The Camera

Topic 1

Week 1 – Jan. 9th, 2019

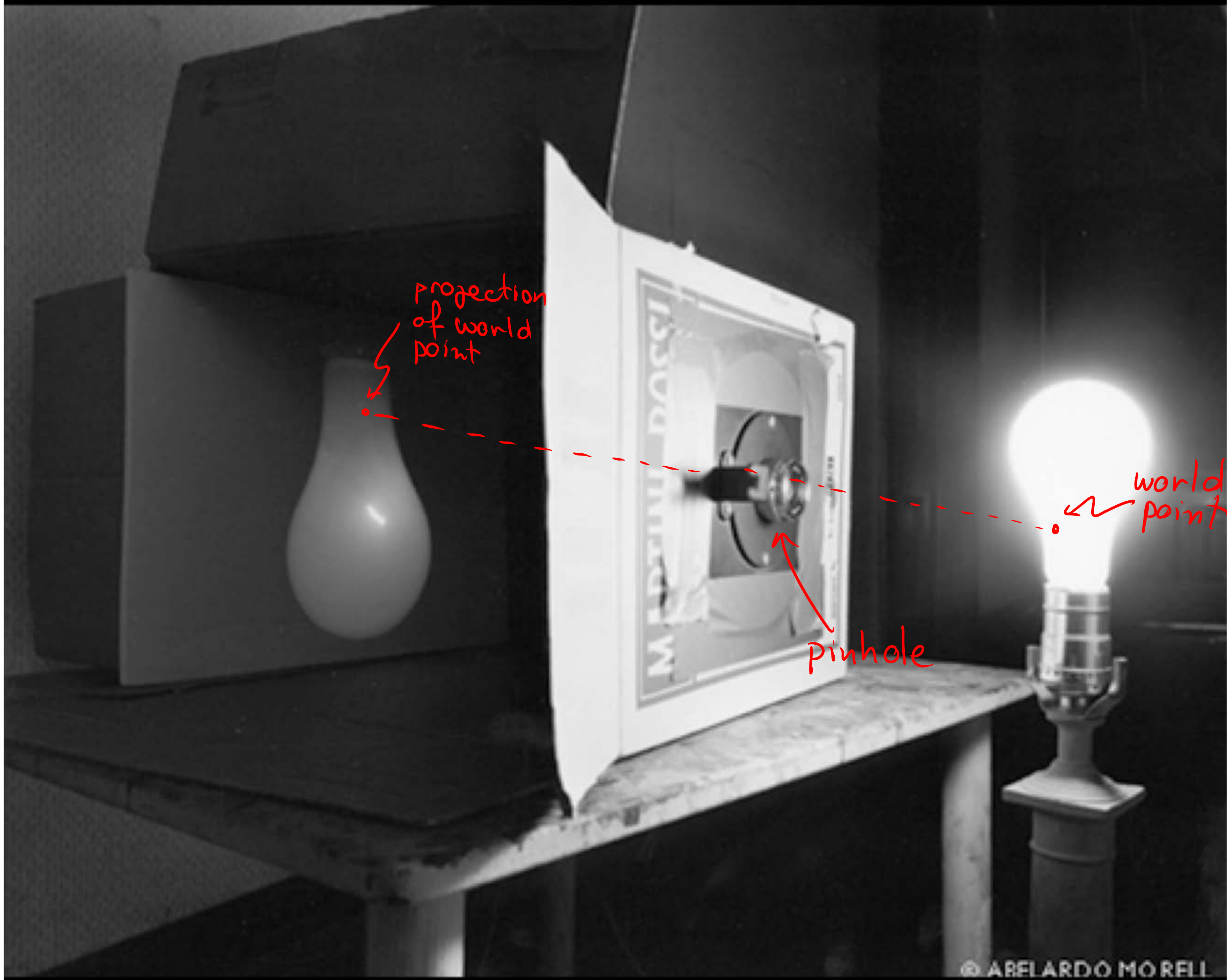
Topic 1: The Camera

- **Pinhole, lens-based cameras & image blur**
- Basic camera controls
- Color image acquisition
- Image formation: from photons to digital numbers
- Key image artifacts
- Understanding image noise

Camera Obscura

Camera Obscura

- Latin: “Dark Room”

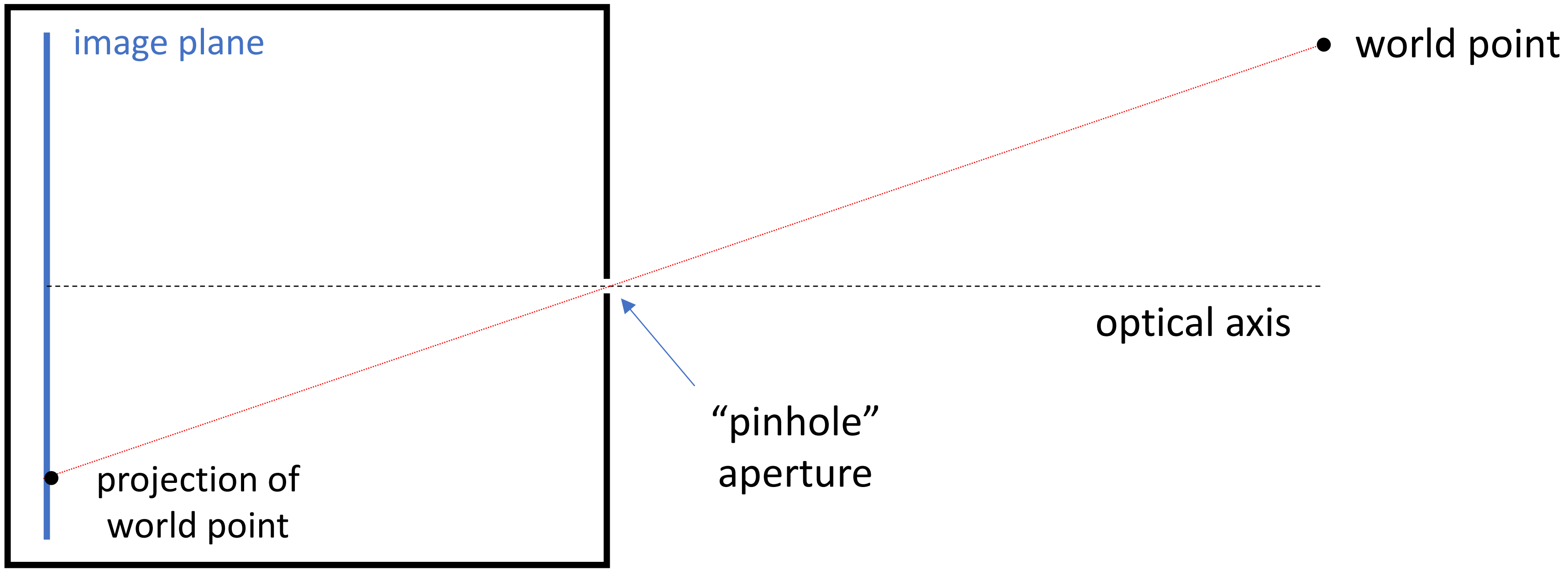


Light Bulb, 1991

Camera Obscura

- Aristotle (350 B.C.) writes about it
- Photos from August 2017 Solar Eclipse

The Pinhole Camera

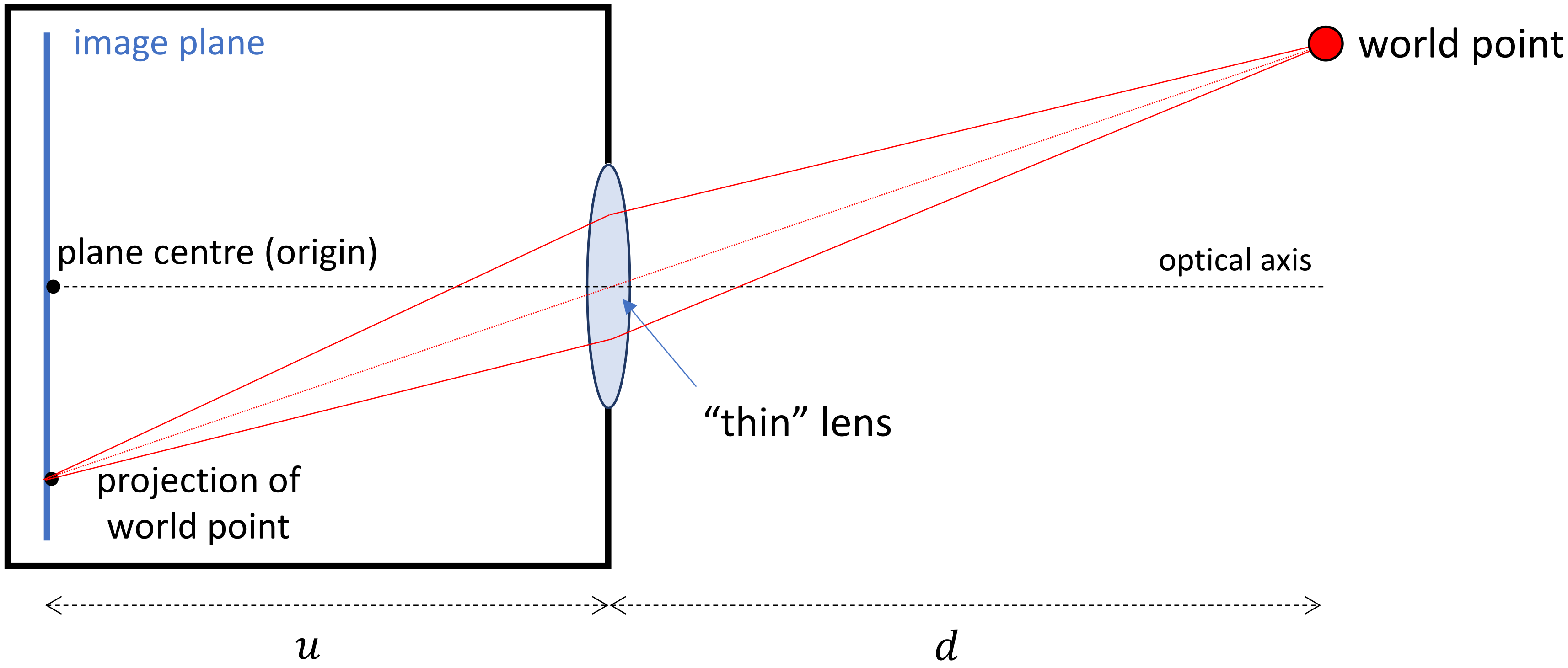


Modern Camera

- Cross-section of the Canon EOS M
- Compound Lens, CMOS sensor…
- Same optical principals

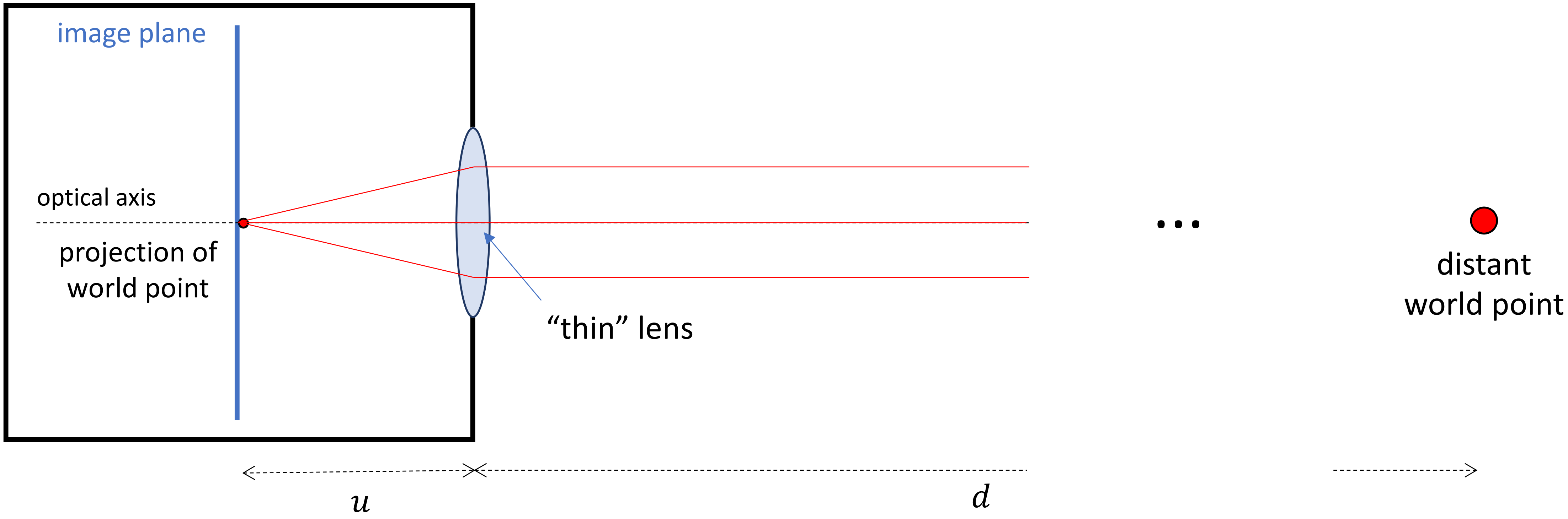
Source: dpreview.com

Simple Camera with Lens



u = image distance
d = object distance

Simple Camera with Lens – Distant



u = image distance
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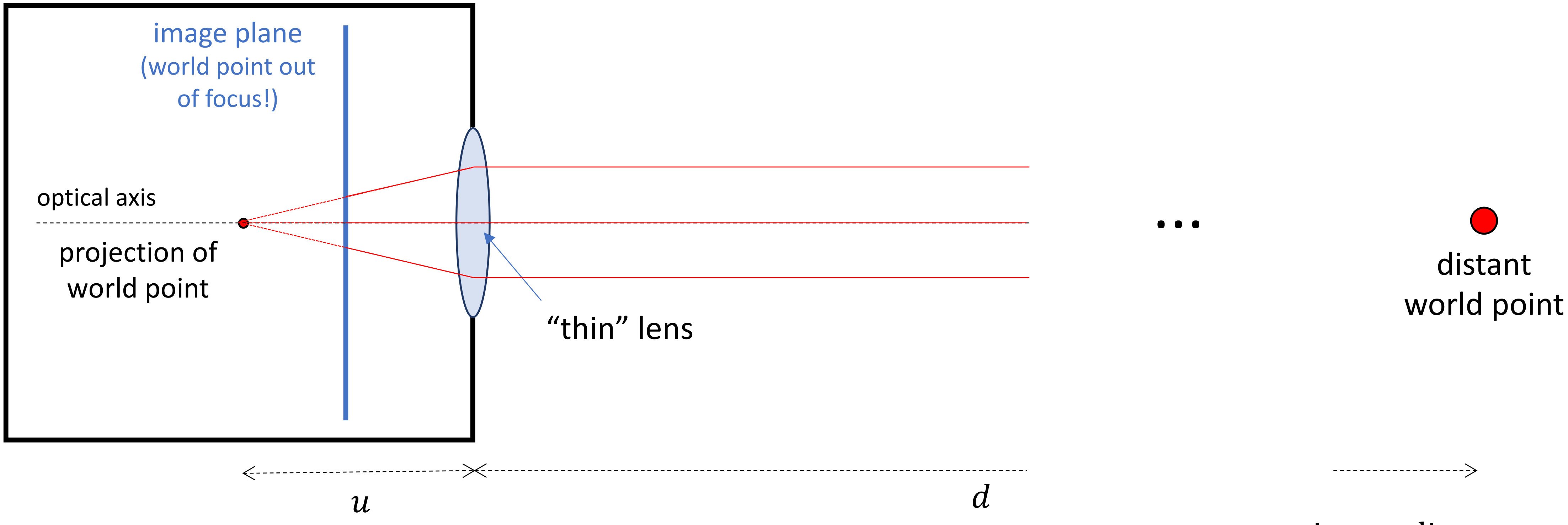
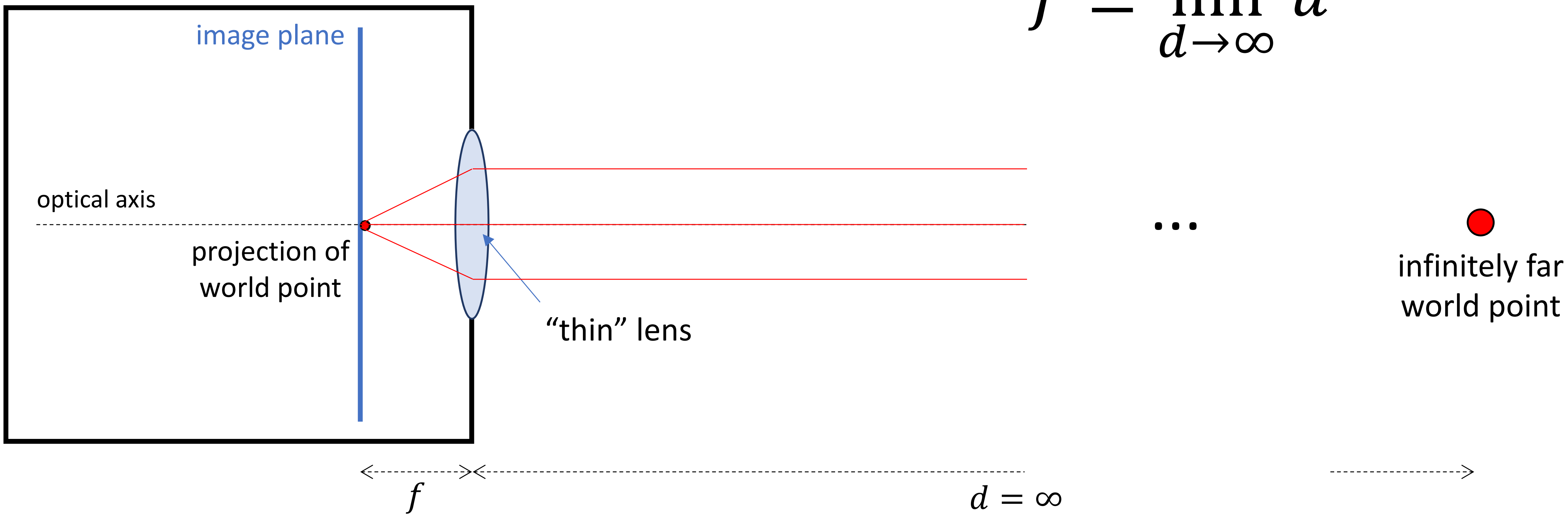
Simple Camera with Lens – Distant



u = image distance
d = object distance

Simple Camera with Lens – Infinity focus

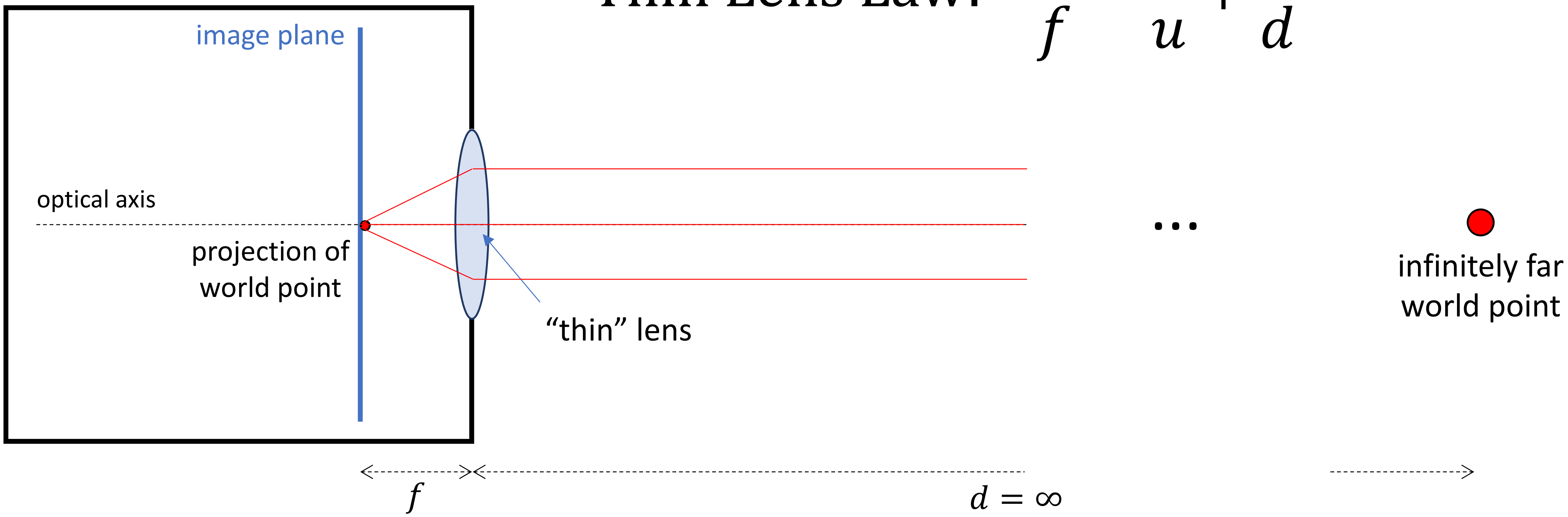
$$f \equiv \lim_{d \to \infty} u$$



f = focal length of lens
u = image distance
d = object distance

Simple Camera with Lens – Infinity focus

Thin Lens Law: $$\frac{1}{f} = \frac{1}{u} + \frac{1}{d}$$



f = focal length of lens
u = image distance
d = object distance

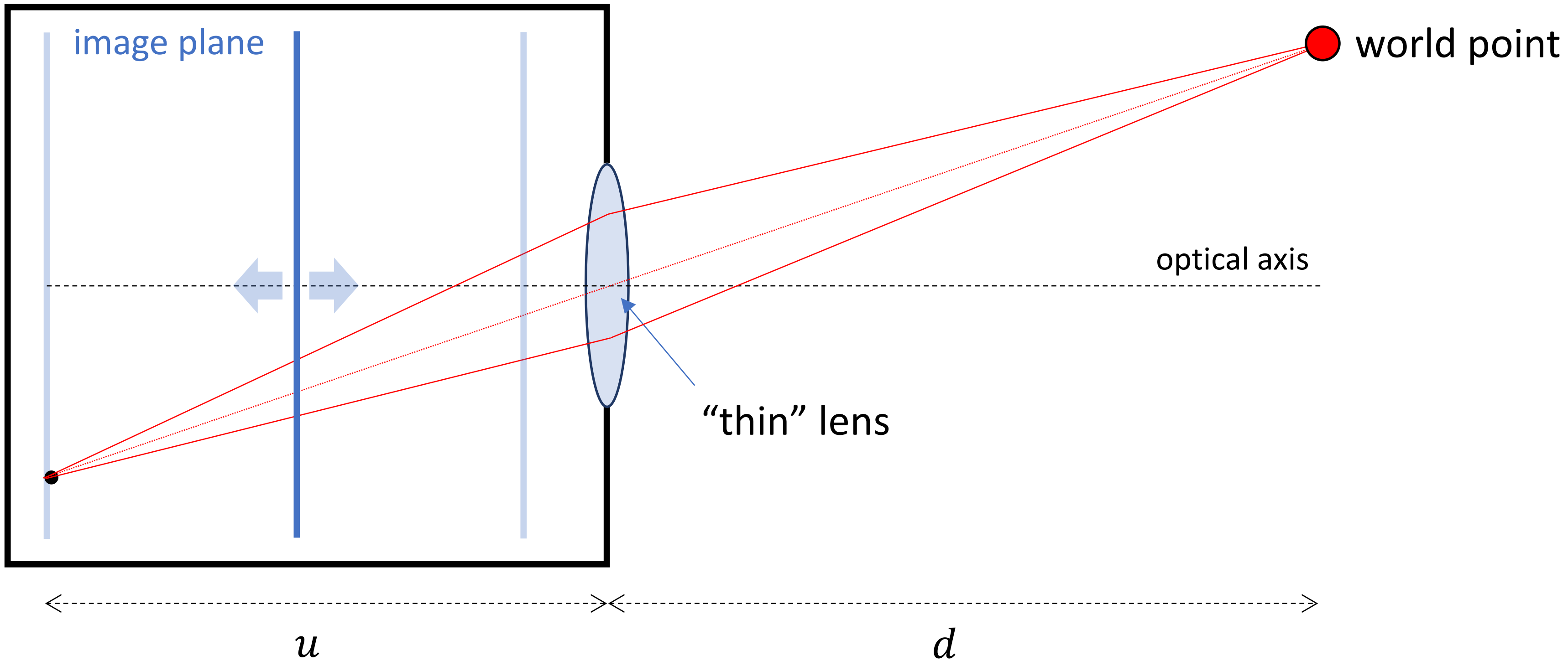
Modern Camera

- In practice the image plane is changed by moving lens elements, rather than moving the sensor
- This is the “focusing” mechanism

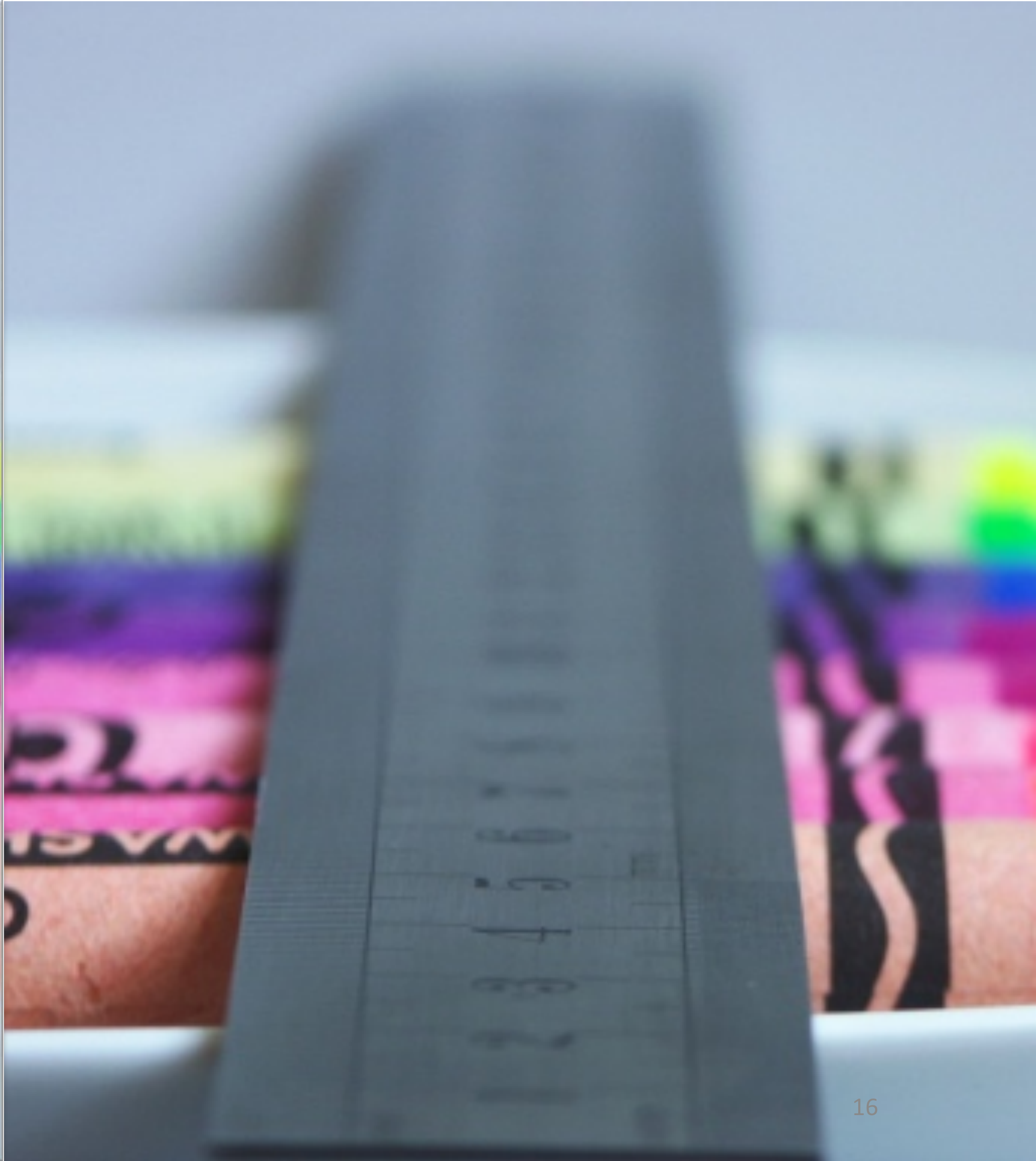
Source: dpreview.com

Focusing

- Imagine slowly moving the image plane
- What does the image of a fixed nearby world point look like?

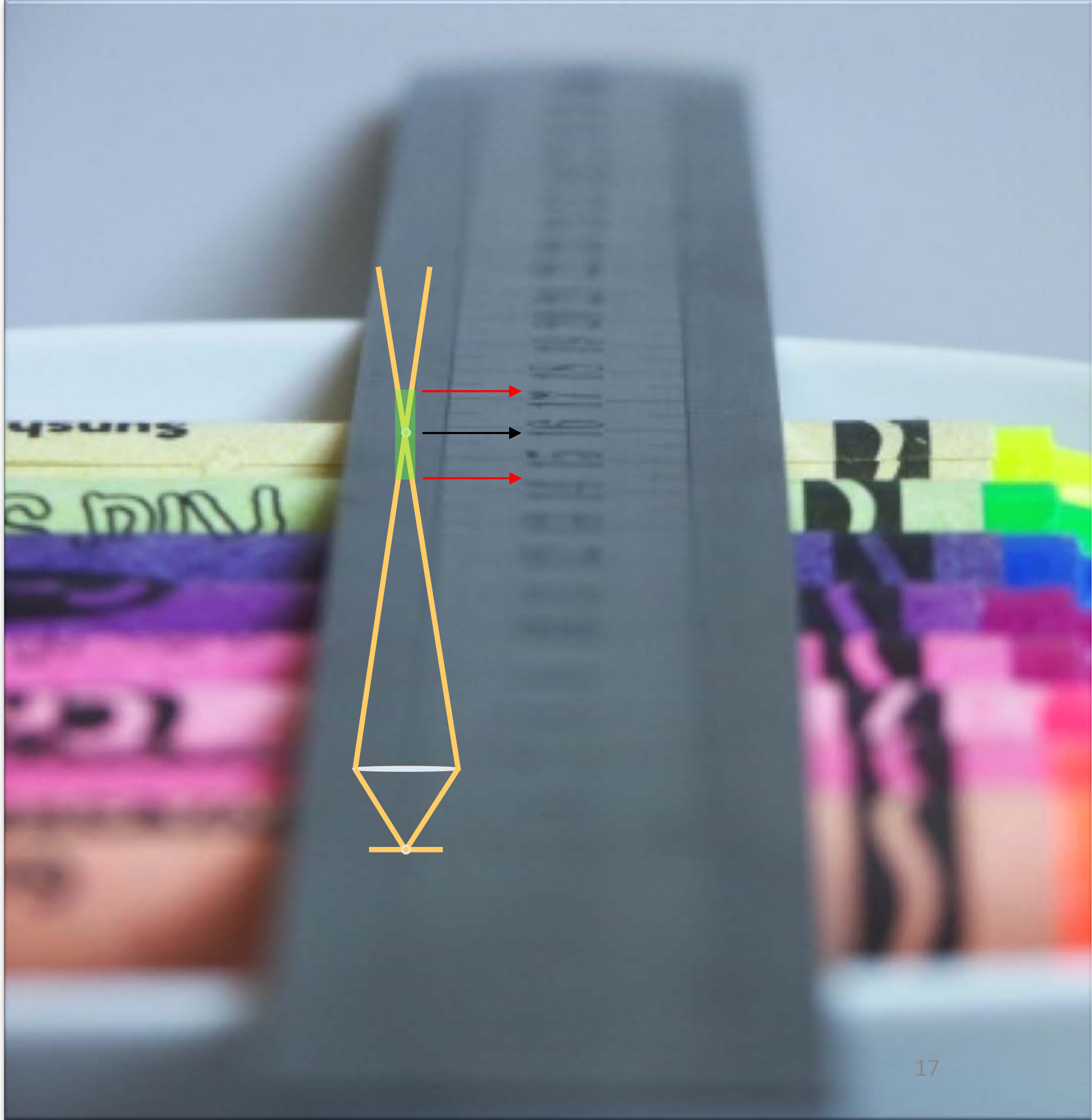


u = image distance
d = object distance



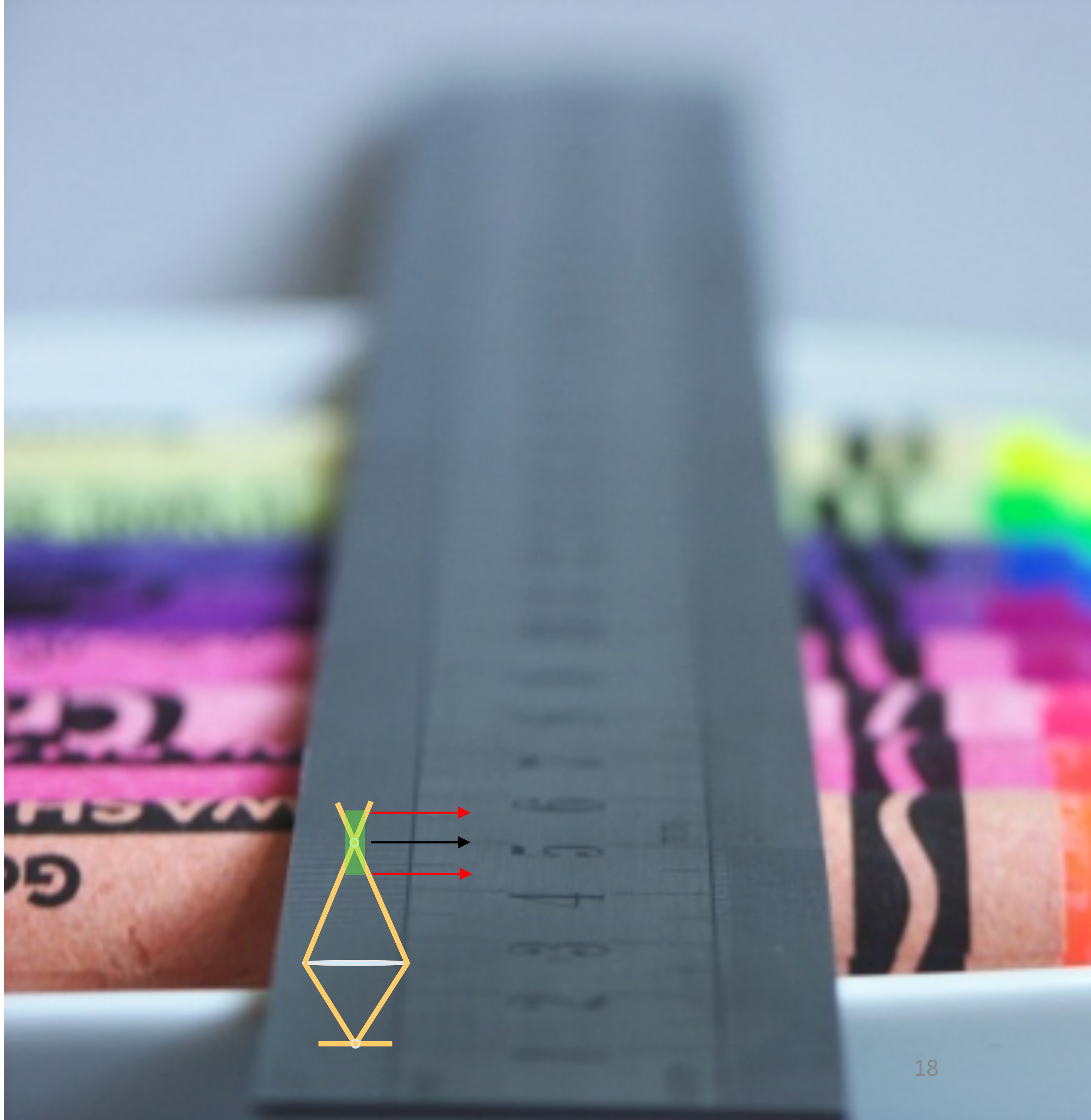
Depth of Field

- This effect is called “depth of field” in photography (DoF)
- Range of distances over which image is in “perfect focus”



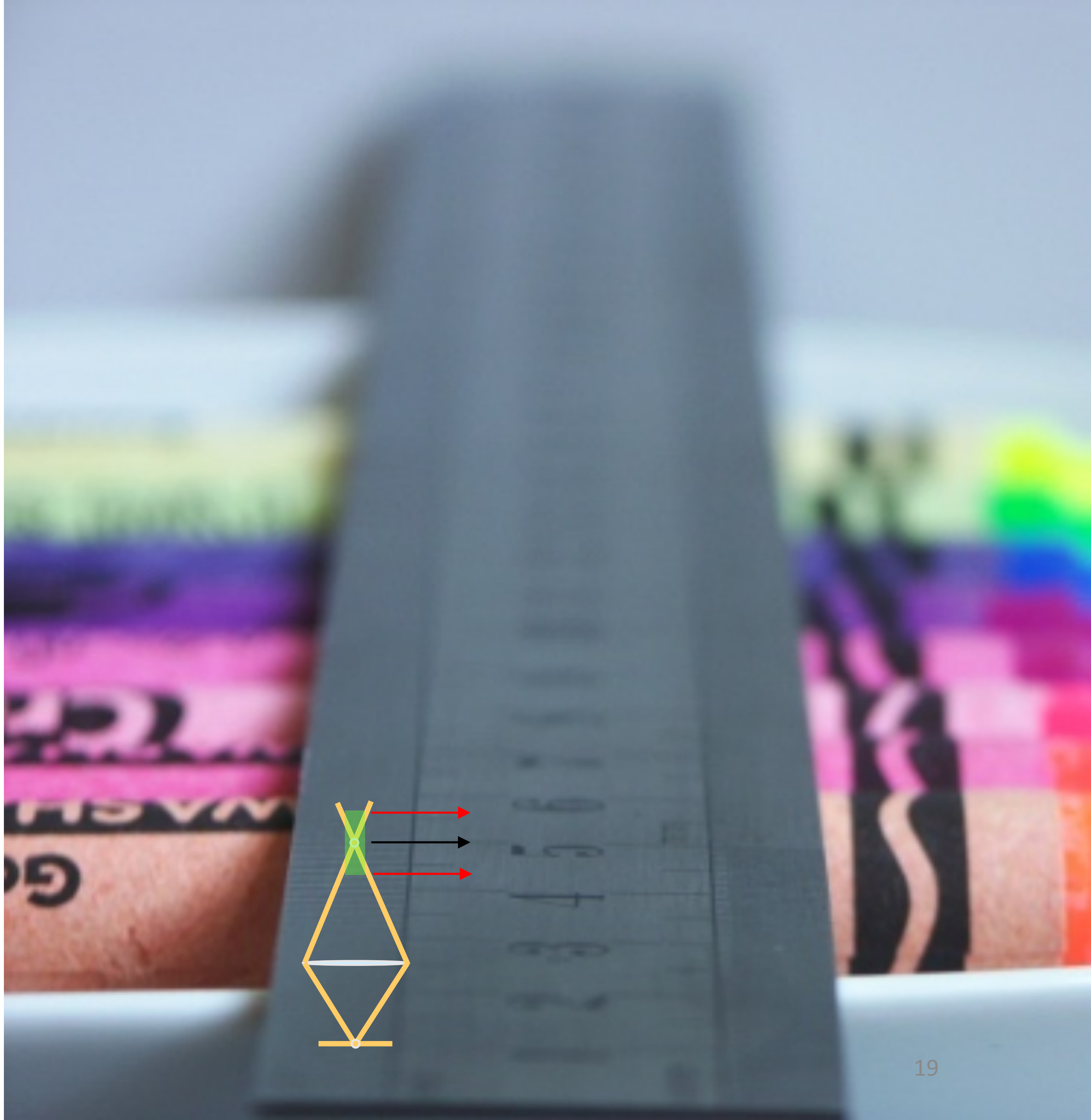
Depth of Field

- But why do we see more than just what is exactly at the distance we focused on?



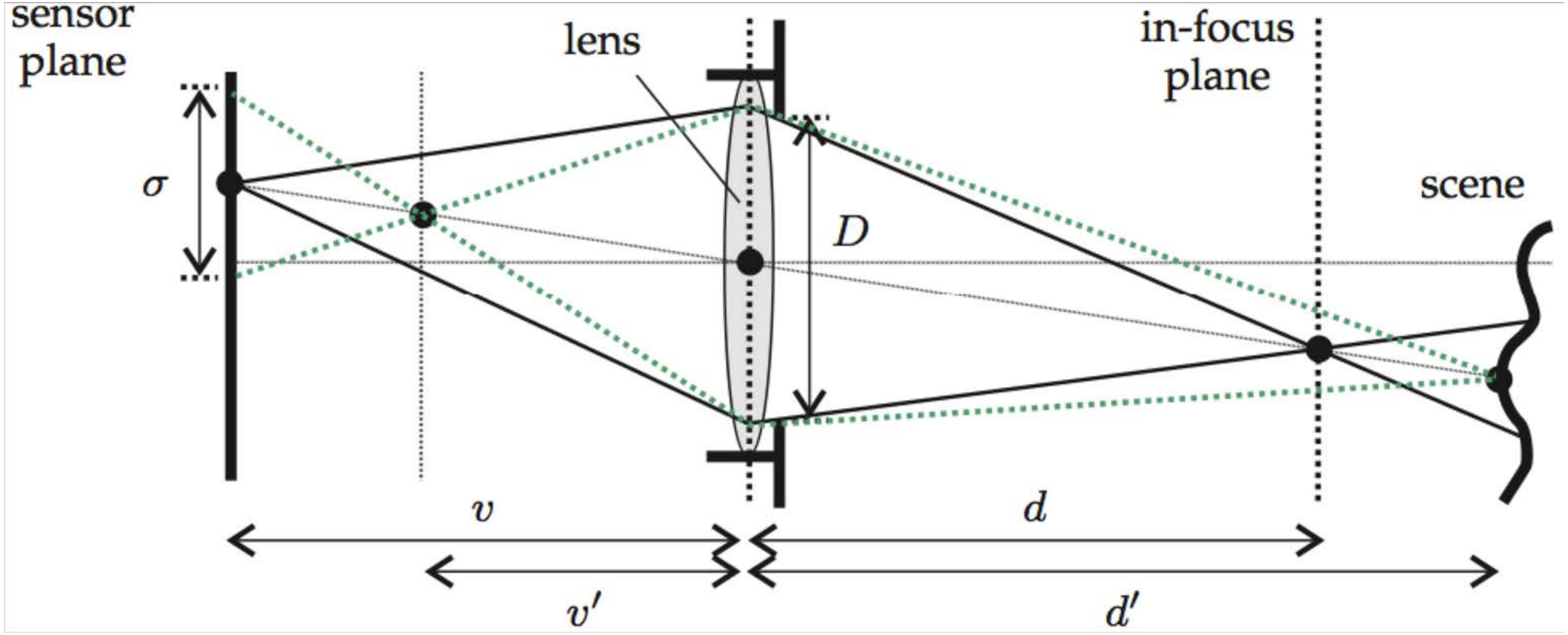
Depth of Field

- DoF = range of distances where blur < 1 sensor pixel!
- Things that affect DoF:
  - pixel size
  - aperture
  - lens focal length
- Cellphone camera:
  - wide-angle lens (short focal length)
  - need to fake DoF! (portrait mode)



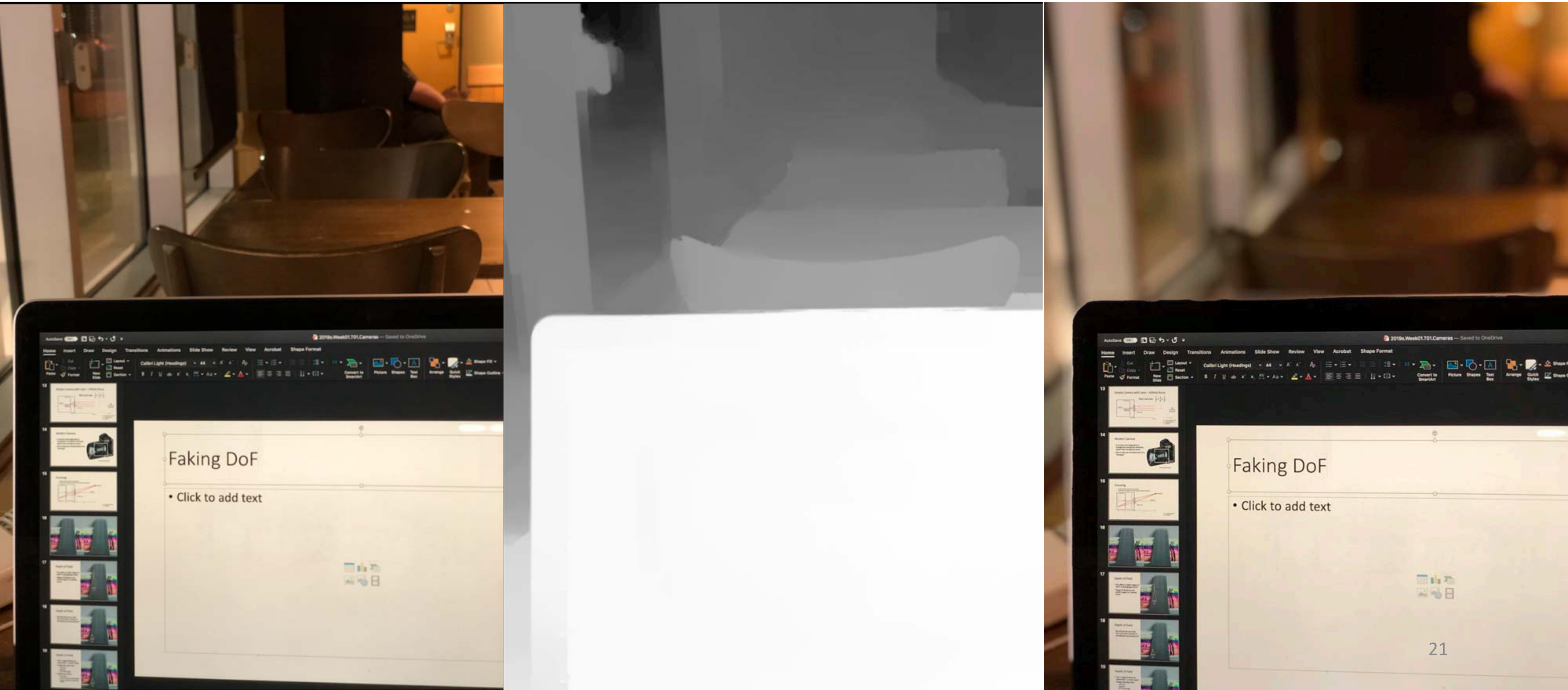
Modelling Defocus Blur

Hasinoff & Kutulakos PAMI 10



$\sigma \equiv$ blur circle, diameter of scene point's image on sensor plane
DoF $\equiv$ range of distance in scene where $\sigma <$ sensor pixel size

Portrait Mode: Faking Depth of Field



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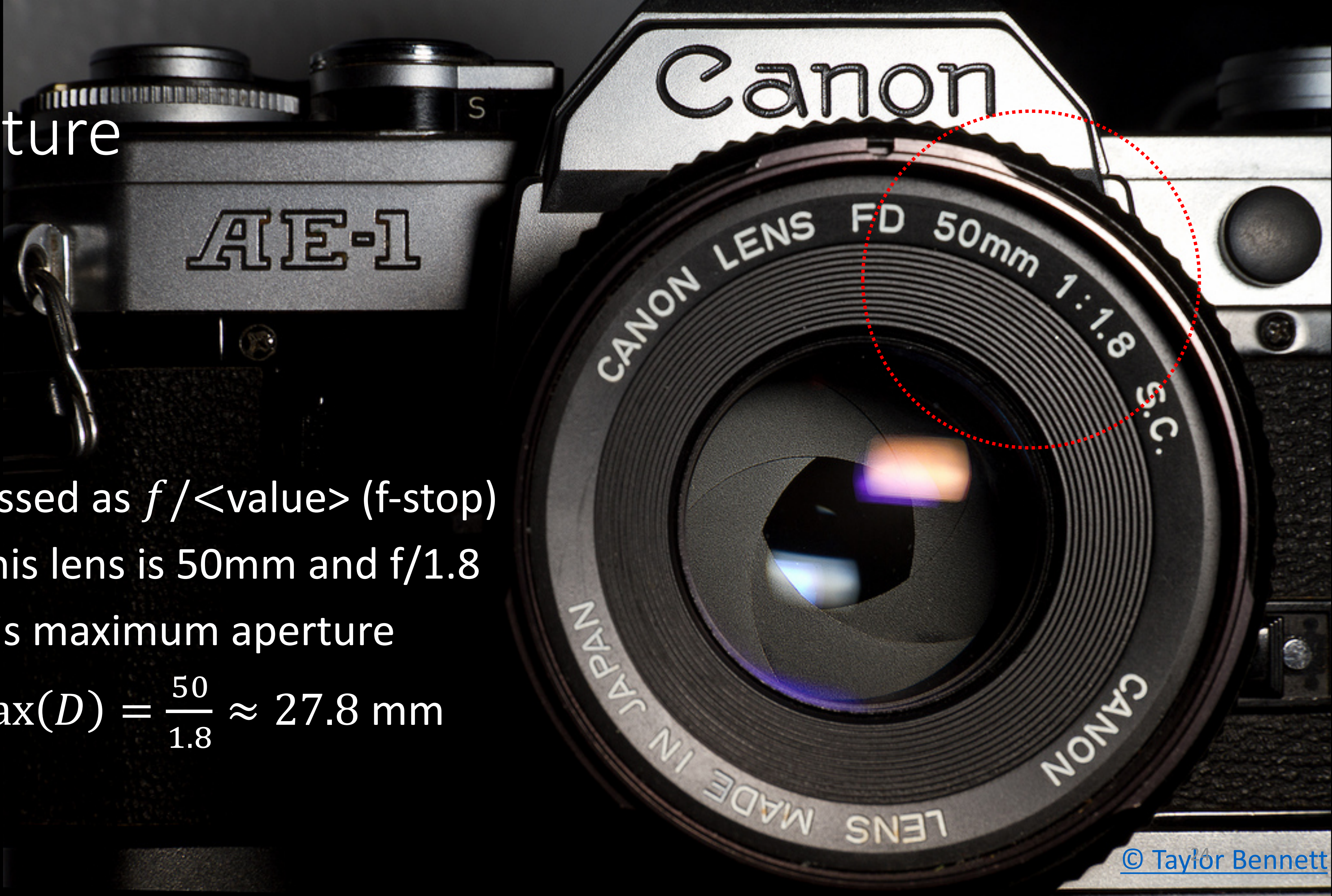
Aperture

- The relative size of the area in which light is collected through the lens
- Typically adjustable with aperture ‘blades’
- You can tell how many aperture blades a lens has from lens flare!

© Taylor Bennett

Aperture



- Expressed as f /<value> (f-stop)
- e.g. this lens is 50mm and f/1.8
- f/1.8 is maximum aperture
- ➔ $\max(D) = \frac{50}{1.8} \approx 27.8$ mm

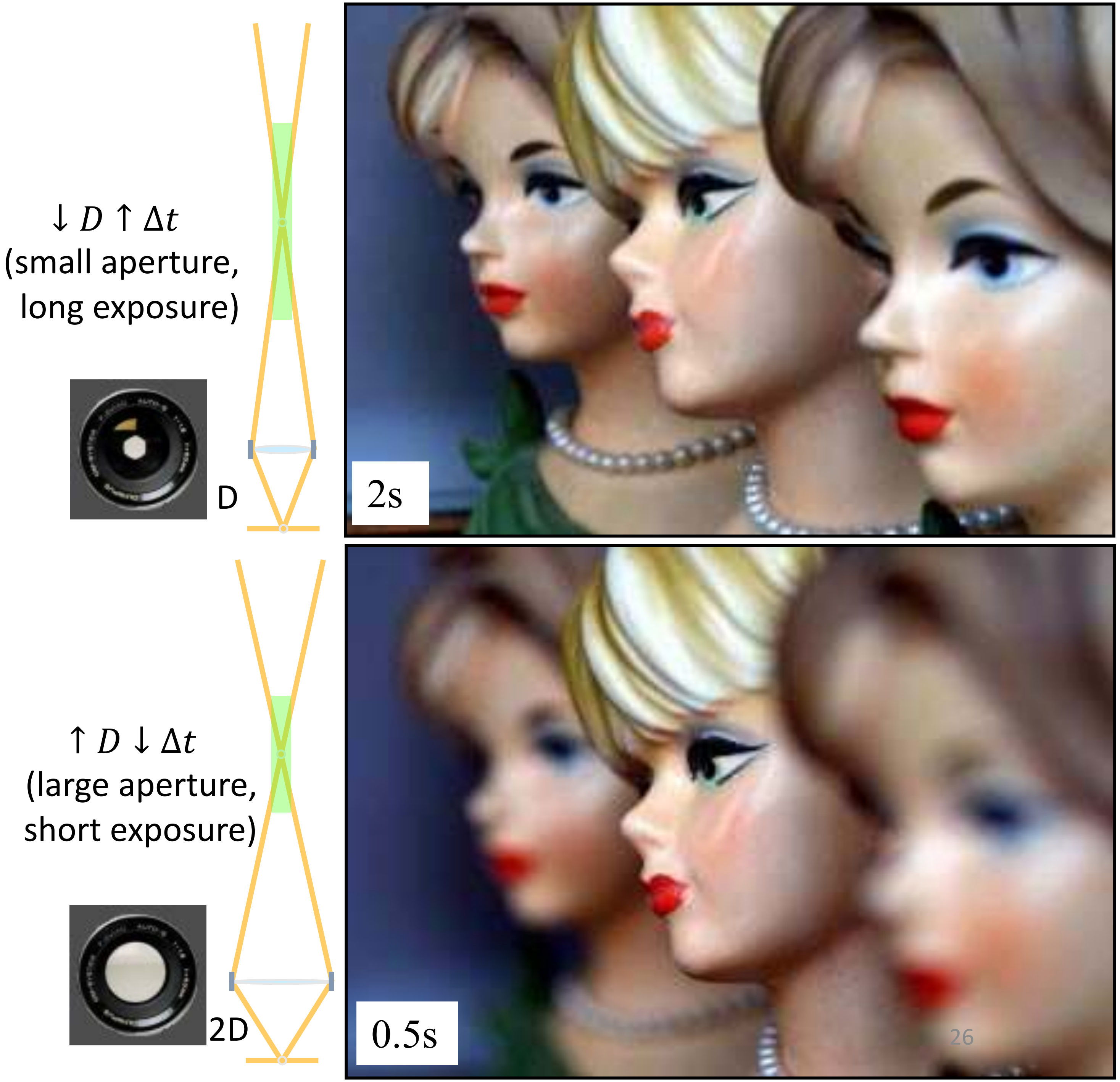
© Taylor Bennett

Shutter Speed

- The duration (Δt) of the exposure
- How long we allow photons to hit the sensor
- Often expressed as fractions of a second (i.e. 1/1000s)

Equal Exposures: Aperture and DoF

- Photons $\propto D^2 \Delta t$
- i.e. get correct exposure with different aperture and exposure times
- However, get different DoF:
  - $\uparrow D \downarrow \Delta t \Rightarrow$ small DoF
  - $\downarrow D \uparrow \Delta t \Rightarrow$ large DoF



ISO Film Speed
& Sensor Sensitivity

- The sensitivity of film/sensor to light
- Often expressed by ISO film speed (i.e. ISO 400)
- For a given exposure
  - High ISO ➔ brighter image
  - High ISO ➔ higher noise
- In a digital camera, translates to sensor's signal gain setting

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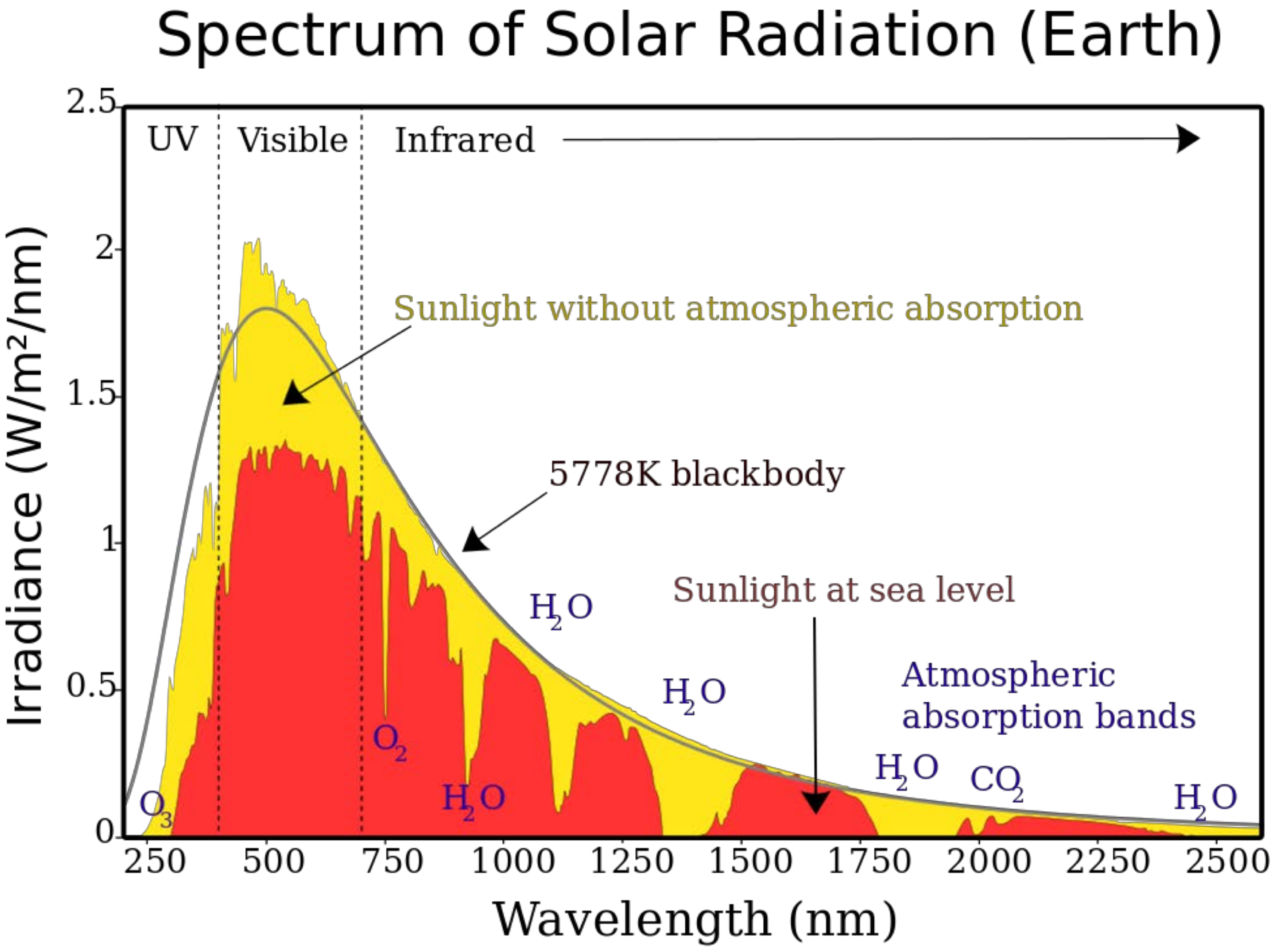
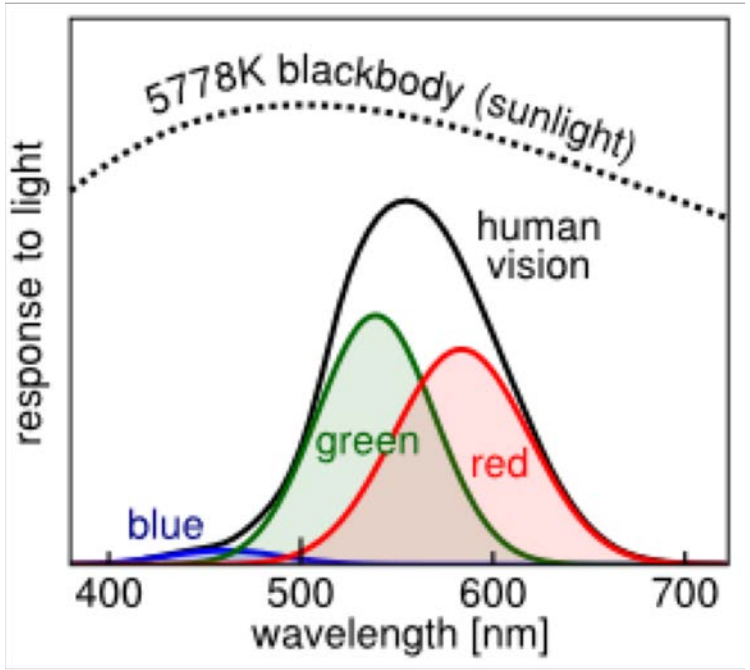
What do we see?

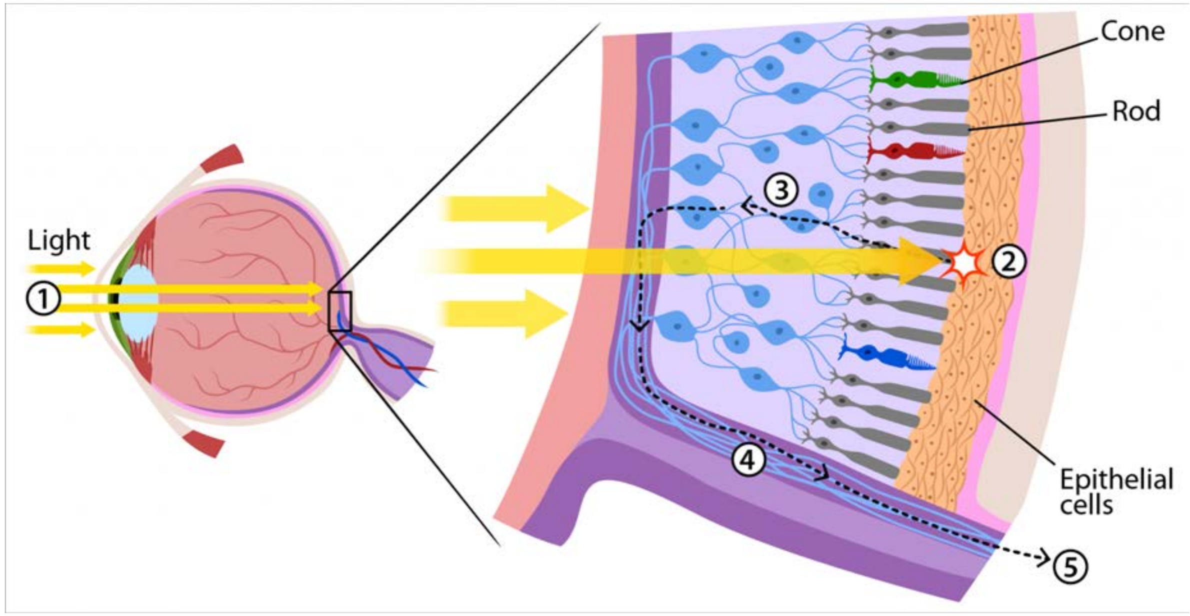
- We model film/sensors based on our own visual perception
- Everything on Earth has evolved in the context of the sun's spectral output
- Digital sensors often have wider spectral sensitivity, and are restricted to visible (IR cut filters)



What is Colour?

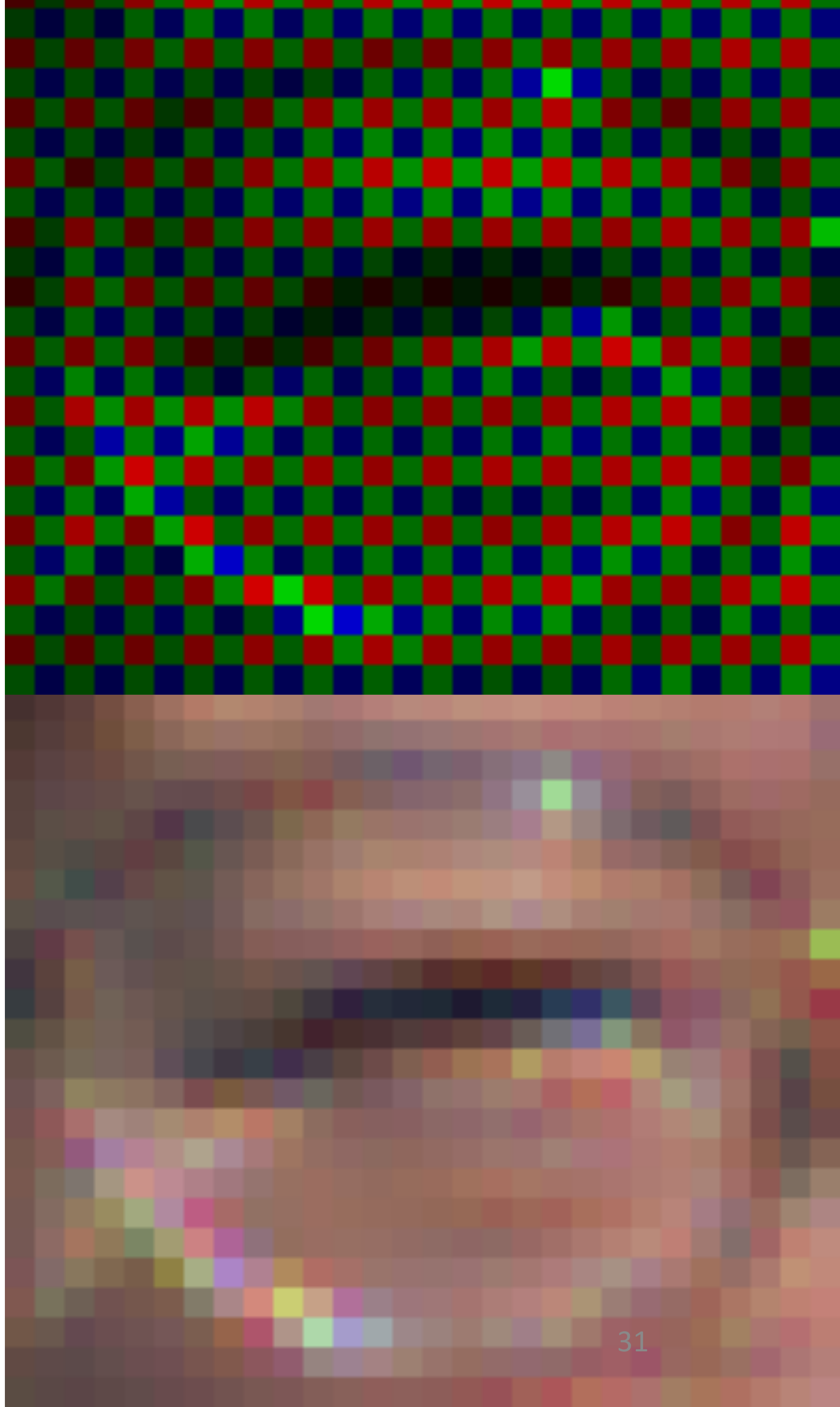
- Rod cells which are very highly sensitive to photos, used in dark. No colour vision!
- Cone cells, 3 types have different spectral sensitivity, roughly correspond to “RGB”





Color image acquisition

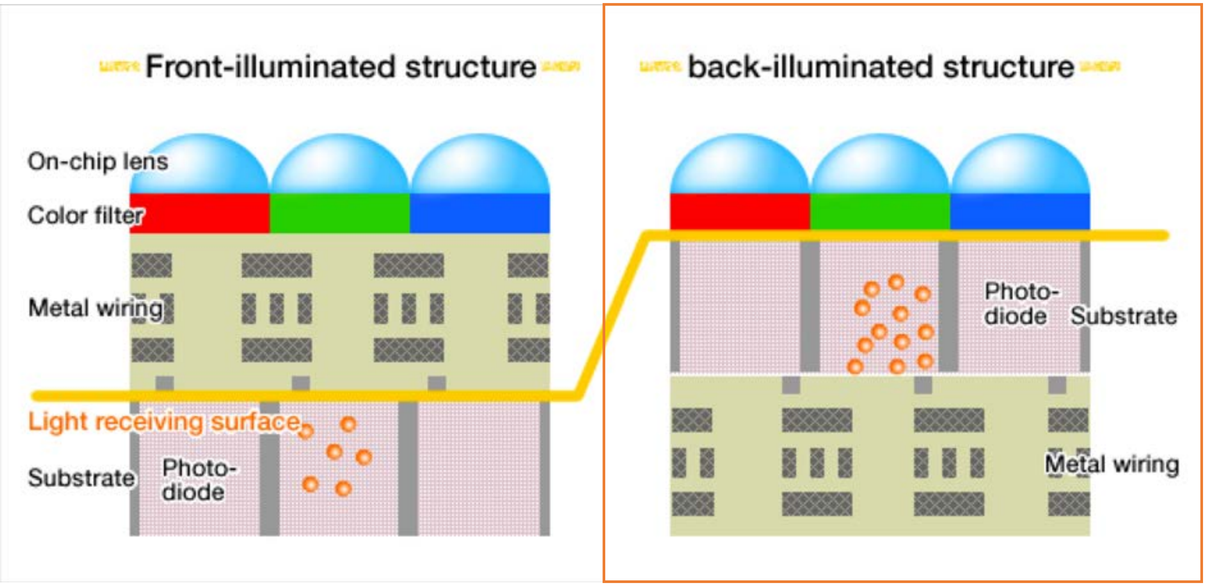
- All sensor pixels have same response curve – i.e. are monochromatic!
- Typically each pixel is made sensitive to one of R, G or B by placing filters over individual pixels
- Typical Bayer filter has 25% red, 25% blue and 50% green
- Full-colour images by computationally filling in missing R/G/B: “demosaicing”



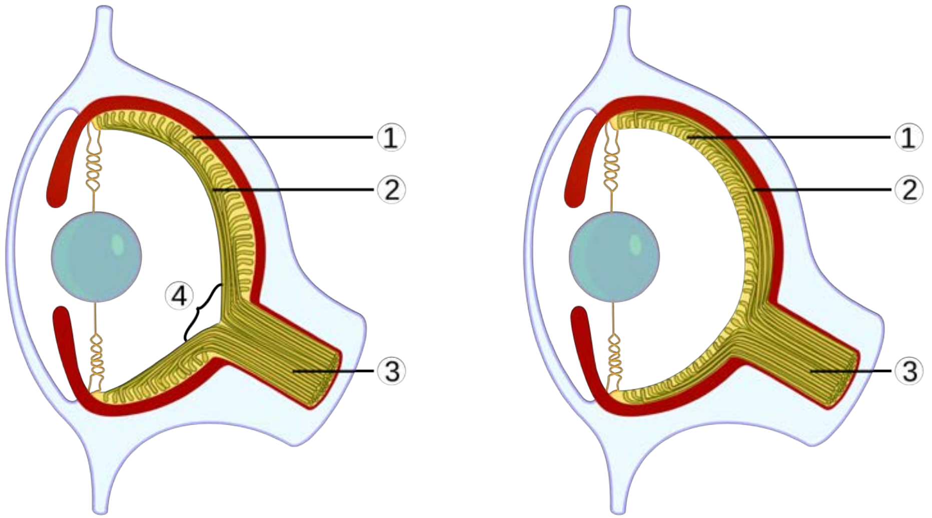
Cross-section of a CMOS Image Sensor

Back-illuminated structure

Aka. back-side illuminated (BSI) CMOS sensor



1. Retina
2. Nerve fibers
3. Optic nerves
4. Blind spot



Vertebrate vs. Cephalopod

RAW vs. Developed Images

The color image before “developing” (linear RAW image)

RAW vs. Developed Images

The color image before “developing” (contrast-enhanced)

RAW vs. Developed Images

The color image

after “developing” :

Demosaicing

+

Intensity mapping

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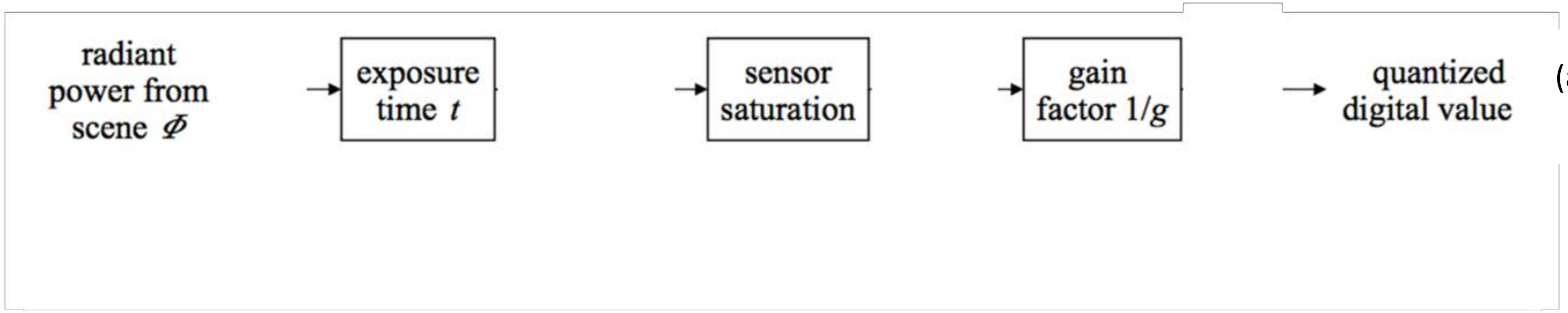
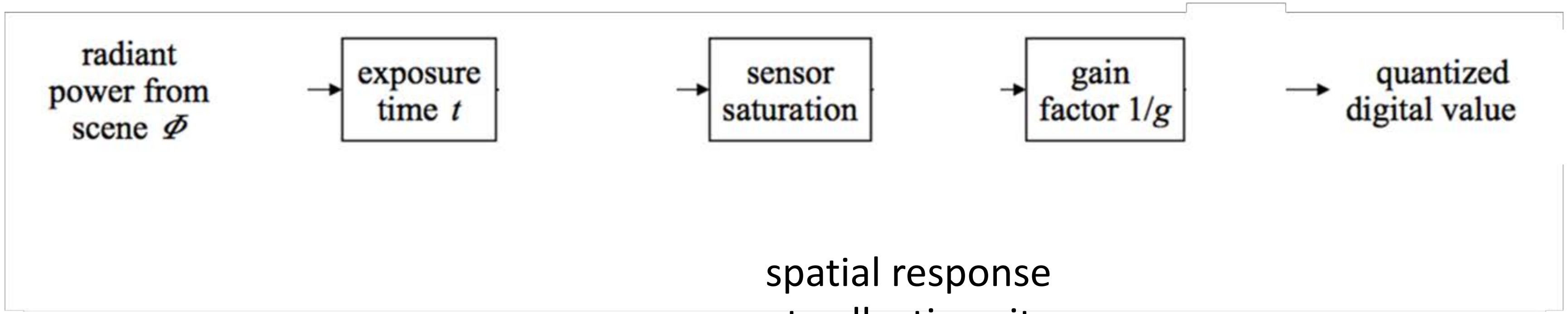
Digital Sensors: Photons → Digital Value



(a.k.a. "data number", or DN)

- Arriving photons cause photo-electrons (due to photoelectric effect)
- Charge accumulates as more photons hit the photo-diode
- After exposure time, amplifier converts charge to measurable voltage
- This voltage is converted to digital reading by an A-to-D converter

Photo-electrons to Radiant Power (Flux)



(DN)

spatial response at collection site (unitless)

$$\Phi = \iint\limits_{\overline{q}\ \lambda} H(\overline{q}, \lambda)\, S(\overline{q})\, Q(\lambda)\, d\overline{q}\, d\lambda$$

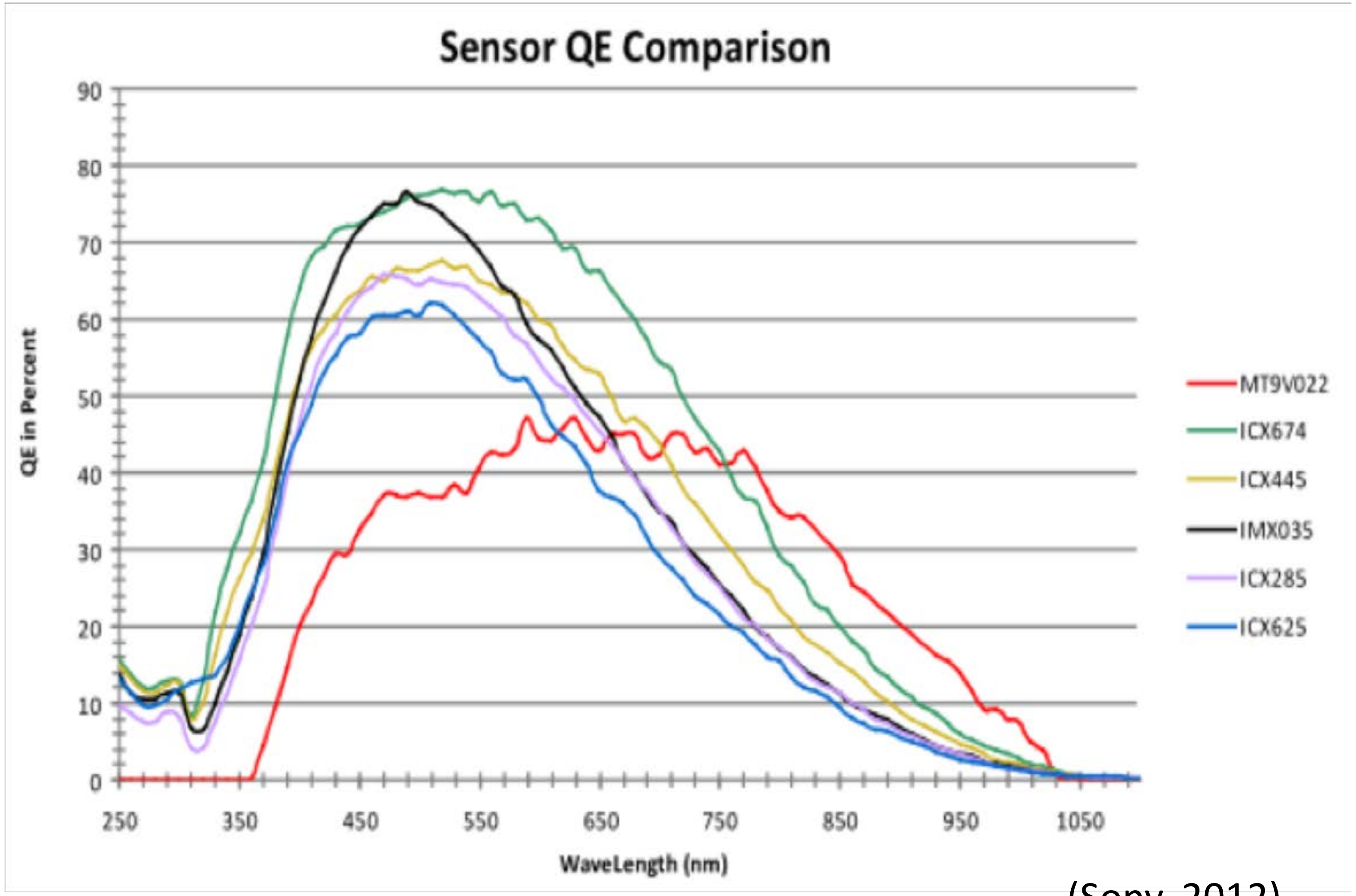
incident spectral irradiance (photons/s at given wavelength)

quantum device efficiency (electrons collected per incident photon at given wavelength)

pixel footprint

wavelength

Quantum Efficiency Curves



(Sony, 2012)

Lighting Levels vs. Average Photon Counts

radiant power from scene Φ → exposure time t → sensor saturation → gain factor $1/g$ → quantized digital value (DN)

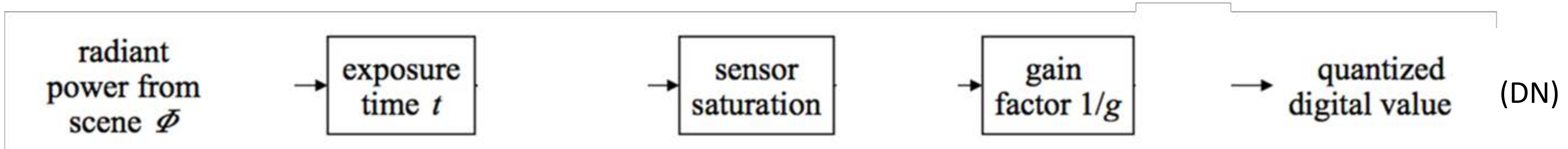
Φ $\quad$ $\Phi\Delta t$

	 Starry night	 Quarter moon	 Full moon	 Twilight	 Indoor Lighting	 Cloudy Day	 Sunny Day
Illuminance/irradiance $I_{src}\,(lux)$	2×10^{-3}	10^{-2}	1	10	10^{2}	10^{3}	10^{4}
$\Phi\Delta t =$ $J\ (e^-)$	7×10^{-4}	4×10^{-3}	.39	3.85	38.49	384.9	3,849

(Assuming: $Q(\lambda) = 0.5, \overline{q} = 1\mu m^2, \Delta t = 1/50$ sec, surface albedo $= 0.5$, aperture $= f/2.1$)

Cossairt et al., "When Does Computational Imaging Improve Performance?", IEEE transactions on Image Processing (TIP), May 2012

Digital Sensors: Photons → Digital Value



Φ $\quad$ $\Phi\Delta t + I_0$ $\quad$ $\min(\Phi\Delta t + I_0, I_m)$ $\quad$ $\dfrac{\min(\Phi\Delta t + I_0, I_m)}{g}$ $\quad$ $\mathrm{DN} = \left\lfloor \dfrac{\min(\Phi\Delta t + I_0, I_m)}{g} \right\rfloor$

black level $\quad$ saturation current $\quad$ gain

I_0 = black level: non-photoelectric (i.e. electrons) current from photo diode
I_m = saturation current: maximum non-discarded current from photodiode
g = amplifier gain: #electrons/DN or ISO (see http://clarkvision.com/articles/iso)

Note: DN obtained above has a linear relationship (up to saturation) with flux

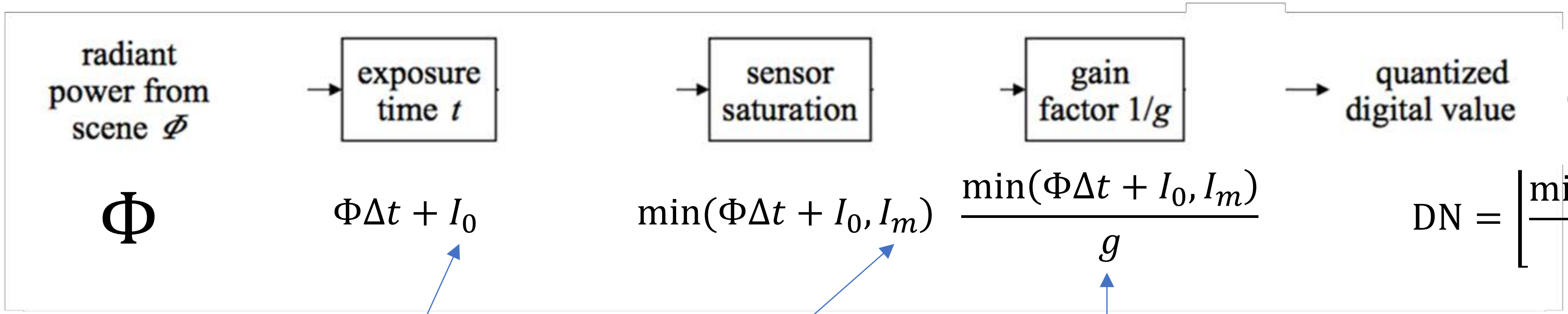
Linear Images Don’t Look good!

- The human visual system (HVS) doesn’t have a linear response

Gamma Correction

- The human visual system (HVS) doesn't have a linear response
- DNs are passed through a "gamma function" to compensate for HVS
- $f(DN) = \beta(DN)^{1/\gamma}$

Digital Sensors: Gamma Correction



(DN)

Φ

$\Phi\Delta t + I_0$

$\min(\Phi\Delta t + I_0, I_m)$

$\frac{\min(\Phi\Delta t + I_0, I_m)}{g}$

$\mathrm{DN} = \left\lfloor \frac{\min(\Phi\Delta t + I_0, I_m)}{g} \right\rfloor$

black level

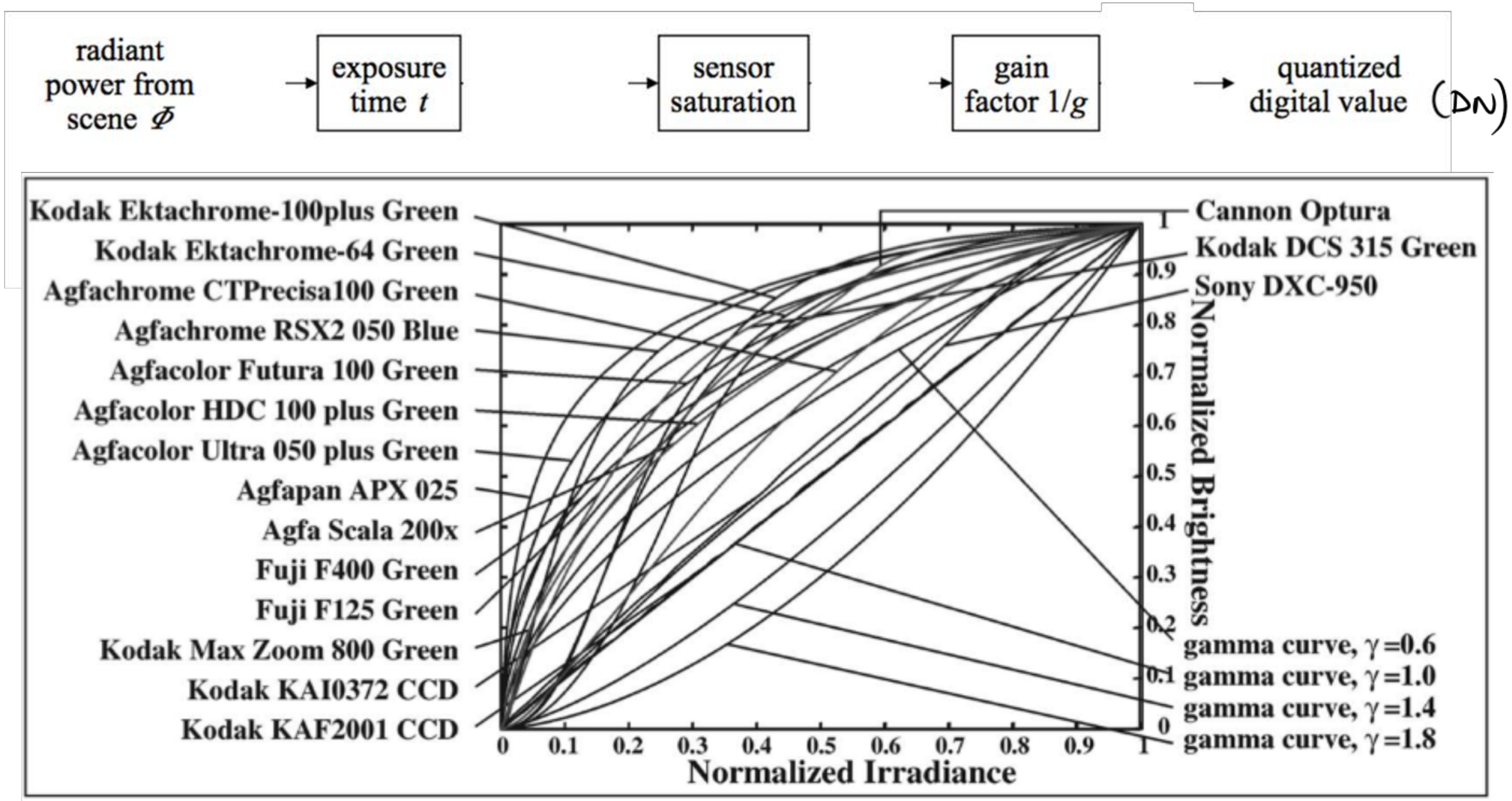
saturation current

gain

gamma correction: $$f(DN) = f\left(\left\lfloor \frac{\min(\Phi\Delta t + I_0, I_m)}{g} \right\rfloor\right)$$

This is also called the camera response function

Digital Sensors: Camera Response Functions



Grossberg et al., Modeling the Space of Camera Response Functions, PAMI 2004

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- **Key image artifacts**
- Understanding image noise

Defocus Blur

- Scene points of interest are “out of focus”
- not within the Dof

subject in focus

subject out of focus

Motion blur

- Camera moves significantly during exposure time
- More likely with:
  - Long exposures
  - Long focal length (zoom)

camera on tripod

4 sec @ f11 (ISO 100)

camera hand-held

4 sec @ f11 (ISO 100)

Pixel noise

- Incorrect exposure, not enough photons reaching sensor
- High ISO (gain) causes noise

ideally-exposed photo

4 sec @ f11 (ISO 100)

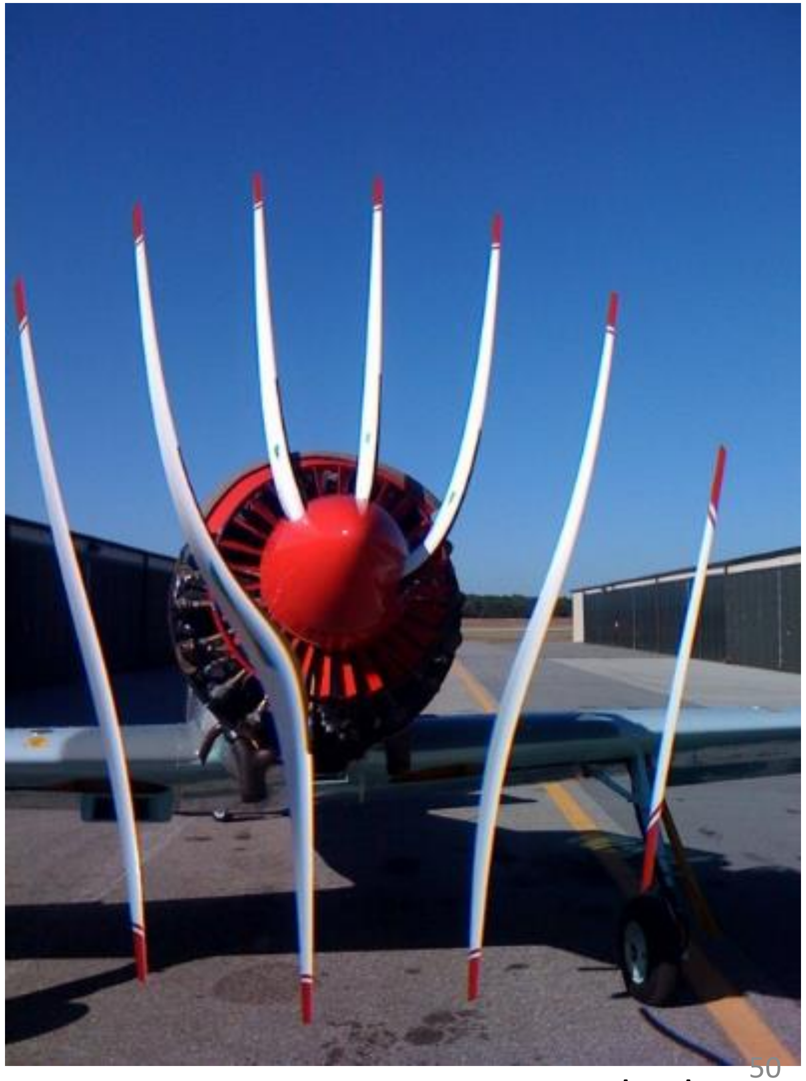
under-exposed photo

1/15 sec @ f11 (ISO 1600)

What’s Going on in These Photos?

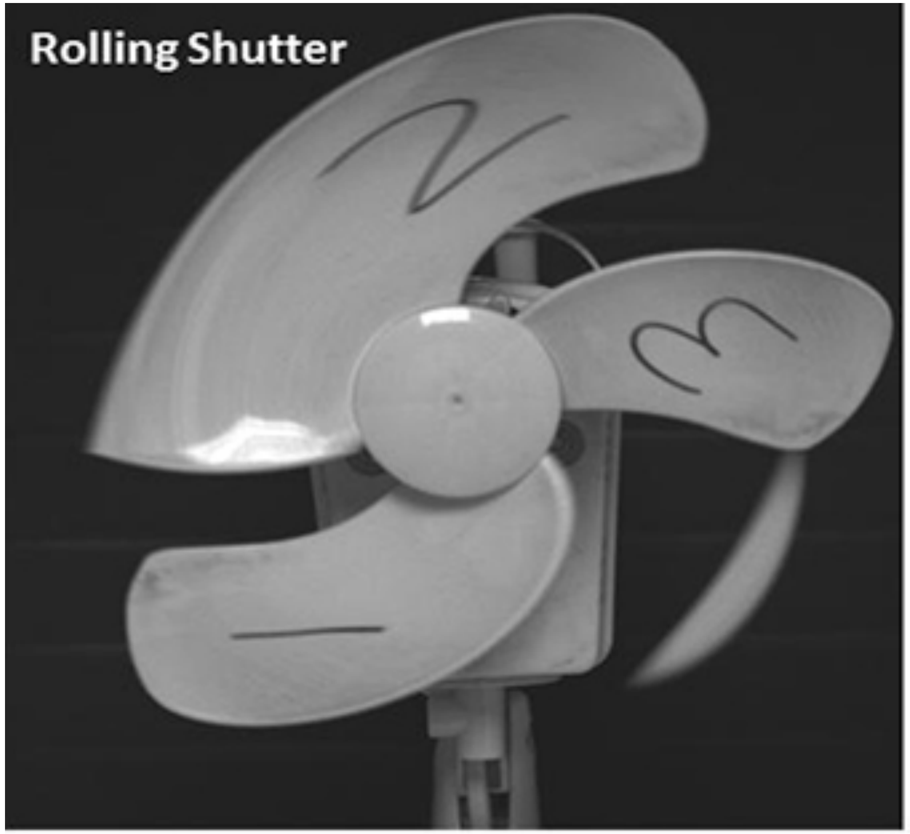
https://petapixel.com/2014/10/13/math-behind-rolling-shutter-phenomenon/

www.silent9.com



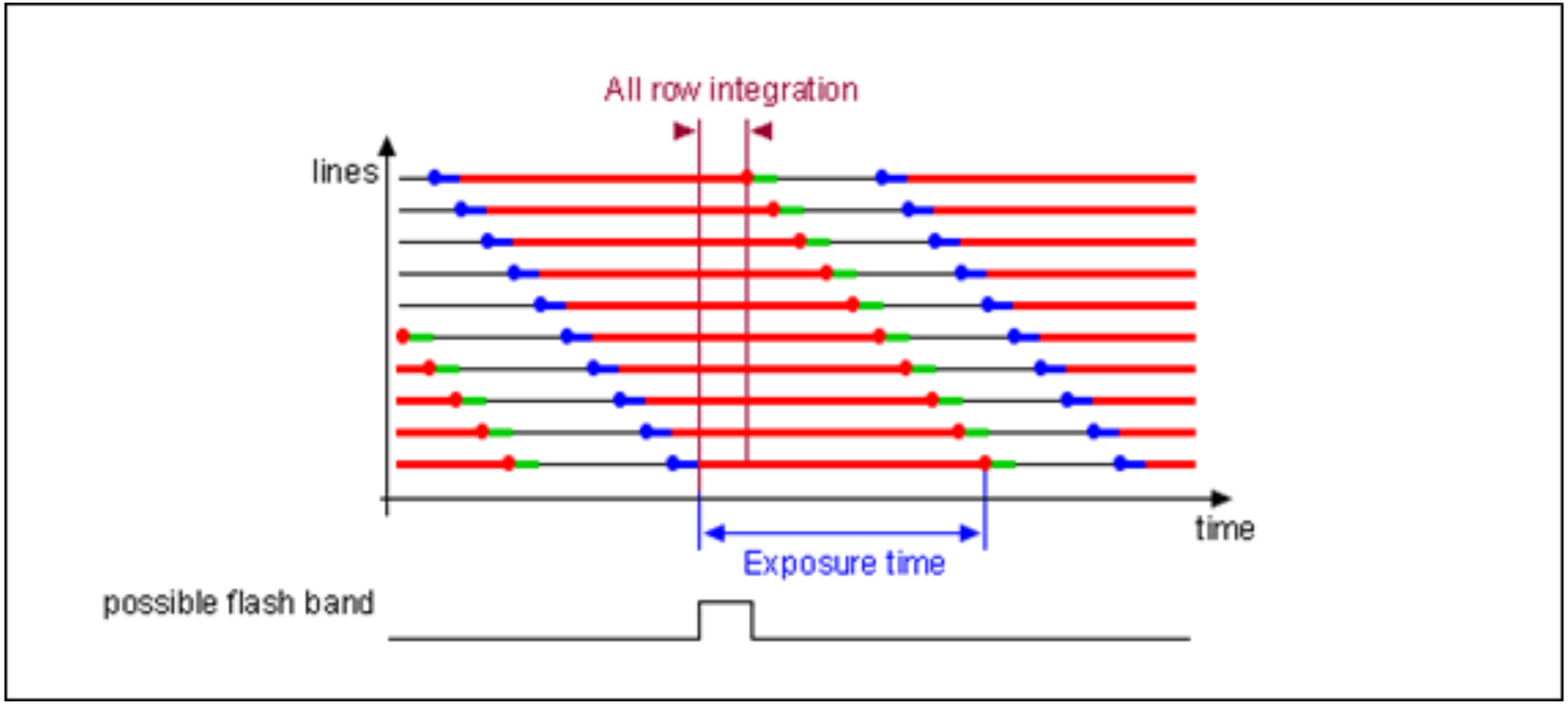
Joel Johnson

Rolling Shutter vs. Global Shutter



https://andor.oxinst.com/learning/view/article/rolling-and-global-shutter

Rolling Shutter Timing Diagram



https://www.matrix-vision.com/glossario.html

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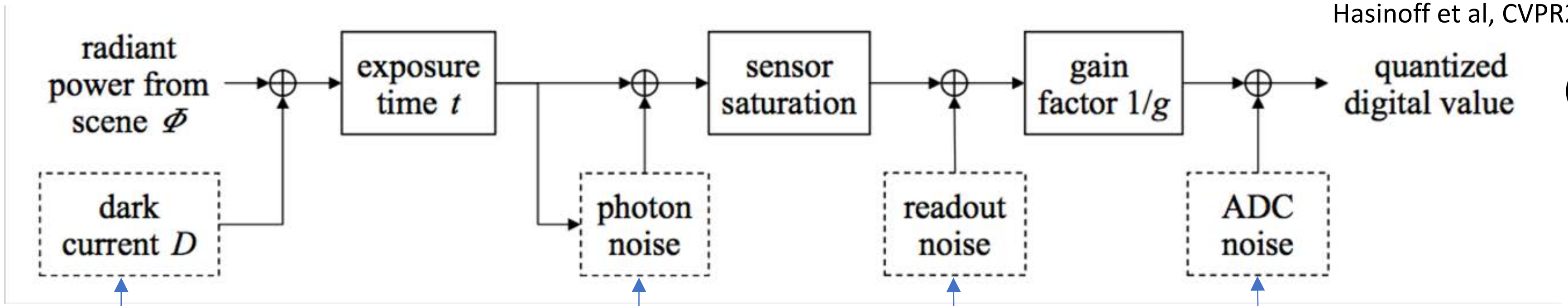
- **Understanding image noise**

Digital Sensors: Sources of Noise

Hasinoff et al, CVPR2010

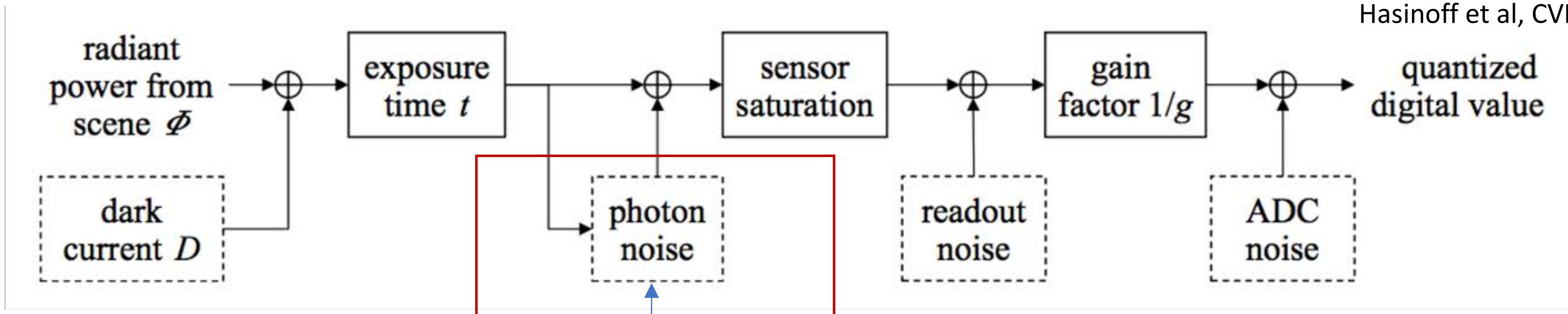


(DN)

Free electrons due to thermal energy	Photon arrival timing is random	Noise from readout electronics	Amplifier, A-to-D, quantization noise
Depends on temperature, measured in electrons/sec, independent of $\Phi\Delta t$	Depends on total photon arrivals, i.e. $\Phi\Delta t$	Independent Of $\Phi\Delta t$	Independent of $\Phi\Delta t$

Sources of Noise: Photon (a.k.a. Shot) Noise

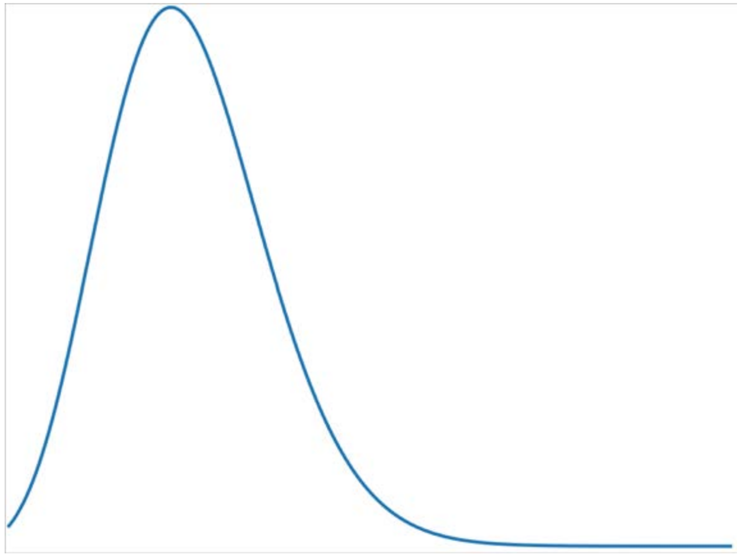
Hasinoff et al, CVPR2010



(DN)

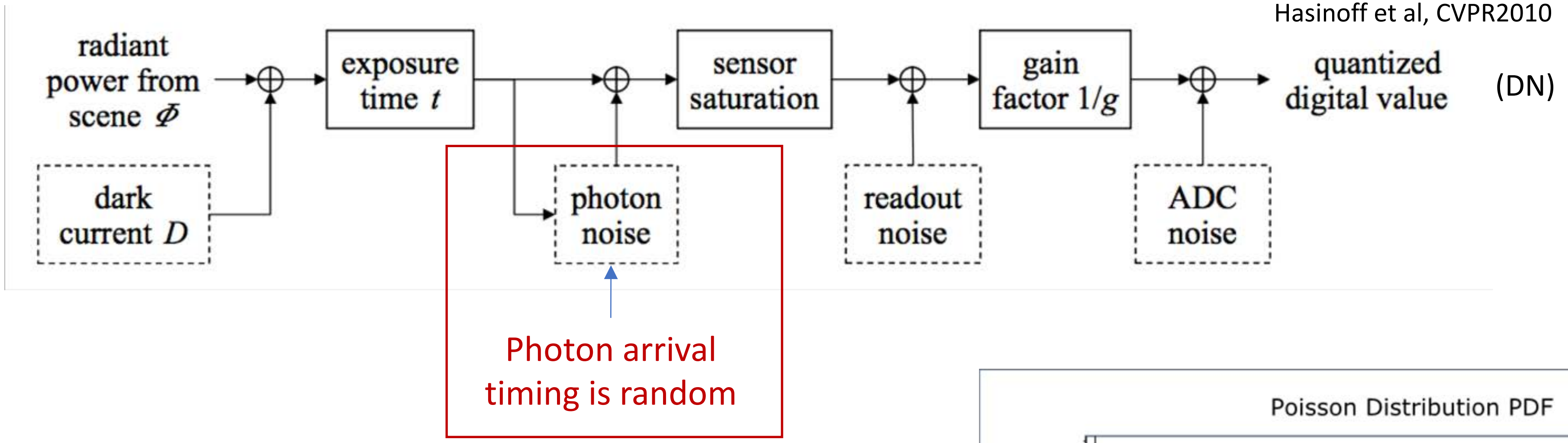
Photon arrival timing is random

- Shot noise is Poisson distribution with mean $\Phi\Delta t$
- Poisson: $P(\text{k events in } \Delta t, \text{mean } \lambda) = \frac{\lambda^k}{k!}e^{-\lambda}$
- $P(\text{\#received photons = k}) = \frac{\Phi\Delta t^k}{k!}e^{-\Phi\Delta t}$
- Largest source of noise for high exposures

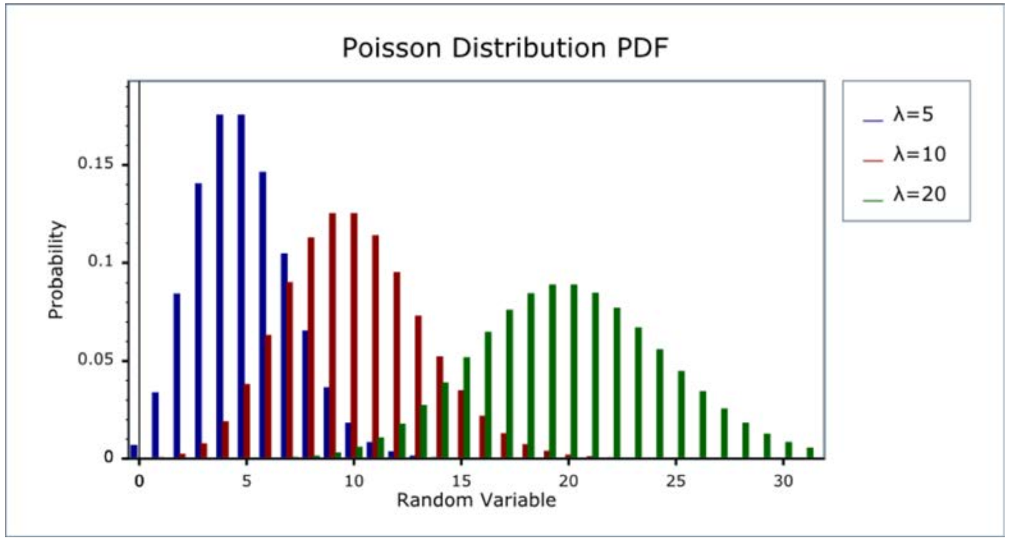


Sources of Noise: Photon (a.k.a. Shot) Noise

Hasinoff et al, CVPR2010

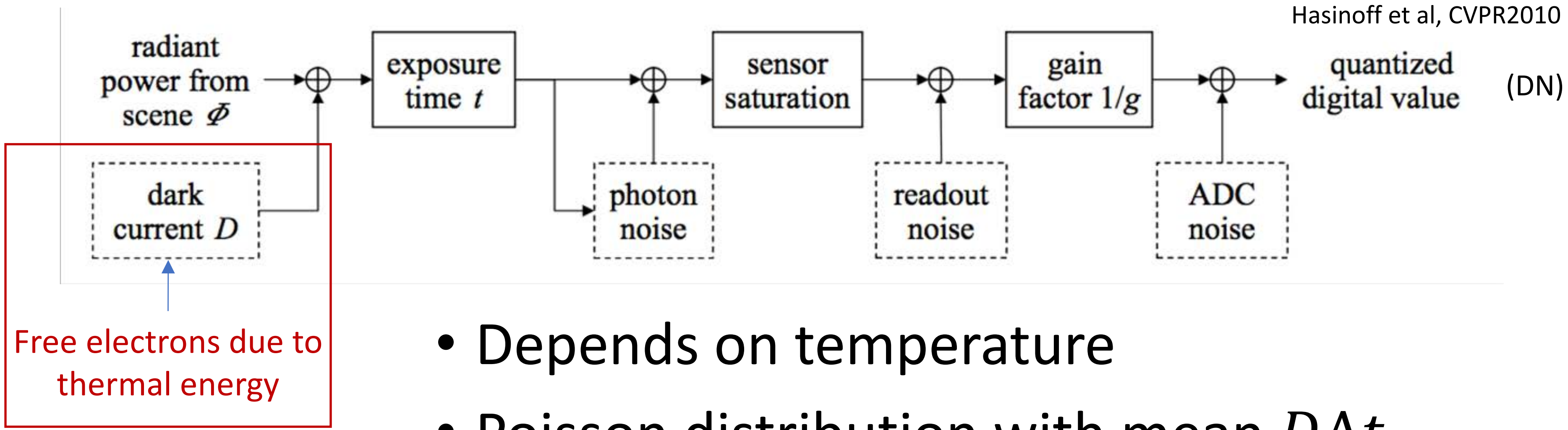


- For large enough mean λ $(\Phi\Delta t)$: $\text{Poisson}(\lambda) \approx \text{Normal}(\mu = \lambda, \sigma = \sqrt{\lambda})$
- Can approximate with Normal distribution for large $\Phi\Delta t$



http://www.boost.org/doc/libs/1_55_0/libs/math/doc/html/math_toolkit/dist_ref/dists/poisson_dist.html

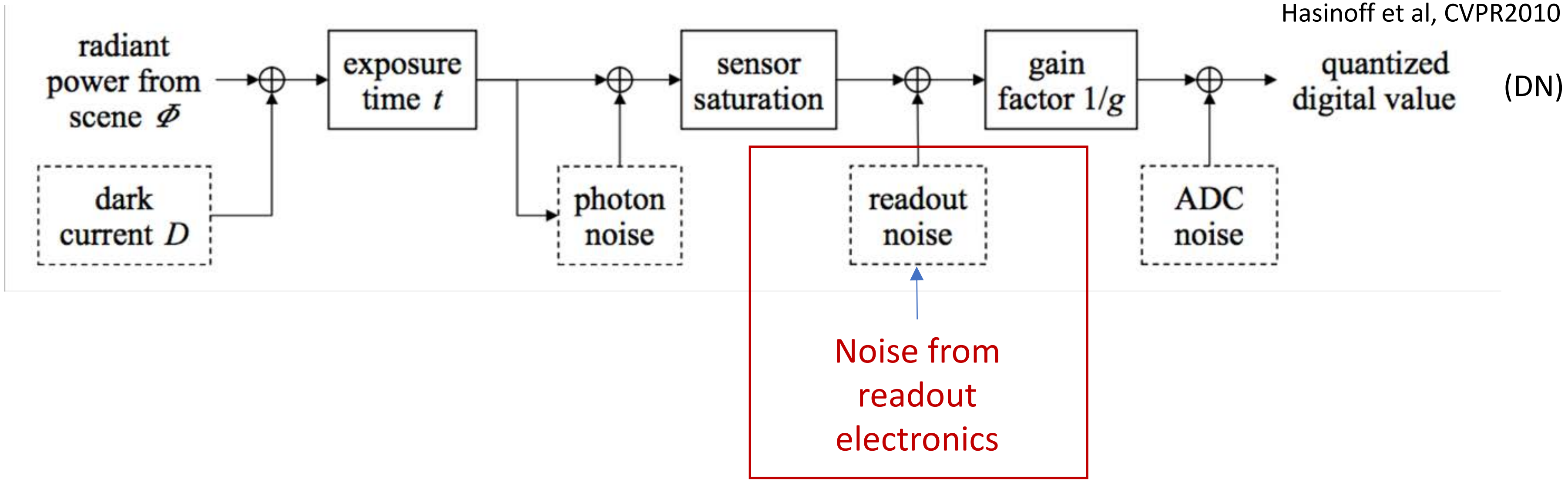
Sources of Noise: Dark Current Noise



- Depends on temperature
- Poisson distribution with mean $D\Delta t$
  - D is thermal electron rate (electrons/s)
- P(#received thermal electrons = k) $= \frac{D\Delta t^k}{k!} e^{-D\Delta t}$

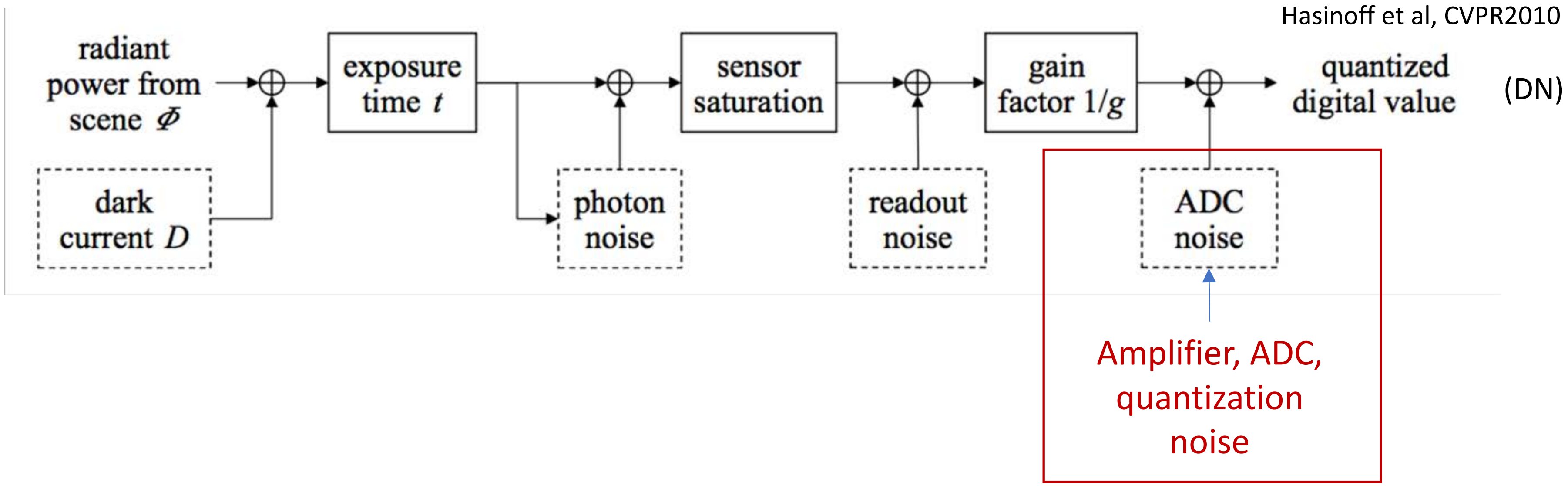
Sources of Noise: Readout Noise

Hasinoff et al, CVPR2010



- Normal distribution with $\mu = 0, \sigma = \sigma_r$
- Only depends on characteristics of electronics

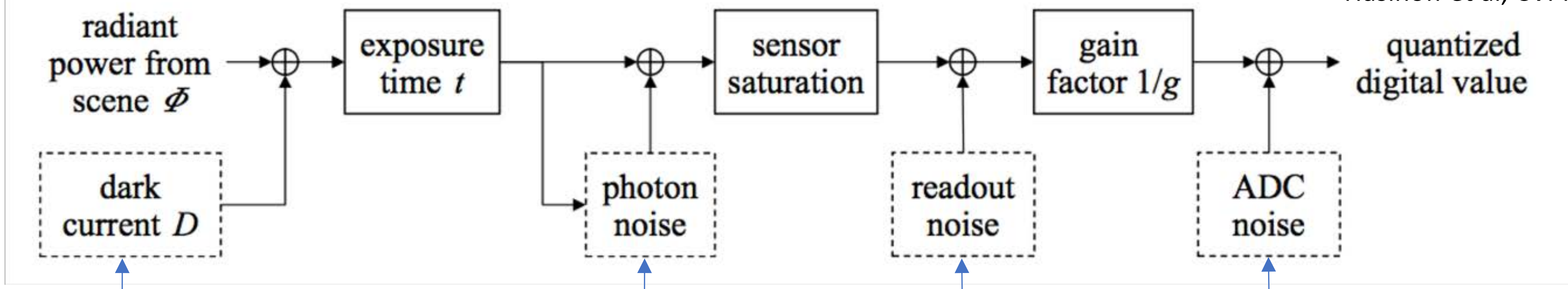
Sources of Noise: ADC & Quantization Noise



- Normal distribution with $\mu = 0, \sigma = \sigma_{ADC}$
- Amplifier noise (depends on gain/ISO) is largest source of noise for low exposures

Sources of Noise: Putting it all Together

Hasinoff et al, CVPR2010



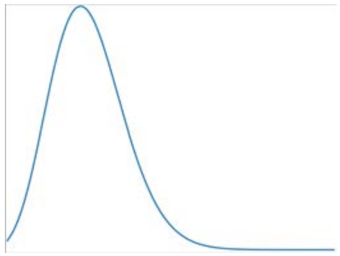
(DN)

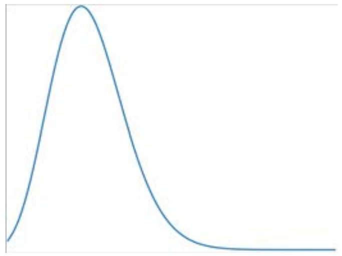
Free electrons due to thermal energy

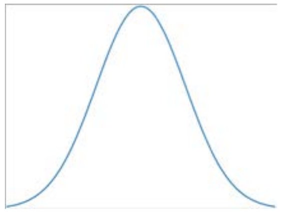
Photon arrival timing is random

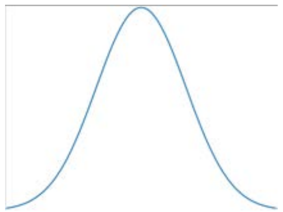
Noise from readout electronics

Amplifier, A-to-D, quantization noise









Poisson$(\lambda = \Phi\Delta t)$

Large $\Phi\Delta t$:

$\approx \mathrm{Normal}(\mu = \lambda, \sigma = \sqrt{\lambda})$

Poisson$(\lambda = D\Delta t)$

Large $D\Delta t$:

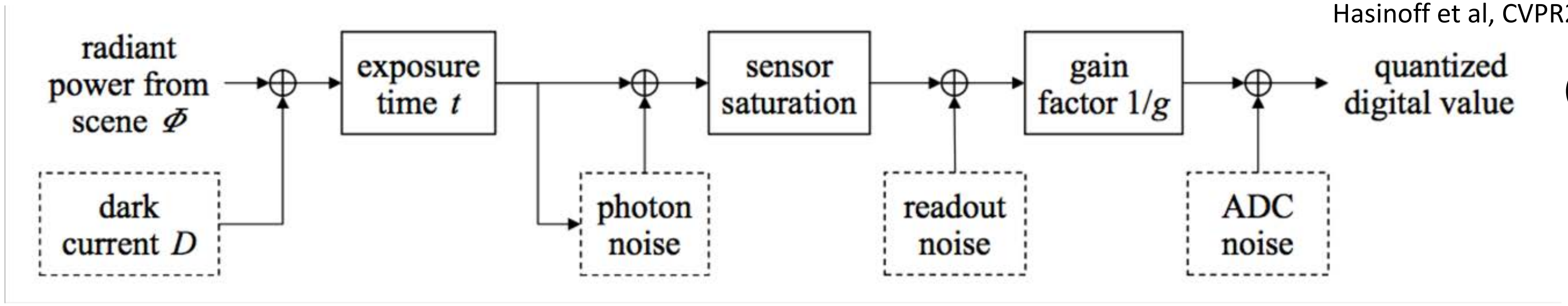
$\approx \mathrm{Normal}(\mu = \lambda, \sigma = \sqrt{\lambda})$

Normal$(\mu = 0, \sigma = \sigma_r)$

Normal$(\mu = 0, \sigma = \sigma_{ADC})$

Sources of Noise: E.g., Canon EOS 5D Mark 2

Hasinoff et al, CVPR2010



(DN)

$$\sigma_r + \sigma_{ADC} \cdot g$$

$$\log_2\left(\frac{max\ intensity}{\min intensity}\right) = \log_2\left(\frac{I_m}{\sigma_r + \sigma_{ADC} \cdot g}\right)$$

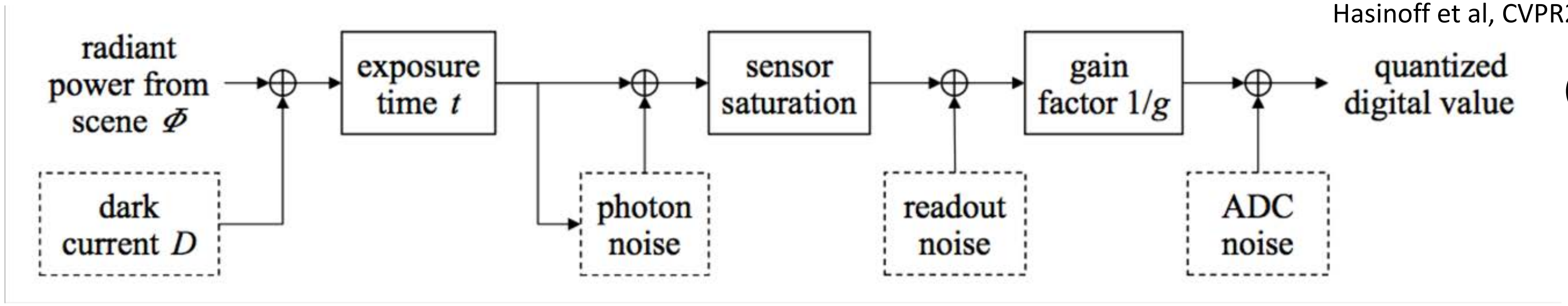
g $\quad$ I_m

ISO	Gain e/DN	Apparent Read Noise (electrons)	Maximum signal (electrons)	Measured Dynamic range stops
100	5.04	34.9	68900	10.9
200	2.52	18.3	32400	10.8
400	1.26	9.8	16200	10.7
800	0.63	5.6	8100	10.5
1600	0.315	3.6	4050	10.1
3200	0.157	2.7	2030	9.6
6400	0.079	2.5	1000	8.6
12800	0.039	2.1	500	7.9
25600	0.0197	2.05	250	6.9

http://www.clarkvision.com

Putting It All Together

Hasinoff et al, CVPR2010



(DN)

$$\text{mean}(e^-) = \min\{I_0 + \phi t + Dt, I_m\}$$
$$\text{variance}(e^-) = \phi t + Dt + I_0 + \sigma_r^2 + \sigma_{ADC}^2 \cdot g^2$$

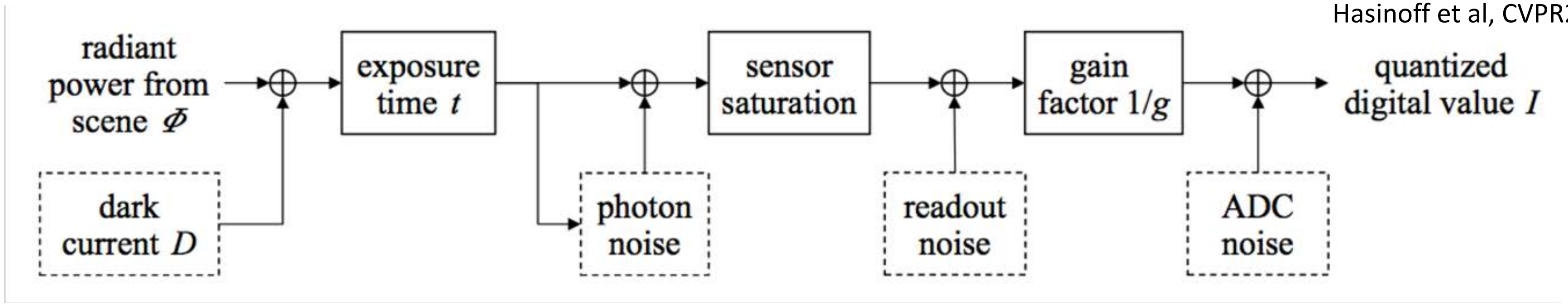
$$\text{mean}(DN) = \min\{\frac{I_0+\phi t+Dt}{g}, \frac{I_m}{g}\}$$
$$\text{variance}(DN) = \frac{\phi t}{g^2} + \frac{Dt}{g^2} + \frac{I_0+\sigma_r^2}{g^2} + \sigma_{ADC}^2$$

Photon term & dark current term are additive

Hasinoff et al, CVPR2010

Quantifying the Effect of Noise: the SNR

Hasinoff et al, CVPR2010



- Signal-to-noise ratio (SNR) = $10\log_{10}\frac{mean(DN)^2}{variance(DN)}$

mean(DN)= $\min\{\frac{I_0+\phi t+Dt}{g}, \frac{I_m}{g}\}$

variance(DN)= $\frac{\phi t}{g^2}+\frac{Dt}{g^2}+\frac{I_0+\sigma_r^2}{g^2}+\sigma_{ADC}^2$

Quantifying the Effect of Noise: Example

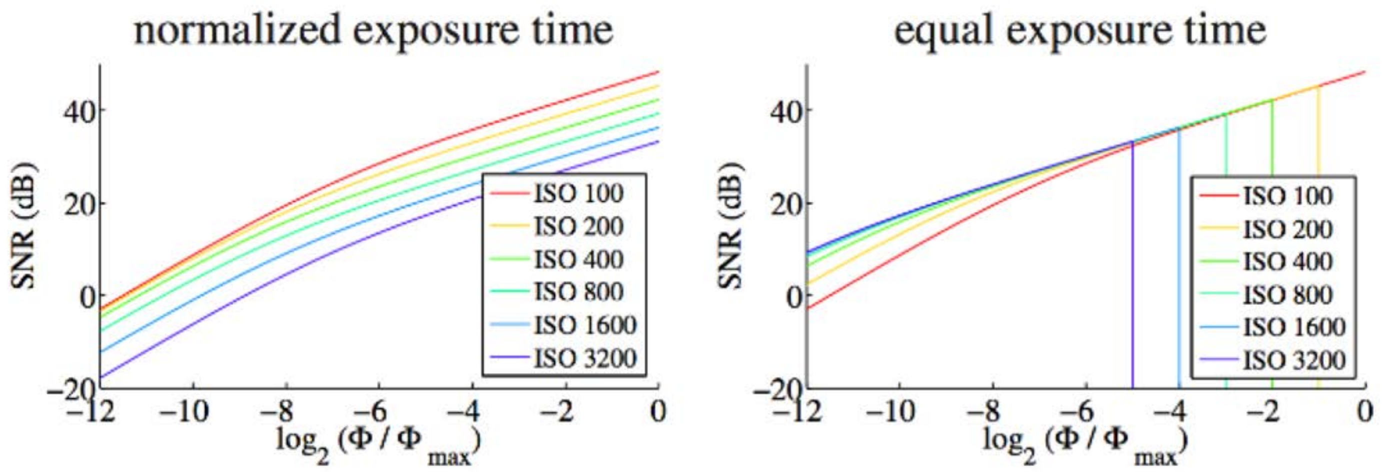
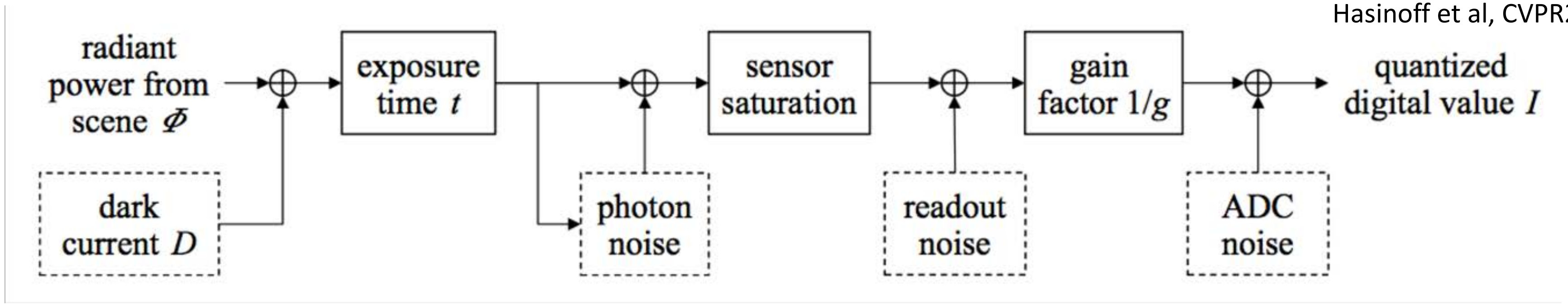


Figure 2. SNR for the Canon 1D Mark III, at various ISO settings, as a function of the radiant power from the scene, Φ. **Left:** Exposure time adjusted for each ISO to keep $\Phi t/g$ constant (*e.g.*, at ISO 800, we expose for 1/8 the time as for ISO 100). In this setting, higher ISOs record less electrons and so have lower SNR. **Right:** Exposure time held constant, so that all ISOs record the same number of electrons. Higher ISOs have higher SNR for a given scene brightness, especially in the darkest parts of the scene, but they also lead to earlier pixel saturation.

Hasinoff et al, CVPR2010

Putting It All Together

Hasinoff et al, CVPR2010



- Most common (but inaccurate) simplifications:
  - Ignore photon + dark current
  - Ignore camera response function

$$\text{mean}(DN) = \min\{\frac{I_0+\phi t+Dt}{g}, \frac{I_m}{g}\}$$

$$\text{variance}(DN) = \frac{\phi t}{g^2} + \frac{Dt}{g^2} + \frac{I_0+\sigma_r^2}{g^2} + \sigma_{ADC}^2$$