University of Toronto
Department of Computer Science

CSC420

Introduction to Image Understanding

Tutorial 5: digital photography

Fall 2026

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Teaching Assistant

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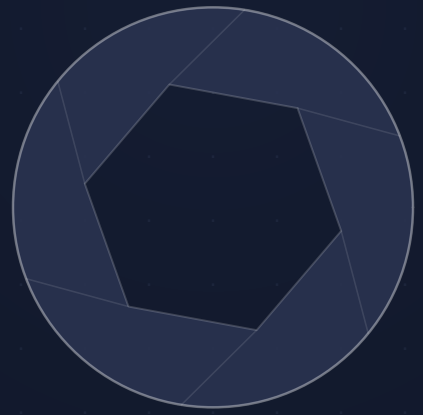


f/2: shallow focus

CSC420 Tutorial 5

Inside the camera

Optics, exposure, sensors and denoising



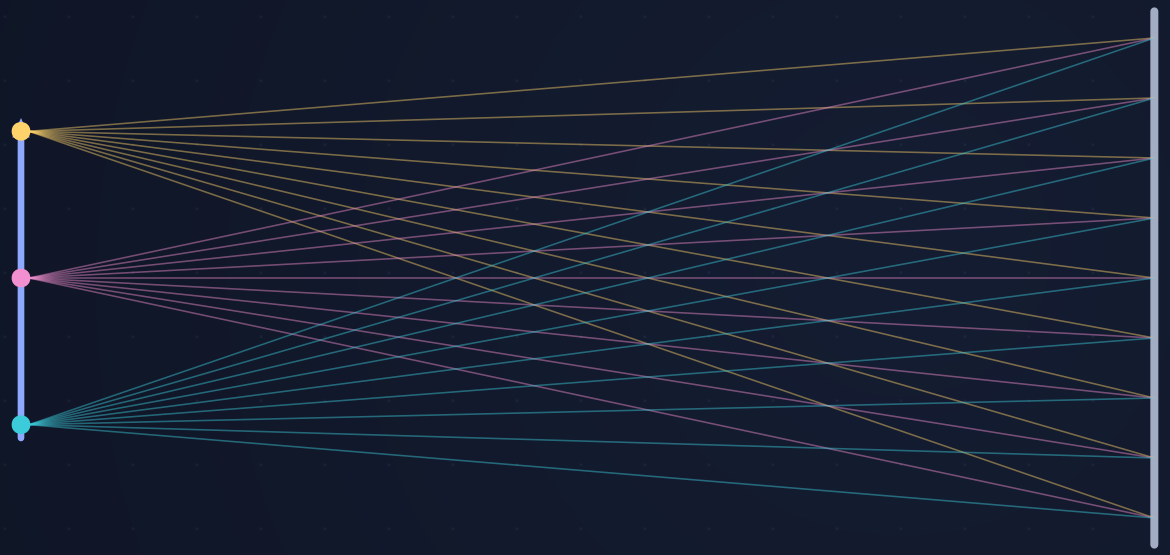
What we will cover

1. Pinhole cameras
2. Lenses and the thin lens formula
3. Defocus and depth of field
4. Aperture, stops and field of view
5. Aberrations
6. Exposure, ISO and dynamic range
7. Sensors, colour and noise
8. Demosaicking
9. Denoising
10. Practice problems
11. Recap

1 Pinhole cameras

Why a bare sensor is not enough

1 Pinhole cameras

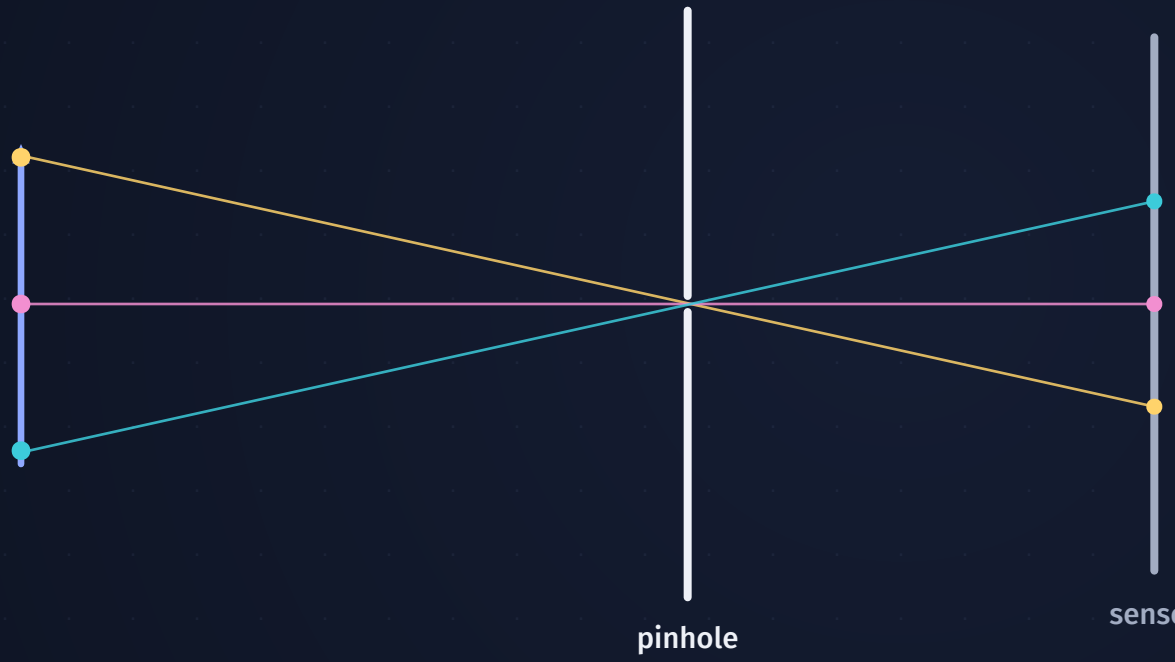


sensor



what the sensor records

1 Pinhole cameras





sharp, inverted image

1 Pinhole cameras

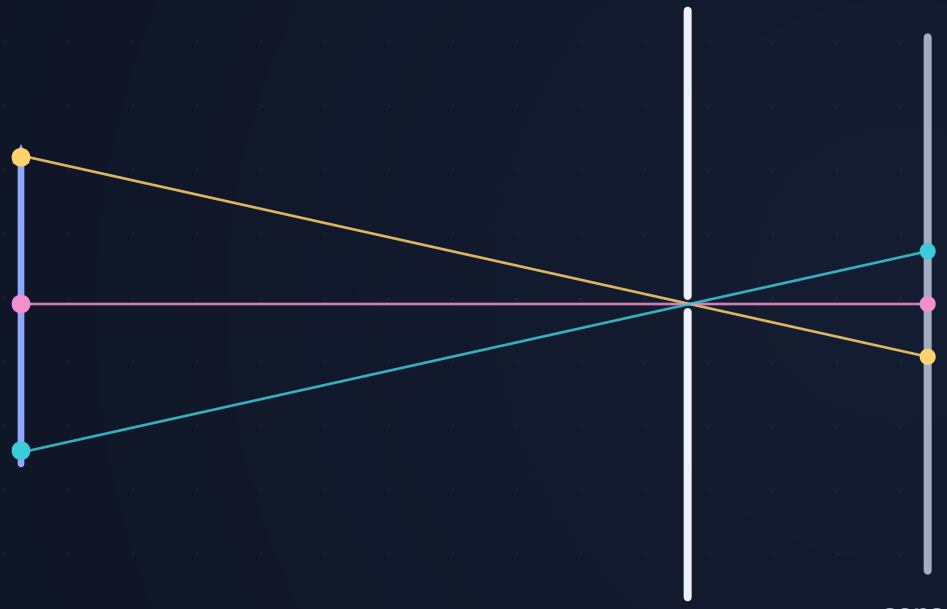




image size grows with f

diffraction pattern = Fourier transform of the pinhole



tiny hole
diffraction blur



well-chosen hole
sharpest



large hole
geometric blur



diameter D

diameter 2D

4× the area: 4× the light



focal length f



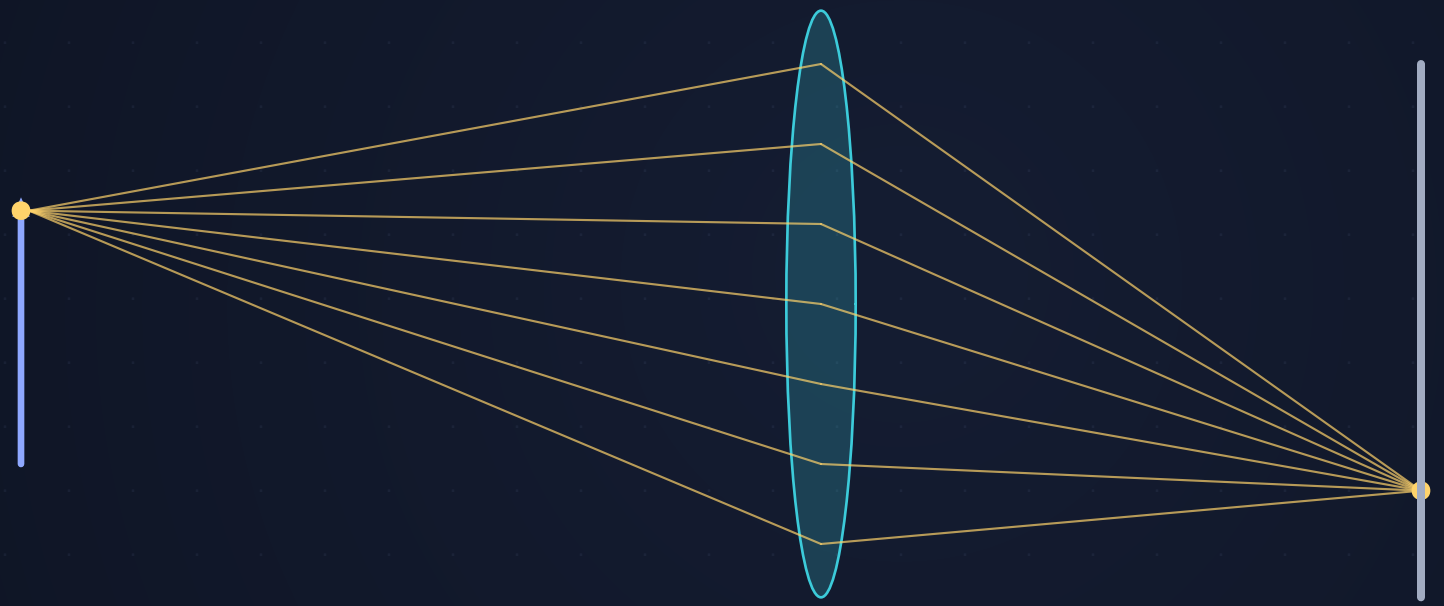
focal length 2f

image 4× larger: ¼ the light per pixel

$$\text{brightness} \propto \left(\frac{D}{f}\right)^2$$

2 Lenses and the thin lens formula

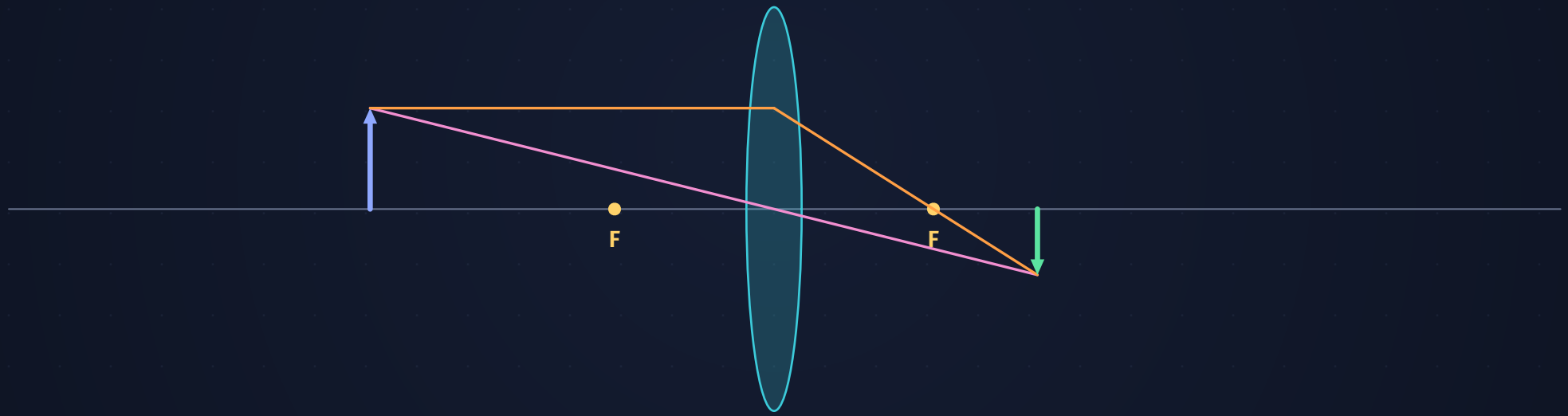
Sharp and bright at the same time



wide opening: lots of light

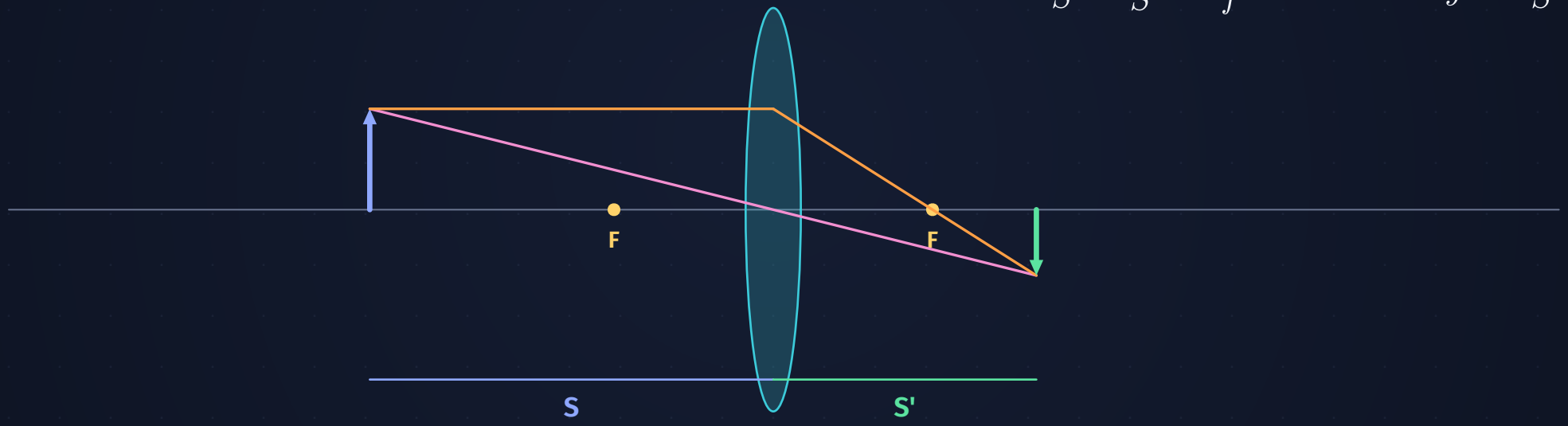
all rays from a point meet again: sharp

1. through the center: straight
2. parallel: bends through the focal point



1. through the center: straight
2. parallel: bends through the focal point

$$\frac{1}{S} + \frac{1}{S'} = \frac{1}{f}, \qquad m = \frac{y'}{y} = \frac{S'}{S}$$



f = 50 mm, S = 2 m = 2000 mm

$$\frac{1}{S'} = \frac{1}{50} - \frac{1}{2000} = \frac{39}{2000}$$

$$S' = \frac{2000}{39} \approx 51.3 \text{ mm}$$

$$m = \frac{S'}{S} = \frac{51.3}{2000} \approx \frac{1}{39}$$

Infinity focus

$$S = \infty \;\Rightarrow\; S' = f, \quad m = 0$$

parallel rays meet on the focal plane

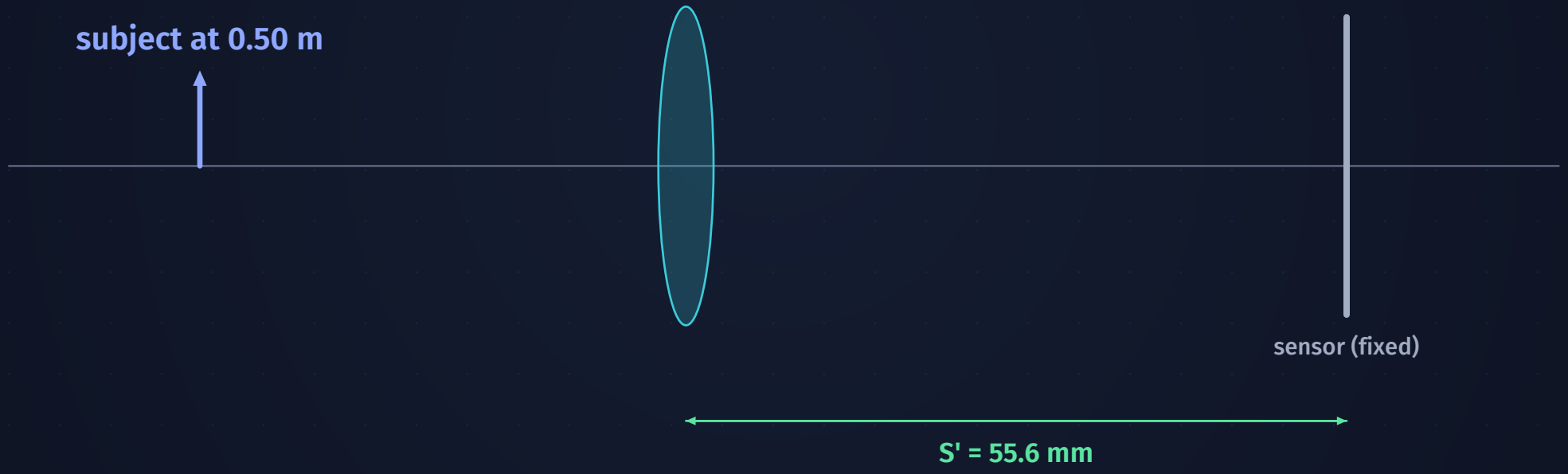
Life size

$$S = 2f \;\Rightarrow\; S' = 2f, \quad m = 1$$

macro photography at 1:1

closer subject → lens moves away from the sensor

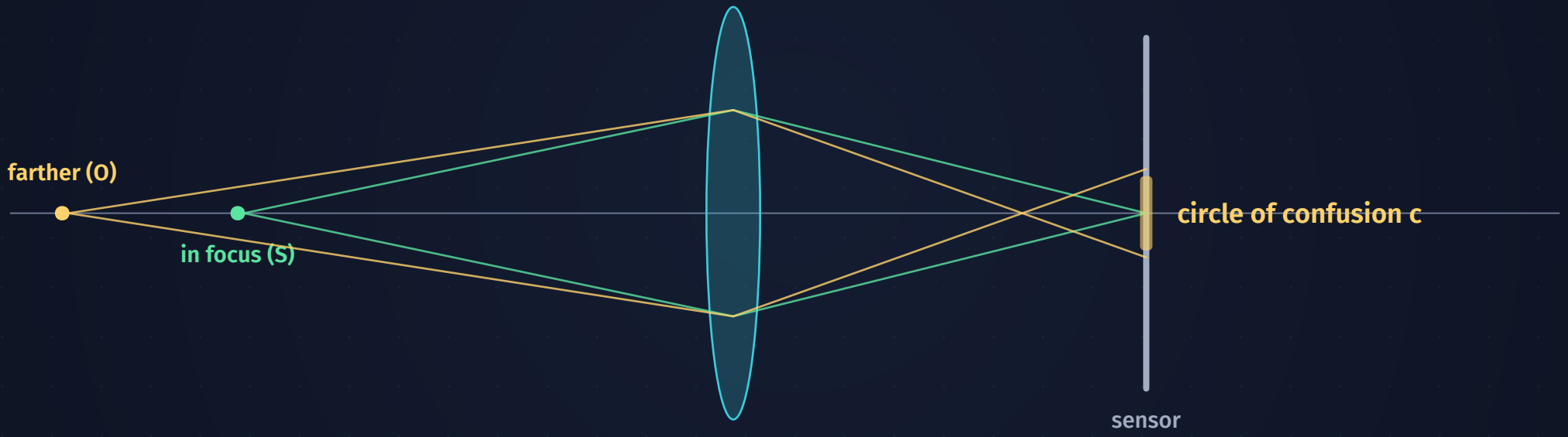
$$\frac{1}{1/50 - 1/500} = 55.6 \text{ mm}: \quad 4.3 \text{ mm further}$$



3 Defocus and depth of field

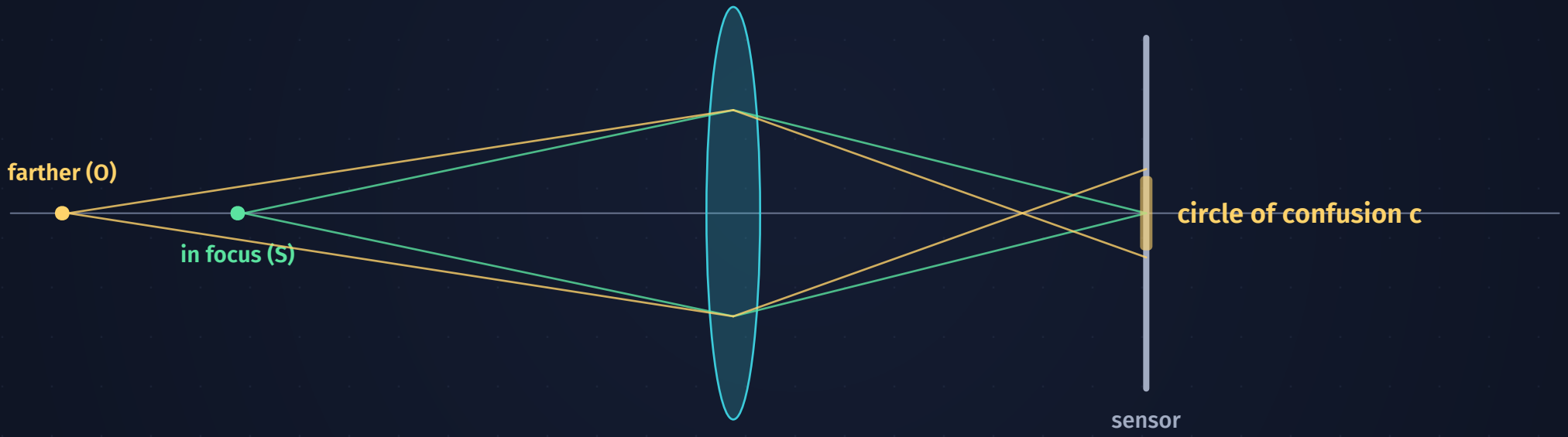
What is sharp, and how much

3 Defocus and depth of field



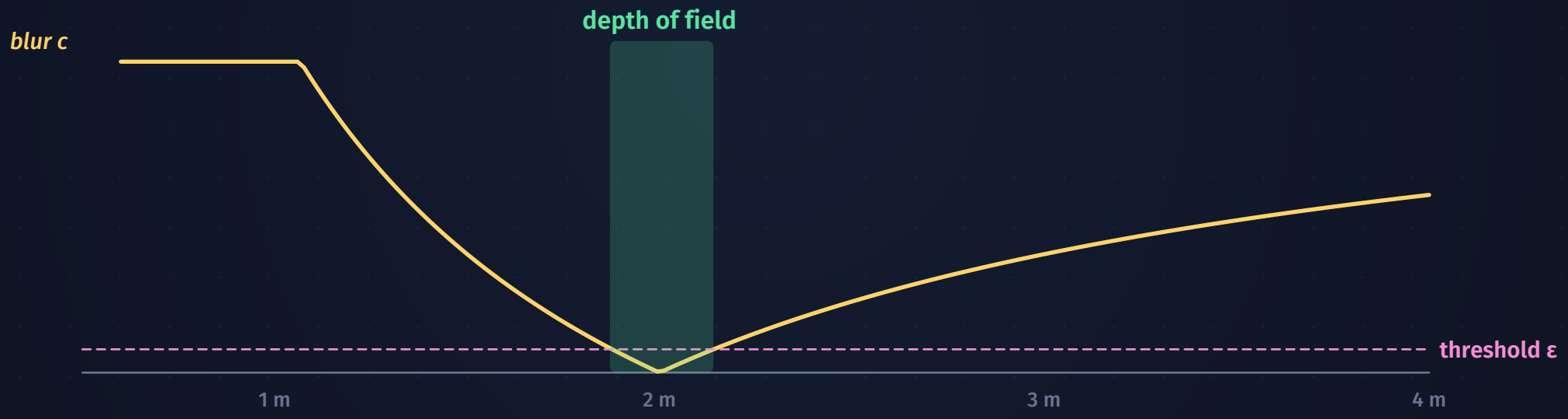
3 Defocus and depth of field

$$c = m\,D\,\frac{O - S}{O}$$



m: magnification D: aperture diameter S: focus distance O: object distance

$$c < \varepsilon \quad \Rightarrow \quad \mathrm{DOF} \approx \frac{2\,\varepsilon\,O}{m\,D}$$



$$m = \frac{50}{2000 - 50} \approx 0.0256, \qquad D = \frac{50}{2.8} \approx 17.9 \text{ mm}$$

$$\text{DOF} \approx \frac{2 \cdot 0.03 \cdot 2000}{0.0256 \cdot 17.9} \approx 262 \text{ mm}$$

$$f/8: \; D = 6.25 \text{ mm} \; \Rightarrow \; \text{DOF} \approx 750 \text{ mm}$$

depth of field grows in proportion to the f-number

out-of-focus lights take the shape of the aperture: a six-blade iris here





f/2

background lights at 30 m: blur circle c ≈ 0.80 mm on the sensor

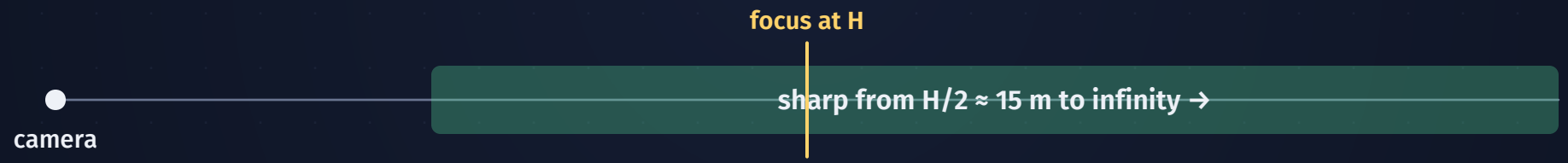




f/8

background lights at 30 m: blur circle c ≈ 0.20 mm on the sensor

$$H = \frac{f^2}{Nc} = \frac{50^2}{2.8 \cdot 0.03} \approx 29{,}800 \text{ mm} \approx 30 \text{ m}$$



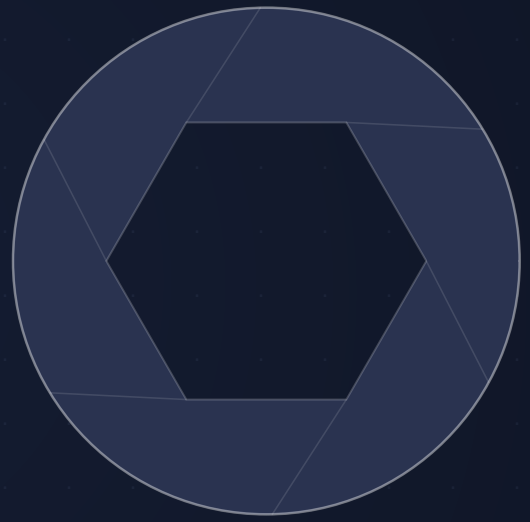
useful for landscapes and street photography

4 Aperture, stops and field of view

The numbers on your lens

$$N = \frac{f}{D}$$

50 mm / 2.8 ≈ 17.9 mm

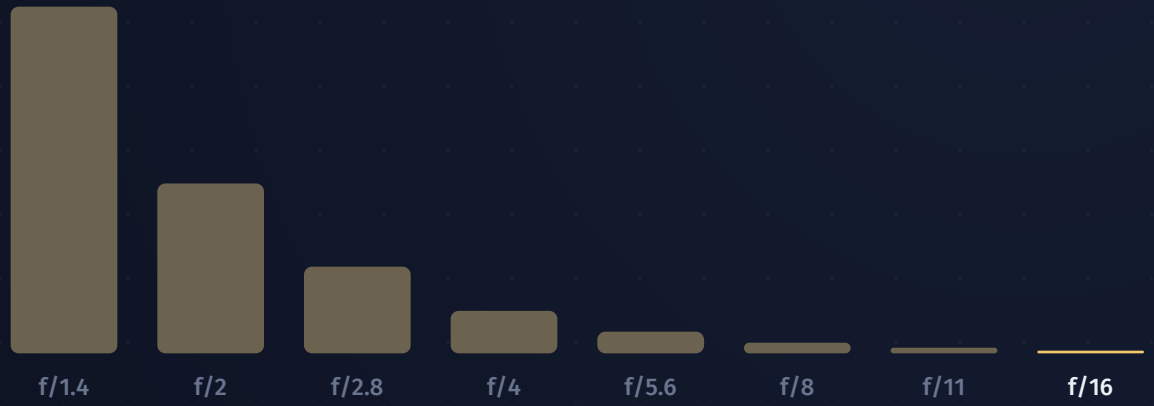


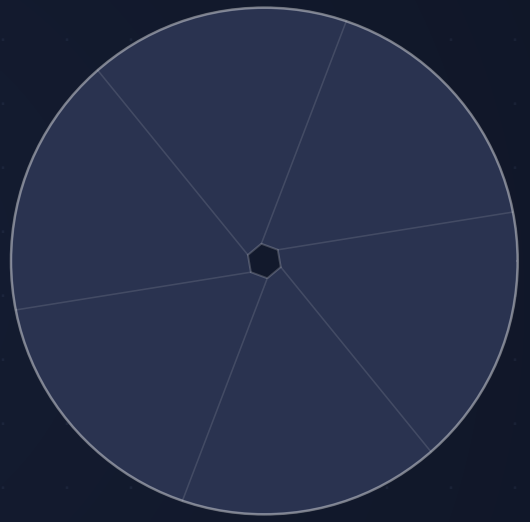
f/2.8

$$N = \frac{f}{D}$$

$$\text{light} \propto \frac{1}{N^2}$$

each step: half the light





f/16



wide aperture (small N)

more light

shallow depth of field

blurry background



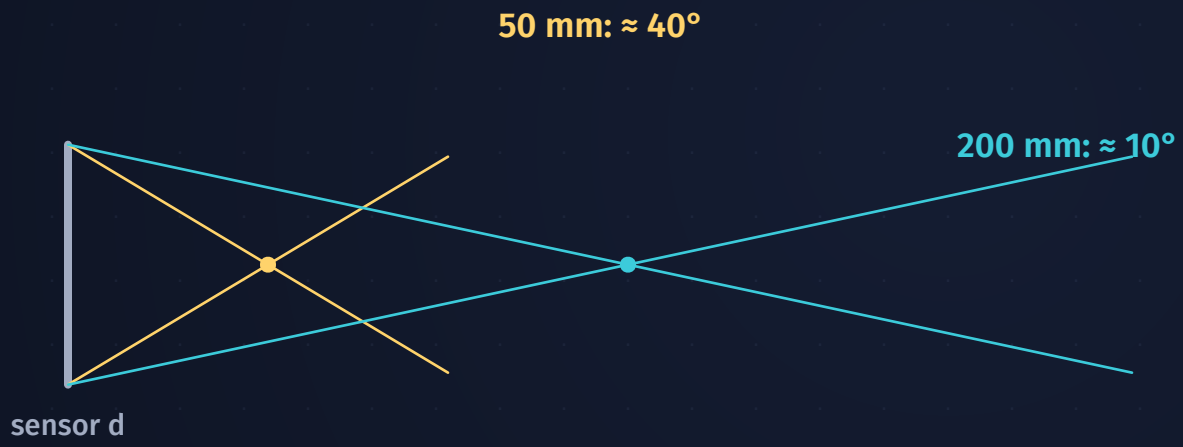
narrow aperture (large N)

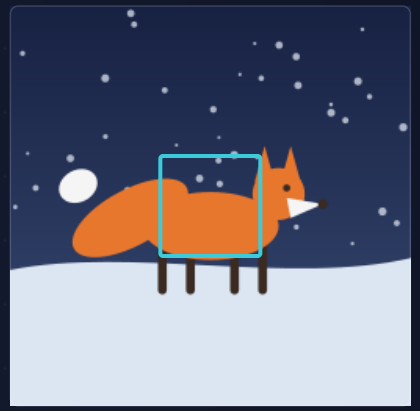
less light

deep depth of field

diffraction at extremes

$$\mathrm{FOV} = 2 \arctan \frac{d}{2f}$$





wide (50 mm)



tele (200 mm)

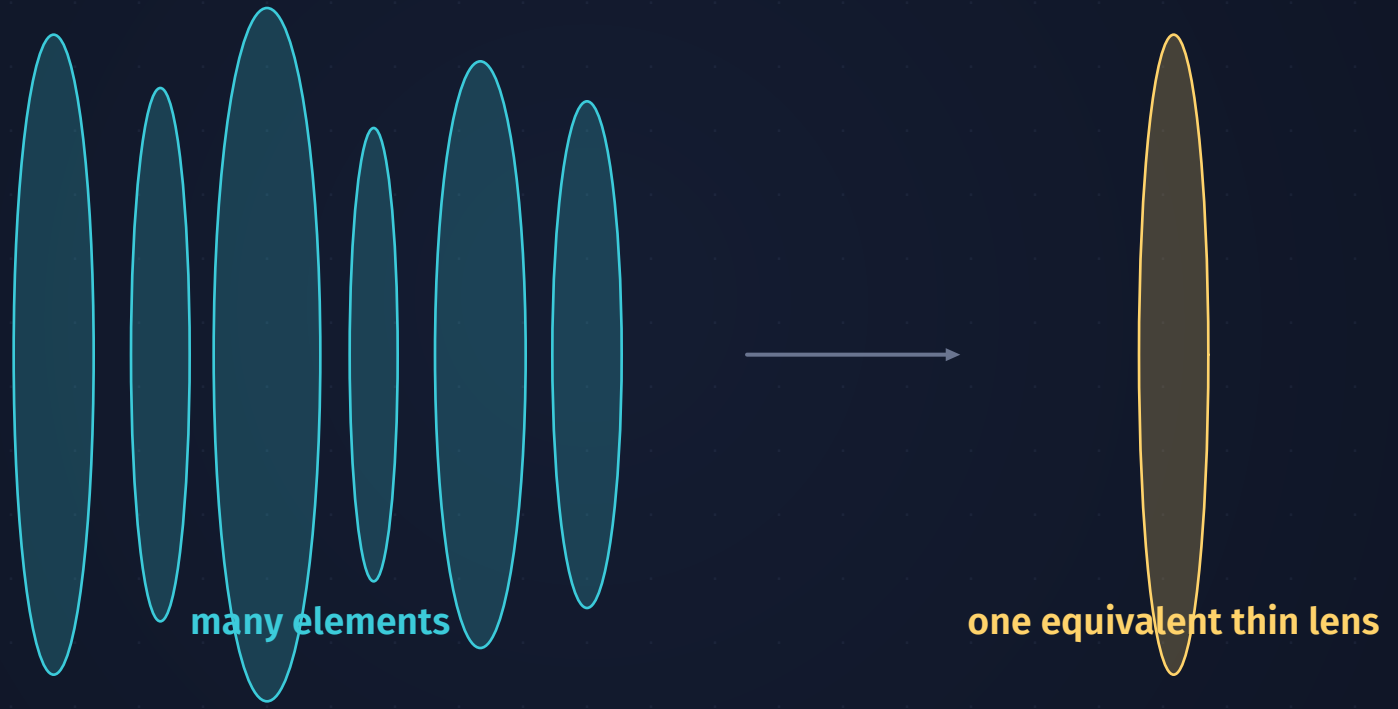
$$\left(\frac{8}{2.8}\right)^2 \approx 8.2 \approx 2^3$$

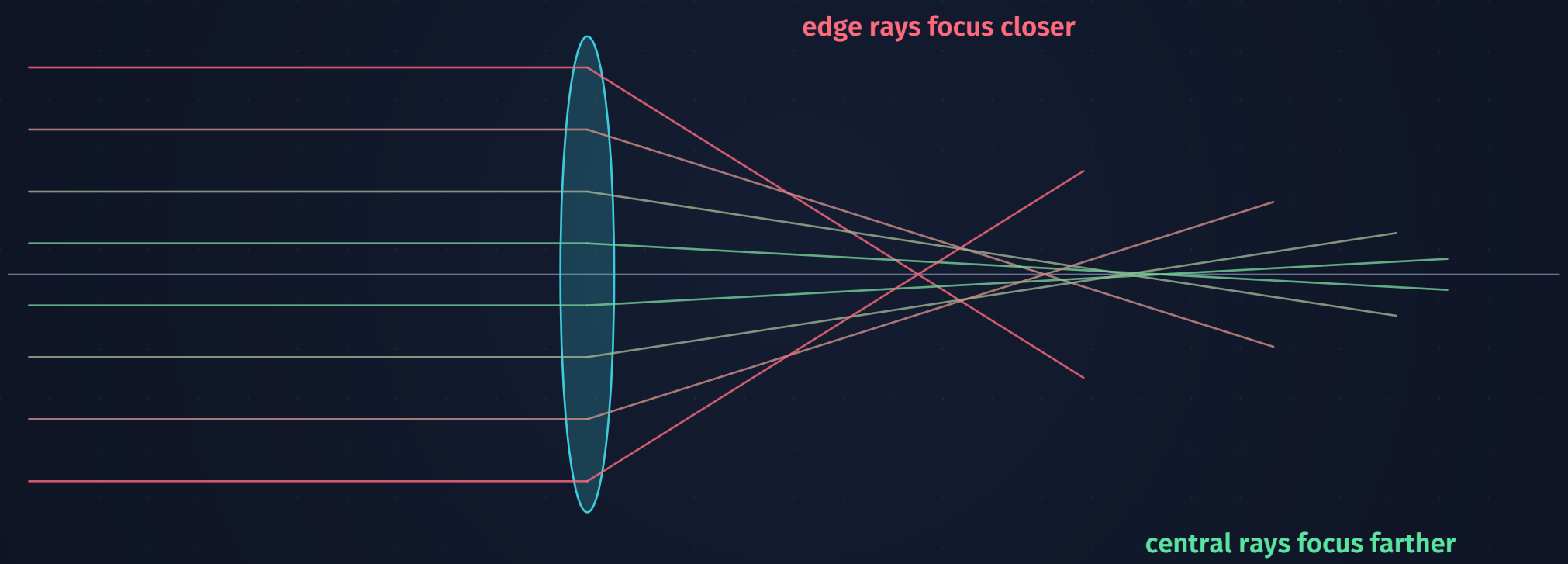
three stops less light

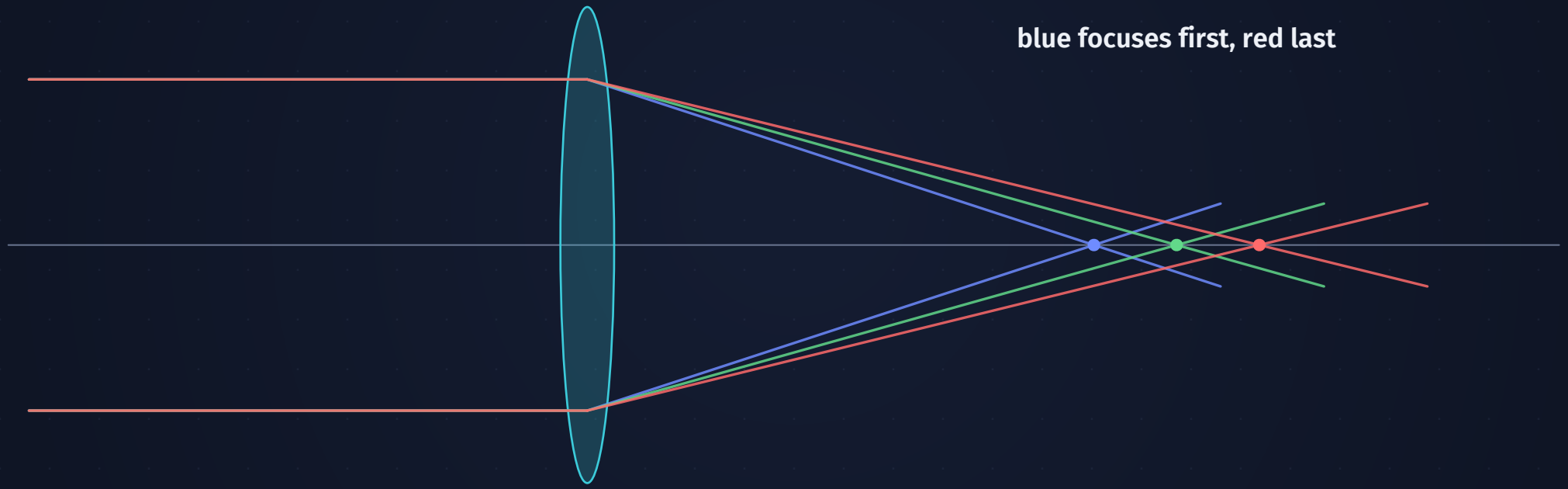
f/2.8 → f/4 → f/5.6 → f/8

5 Aberrations

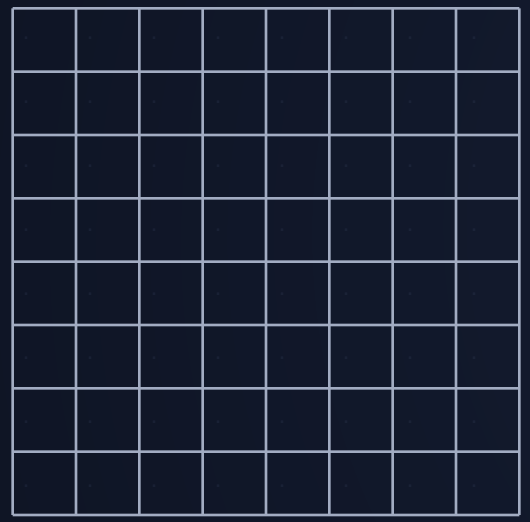
Where real lenses fall short


many elements
one equivalent thin lens


edge rays focus closer
central rays focus farther



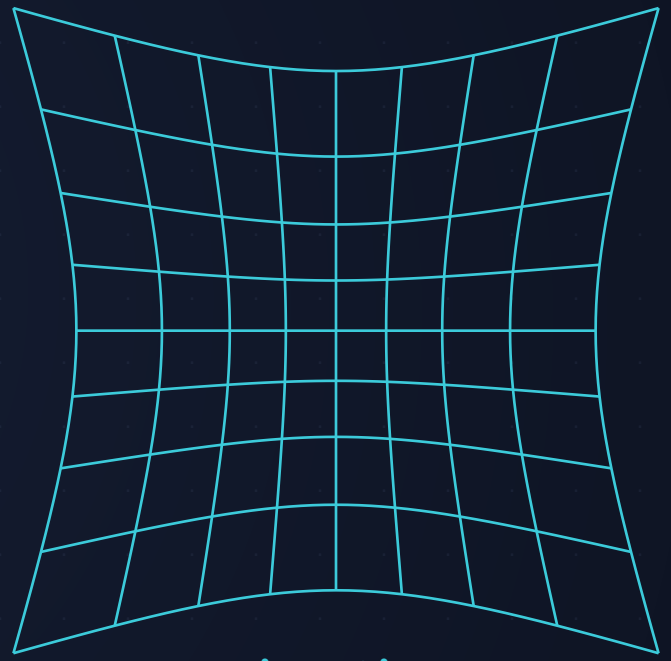
fix: an achromatic doublet of two glasses



no distortion



barrel



pincushion

Hubble, 1990

mirror shape slightly wrong

1993: corrective optics installed

6 Exposure, ISO and dynamic range

Getting the brightness right



Shutter time

longer: motion blur



Aperture

wider: shallow focus



ISO

higher: more noise

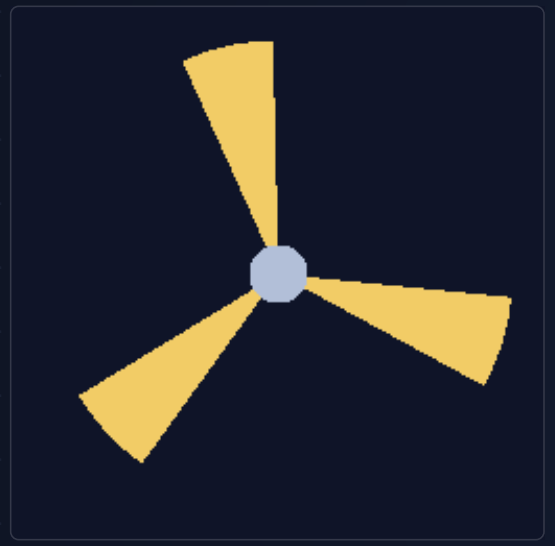
shutter 1/1000 · 1/500 · 1/250 · 1/125 · 1/60 · 1/30

more light →

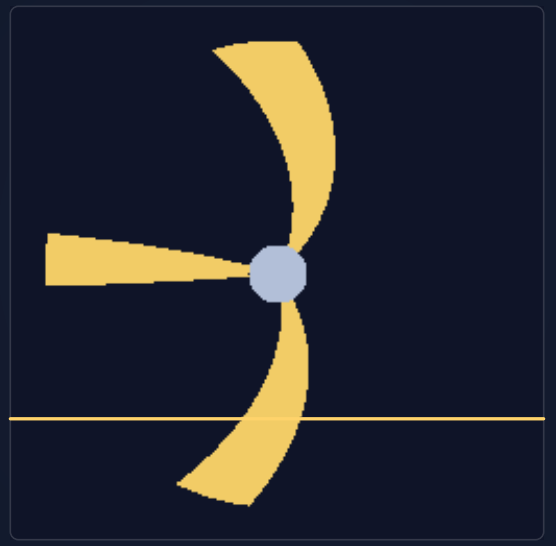
aperture f/2 · f/2.8 · f/4 · f/5.6 · f/8 · f/11

less light →

+2 stops (time) and −2 stops (aperture) = same exposure



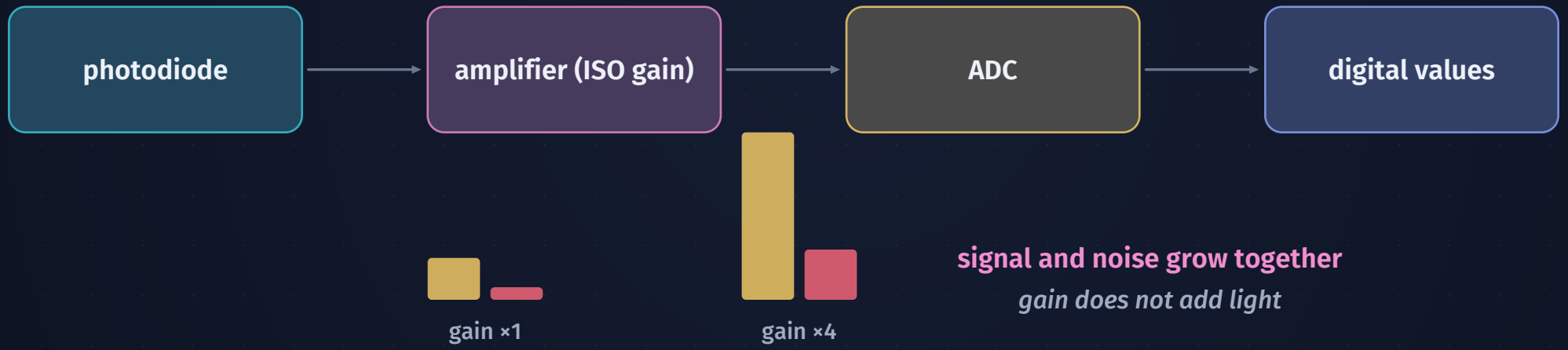
global shutter



rolling shutter: skewed blades



flickering light: dark bands



signal and noise grow together

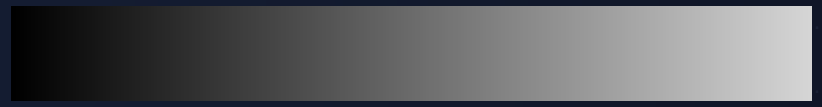
gain does not add light

$$\text{dynamic range} = \frac{\text{largest value}}{\text{smallest value}}$$

8 bits: 256 levels



14 bits: 16,384 levels



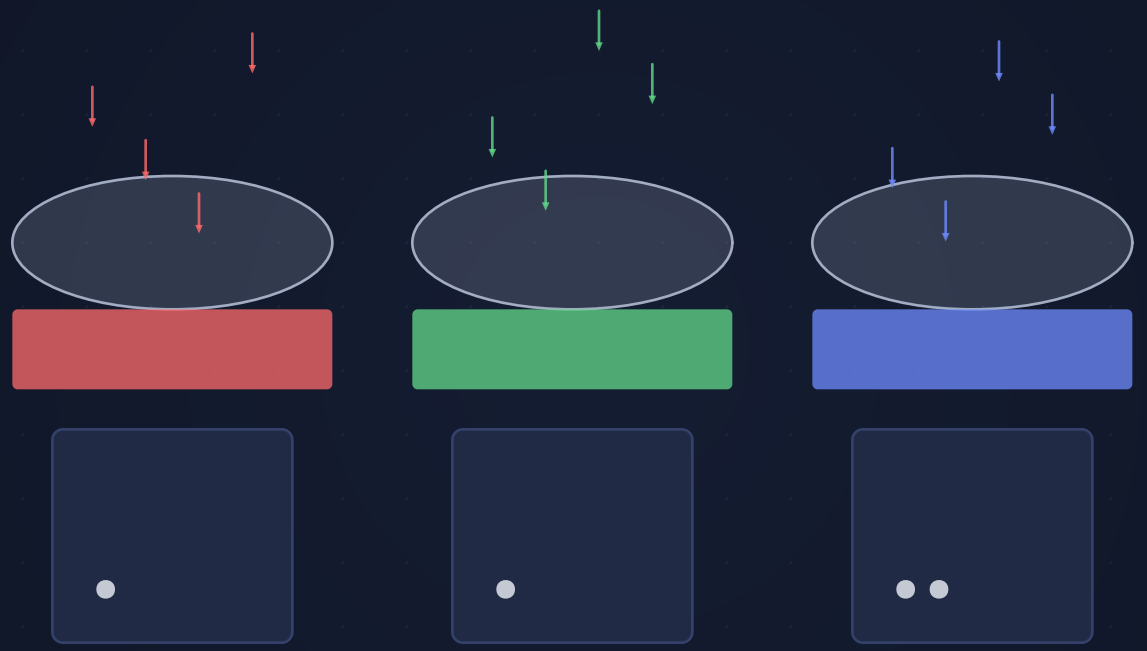
the same dark gradient, brightened 14× after capture

banding **smooth**

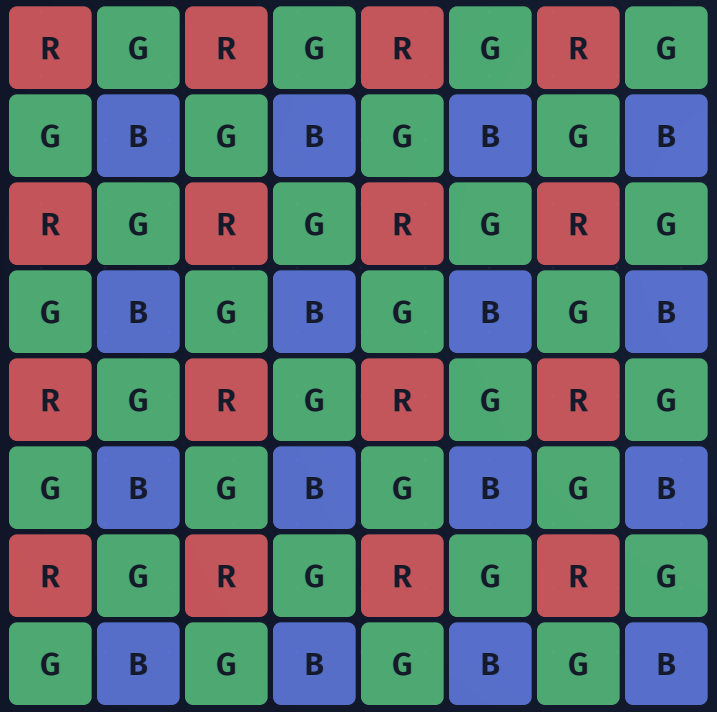
shoot RAW if you plan to edit

7 Sensors, colour and noise

From photons to a RAW image



quantum efficiency ≈ 50%



green: 50%

red: 25%

blue: 25%

each pixel sees only one colour



3 photons per pixel (mean)

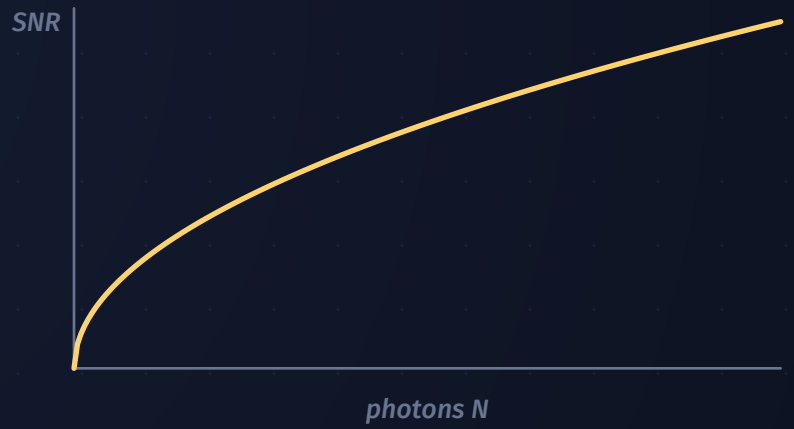


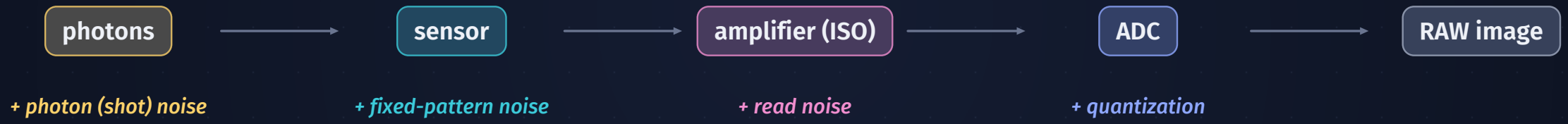
30 photons per pixel (mean)



300 photons per pixel (mean)

$$\mathrm{SNR} = \frac{N}{\sqrt{N}} = \sqrt{N}$$




photons
sensor
amplifier (ISO)
ADC
RAW image
+ photon (shot) noise
+ fixed-pattern noise
+ read noise
+ quantization



next two chapters

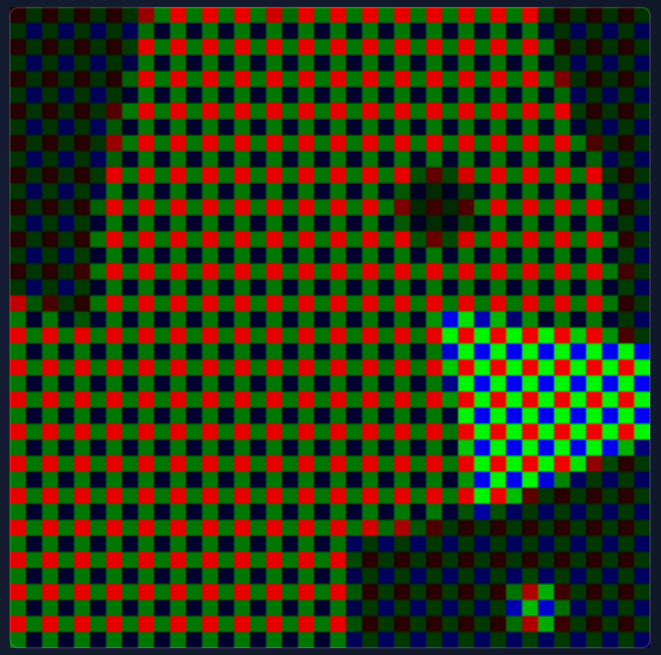
8 Demosaicking

Filling in the missing colours

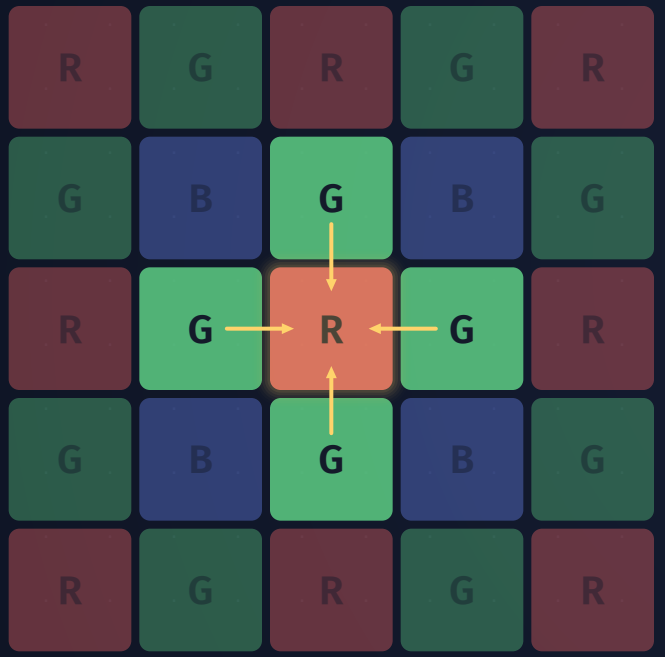
8 Demosaicking



scene



what the sensor records (zoomed)



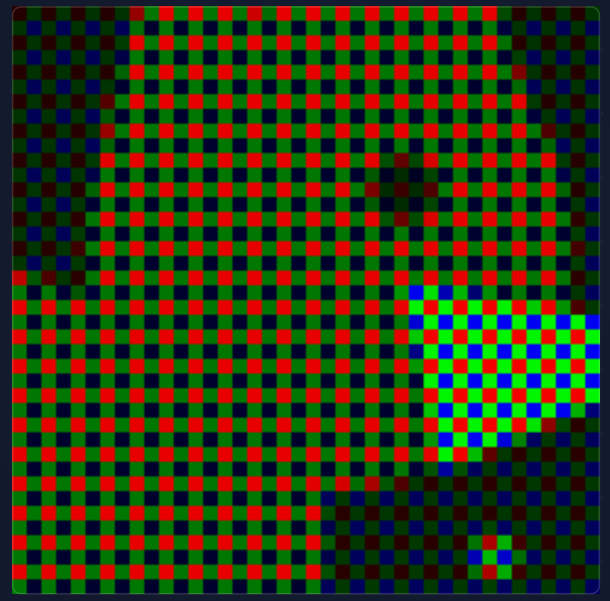
$$G_c = \frac{G_N + G_S + G_E + G_W}{4}$$

red at a green pixel: average of its 2 red neighbours

red at a blue pixel: average of its 4 diagonal reds



true colours

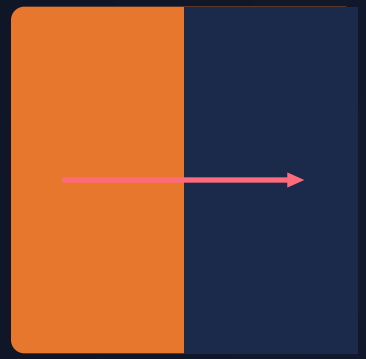


Bayer mosaic



bilinear demosaicking

look at the edges: colour fringes



Across an edge

mixes the two sides: fringes



Along an edge

keeps colours consistent

modern cameras: edge-aware or learned demosaicking

9 Denoising

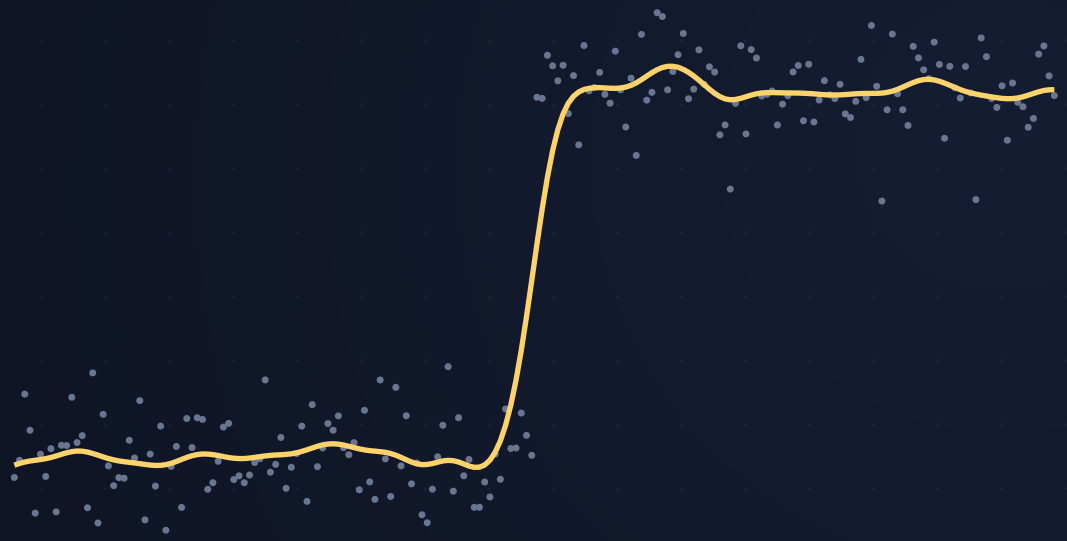
Averaging the right pixels

$$\sigma_{\text{avg}} = \frac{\sigma}{\sqrt{N}}$$



average of 1 average of 4 average of 16

Gaussian: edge smeared



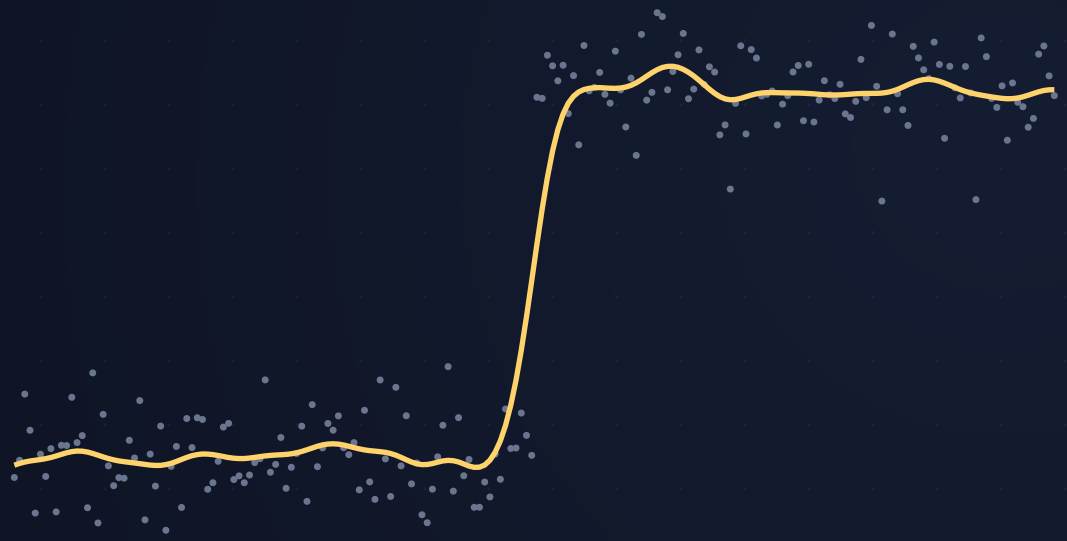


noisy (20.5 dB)



Gaussian (25.9 dB)

Gaussian: edge smeared



0.21	0.19	0.95
0.22	0.20	0.18
0.23	0.20	0.21

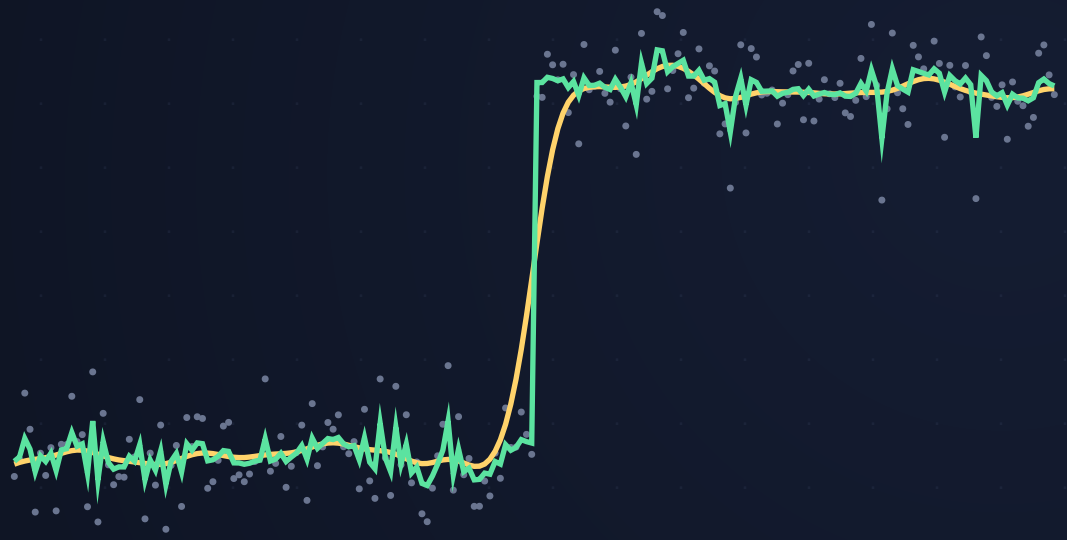


sorted: take the middle value → 0.21 (the outlier 0.95 is ignored)



median 5×5 (28.1 dB)

Gaussian: edge smeared

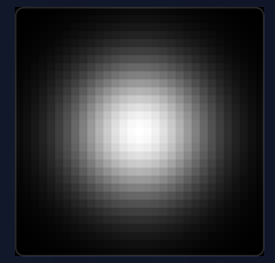


bilateral: edge kept

$$w(p,q) = e^{-\frac{\|p-q\|^2}{2\sigma_s^2}} \cdot e^{-\frac{(I_p - I_q)^2}{2\sigma_r^2}}$$



patch at an edge



spatial weight



range weight

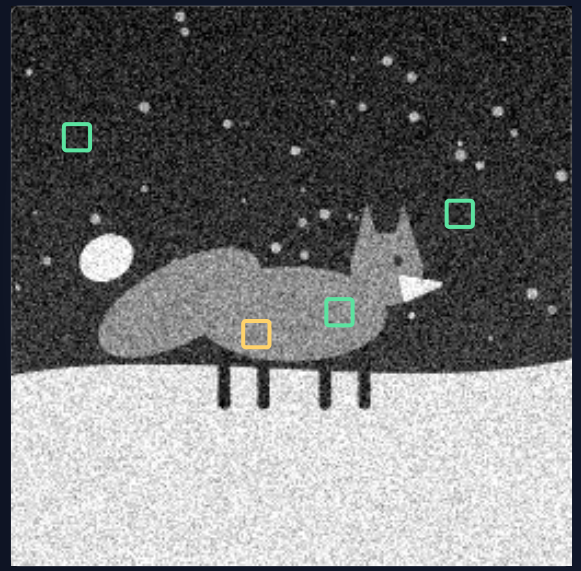


product

σ_s spatial width: how far the filter reaches

σ_r range width: which jumps count as edges

$$\sigma_r \to \infty \quad \Rightarrow \quad \text{Gaussian blur}$$



similar patches can be far apart

PSNR against the clean image (higher is better)



Gaussian: 25.9 dB



median: 28.1 dB



bilateral: 28.8 dB



non-local means: 33.5 dB

9 Denoising



original



bilateral smoothing + edges = cartoon

10 Practice problems

Try each one before looking at the answer

Problem 1

A bare sensor faces a scene, with no pinhole and no lens. What image does it record?

try it first

Problem 1

A bare sensor faces a scene, with no pinhole and no lens. What image does it record?

Answer

A **uniform blur**: every scene point reaches every pixel.

Problem 2

Why does a pinhole image get blurrier again when the hole is made very small?

try it first

Problem 2

Why does a pinhole image get blurrier again when the hole is made very small?

Answer

Diffraction: a smaller hole gives a **wider** diffraction pattern.

Problem 3

A 100 mm lens should make a life-size image (m = 1) of a flower. Where do the flower and the sensor go?

try it first

Problem 3

A 100 mm lens should make a life-size image (m = 1) of a flower. Where do the flower and the sensor go?

Answer

Both are 200 mm from the lens.

$$m = \frac{S'}{S} = 1 \;\Rightarrow\; \frac{2}{S} = \frac{1}{f} \;\Rightarrow\; S = S' = 2f = 200\ \text{mm}$$

Problem 4

You move the lens farther from the sensor. Does the in-focus plane move closer to the camera, or farther away?

try it first

Problem 4

You move the lens farther from the sensor. Does the in-focus plane move closer to the camera, or farther away?

Answer

It moves closer.

$$\frac{1}{S} = \frac{1}{f} - \frac{1}{S'}: \qquad S' \text{ up} \Rightarrow S \text{ down}$$

Problem 5

A point is farther away than the focus distance. Does it come to focus in front of the sensor, or behind it?

try it first

Problem 5

A point is farther away than the focus distance. Does it come to focus in front of the sensor, or behind it?

Answer

In front of the sensor: a larger O gives a shorter image distance.

$$O > S \;\Rightarrow\; S'_O < S'$$

Problem 6

A 50 mm lens at f/2 is focused at 2 m. How big is the blur circle for a point at 4 m, in pixels of 7.5 µm?

try it first

Problem 6

A 50 mm lens at f/2 is focused at 2 m. How big is the blur circle for a point at 4 m, in pixels of 7.5 µm?

Answer

c ≈ 0.32 mm, about 43 pixels.

$$c = m\,D\,\frac{O - S}{O} \approx 0.0256 \cdot 25\ \text{mm} \cdot \frac{4 - 2}{4} \approx 0.32\ \text{mm}$$

Problem 7

The slides' Canon 5D example: 50 mm, f/2.8, 7.5 µm pixels. What is the hyperfocal distance for a one-pixel blur?

try it first

Problem 7

The slides' Canon 5D example: 50 mm, f/2.8, 7.5 µm pixels. What is the hyperfocal distance for a one-pixel blur?

Answer

H ≈ 119 m; sharp from about 60 m to infinity.

$$H = \frac{f^2}{Nc} = \frac{50^2}{2.8 \cdot 0.0075} \approx 119{,}000 \text{ mm}$$

Problem 8

You change the aperture from f/4 to f/2. How much more light? What happens to the depth of field?

try it first

Problem 8

You change the aperture from f/4 to f/2. How much more light? What happens to the depth of field?

Answer

4× the light (two stops); the depth of field roughly **halves**.

$$\left(\tfrac{4}{2}\right)^2 = 4, \qquad \mathrm{DOF} \propto N$$

Problem 9

How many stops is it from f/1.4 to f/2.8?

try it first

Problem 9

How many stops is it from f/1.4 to f/2.8?

Answer

Two stops: 4× less light.

$$\left(\frac{2.8}{1.4}\right)^2 = 4 = 2^2$$

Problem 10

Why do phone videos of LED lights sometimes show dark horizontal bands?

try it first

Problem 10

Why do phone videos of LED lights sometimes show dark horizontal bands?

Answer

The **rolling shutter** reads rows at different times while the light **flickers**.

Problem 11

Photo A collects 2,500 photons per pixel, photo B 10,000. Which has the better SNR, and by how much?

try it first

Problem 11

Photo A collects 2,500 photons per pixel, photo B 10,000. Which has the better SNR, and by how much?

Answer

Photo B, by a factor of 2.

$$\sqrt{2500} = 50, \qquad \sqrt{10000} = 100$$

Problem 12

At a red pixel, the four green neighbours are 100, 120, 110, 90 and the four diagonal blues are 40, 60, 50, 50. Estimate the missing green and blue.

try it first

Problem 12

At a red pixel, the four green neighbours are 100, 120, 110, 90 and the four diagonal blues are 40, 60, 50, 50. Estimate the missing green and blue.

Answer

G = 105, B = 50.

$$G = \frac{100 + 120 + 110 + 90}{4} = 105, \qquad B = \frac{40 + 60 + 50 + 50}{4} = 50$$

Problem 13



You must remove noise from a photo of text without blurring the letters. Gaussian, median or bilateral?

try it first

Problem 13

You must remove noise from a photo of text without blurring the letters. Gaussian, median or bilateral?

Answer

An edge-aware filter such as bilateral; median for salt-and-pepper noise.

Problem 14

How could you use a Gaussian or bilateral filter to sharpen an image?

try it first

Problem 14

How could you use a Gaussian or bilateral filter to sharpen an image?

Answer

Unsharp masking: add the detail back, amplified. A bilateral blur avoids **halos**.

$$I_{\text{sharp}} = I + \alpha\,(I - \text{blur}(I))$$

11 Recap

Everything on one page

Optics	pinhole → lens; 1/S + 1/S' = 1/f; defocus and depth of field; f-numbers and field of view

Optics	pinhole → lens; 1/S + 1/S' = 1/f; defocus and depth of field; f-numbers and field of view
Exposure and sensors	shutter, aperture, ISO in stops; rolling shutter; Bayer filters; SNR = √N

Optics	pinhole → lens; $1/S + 1/S' = 1/f$; defocus and depth of field; f-numbers and field of view
Exposure and sensors	shutter, aperture, ISO in stops; rolling shutter; Bayer filters; SNR = $\sqrt{N}$
Processing	demosaicking by interpolation; denoising: Gaussian, median, bilateral, non-local means

Thin lens $\frac{1}{S} + \frac{1}{S'} = \frac{1}{f}, \quad m = \frac{S'}{S}$

Circle of confusion $c = m\,D\,\frac{O - S}{O}$

Depth of field $\mathrm{DOF} \approx \frac{2\,\varepsilon\,O}{m\,D}$

Hyperfocal distance $H = \frac{f^2}{N c}$

f-number and light $N = \frac{f}{D}, \quad \mathrm{light} \propto \frac{1}{N^2}$

Field of view $\mathrm{FOV} = 2\arctan\frac{d}{2f}$

Photon noise $\mathrm{SNR} = \sqrt{N}$

Bilateral weight $e^{-\frac{\|p-q\|^2}{2\sigma_s^2}}\, e^{-\frac{(I_p - I_q)^2}{2\sigma_r^2}}$

Further reading

London, Upton and Stone
Photography, 11th edition (2013)

Stanford CS 178
Digital Photography course notes

Tomasi and Manduchi (1998)
Bilateral Filtering for Gray and Color Images

Buades, Coll and Morel (2005)
A Non-Local Algorithm for Image Denoising

CSC420 Tutorial 5: digital photography, University of Toronto

Presented by Javad Rajabi, Teaching Assistant

cs.toronto.edu/~lindell/teaching/420