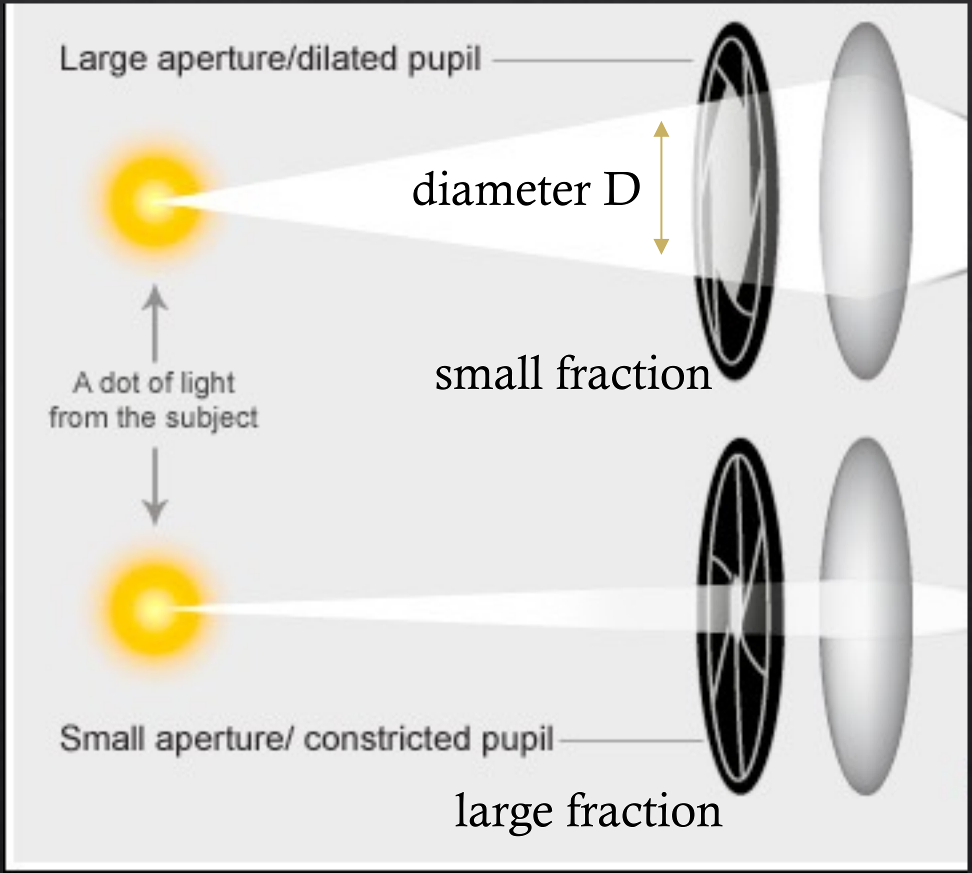
… only focusses part of the world



depth of field

range of depths for which image is sharp

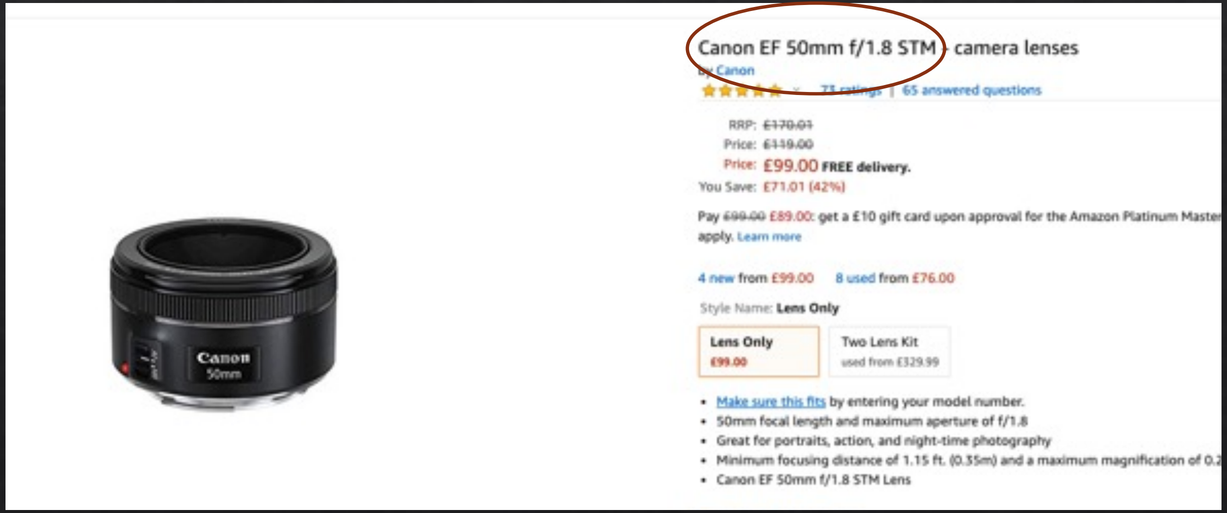
Finite-sized pinhole = aperture



https://www.dpreview.com/forums/post/59717839

aperture specification is a fraction: $\frac{f}{D}$

called f-number of a lens



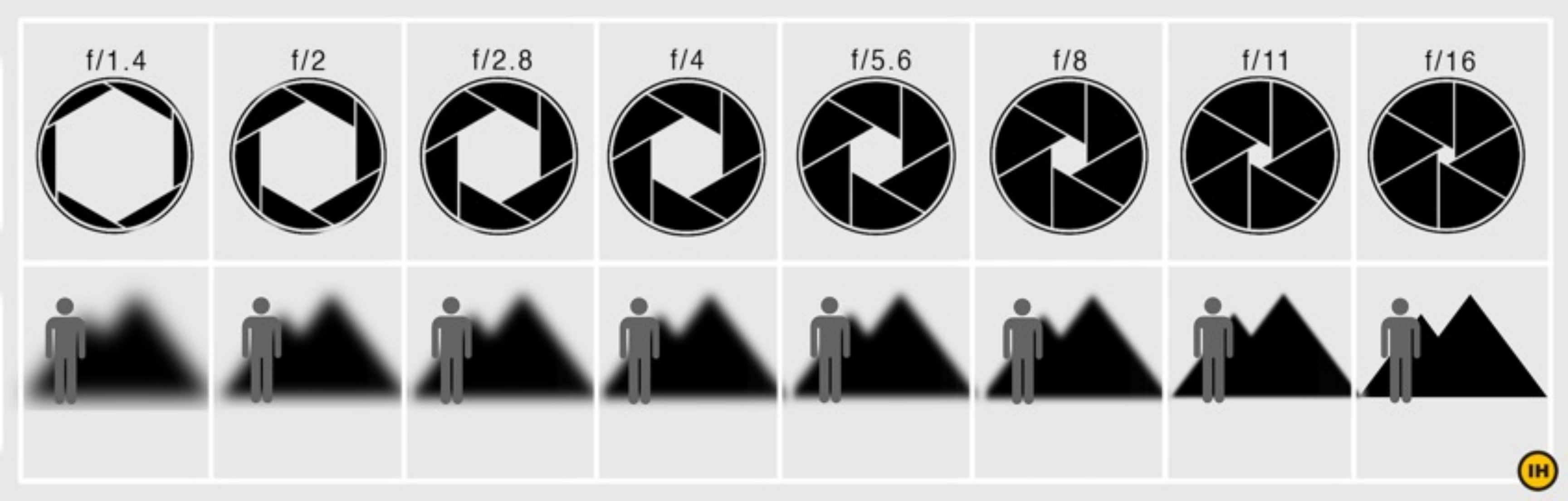
amazon purchase

THE UNIVERSITY of EDINBURGH informatics

Depth of field depends on aperture size

more light allows fast shutter speed – good for dark scenes

less light but large depth of field – good for landscape

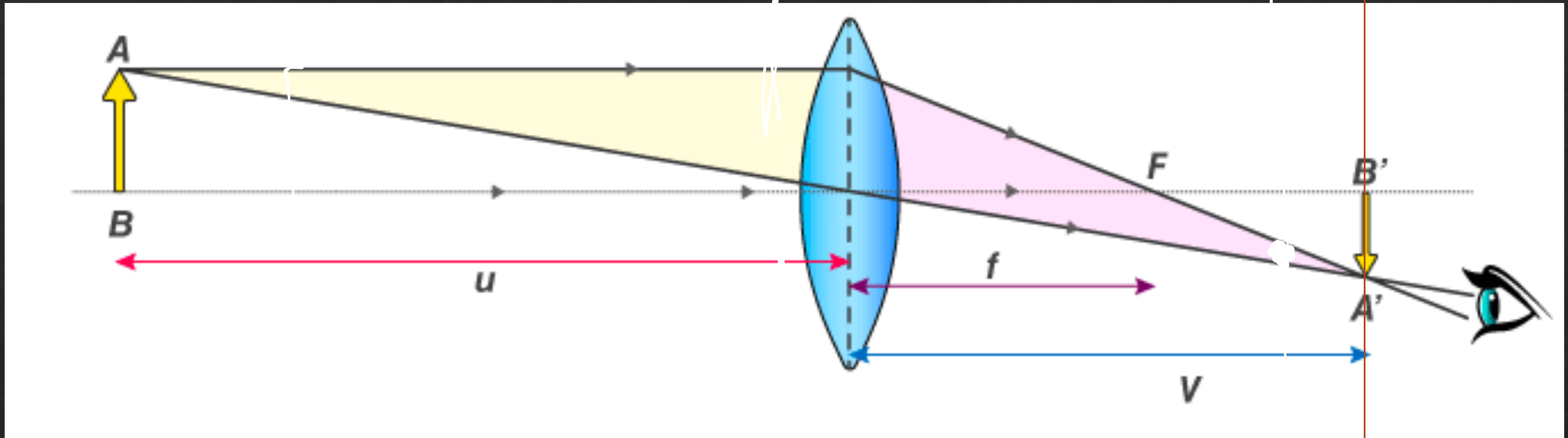


'fast lens'

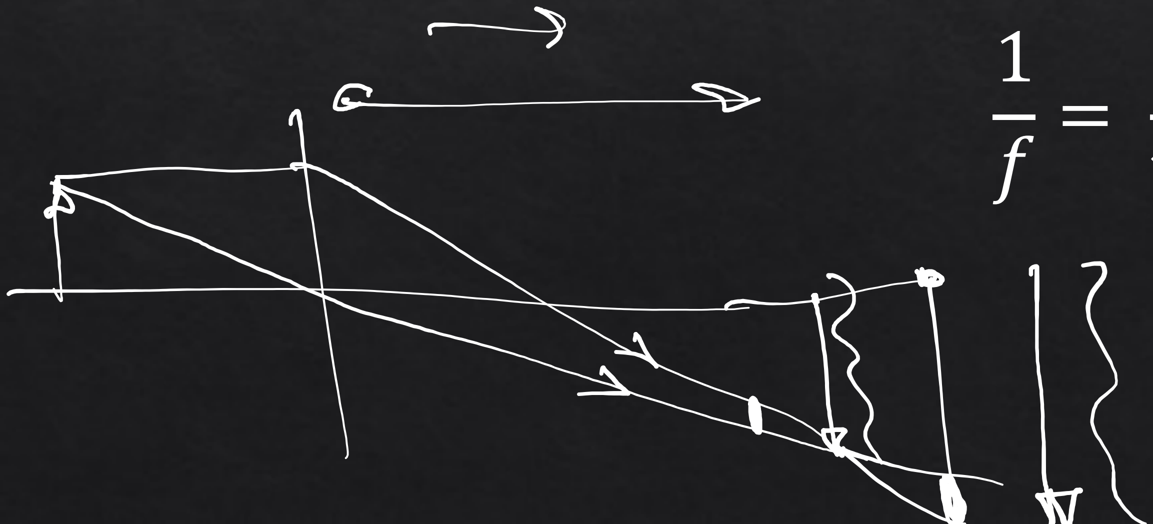
‘slow lens’

https://www.zippi.co.uk/thestudio/landscape-photography/aperture-diagram-indiahikes/

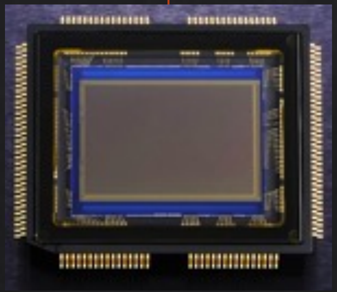
Thin lens formula, independent of aperture



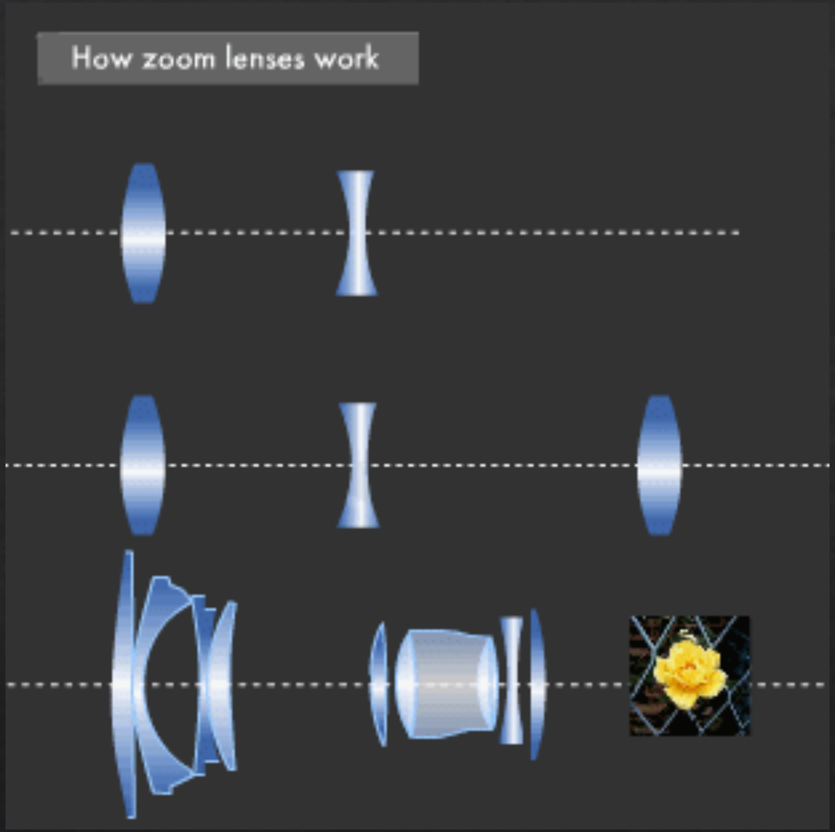
https://byjus.com/physics/derivation-of-lens-formula/



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



Zooming-- changing f



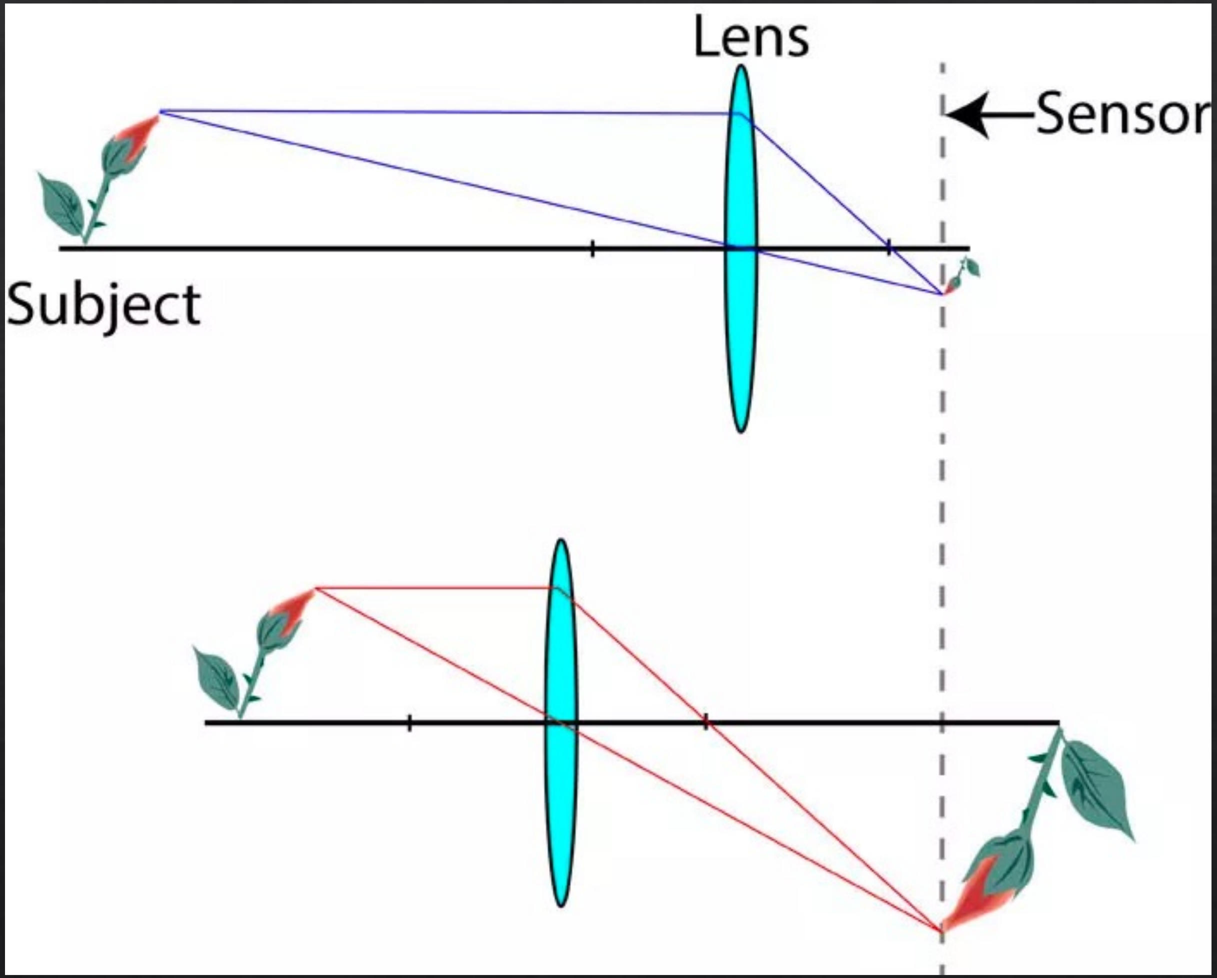
https://global.canon/en/technology/s_labo/light/003/02.html

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

effective
focal
length

Same lens (fixed f), increase v

extension tube



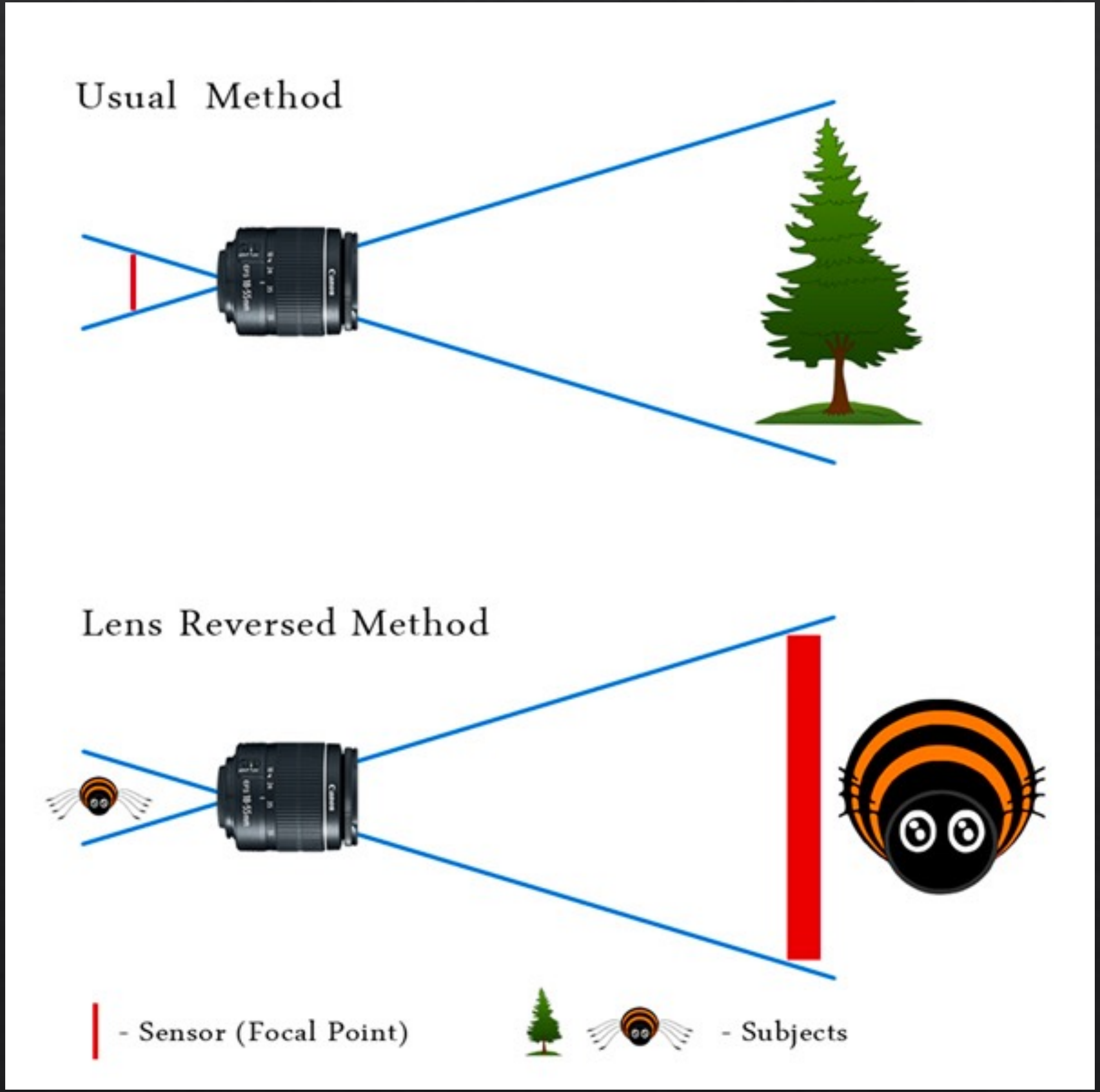
https://expertphotography.com/difference-between-macro-micro-and-close-up-photography/

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

larger image!

Also achieved by swapping subject and sensor!

reverse ring extension tube

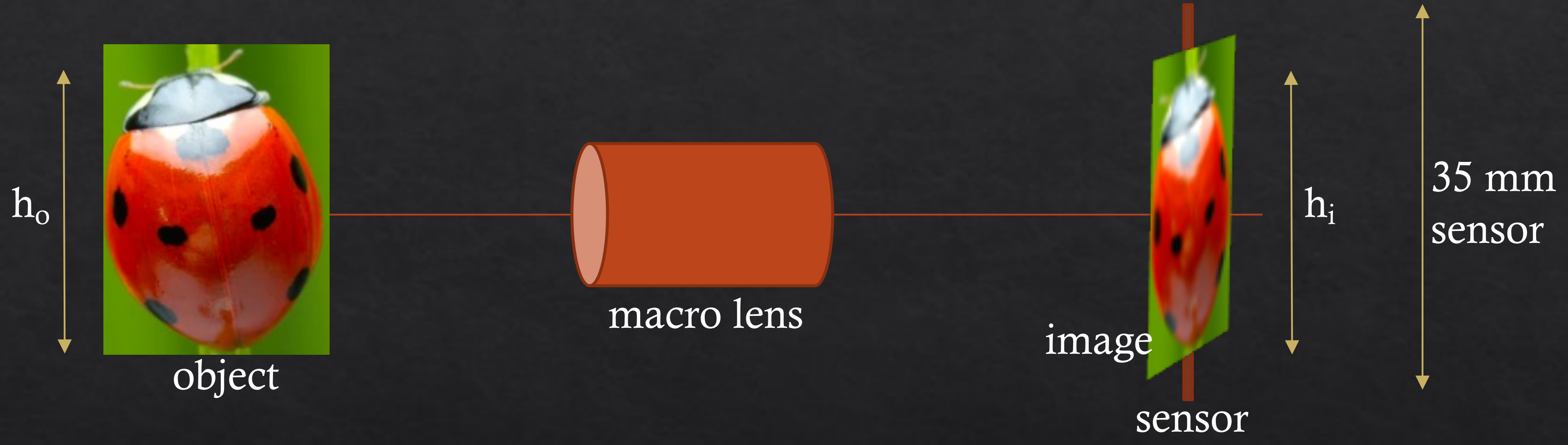


https://121clicks.com/tutorials/use-reverse-ring-extension-tube-macro-photography

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

Macro photography

high magnification ratio $\frac{h_i}{h_o}$

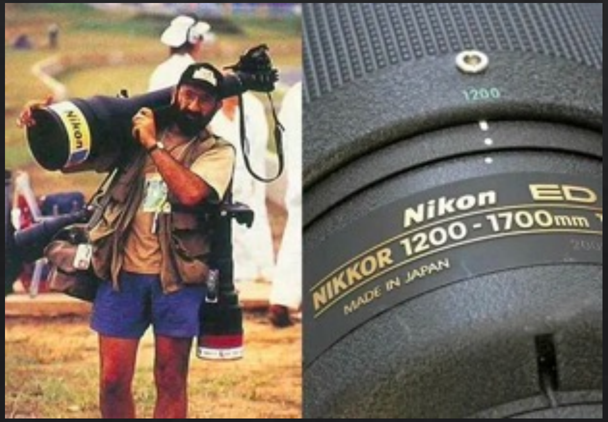


Types of lenses

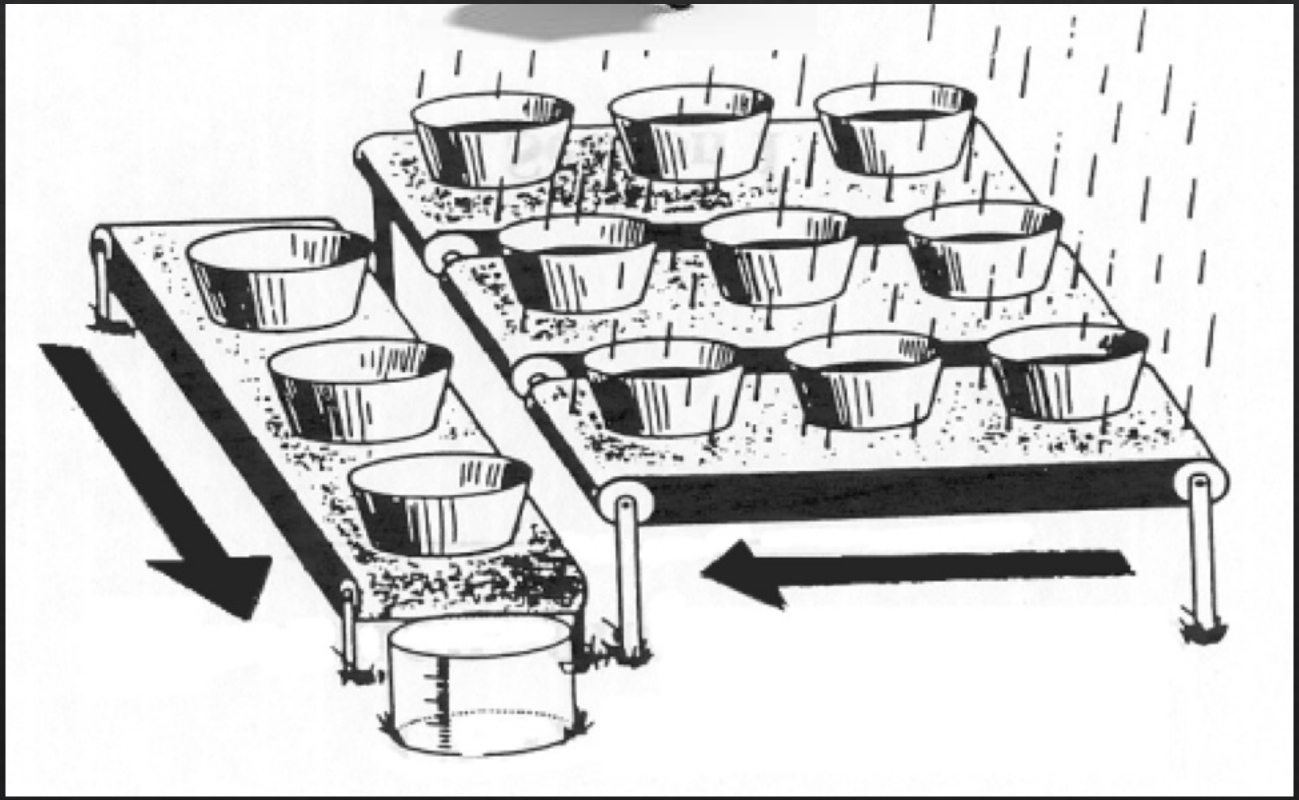
telephoto
- f larger than length of lens construction
- useful to zoom
- compresses range of depths
- usually variable focal lengths
- and variable f-number (depending on f)

standard/prime
- f fixed
- no zoom capability
- usually high quality build = better image quality

wide angle
- f shorter than lens construction
- good for landscape
- could introduce more distortion



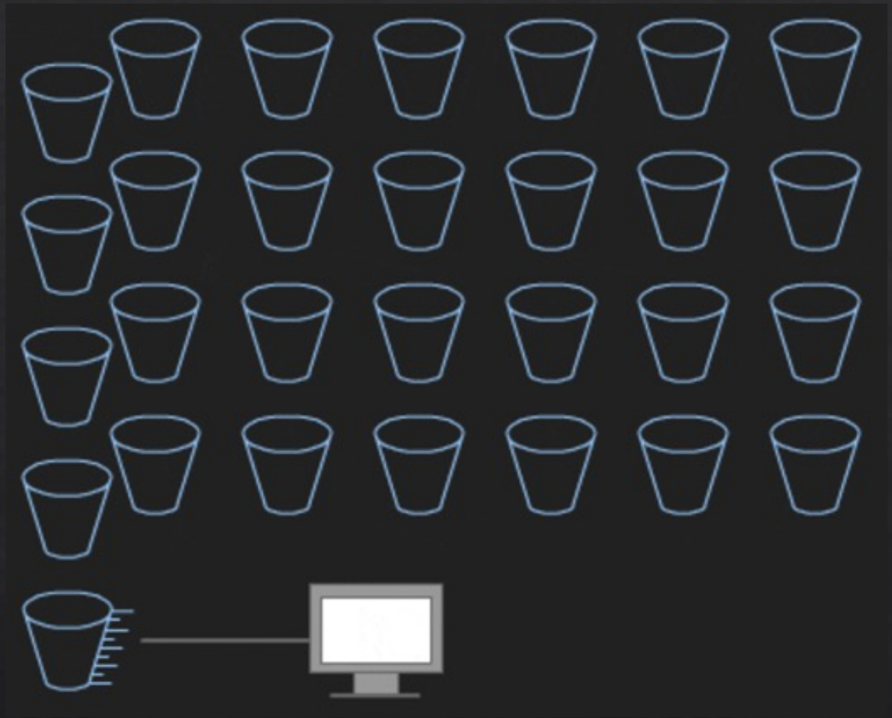
Cameras – sensors



https://www.visiononline.org/userassets/aiauploads/file/cvp_the-fundamentals-of-camera-and-image-sensor-technology_jon-chouinard.pdf

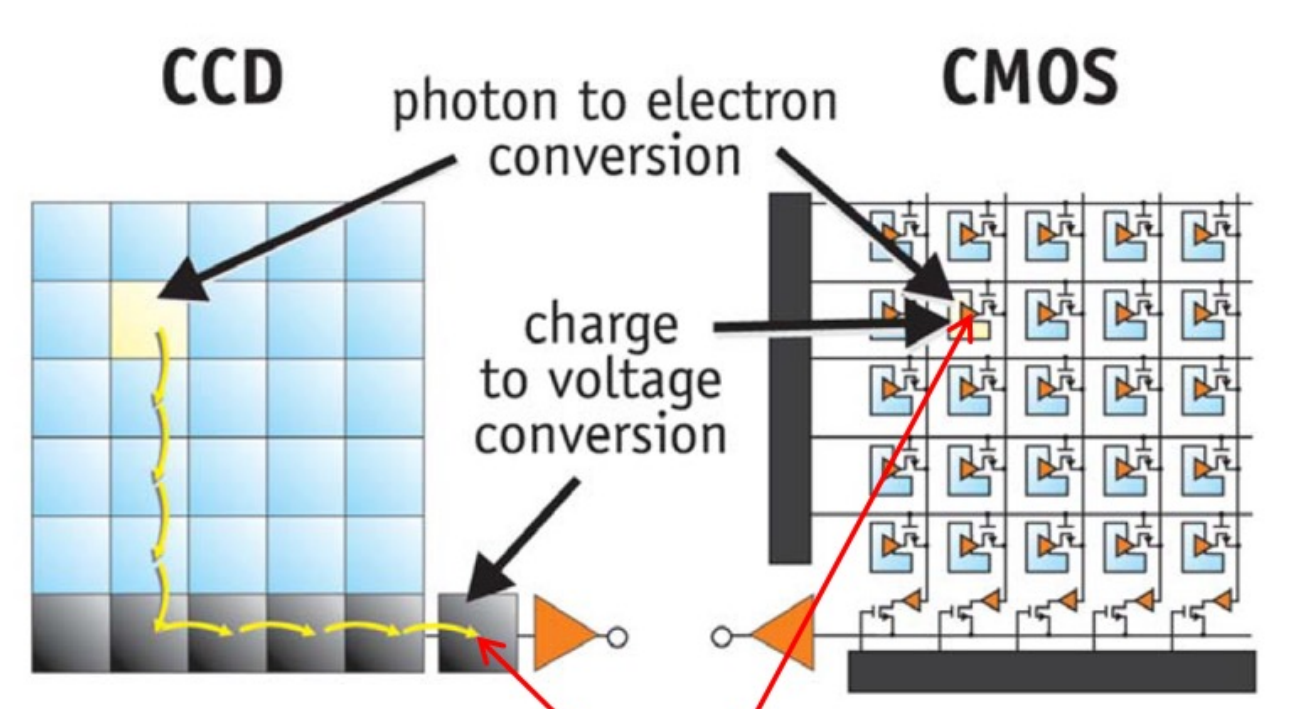
Sensor sensitivity and response

Types of sensors



https://www.photometrics.com/learn/camera-basics/types-of-camera-sensor
https://www.canon-europe.com/pro/infobank/image-sensors-explained/

Types of sensors

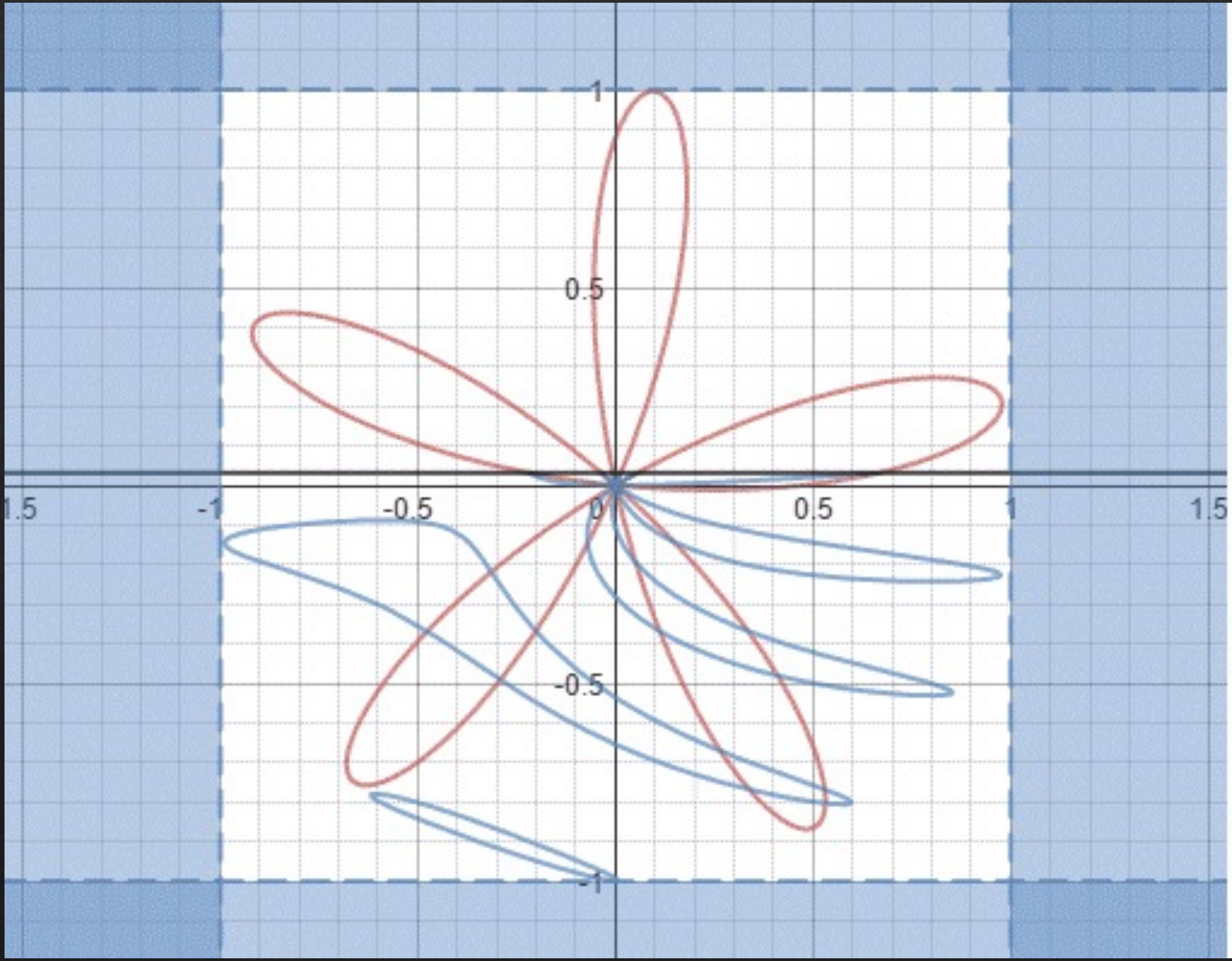


CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

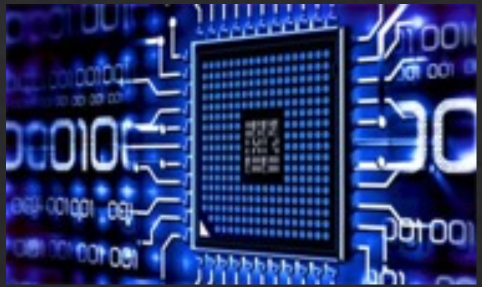
Read-out noise generated

Read more here, and on this canon website (marketing-speak alert)

Rolling shutter



The big picture!



Aperture →

focal length

Sensivity. ISO

CG – account for all factors!