Topic 09:

The Camera

- Basic lens geometry
- Basic camera controls
- Relation of image irradiance to the lens & aperture
- From irradiance to digital numbers
- Image noise
- Rolling-shutter cameras

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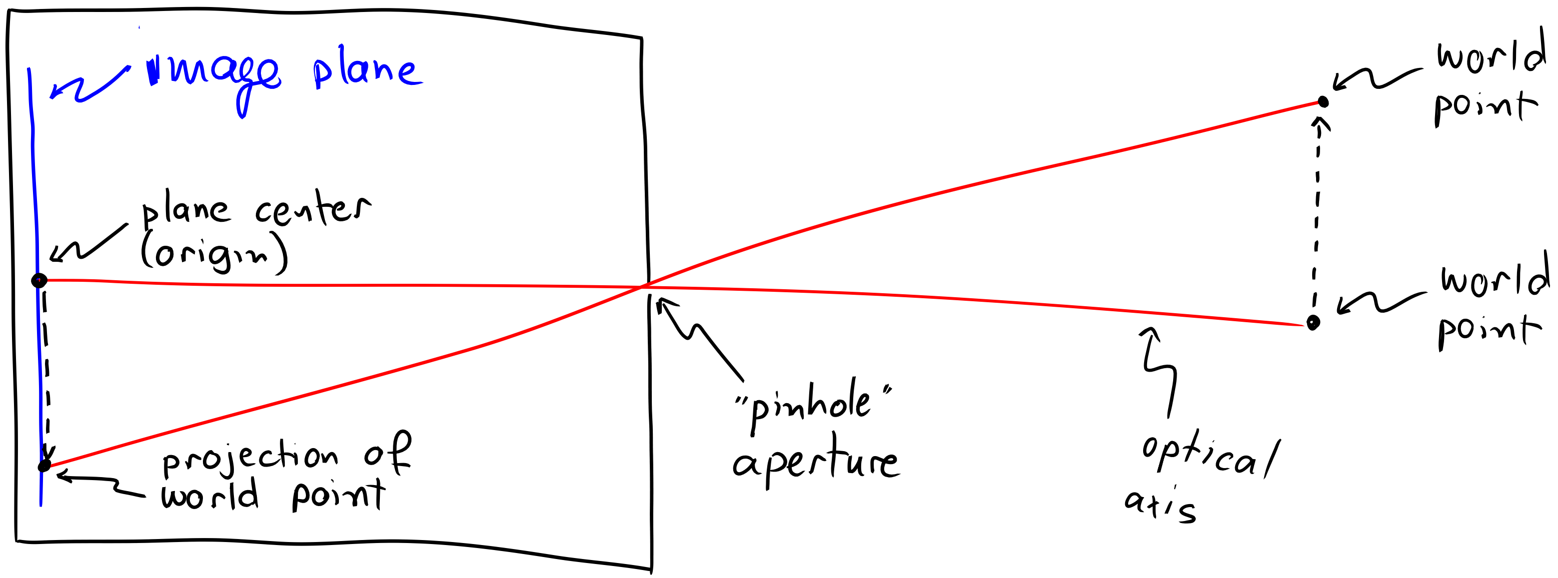
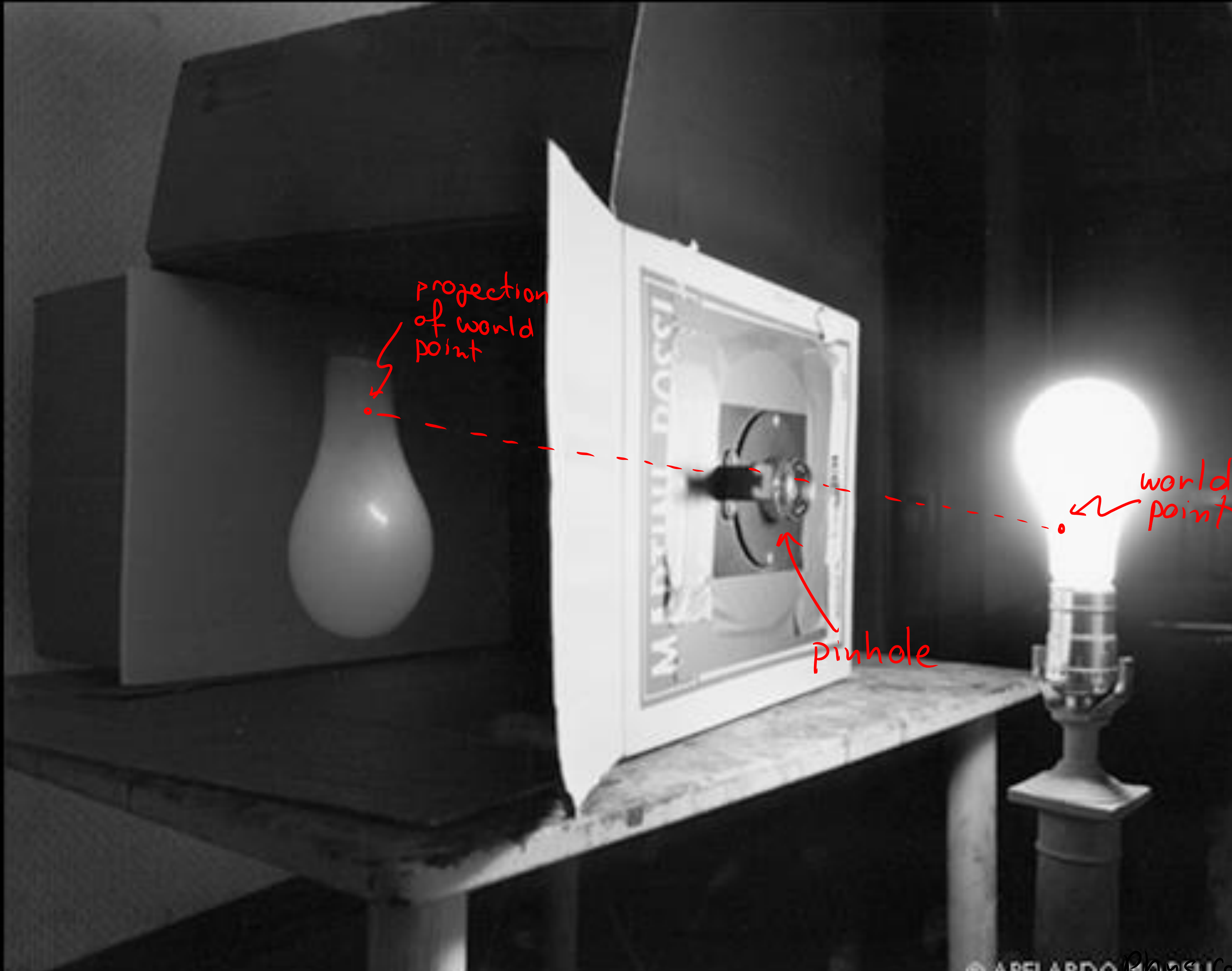
The Pinhole Camera



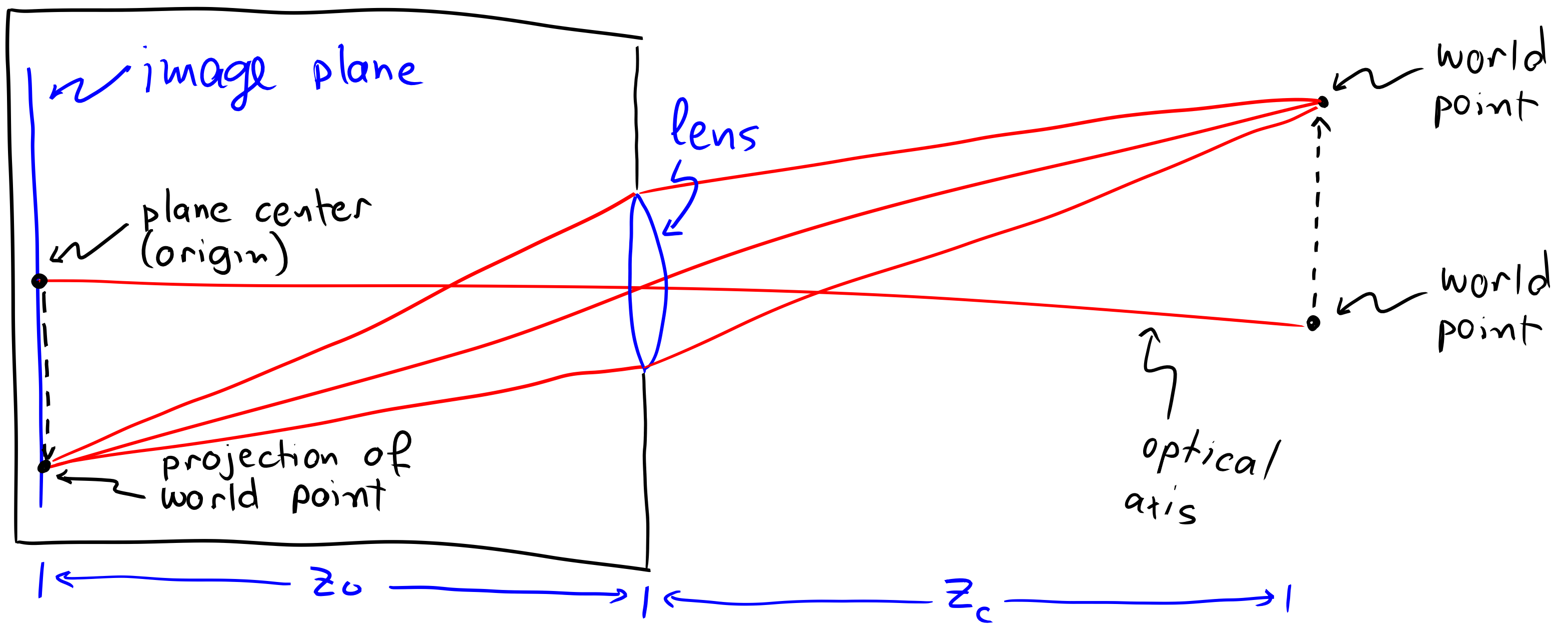


Light Bulb, 1991

www.lensculture.com/morell.html

Camera Obscura Image of Manhattan View Looking South in Large Room, 1996

Simple Lens-Based Camera & Thin-Lens Law



When $z_c \to \infty$, $z_o \to f$

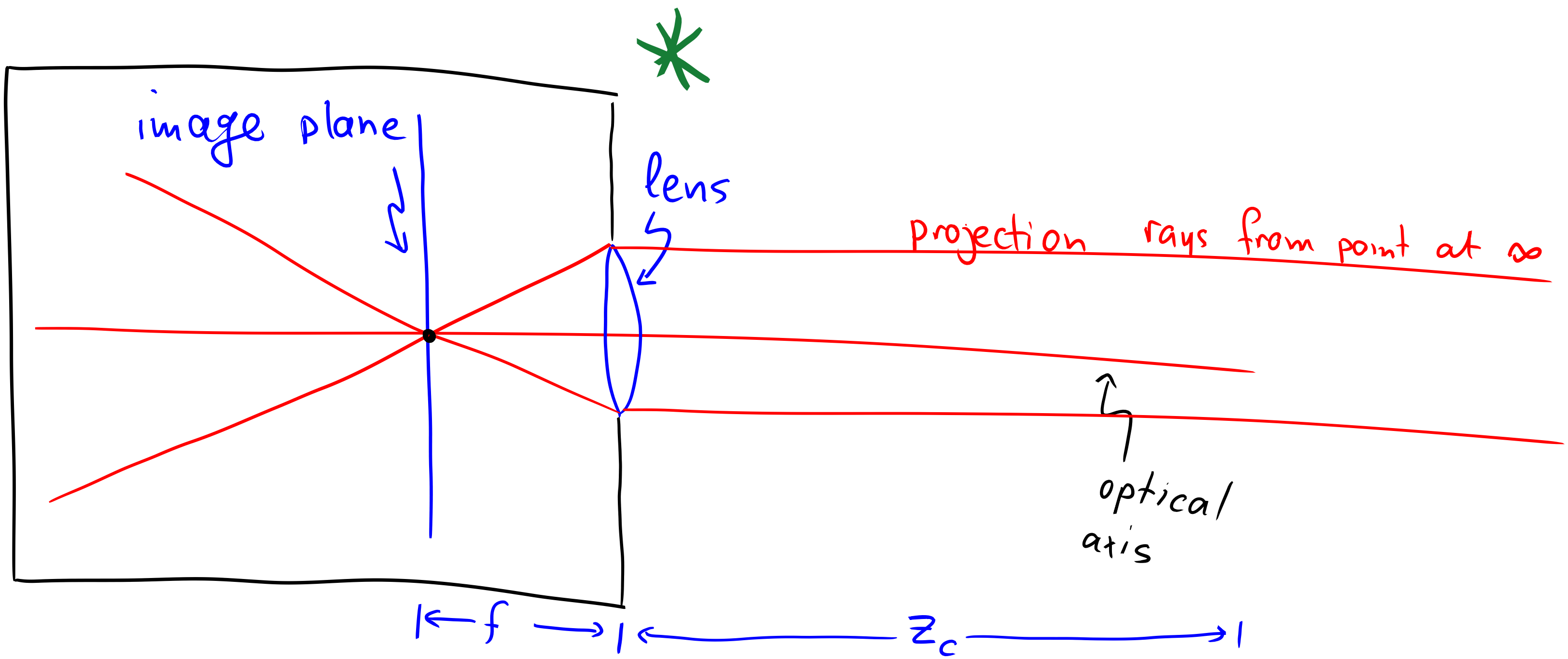
So f is the distance at which rays converge for a world point at ∞

Thin-lens law:

$$\boxed{\frac{1}{z_o} + \frac{1}{z_c} = \frac{1}{f}}$$

focal length of lens

Simple Lens-Based Camera & Thin-Lens Law



When $z_c \to \infty$, $z_0 \to f$

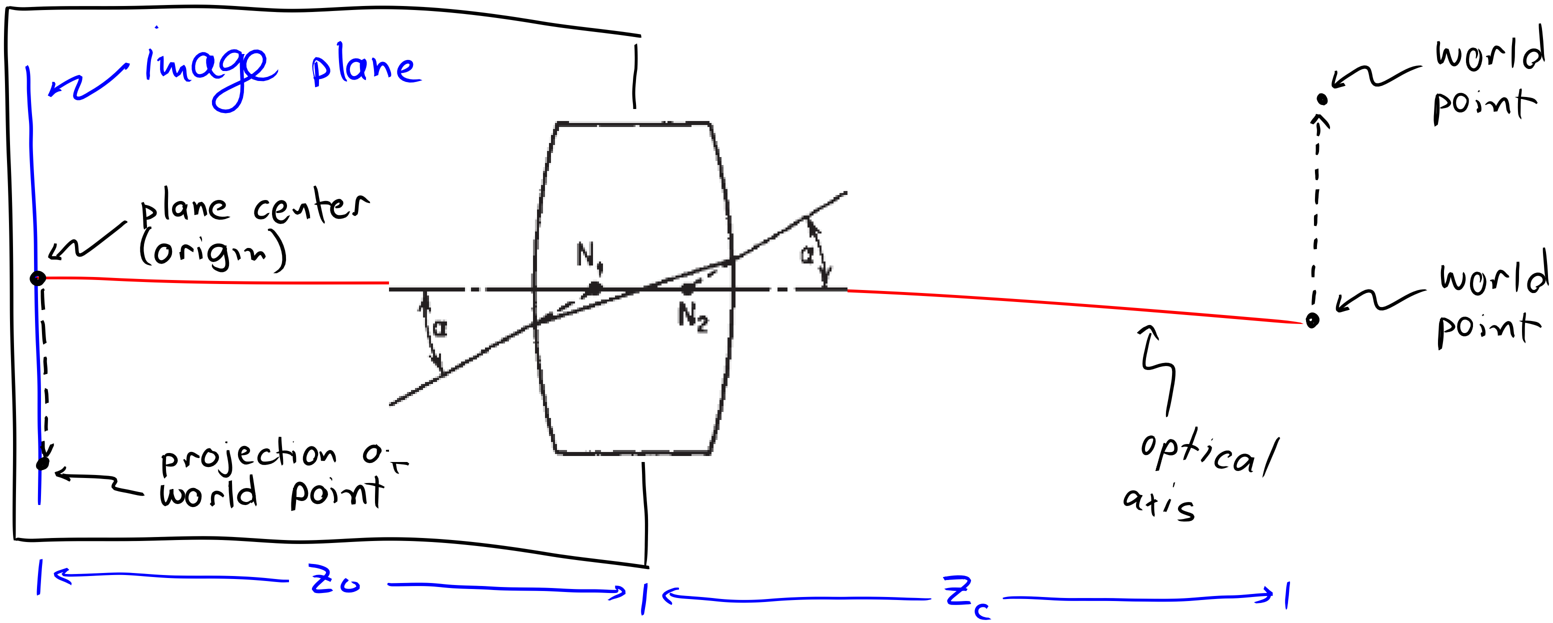
So f is the distance at which rays converge for a world point at ∞

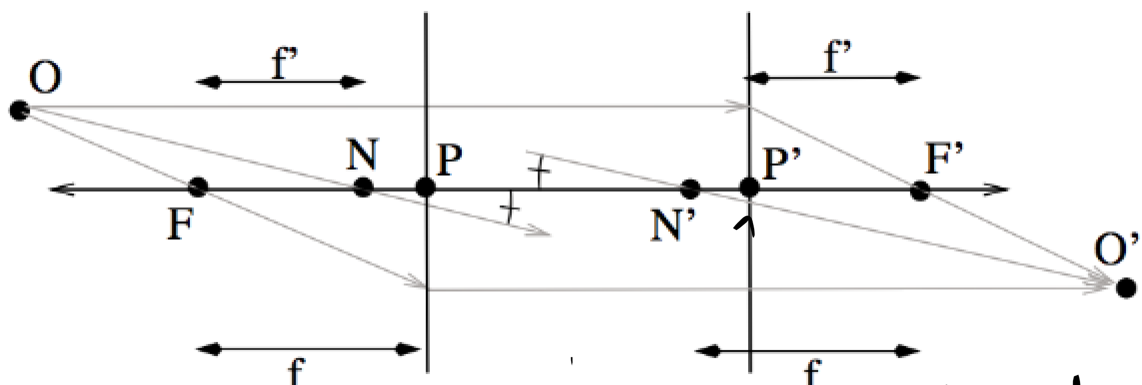
Thin-lens law:

$$\frac{1}{z_0} + \frac{1}{z_c} = \frac{1}{f}$$

When objects are very far, projection is well-approximated by orthographic projection

Thick Lenses





(see handout for explanation)

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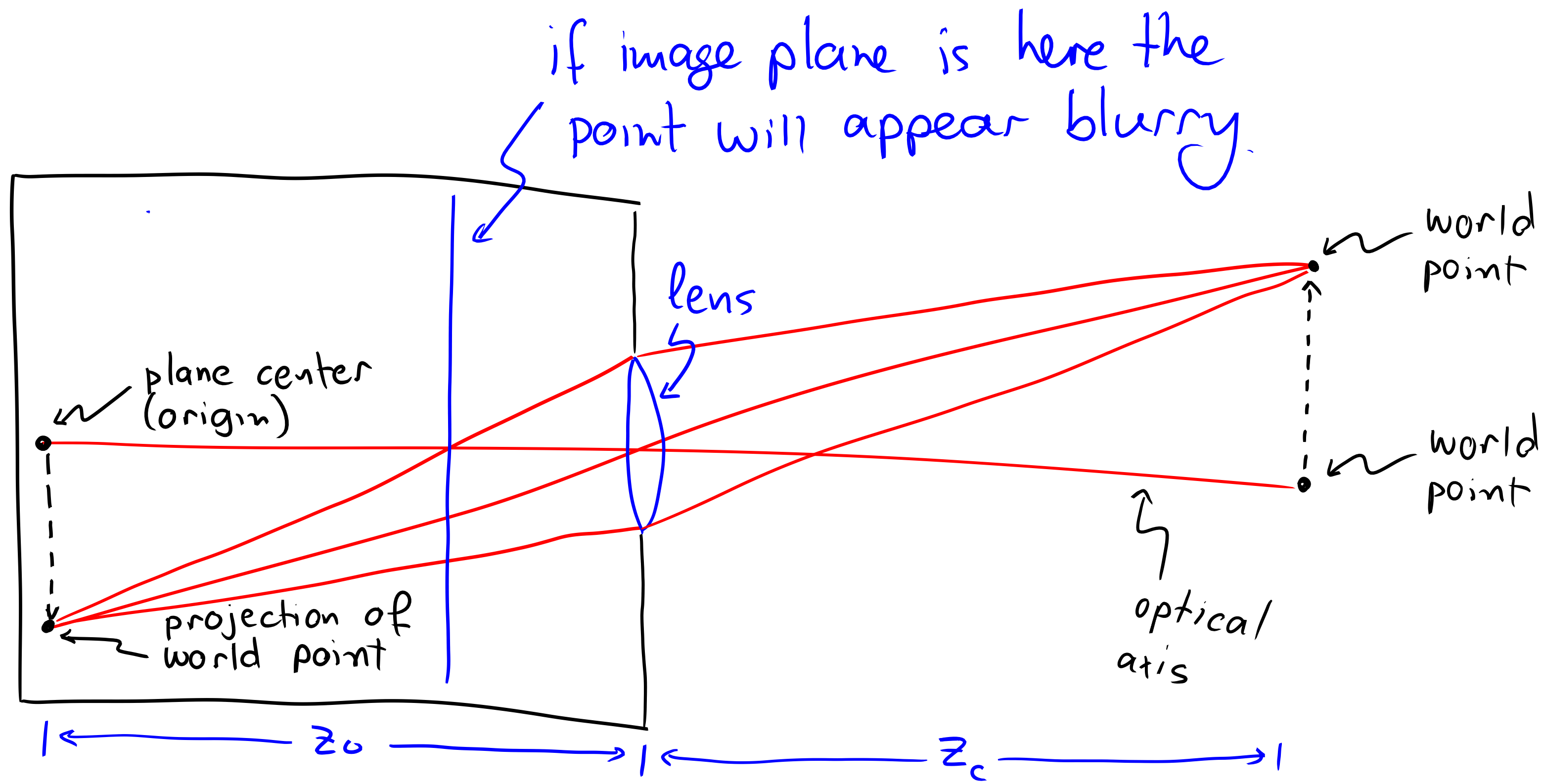
- **Basic camera controls**
- Relation of image irradiance to the lens & aperture
- From irradiance to digital numbers
- Image noise
- Rolling-shutter cameras

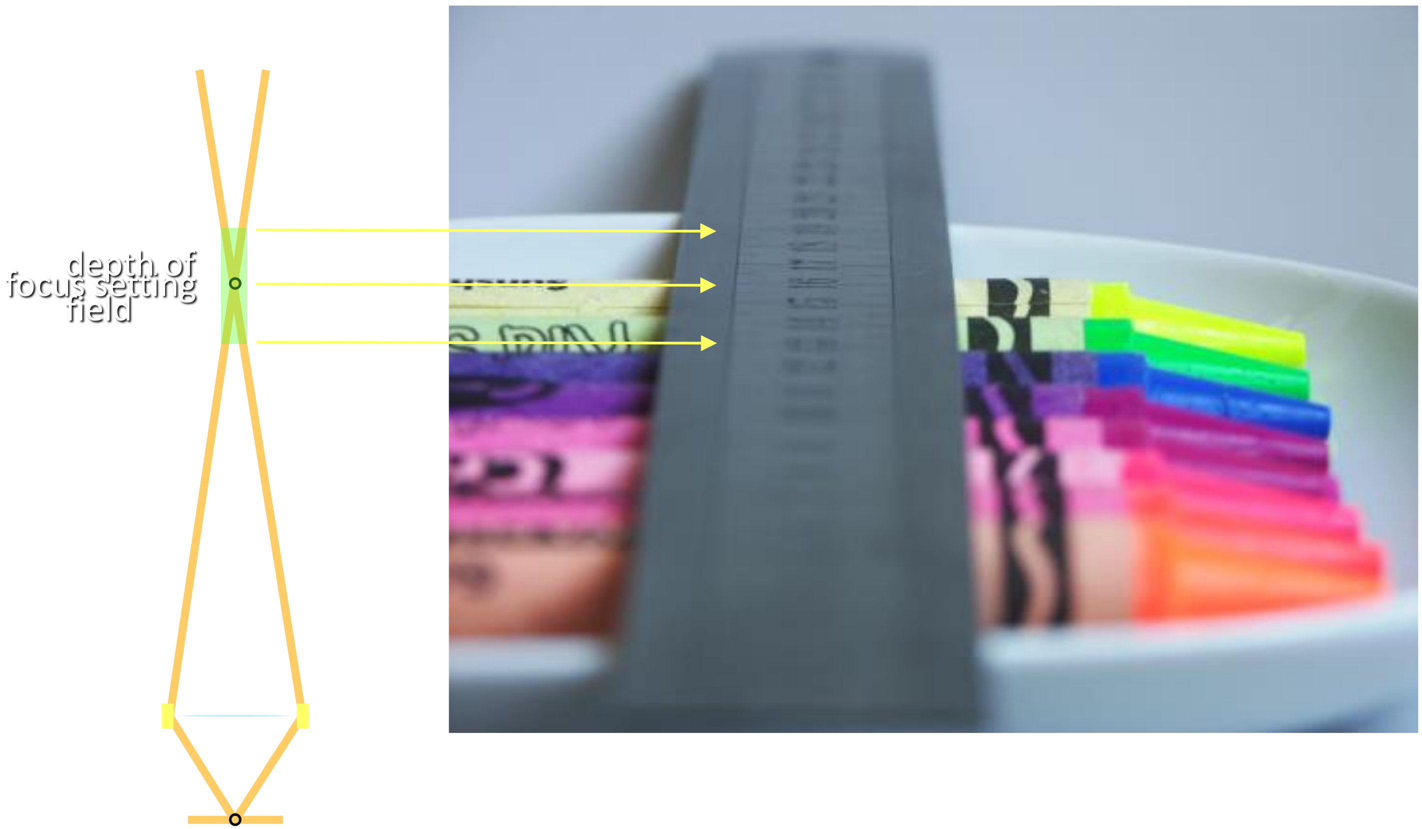
Out-of-Focus Blur (aka Defocus Blur)



Thin-lens law:

$$\frac{1}{z_o} + \frac{1}{z_c} = \frac{1}{f}$$

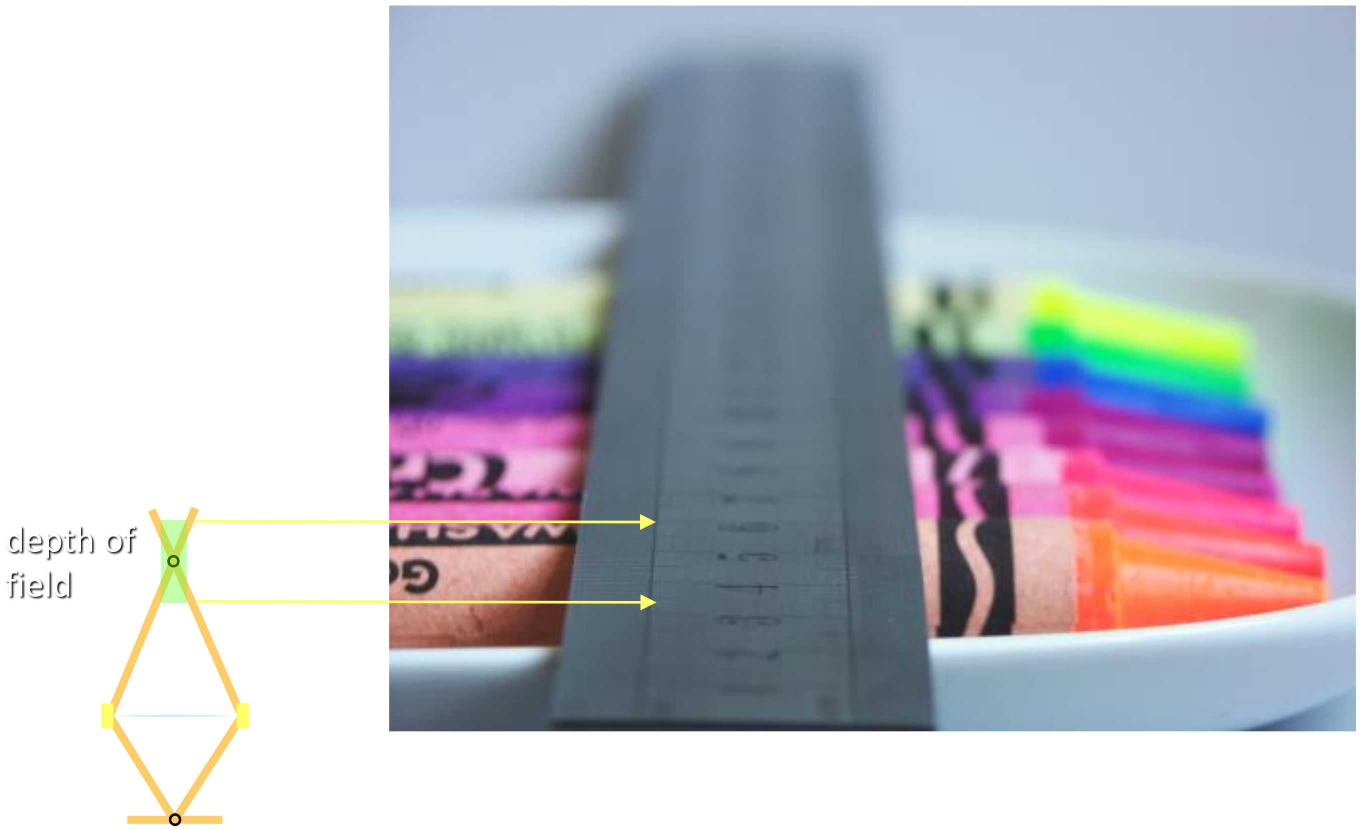
Focus Setting



Controls distance at which scene points are in “perfect focus” (ie. no blur)

Controls position of the depth of field
= range of distances with blur <

Focus Setting



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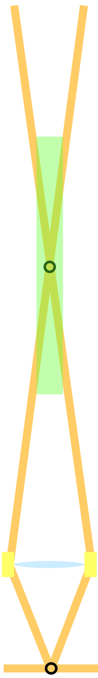
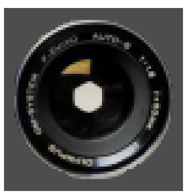
Controls position of the depth of field

= range of distances with blur <

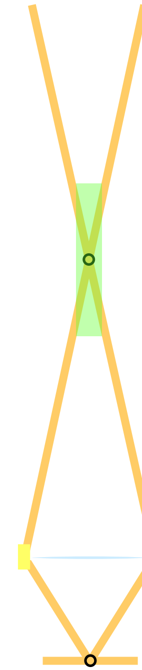
Aperture Diameter





narrow aperture
(D)

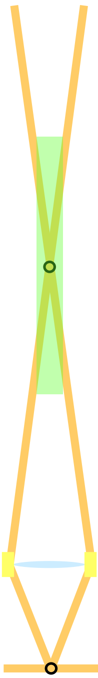
wide aperture
(2D)

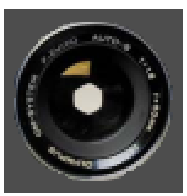


Controls number of photons
reaching
the sensor per unit time interval

Controls extent of the depth of

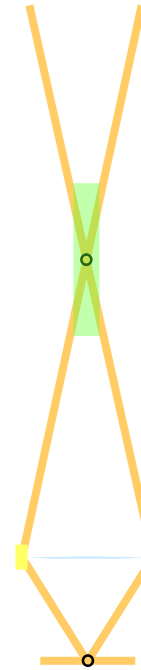
~~The Exposure Time vs. Depth of Field Tradeoff~~





narrow aperture
(D)

wide aperture
(2D)



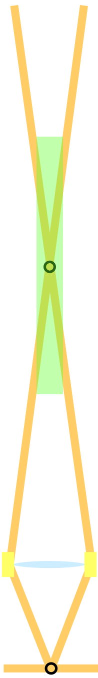
Can capture an equally well-exposed photo using

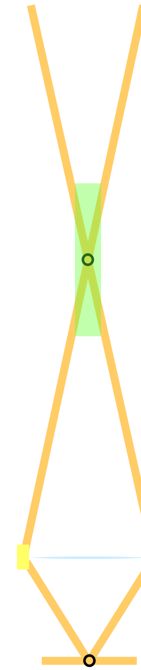
large depth of field + long exposure time

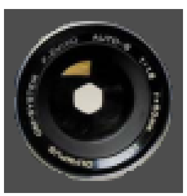
or

small depth of field + short exposure time

The Exposure Time vs. Depth of Field Tradeoff







narrow aperture
(D)

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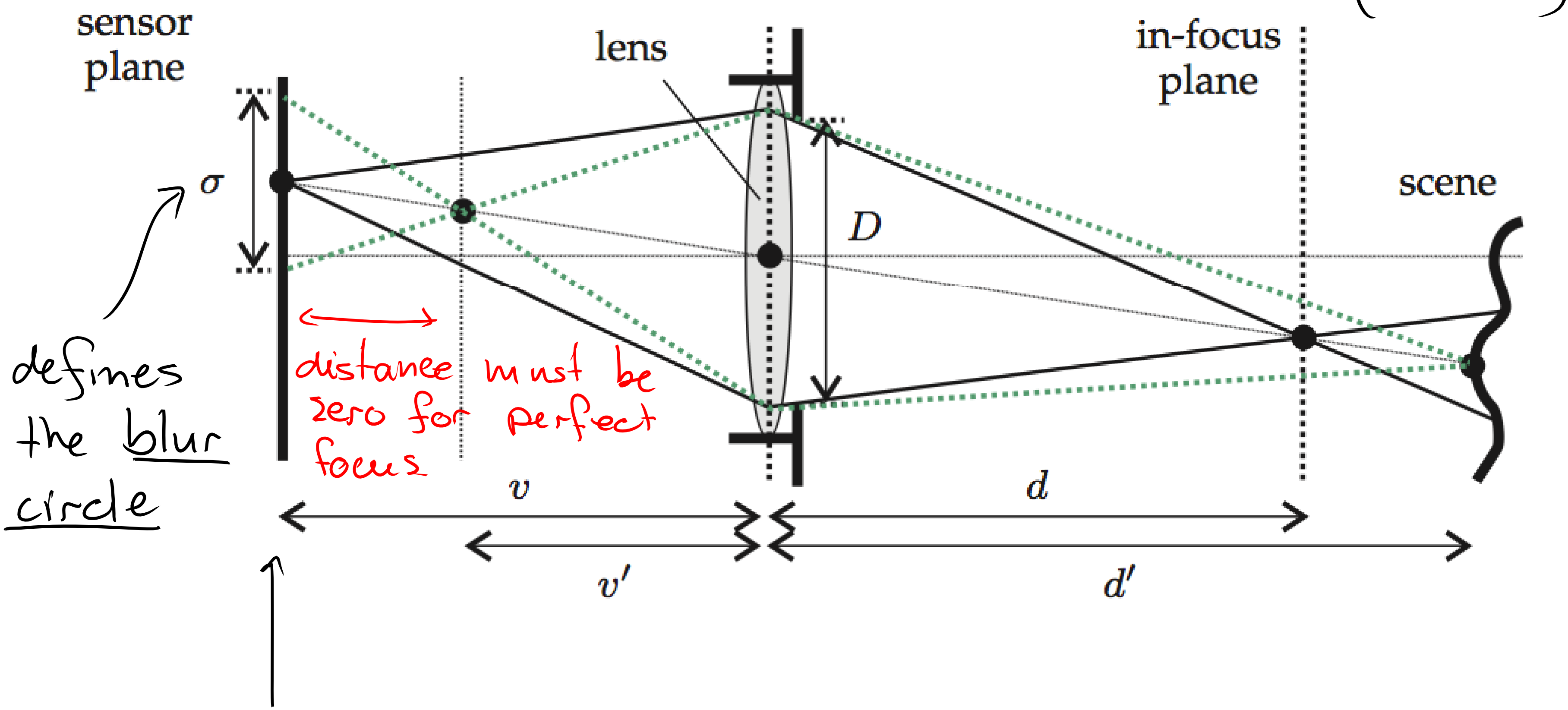
Modeling Defocus Blur

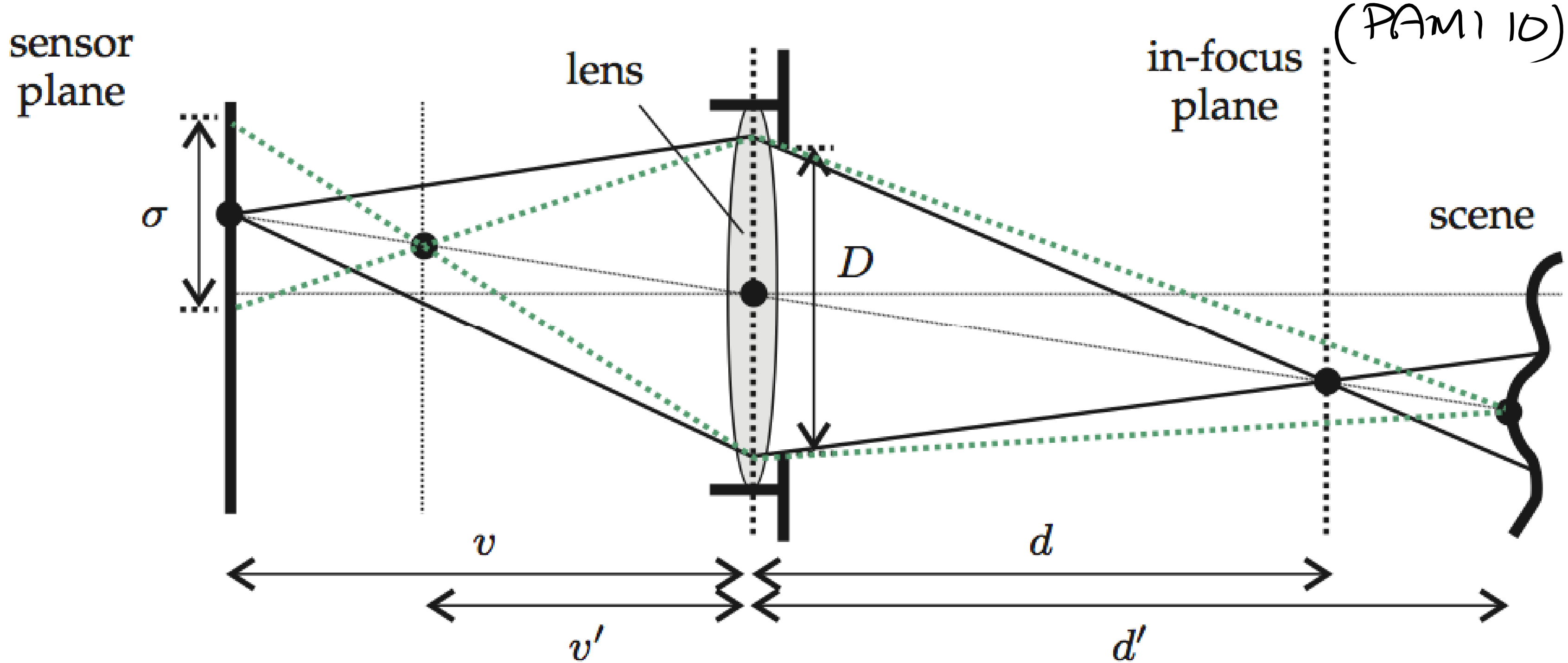
Hasinoff & Kutulakos (PAMI 10)



focus setting = sensor-to-aperture distance

Modeling Defocus Blur

Hasinoff & Kutulakos (PAMI 10)



Blur circle (σ): radius of scene point's image on sensor plane

Depth of field: range of object distances where σ < 1/2 sensor pixel

Modeling Defocus Blur

Hasinoff & Kutulakos (PAMI 10)

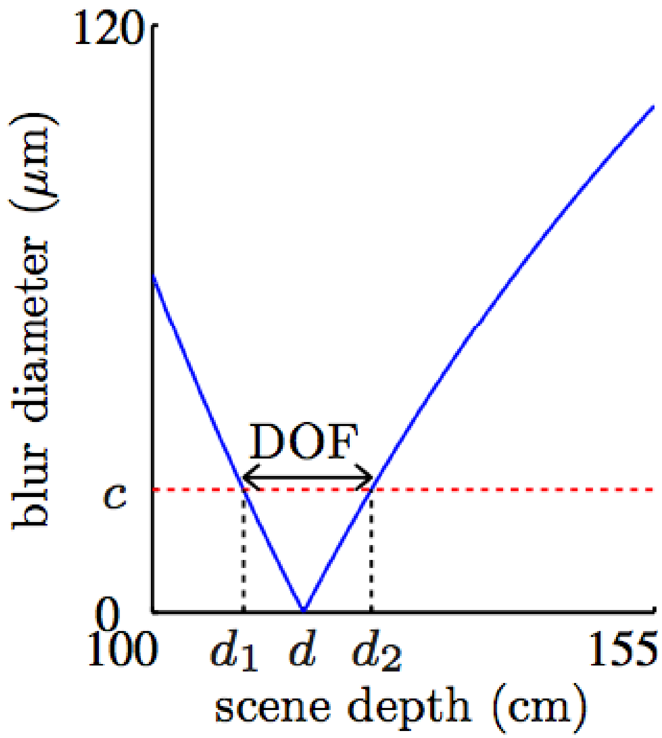
thin lens law	$\frac{1}{v} + \frac{1}{d} = \frac{1}{f}$	(2)
focus setting for distance d	$v = \frac{df}{d-f}$	(3)
blur diameter for out-of-focus distance d'	$\sigma = D \frac{\lvert d' - d \rvert}{d'} \frac{v}{d}$	(4)
aperture diameter whose DOF is interval $[\alpha, \beta]$	$D = c \frac{\beta + \alpha}{\beta - \alpha}$	(5)
focus setting whose DOF is interval $[\alpha, \beta]$	$v = \frac{2\,\alpha\,\beta}{\alpha + \beta}$	(6)
DOF endpoints for aperture diameter D and focus v	$\alpha, \beta = \frac{Dv}{D \pm c}$	(7)

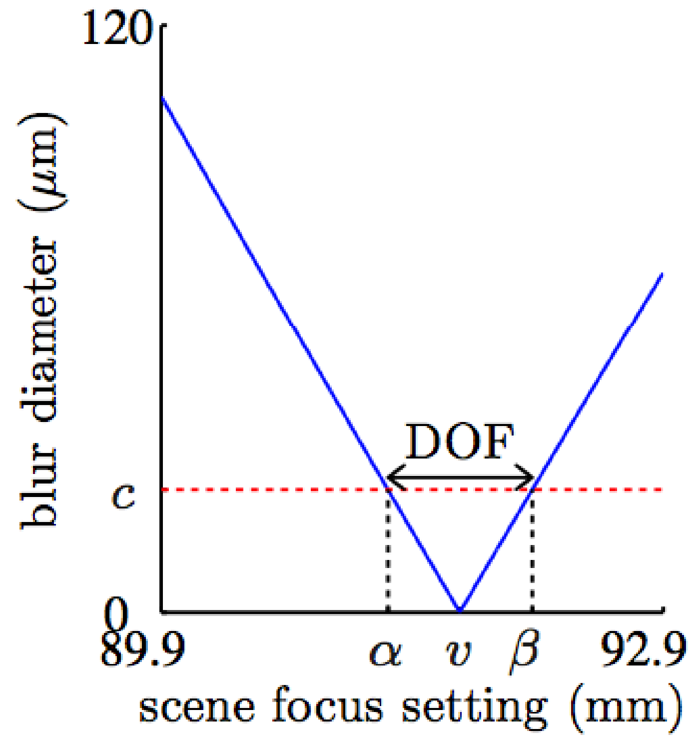
TABLE 1
Basic equations governing focus and depth of field for the thin-lens model (Fig. 3).

optional: try to derive these from the figure on previous slide using thin-lens law

Modeling Defocus Blur

Hasinoff & Kutulakos
(PAMI 10)





Example: DOF calculations for the Canon EOS 1Ds Mk II sensor and the 85mm f/1.2 L lens

To probe further

- Hasinoff & Kutulakos, Light Efficient Photography, IEEE T-PAMI, 2011 (and references therein)
- Marc Levoy's Digital Photography course (Spring 2014): http://graphics.Stanford.edu/courses/cs178

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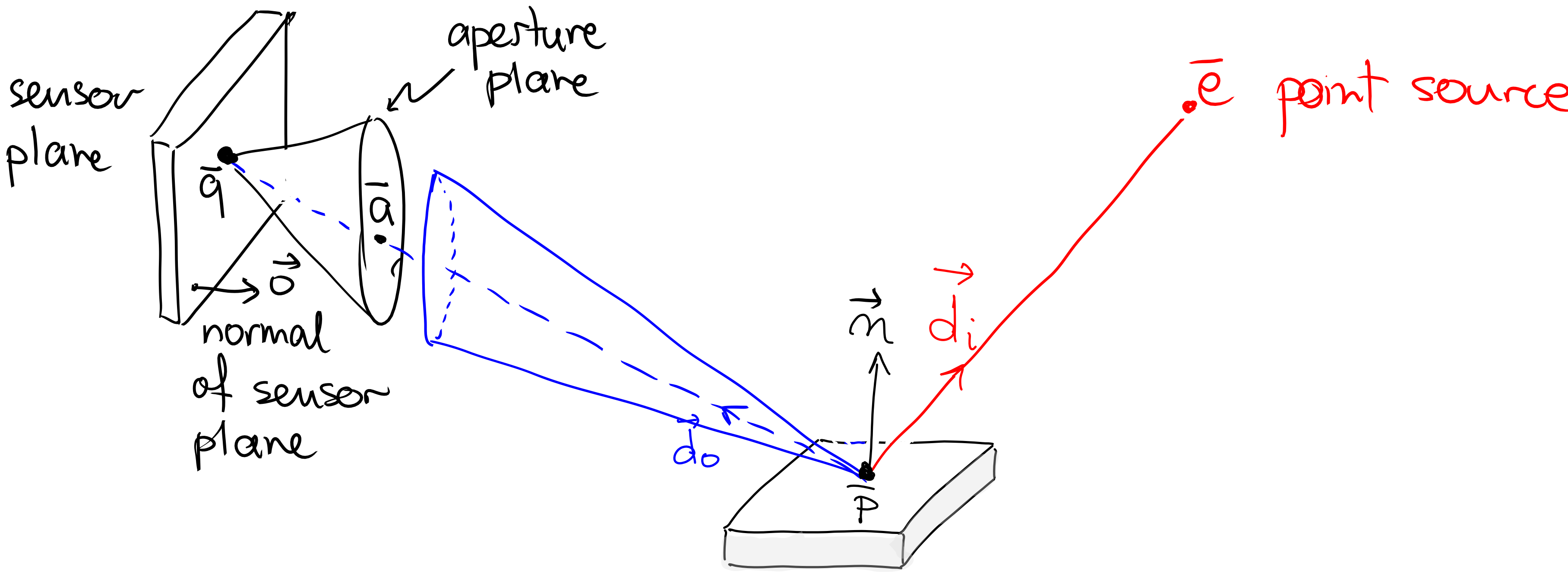
Image Irradiance from a Diffuse Surface Point



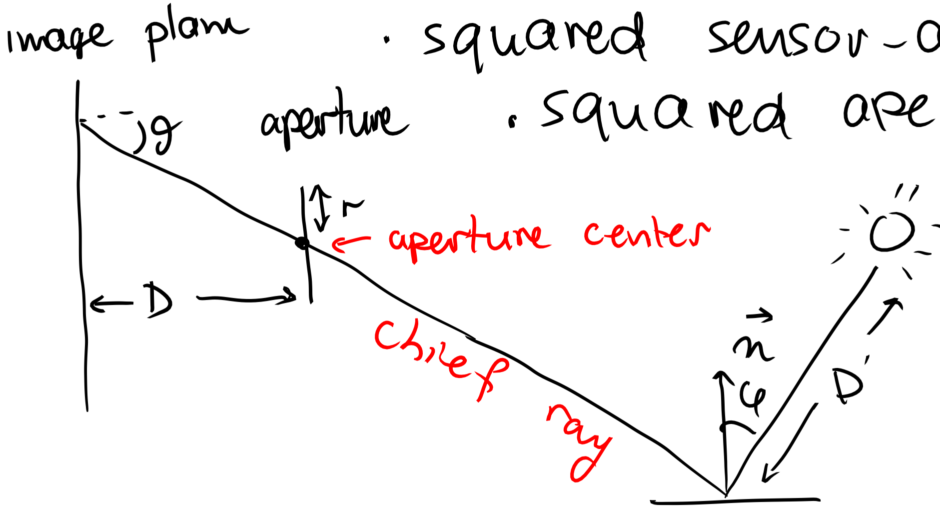
Common assumption:

Sensor plane and aperture plane are parallel

Image Irradiance from a Diffuse Surface Point

* Observed brightness of scene patch falls off with
  - squared distance from source $(D')^2$
  - cosine-slant relative to source $\cos\varphi$
  - squared sensor-aperture distance D^2
  - squared aperture radius r^2
  - cosine-fourth of slant of chief ray $(\cos\theta)^4$

known as "vignetting"



Vignetting

chief rays at these pixels fall very obliquely.

Image Irradiance from a Diffuse Surface Point

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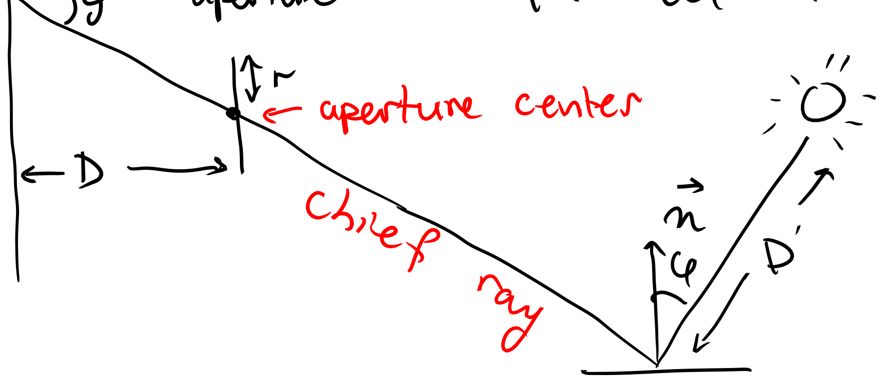


Image irradiance

$$H = \frac{d\Phi}{dA_{\bar{a}}} = \frac{1}{\pi} I(-\vec{d}_i) \frac{\cos\varphi}{(D')^2} \frac{(\cos\theta)^4}{D^2} \pi r^2$$

Derivation: Step 1 (flux through aperture)

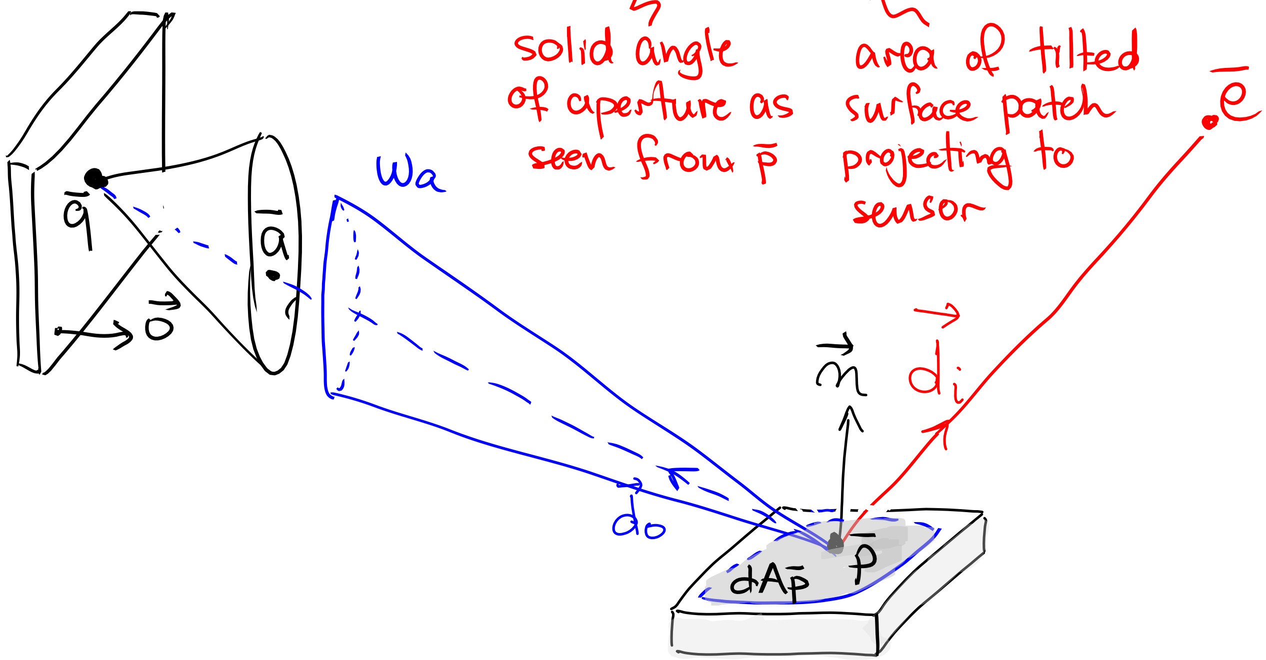
Radiance $$L(\bar{p}, \vec{d_o}) = \frac{d^2\Phi}{d\omega_{\bar{a}} \, dA_{\bar{p}} \cdot (\vec{n} \cdot \vec{d_o})}$$

flux passing through aperture

foreshortening due to tilted patch

solid angle of aperture as seen from $\bar{p}$

area of tilted surface patch projecting to sensor



Flux through a differential solid angle of the aperture due to differential surface patch $dA_{\bar{p}}$

$$* \quad d^2\Phi = L(\bar{p}, \vec{d_o}) \, dA_{\bar{p}} \cdot (n \cdot \vec{d_o}) \, d\omega_{\bar{a}}$$

Derivation: Step 1 (flux through aperture)

Radiance $L(\bar{p}, \vec{d_o}) = \dfrac{d^2\Phi}{d\omega_{\bar{a}} \, dA_{\bar{p}} \cdot (\vec{n} \cdot \vec{d_o})}$

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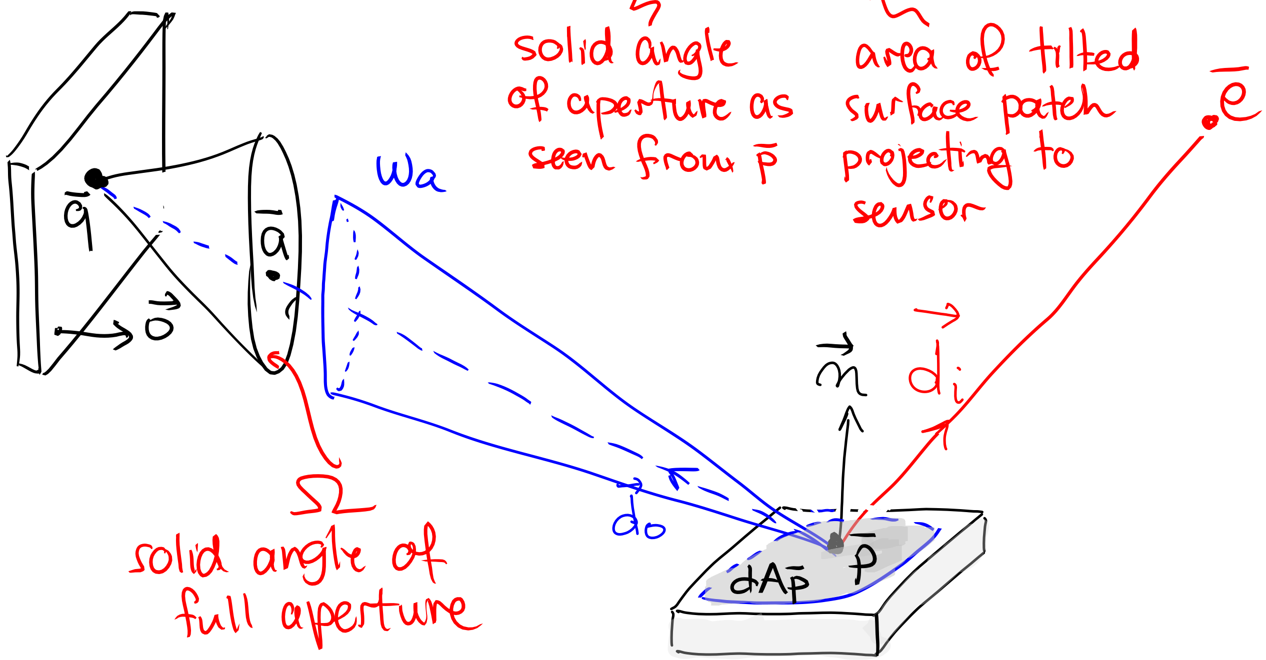


Total flux through the aperture due to differential surface patch $dA_{\bar{p}}$

$$* \quad d\Phi = \int_{\Omega} L(\bar{p}, \vec{d_o}) \, dA_{\bar{p}} \cdot (n \cdot \vec{d_o}) \, d\omega_{\bar{a}}$$

Derivation: Step 1 (flux through aperture)

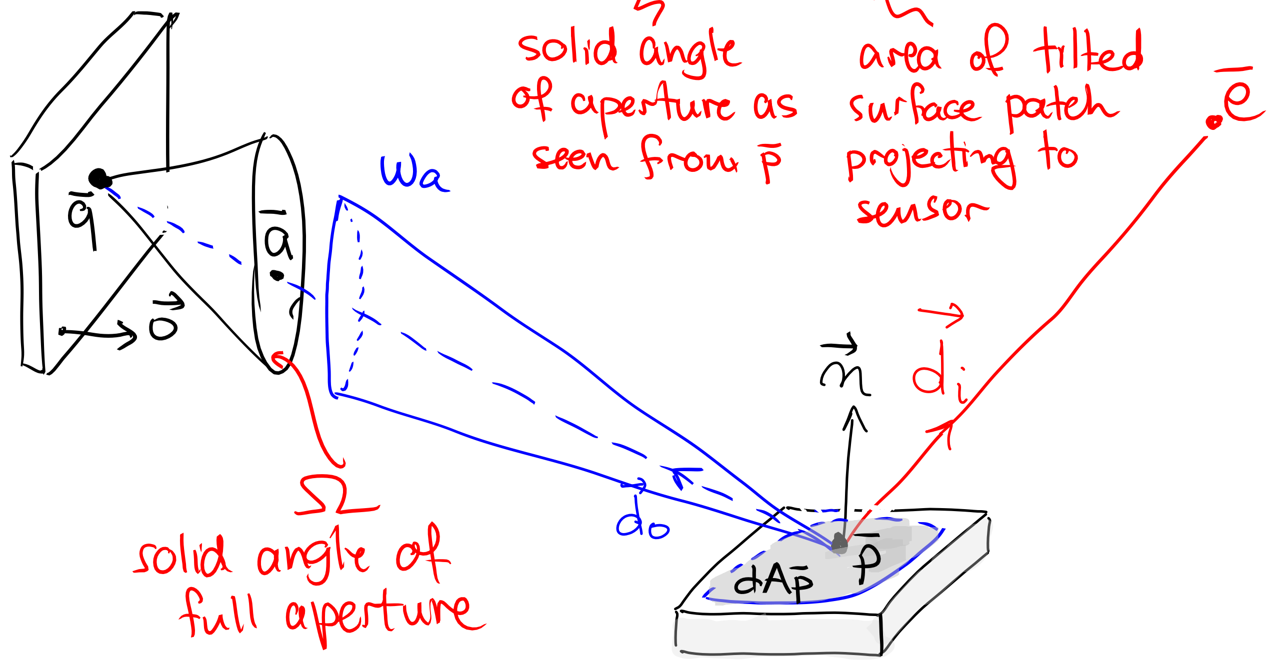
Radiance $$L(\bar{p}, \vec{d_o}) = \frac{d^2\Phi}{d\omega_{\bar{a}} \, dA_{\bar{p}} \cdot (\vec{n} \cdot \vec{d_o})}$$

$d^2\Phi$: flux passing through aperture

$(\vec{n} \cdot \vec{d_o})$: foreshortening due to tilted patch

$d\omega_{\bar{a}}$: solid angle of aperture as seen from $\bar{p}$

$dA_{\bar{p}}$: area of tilted surface patch projecting to sensor



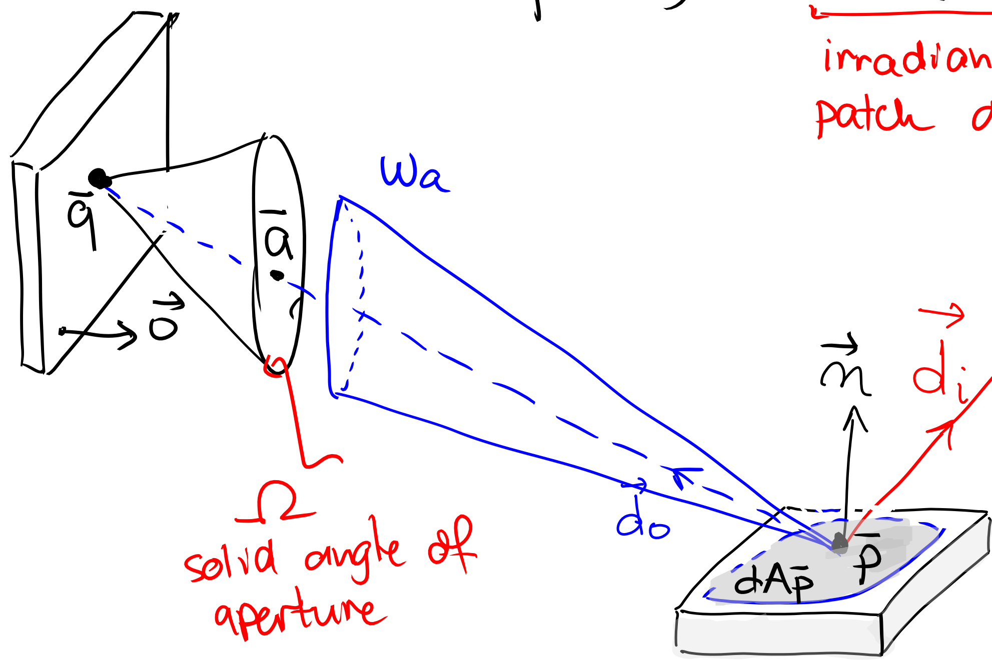
Total flux through the aperture due to differential surface patch $dA_{\bar{p}}$

$$* \quad d\Phi = L(\bar{p}, \vec{d_o}) \, dA_{\bar{p}} \cdot (n \cdot \vec{d_o}) \, \Omega$$

Derivation: Step 2 (radiance)

For diffuse reflectance & point source (see ex.5 in lec.1)

$$L(\bar{p},\vec{d_o}) = \underbrace{I(-\vec{d_i})\cdot(\vec{n}\cdot\vec{d_i})\frac{1}{\|\bar{p}-\bar{e}\|^2}}_{\text{irradiance of patch } dA_{\bar{p}}} \cdot \underbrace{\frac{1}{\pi}}_{\text{BRDF}} \quad *$$



Total flux through aperture due to patch $dA_{\bar{p}}$:

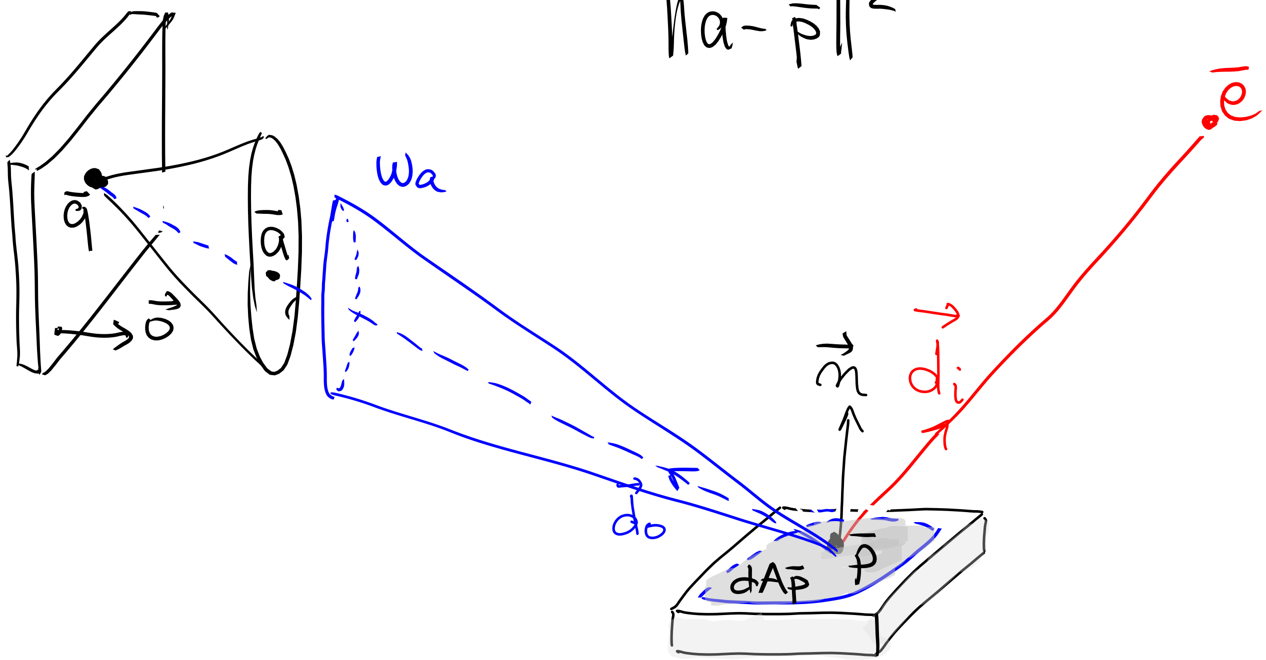
$$d\Phi = \boxed{L(\bar{p},\vec{d_o})}\; dA_{\bar{p}} \cdot (n\cdot\vec{d_o})\,\Omega$$

Derivation: Step 3 (solid angle of aperture)

area of aperture

foreshortening term because aperture plane not orthogonal to $\vec{d_o}$

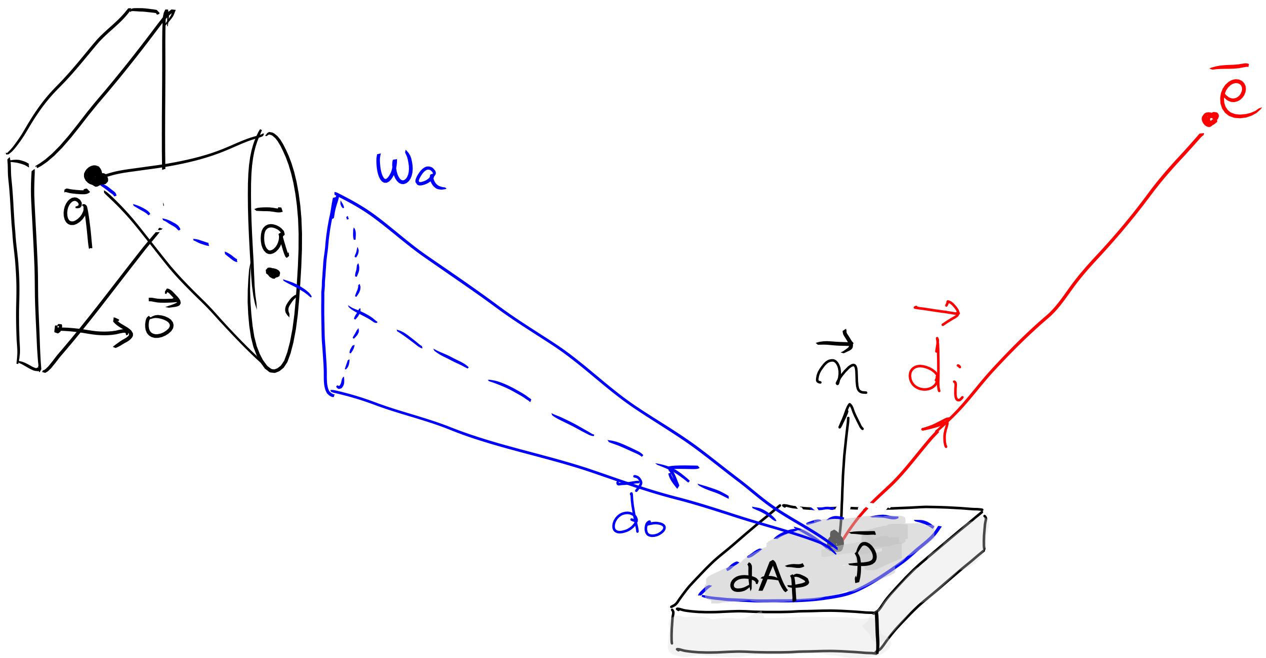
$$\Omega = \frac{A_{\bar{a}} \cdot (\vec{d_o} \cdot \vec{o})}{\|\bar{a} - \bar{p}\|^2}$$



Total flux through aperture due to patch $dA_{\bar{p}}$:

$$d\Phi = L(\bar{p}, \vec{d_o})\ dA_{\bar{p}} \cdot (n \cdot \vec{d_o}) \boxed{\Omega}$$

Derivation: Step 4 (differential sensor patch)



Total flux through aperture due to patch $dA_{\bar{p}}$:

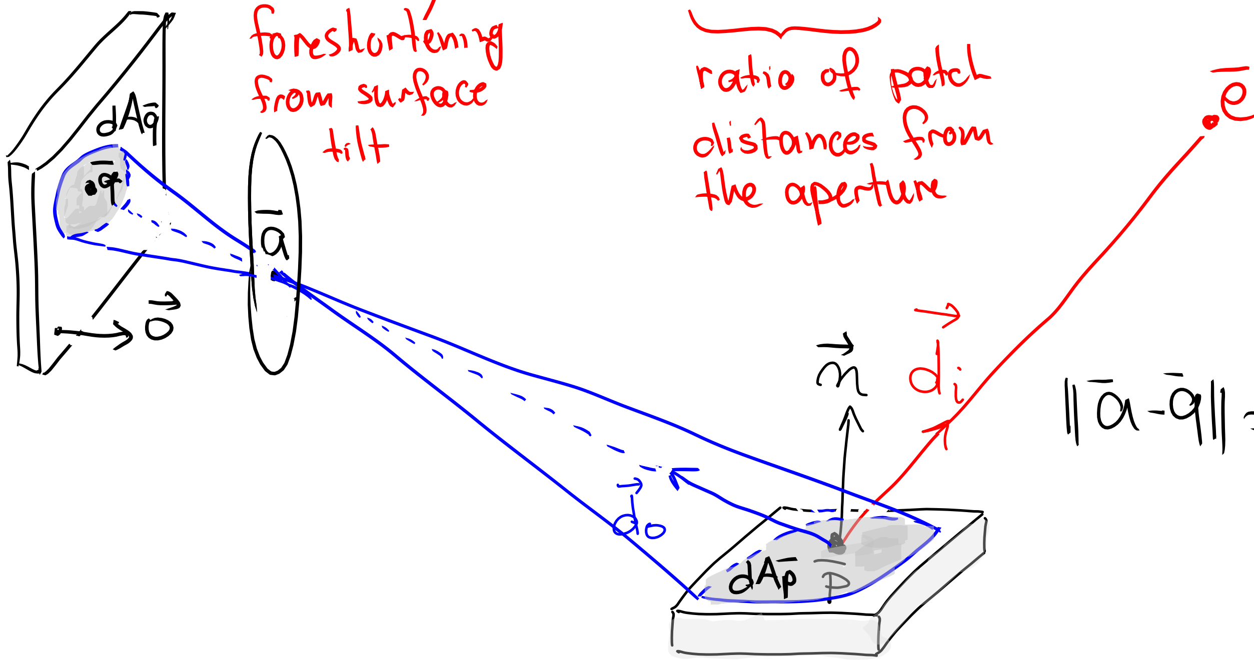
$$d\Phi = L(\bar{p}, \vec{d_o}) \, \boxed{dA_{\bar{p}} \cdot (n \cdot \vec{d_o})} \, \Omega$$

Derivation: Step 4 (differential sensor patch)

$$* \quad dA_{\bar{p}}\,(n\cdot\vec{d}_o) = \underbrace{\frac{\|\bar{a}-\bar{p}\|^2}{\|\bar{a}-\bar{q}\|^2}}_{\text{ratio of patch distances from the aperture}} dA_{\bar{q}}\,(\vec{d}_o\cdot\vec{o})$$

foreshortening from surface tilt

foreshortening from image tilt



$$\|\bar{a}-\bar{q}\| = \frac{\text{sensor-aperture dist}}{\vec{d}_o\cdot\vec{o}}$$

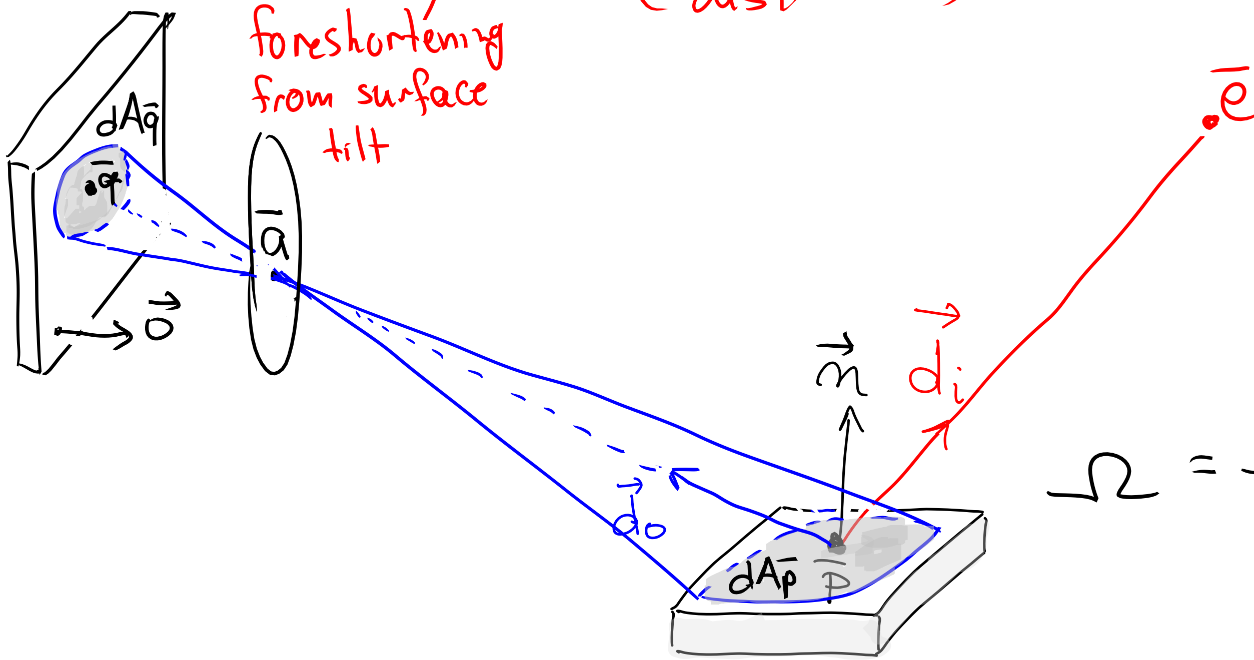
Total flux through aperture due to patch $dA_{\bar{p}}$:

$$d\Phi = L(\bar{p},\vec{d}_o)\ \boxed{dA_{\bar{p}}\cdot(n\cdot\vec{d}_o)}\ \Omega$$

Derivation: Step 4 (differential sensor patch)

$$dA_{\bar{p}}\,(n\cdot\vec{d}_o) = \frac{\|\bar{a}-\bar{p}\|^2}{(\text{sensor-aperture dist})^2}\, dA_{\bar{q}}\,(\vec{d}_o\cdot\vec{o})^3$$

foreshortening from surface tilt



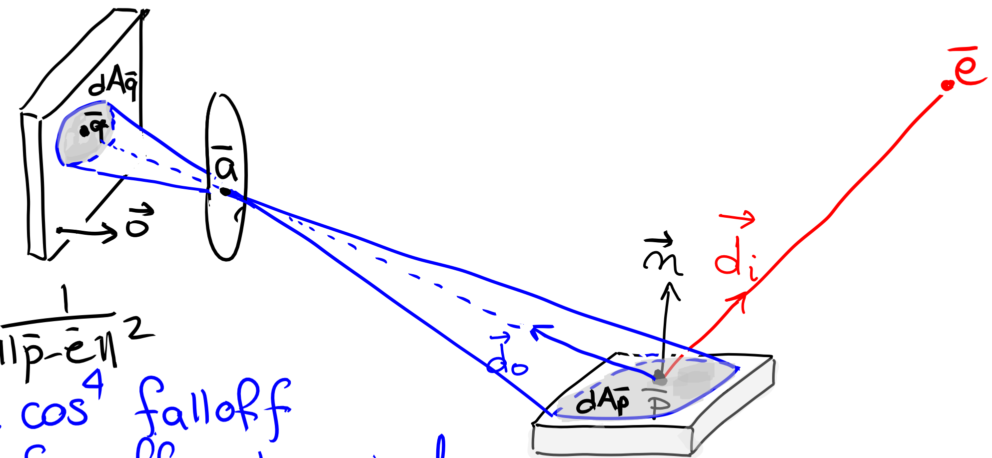
$$\Omega = \frac{A_{\bar{a}}\cdot(\vec{d}_o\cdot\vec{o})}{\|\bar{a}-\bar{p}\|^2}$$

Total flux through aperture due to patch $dA_{\bar{p}}$:

$$d\Phi = L(\bar{p},\vec{d}_o)\ \boxed{dA_{\bar{p}}\cdot(n\cdot\vec{d}_o)}\ \boxed{\Omega}$$

Derivation: final expression

Putting it all together …



depends on source

$$d\phi = \frac{1}{\pi} I(-d_i)(\vec{n}\cdot\vec{d_i}) \frac{1}{\|\bar{p}-\bar{e}\|^2}$$

$\cos^4$ falloff for off-center pixels

depends on camera

$$\frac{(\vec{d_o}\cdot\vec{o})^4}{(\text{sensor-aperture dist})^2}\, dA_{\bar{q}} \cdot A_{\bar{a}}$$

area of the aperture

Image irradiance *

$$H = \frac{d\Phi}{dA_{\bar{a}}} = \frac{1}{\pi} I(-\vec{d_i})(\vec{n}\cdot\vec{d_i}) \frac{1}{\|\bar{p}-\bar{e}\|^2} \frac{(\vec{d_o}\cdot\vec{o})^4}{(\text{sensor-aperture dist})^2} \cdot A_{\bar{a}}$$

Derivation: final expression

Putting it all together ...

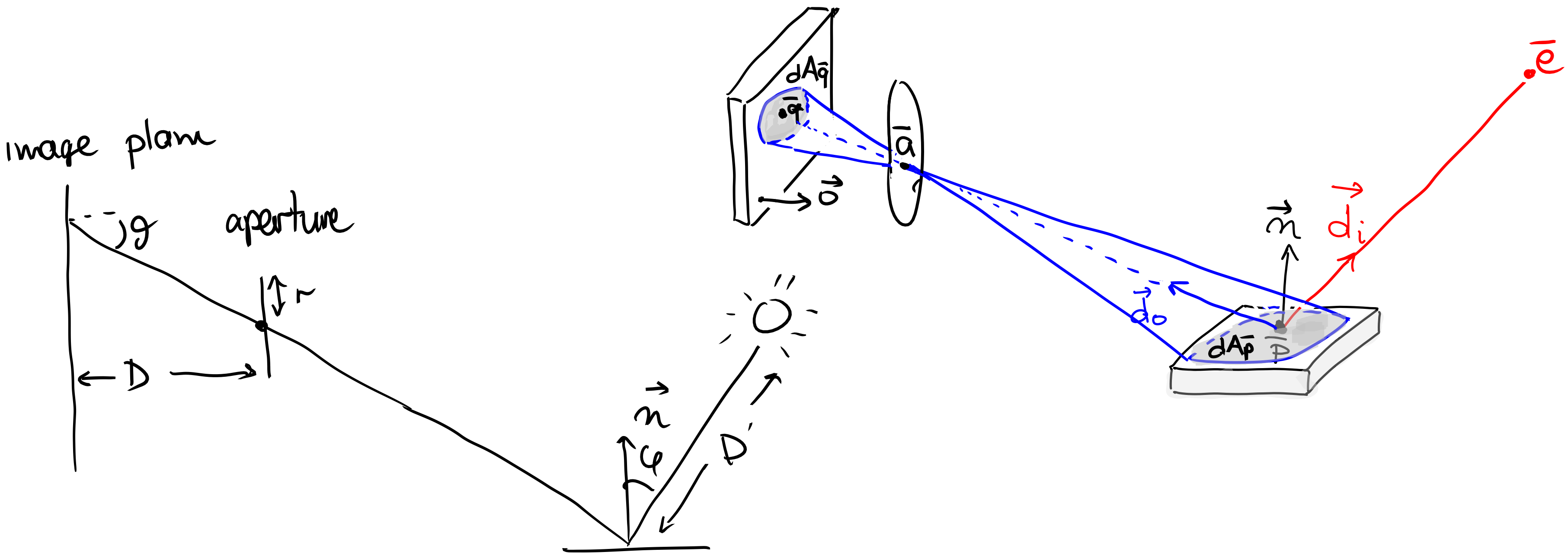


Image irradiance *

$$H = \frac{d\Phi}{dA_{\bar{a}}} = \frac{1}{\pi} I(-\vec{d_i}) \frac{\cos\varphi}{(D')^2} \frac{(\cos\theta\;)^4}{D^2} \pi r^2$$

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known as "vignetting"

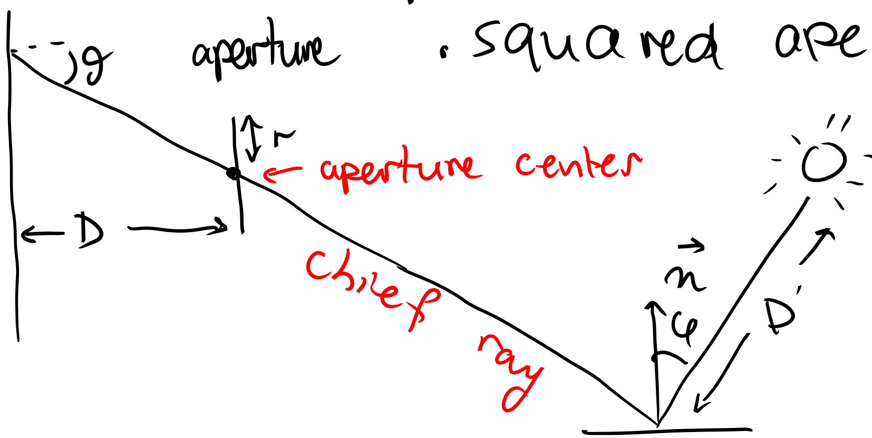

Image irradiance

$$H = \frac{d\Phi}{dA_{\bar{a}}} = \frac{1}{\pi} I(-\vec{d}_i) \frac{\cos\varphi}{(D')^2} \frac{\boxed{(\cos\theta)^4}}{D^2} \pi r^2$$

Vignetting

principal rays at these pixels fall very obliquely.

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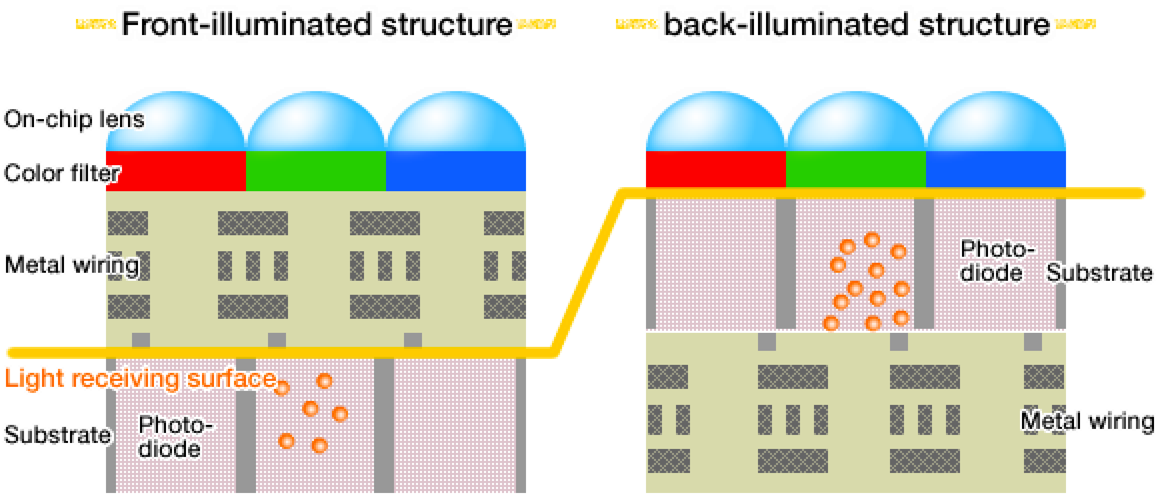
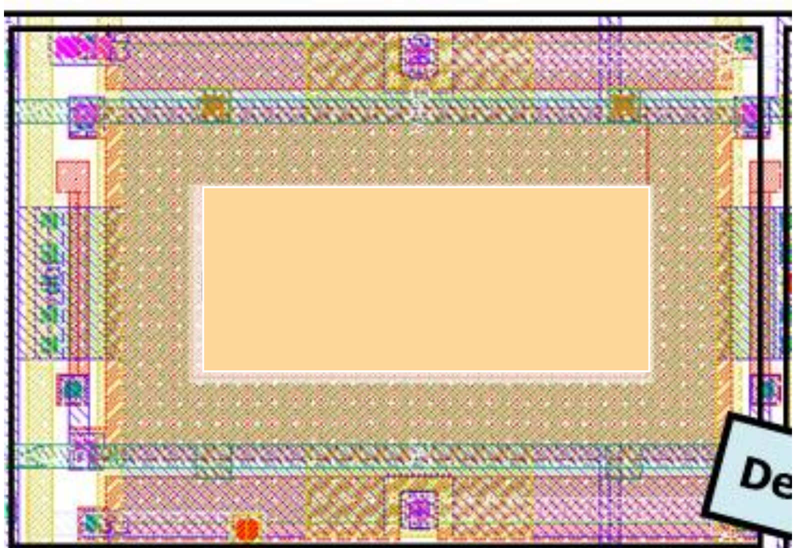
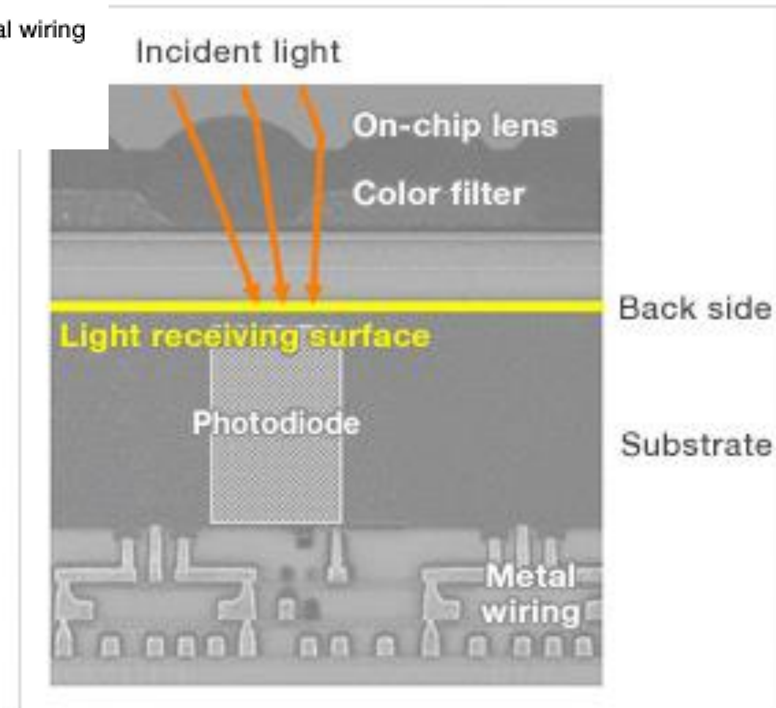
Cross-Section of a CMOS Image Sensor



(sony)



(UofT)



Cross section of a pixel in a Back-Illuminated CMOS Sensor

(sony)

From Irradiance to Digital Numbers

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

- Photons arriving at a pixel generate photo-electrons
- Photo-electrons pass through an amplifier that converts accumulated charge to a measurable voltage
- Voltage converted to a digital number with an A-to-D converted
- This number may be further transformed before being output as a pixel intensity (or color) value

Photo-Electrons Collected at a Pixel

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

a.k.a. flux
(photo-electrons per second)

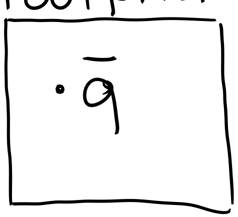
(photons per second per wavelength)
incident spectral irradiance

spatial response at collection site (unit-less)

$$\Phi = \iint_{\bar{q}\,\lambda} H(\bar{q},\lambda)\cdot S(\bar{q})\cdot Q(\lambda)\, d\bar{q}\, d\lambda$$

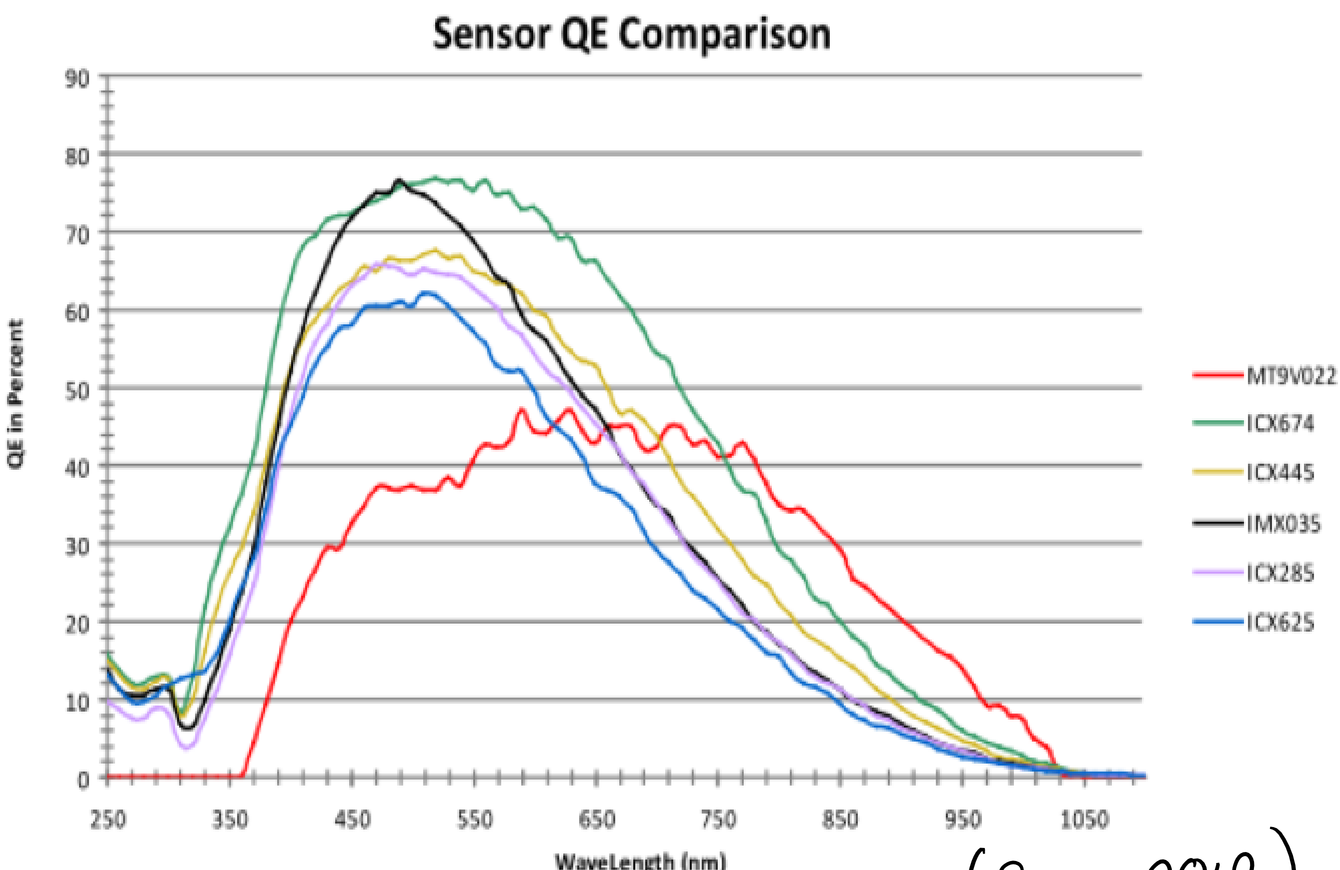
quantum device efficiency
(electrons collected per incident photons per wavelength)

pixel footprint



Quantum Efficiency Curves

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



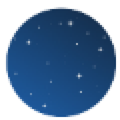
(Song, 2012)

Lighting Levels vs Average Photon Counts

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

ϕ $\qquad$ ϕt

illuminance/irradiance

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

(Cossairt et al, IEEE TIP, 2012)

Assumptions: $Q(\lambda) = 0.5$, pixel area $= 1\,\mu m^2$, $t = 1/50$ sec

surface albedo $= 0.5$, aperture $= F/2.1$

From Irradiance to Digital Numbers *

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

$$\Phi \qquad \Phi t + I_0 \qquad \min(I_0+\Phi t,\ I_m) \qquad \frac{\min(I_0+\Phi t,\ I_m)}{g} \qquad \left\lfloor \frac{\min(I_0+\Phi t,\ I_m)}{g} \right\rfloor$$

I_0: black level (electrons)

I_m: (electrons)

g: (electrons per DN)

$\left\lfloor \cdot \right\rfloor$: (DN)

- The DN's obtained above have a <u>linear</u> relationship to photo-electrons (and sensor irradiance)

Linear Images Don't Look Good…

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

Gamma-Corrected Images

DNs are passed through a gamma function to approximately compensate for the HVS $f(DN) = \beta(DN)^{1/\gamma}$

From Irradiance to Digital Numbers

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

ϕ

$\phi t + I_0$

black level (electrons)

$\min(I_0 + \phi t, I_m)$

(electrons)

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

(electrons per DN)

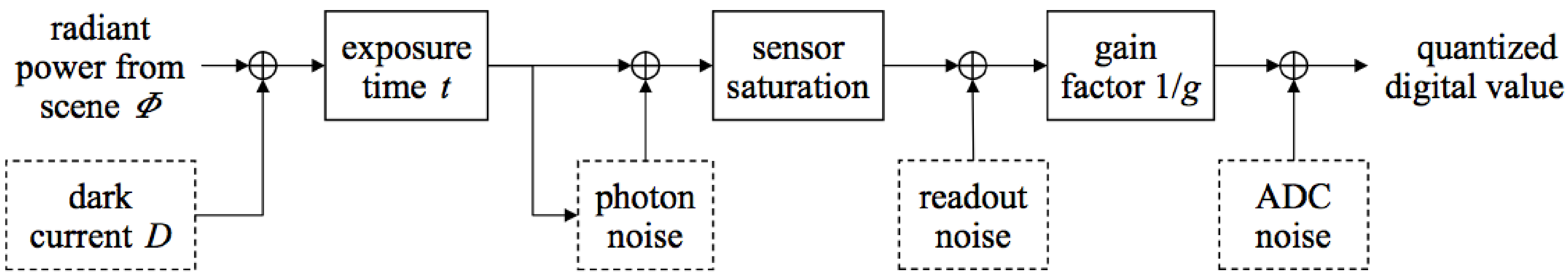
$$\left\lfloor \frac{\min(I_0 + \phi t, I_m)}{g} \right\rfloor$$

(DN)

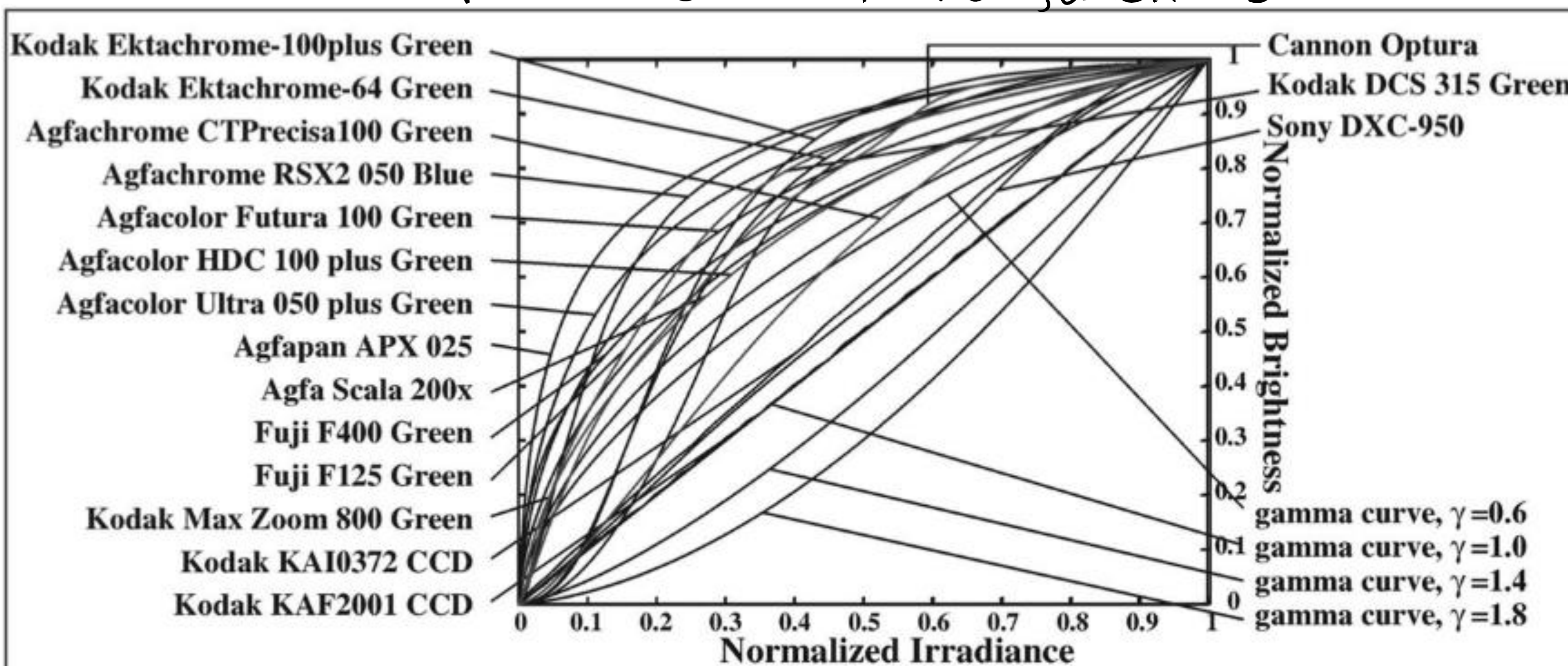
usually called the camera response function

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

From Irradiance to Digital Numbers



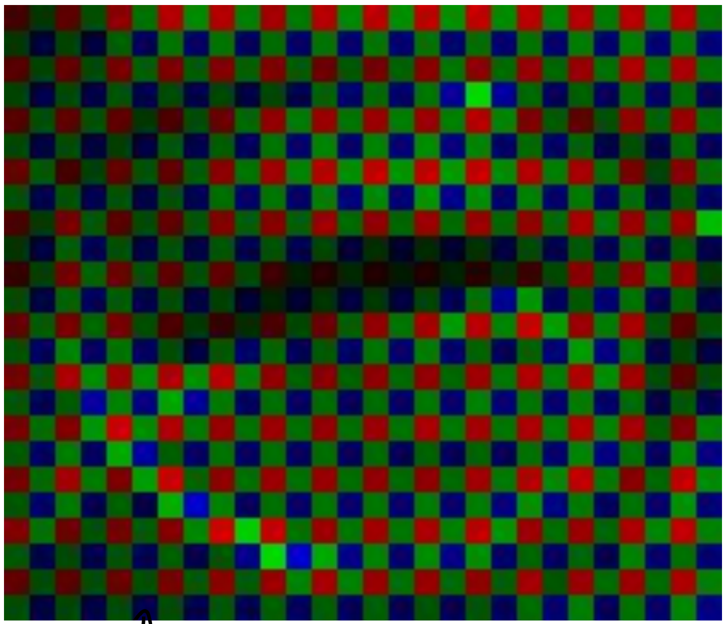
Sample camera response functions



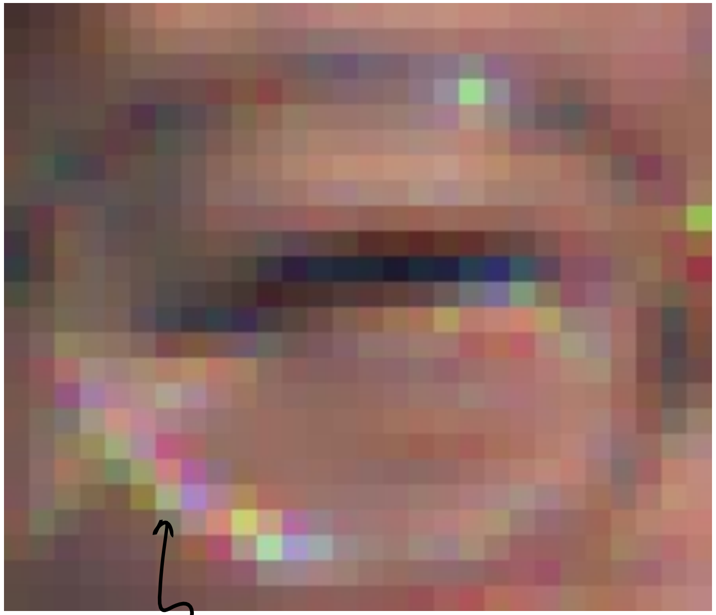
(Grossberg & Nayar, PAMI 2004)

Color Image Acquisition

Most common approach is to place an array of R, G, B filters over the sensor



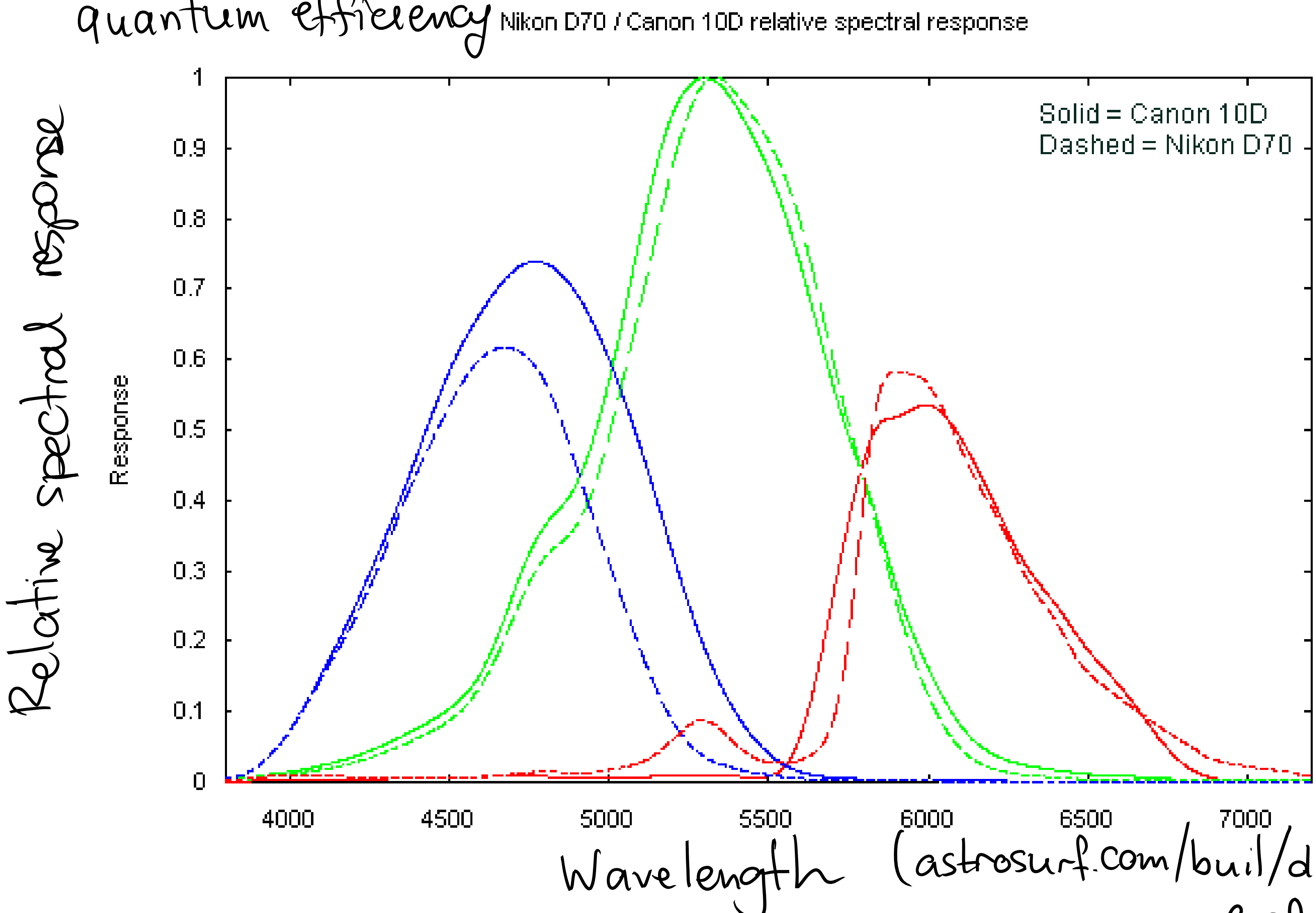
each pixel only measures irradiance due to a specific color channel



"missing" R/G/B values filled in computationally through a process called demosaicing

Typical Spectral Response Curves

These curves take into account filter transmittance and quantum efficiency



(astrosurf.com/buil/d70v10d/eval.htm)

RAW vs. Developed Images

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

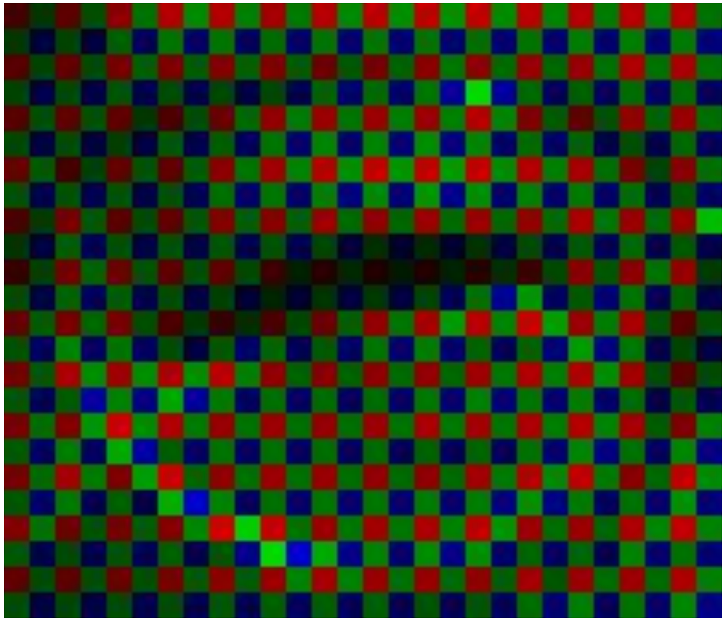
RAW vs. Developed color images

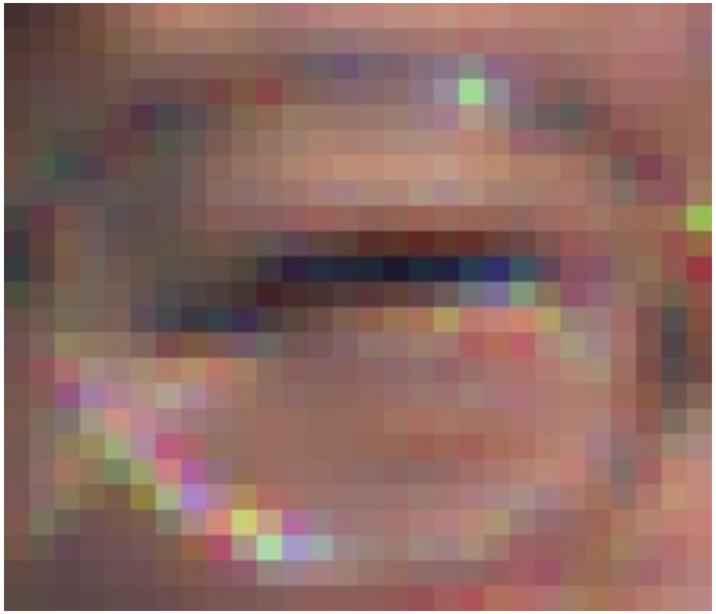
The color image before "developing" (contrast-enhanced)

RAW vs. Developed color images

The color image after "developing" (= de-mosaicing + intensity mapping)

Image Acquisition: Color Cameras





Freeware tools for working with RAW images:

dcraw (RAW → TIFF) CHDK firmware (for CANON)

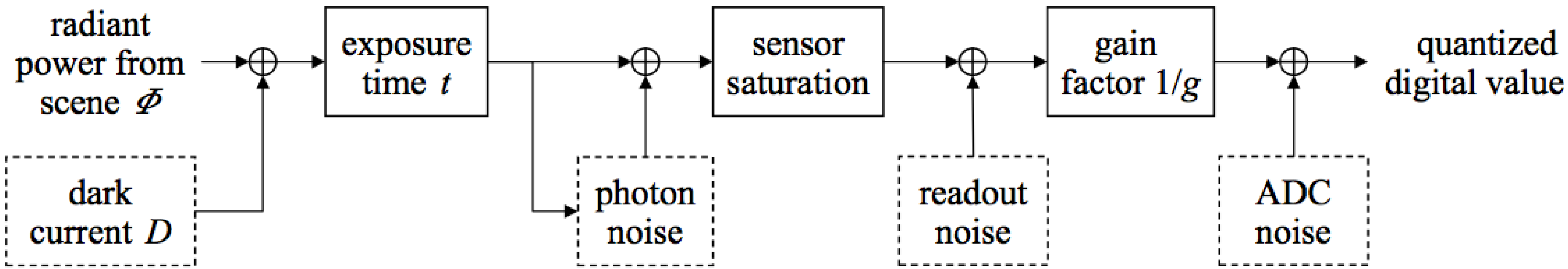
Topic 09:

The Camera

- Basic lens geometry
- Basic camera controls
- Relation of image irradiance to the lens & aperture
- From irradiance to digital numbers
- Image noise
- Rolling-shutter cameras

Sources of Noise

(Hasinoff et al, CVPR 2010)



free electrons due to thermal energy

depends on temperature, measured in electrons/sec

independent of Φt

photon arrivals are random

depends on total photon arrivals, Φt

noise from readout electronics

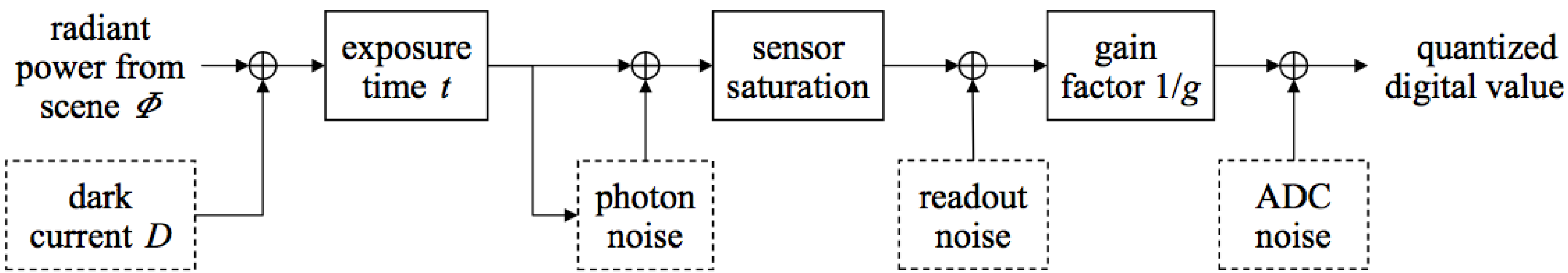
independent of Φt

amplifier, A-to-D, quantization noise

independent of Φt

Sources of Noise: Photon (aka Shot) Noise

(Hasinoff et al, CVPR 2010)



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$\Downarrow$

Poisson distribution with mean $= \Phi t$

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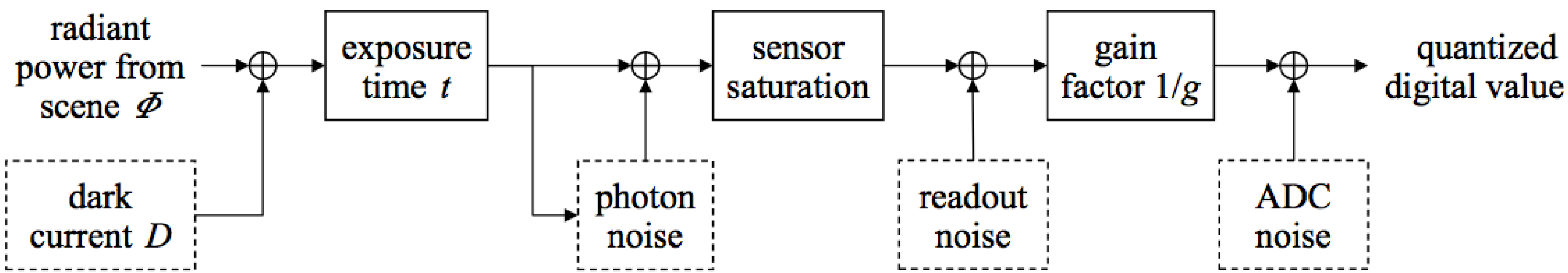


free electrons due to thermal energy

photon arrivals are random

noise from readout electronics

amplifier, A-to-D, quantization noise

depends on total photon arrivals, Φt

$\Downarrow$

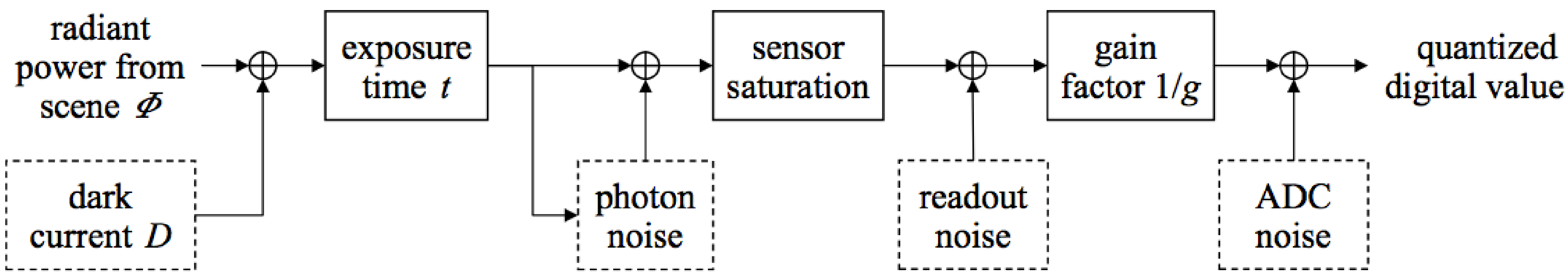
$$\boxed{\text{Prob}(\#\text{received photons} = k) = \frac{(\Phi t)^k}{k!} e^{-\Phi t}}$$

* Poisson distribution with mean $= \Phi t$

$\Rightarrow$ variance is also Φt

Sources of Noise: Dark Current Noise

(Hasinoff et al, CVPR 2010)



free electrons due to thermal energy

photon arrivals are random

noise from readout electronics

amplifiers, A-to-D, quantization noise

depends on temperature, measured in electrons/sec

independent of Φt

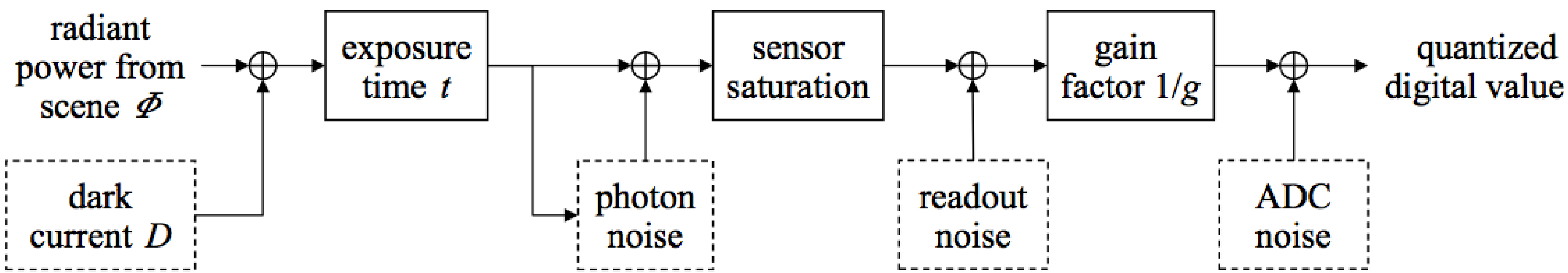
$\Rightarrow$ Poisson distribution with

mean = variance = Dt

rate of "creation" of thermal photons.

Sources of Noise: Readout Noise

(Hasinoff et al, CVPR 2010)



free electrons due to thermal energy

photon arrivals are random

noise from readout electronics

amplifier, A-to-D, quantization noise

independent of Φt

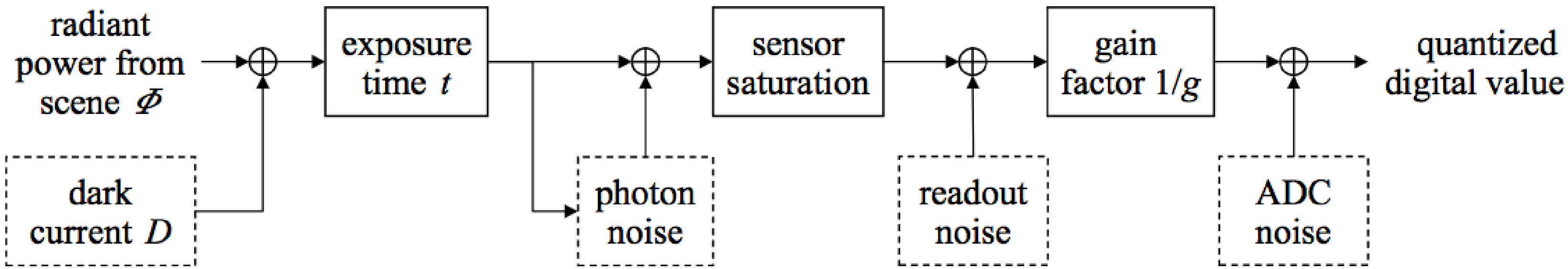
$\Downarrow$

normal distribution with mean=0 and standard deviation $= \sigma_r$

$$\boxed{\text{Prob}(\text{read noise} = x) = \frac{1}{\sigma_r\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma_r^2}}}$$

Sources of Noise: ADC & Quantization Noise

(Hasinoff et al, CVPR 2010)



free electrons due to thermal energy

photon arrivals are random

noise from readout electronics

amplifier, A-to-D, quantization noise

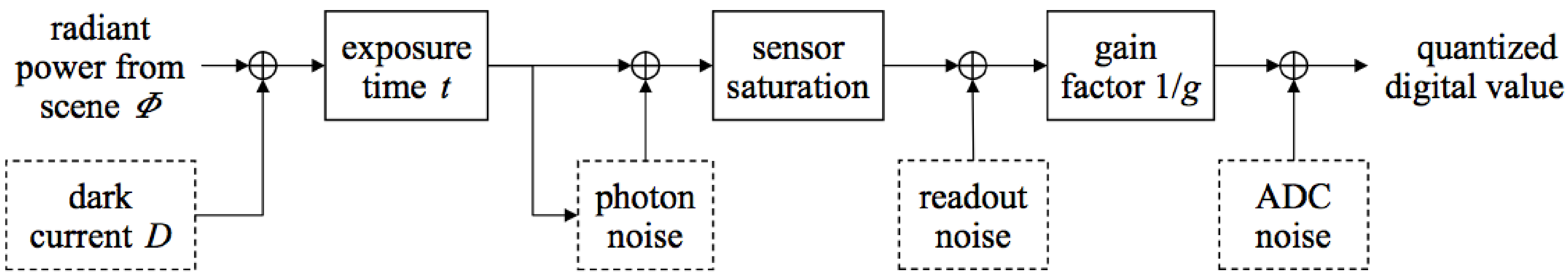
independent of Φt

$\Downarrow$

normal distribution with mean $= 0$ and standard dev $= \sigma_{ADC}$

Sources of Noise: ADC & Quantization Noise

(Hasinoff et al, CVPR 2010)



free electrons due to thermal energy

photon arrivals are random

noise from readout electronics

amplifier, A-to-D, quantization noise

* Poisson
mean $= Dt$
std $= \sqrt{Dt}$

* Poisson
mean $= \Phi t$
std $= \sqrt{\Phi t}$

* Normal
mean $= 0$
std $= \sigma_r$

* Normal
mean $= 0$
std $= \sigma_{ADC}$

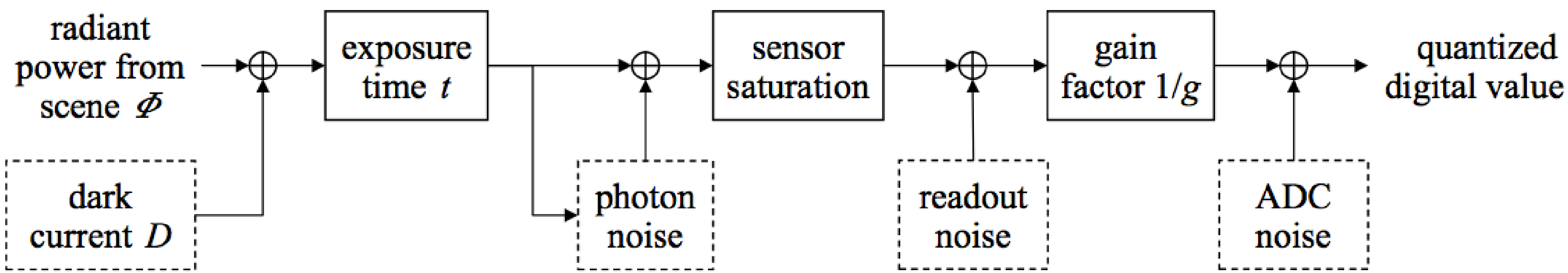
$\approx$ for $Dt, \Phi t$ large $\approx$

Normal
mean $= Dt$
std $= \sqrt{Dt}$

Normal
mean $= \Phi t$
std $= \sqrt{\Phi t}$

Example: The Canon EOS 5D Mark 2

(Hasinoff et al, CVPR 2010)



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

$\log_2 \frac{I_m}{\sigma_r + \sigma_{ADC}}$

ISO	Gain e/DN (g)	Apparent Read Noise (electrons)	Maximum signal (electrons) (I_m)	Measured Dynamic range stops (# useful bits)
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

(www.clarkvision.com)

Exercise : determining the # of electrons

Suppose you have a camera that allows you to capture RAW images but know nothing about how it converts electrons to digital numbers (ie. the table below is unknown)

Q: Give a procedure for determing a row from the table from one or more captured photos.

ISO	Gain e/DN	Apparent Read Noise (electrons)	Maximum signal (electrons)	Measured Dynamic range stops
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(www.clarkvision.com)

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Suppose you have a camera that allows you to capture RAW images but know nothing about how it converts electrons to digital numbers (ie. the table below is unknown)

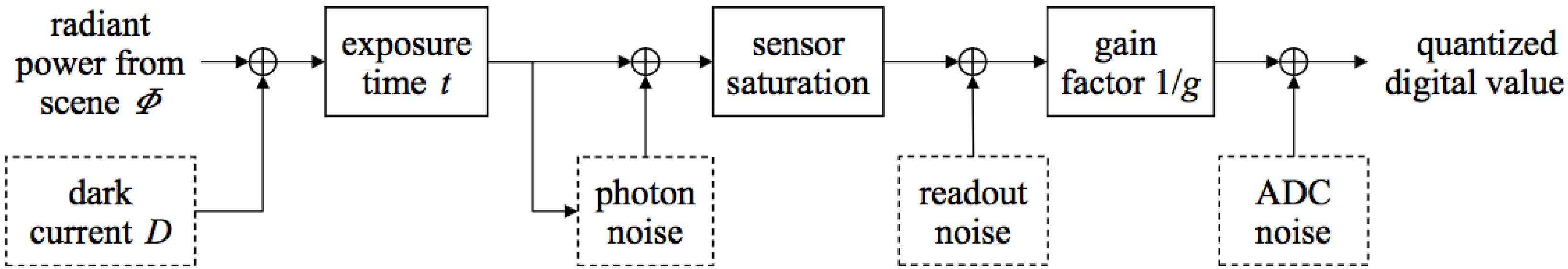
Q: Give a procedure for determing a row from the table from one or more captured photos.

If you can't work it out, see

www.clarkvision.com/articles/evaluation-1d2

Putting It All Together...

(Hasinoff et al, CVPR 2010)



$$\text{mean}(e^-) = \min\{ I_0 + \Phi t + Dt ,\ I_m \}$$

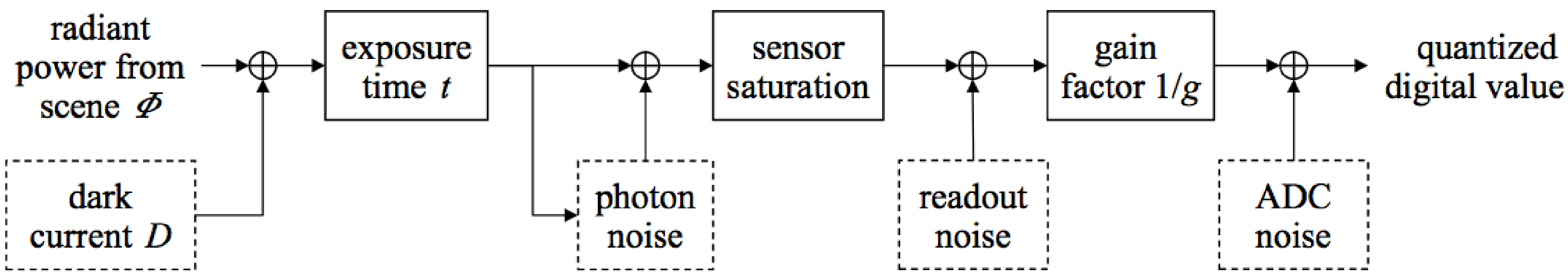
$$\text{variance}(e^-) = \Phi t + Dt + I_0 + \sigma_r^2 + \sigma_{ADC}^2 \cdot g^2$$

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

$$\text{variance}(DN) = \underbrace{\frac{\Phi t}{g^2}}_{\text{photon}} + \underbrace{\frac{Dt}{g^2}}_{\text{dark current}} + \underbrace{\frac{I_0 + \sigma_r^2}{g^2} + \sigma_{ADC}^2}_{\text{additive}}$$

Quantifying the Effect of Noise

(Hasinoff et al, CVPR 2010)



signal-to-noise ratio (SNR)

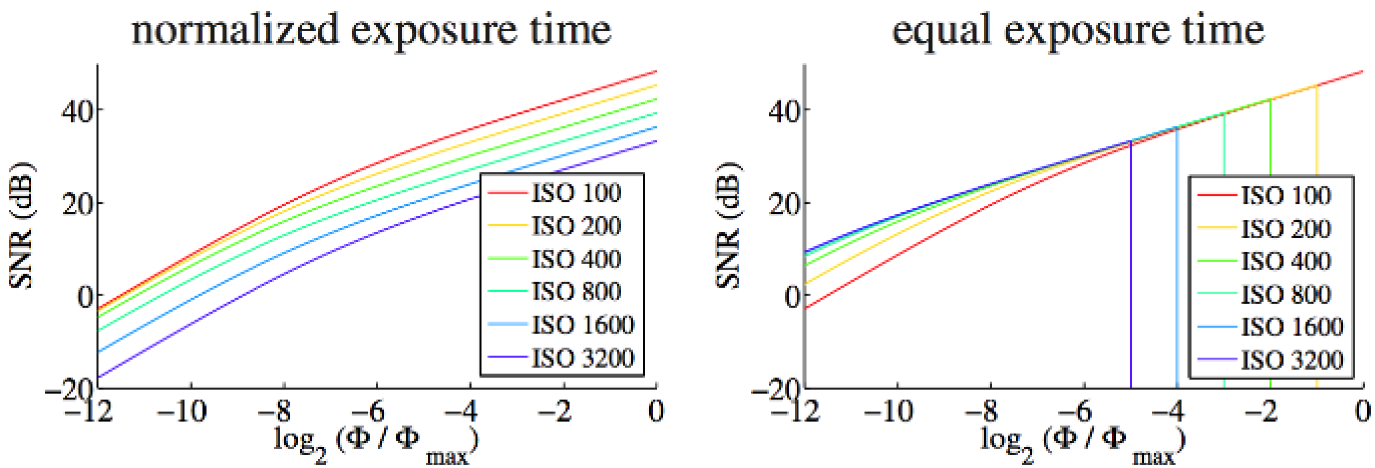
$$SNR = 10 \log_{10} \frac{\text{mean}(DN)^2}{\text{var}(DN)}$$

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

$$\text{variance}(DN) = \underbrace{\frac{\Phi t}{g^2}}_{\text{photon}} + \underbrace{\frac{Dt}{g^2}}_{\text{dark current}} + \underbrace{\frac{I_0 + \sigma_r^2}{g^2} + \sigma_{ADC}^2}_{\text{additive}}$$

Quantifying the Effect of Noise: Example

(Hasinoff et al, CVPR 2010)

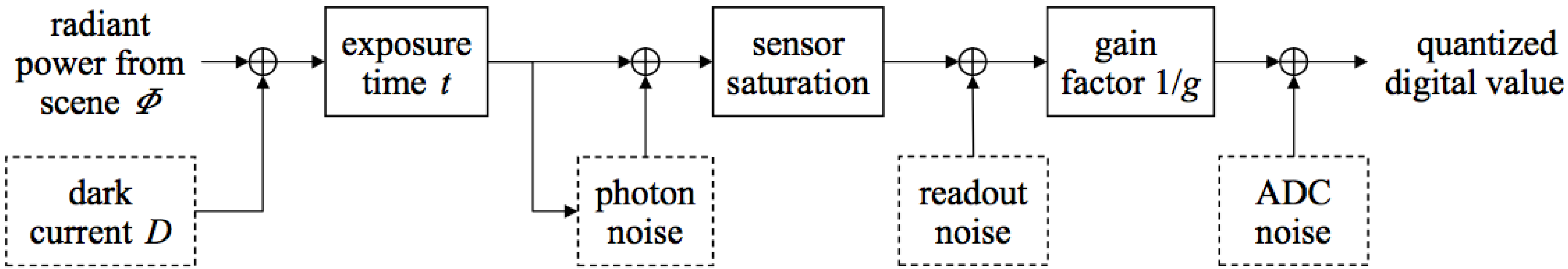


*

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.

Putting It All Together...

(Hasinoff et al, CVPR 2010)



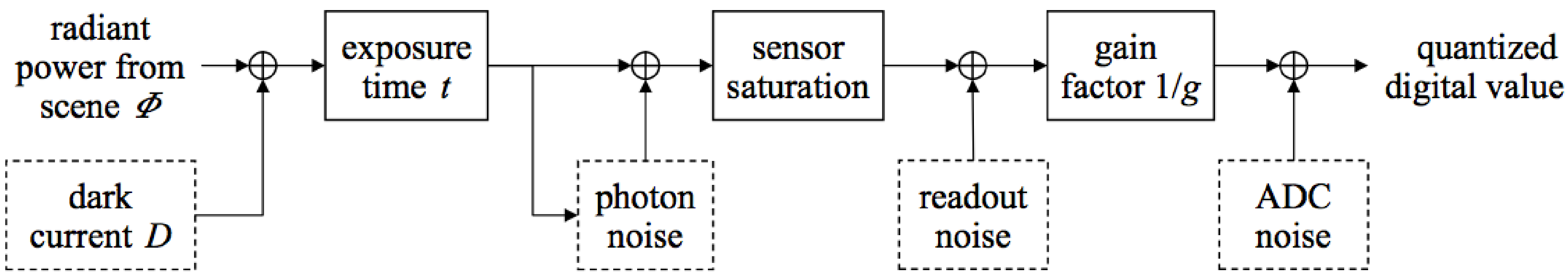
most common (but inaccurate) simplification:

- ignore photon + dark current
- ignore camera response function

$$\text{mean}(DN) = \min\left\{ \left(I_0 + \Phi t + Dt \right)/g,\ I_m/g \right\}$$

$$\text{variance}(DN) = \underbrace{\frac{\Phi t}{g^2}}_{\text{photon}} + \underbrace{\frac{Dt}{g^2}}_{\text{dark current}} + \underbrace{\frac{I_0 + \sigma_r^2}{g^2}}_{\text{additive}} + \sigma_{ADC}^2$$

The Anscombe transform



An transformation that turns a Poisson-distributed random variable x to a variable with approximately Gaussian distribution

$$y = f(x) = 2\sqrt{x + 3/8}$$

---

x = Poisson-distributed variable with mean m

$$\text{mean}(y) = 2\sqrt{m + 3/8} - \frac{1}{4\sqrt{m}} + O\left(\frac{1}{m^{3/2}}\right)$$

$$\text{variance}(y) = 1 + O\left(\frac{1}{m^2}\right) \quad (\approx 1 \text{ for } m \geq 4)$$

To probe further

- www.clarkvision.com/articles/index.html#part_4
- Healey & Kondepudy, Radiometric CCD camera calibration and noise estimation, PAMI 1994
- Debevec & Malik, Recovering high dynamic range radiance maps from images, Siggraph 1997
- Hasinoff et al, Noise-optimal capture for high dynamic range photography, CVPR 2010
- Canon firmware hacks for added control: chdk.wikia.com/wiki
- Makitalo & Foi, Optimal inversion of the Anscombe transform in low-count Poisson image denoising, IEEE Trans. Image Processing, v.20, no.1, 2011
- Heide et al, ProxImaL: Efficient image optimization using proximal algorithms, Proc. ACM SIGGRAPH 2016

Topic 09:

The Camera

- Basic lens geometry
- Basic camera controls
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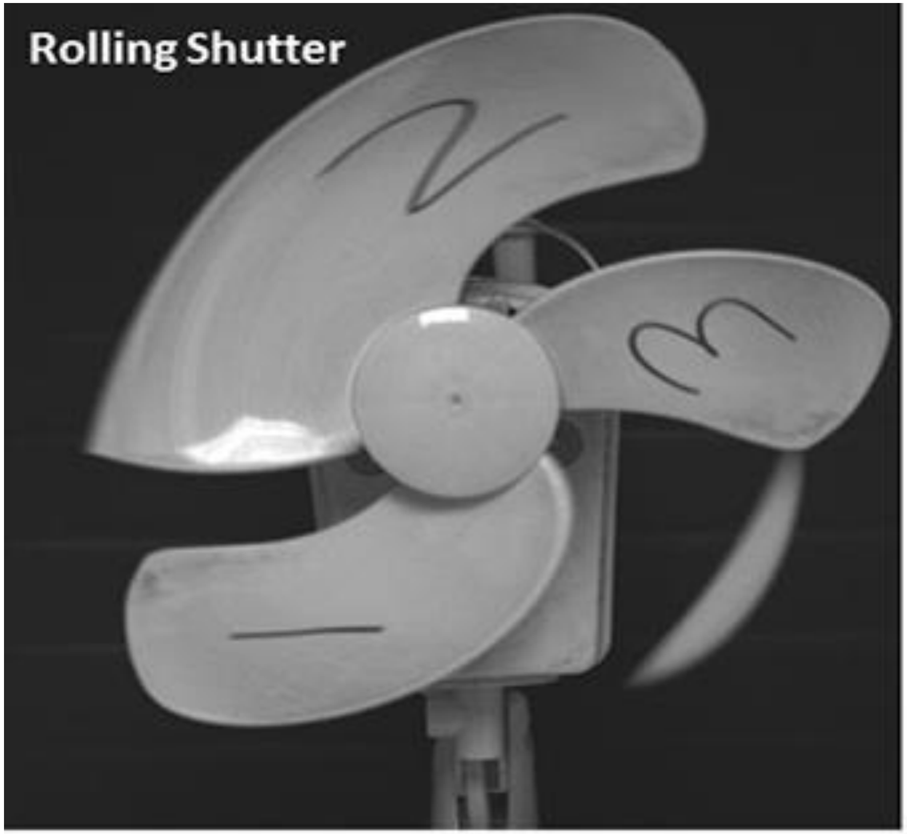
- From irradiance to digital numbers
- Image noise
- Rolling-shutter cameras

What's Going on in These Photos?

www.silent9.com

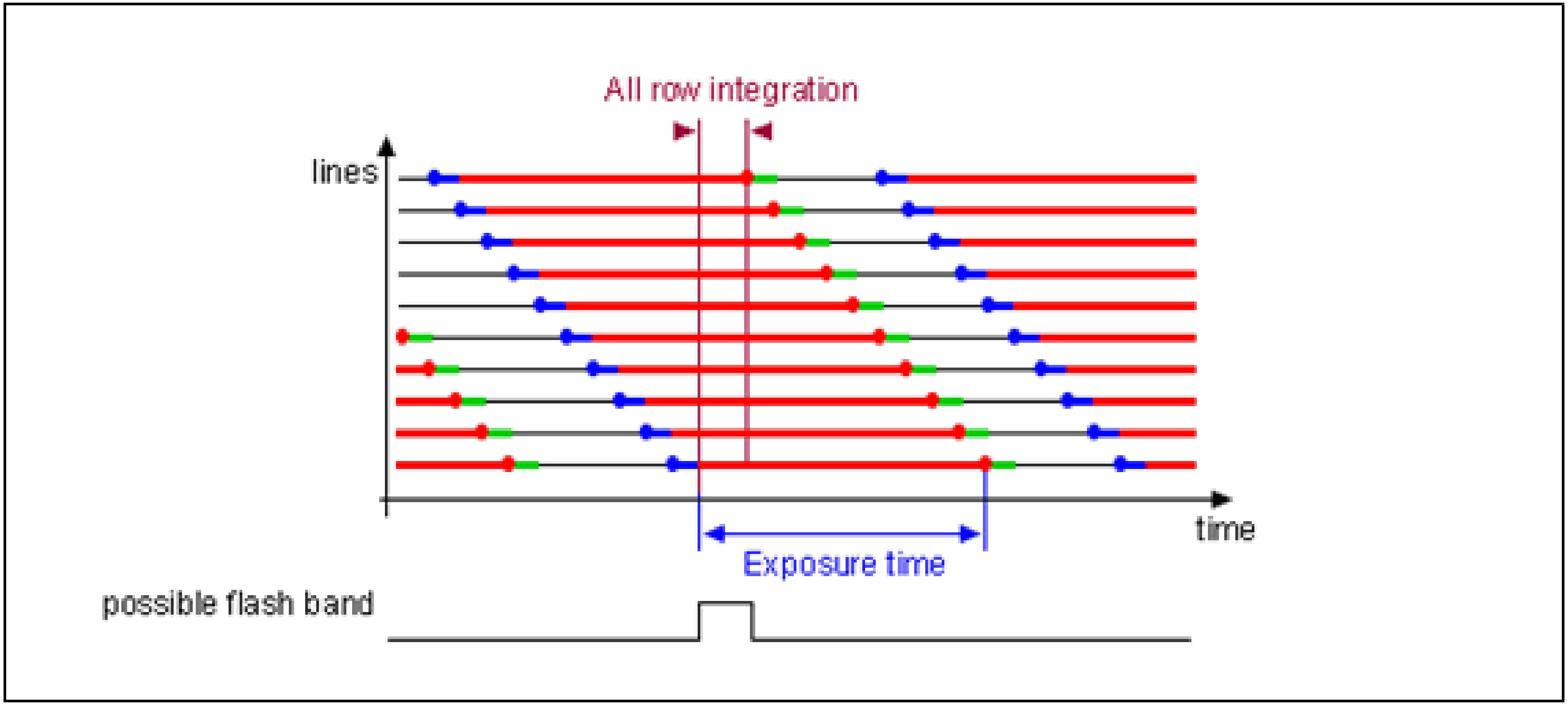
Joel Johnson

Rolling Shutter vs. Global Shutter



www.andor.com

Rolling Shutter Timing Diagram



www.matrix-vision.com

Rolling shutter correction on YouTube

Figure 1: Two examples rectified using our calibration free rolling shutter technique. Original frames on the left, our rectified result on the right. Our model accounts for frame global distortions such as skew (left example) as well as local wobble distortions which compress and stretch different parts of the frame (right example). Please see accompanying video.

- M. Grundmann et al, Calibration-Free Rolling Shutter Removal, Proc. Int. Conf. Computational Photography, 2012