CS5630 Physically Based Realistic Rendering

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Spring 2026

13 Camera modeling

Topics

(Shading and geometric normals)

Cameras and camera optics (in the real world)

Modeling cameras in rendering

Aliasing and pixel filters

The measurement equation

Cameras

Roles of camera in a renderer

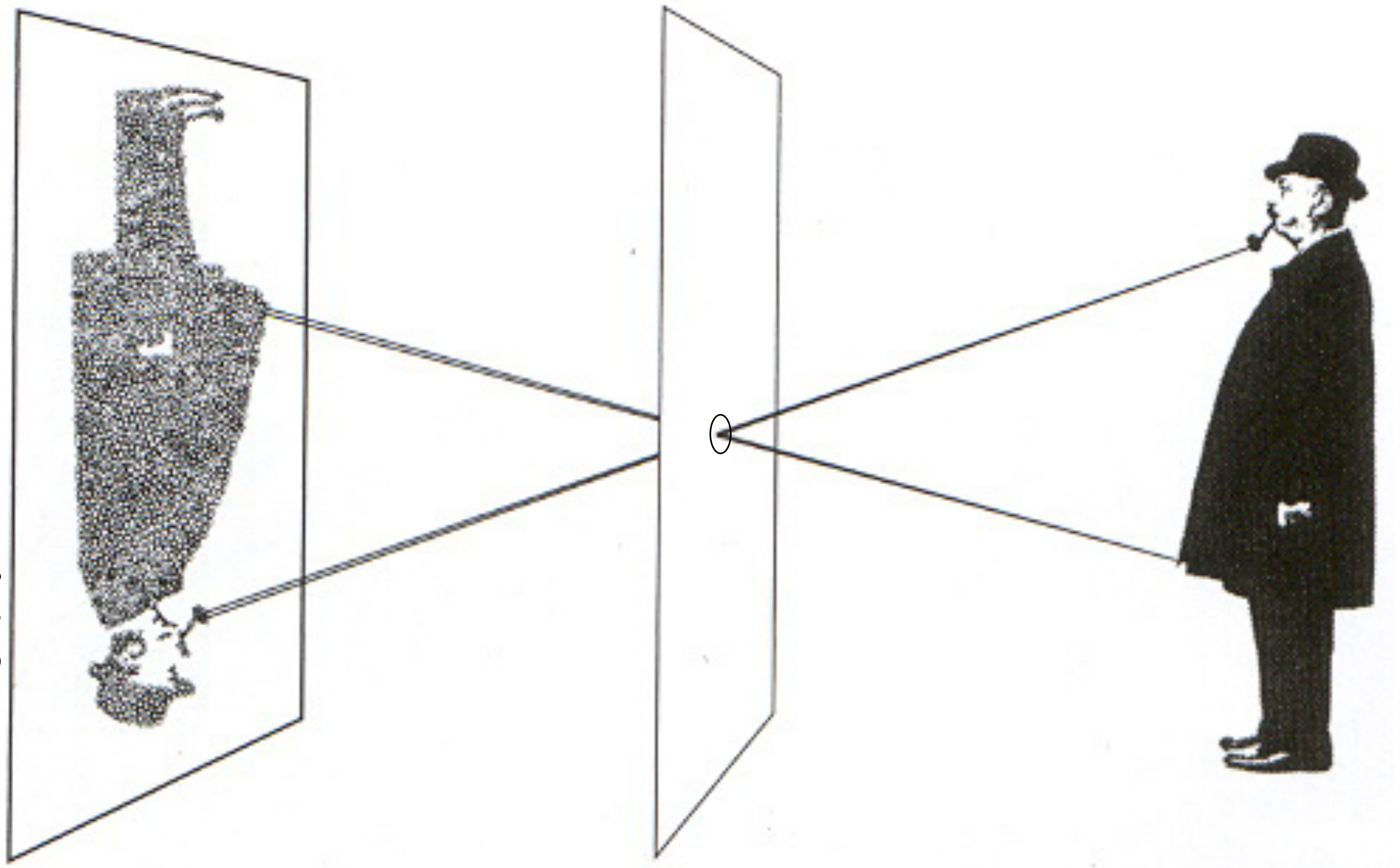
- controls generation of viewing rays
- determines what part of the scene each pixel sees
- models camera optics to create photographic/cinematographic look

Goals in designing camera model

- reasonable efficiency
- mimic the most obvious effects of camera optics
- sometimes: mimic the look of a particular camera lens

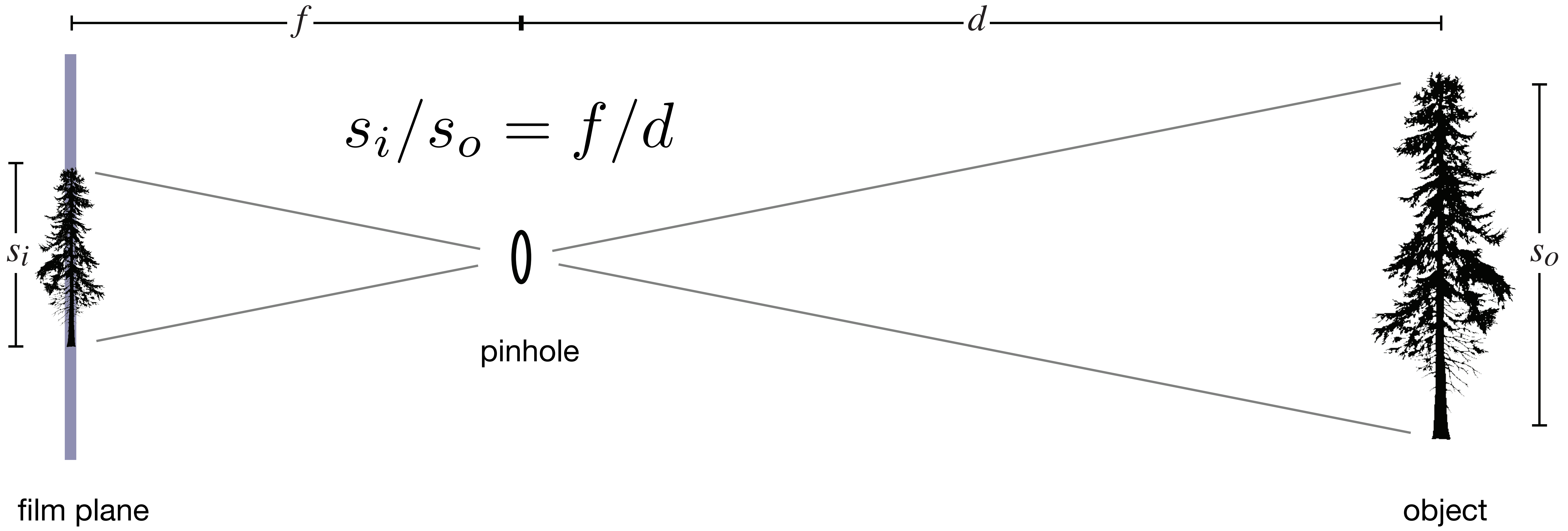
Pinhole camera

- **Simplest possible camera**
  1. light tight box with hole
  2. film
- **Rays are selected simply by occlusion**



From *Photography*, London et al.

“Focal” length



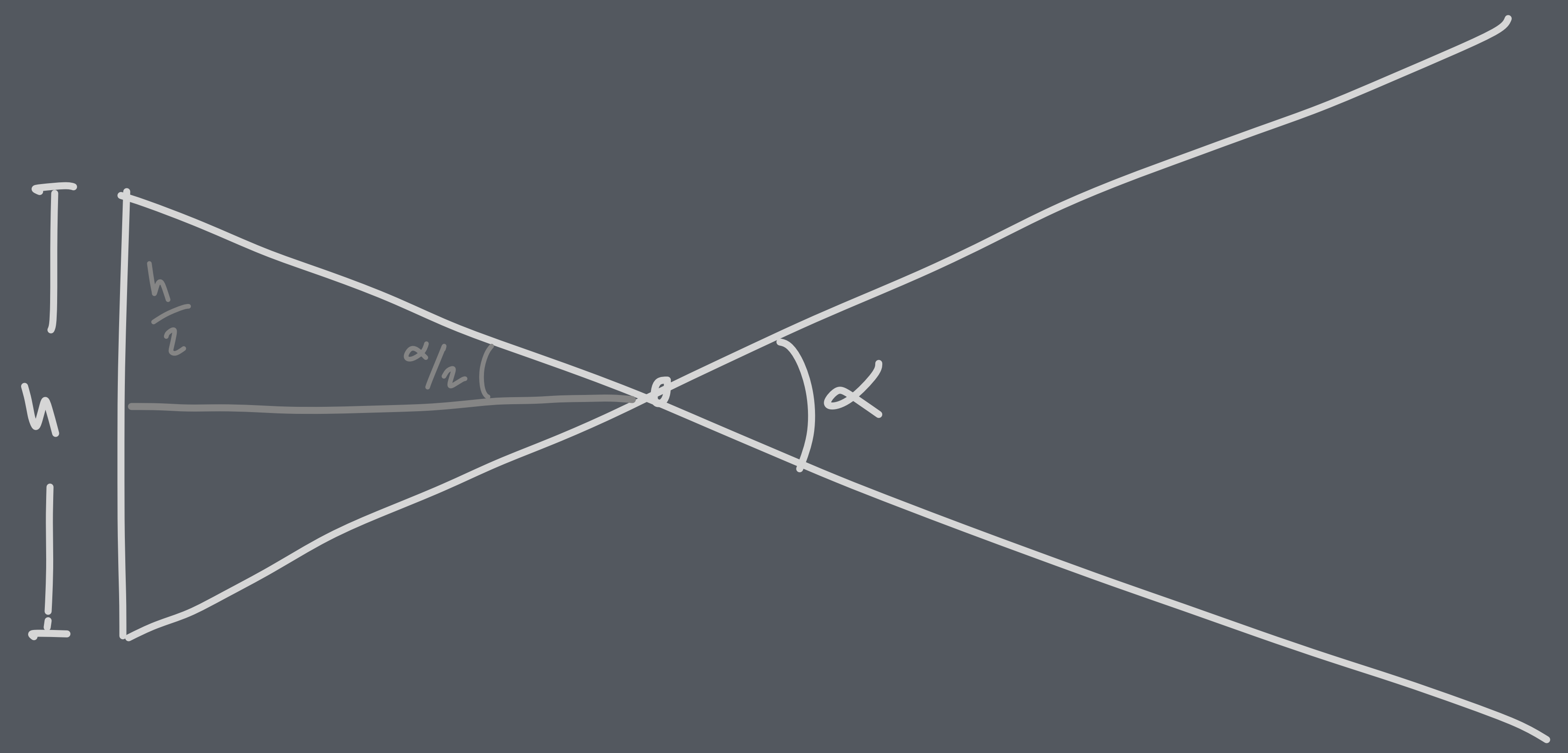
- **Double “focal length” leads to**

  image twice as large

  one fourth as much illumination at image plane

tree image: NRC Canada

Field of view

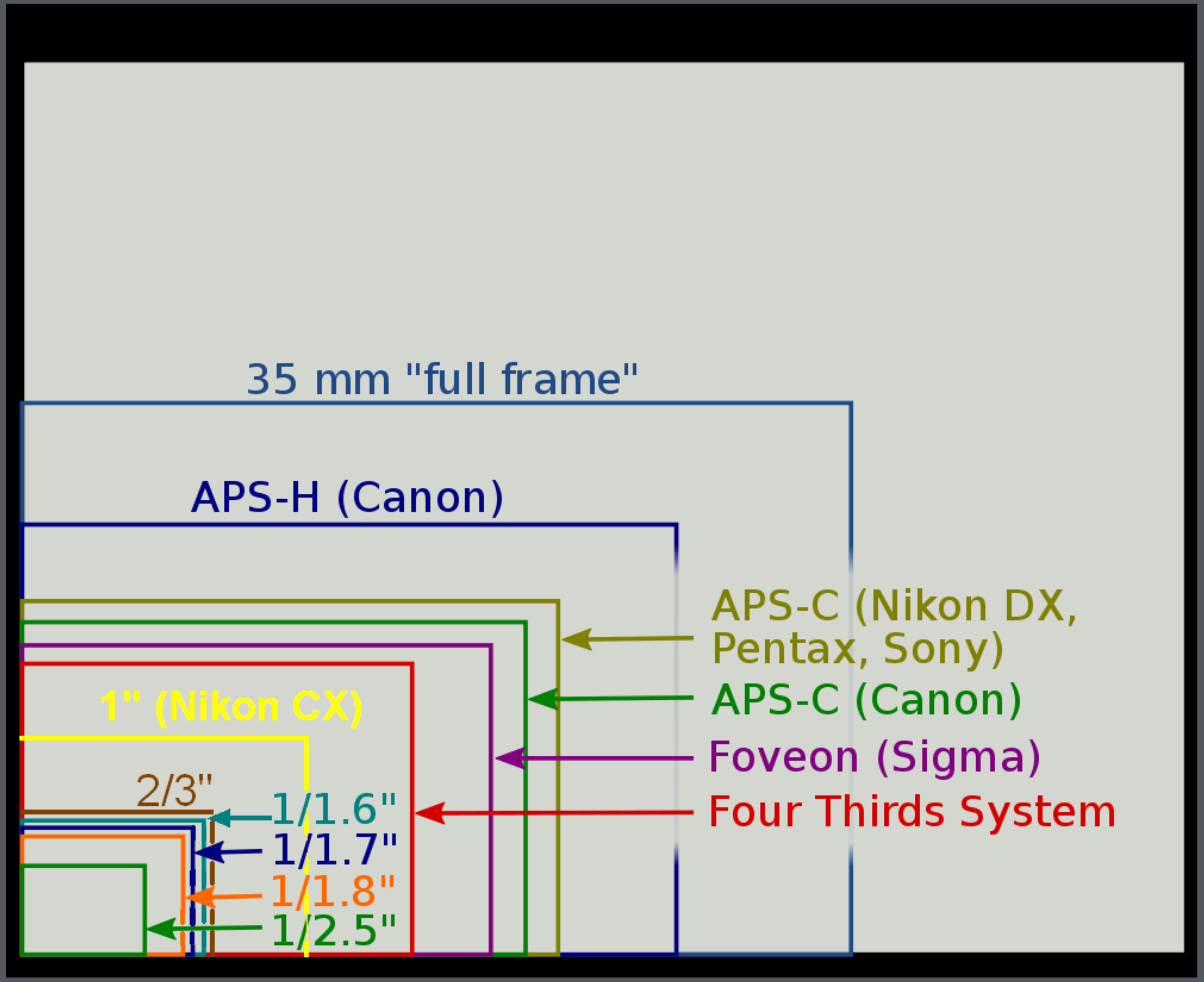


Depends on focal length and image size

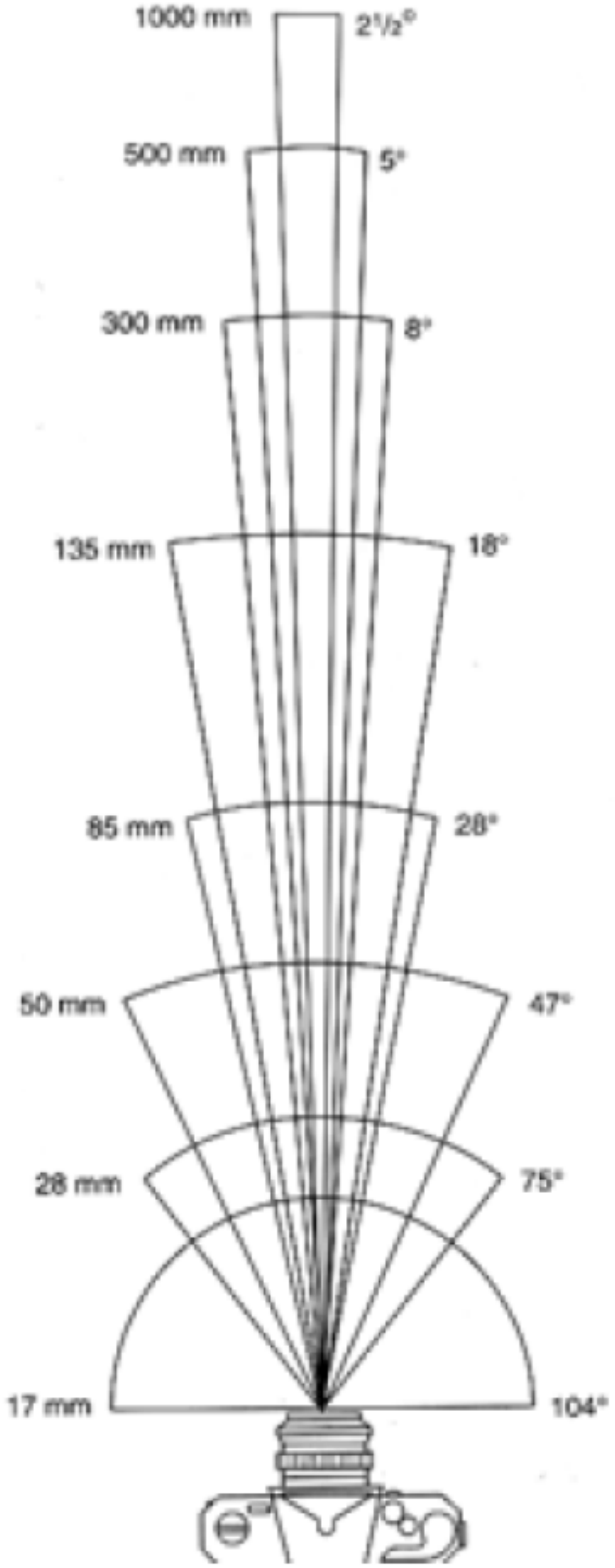
- $\alpha = 2\tan^{-1}\dfrac{h}{2f}$
- h is the size of the image; α is the field of view

Habits were formed with 35mm film cameras

- image is 36 x 24 mm
- fields of view are often discussed in terms of the corresponding focal length in 35mm format
  - 18mm = 67° v.f.o.v. — super-wide angle
  - 28mm = 46° v.f.o.v. — wide angle
  - 50mm = 27° v.f.o.v. — “normal”
  - 100mm = 14° v.f.o.v. — narrow angle (“telephoto”)



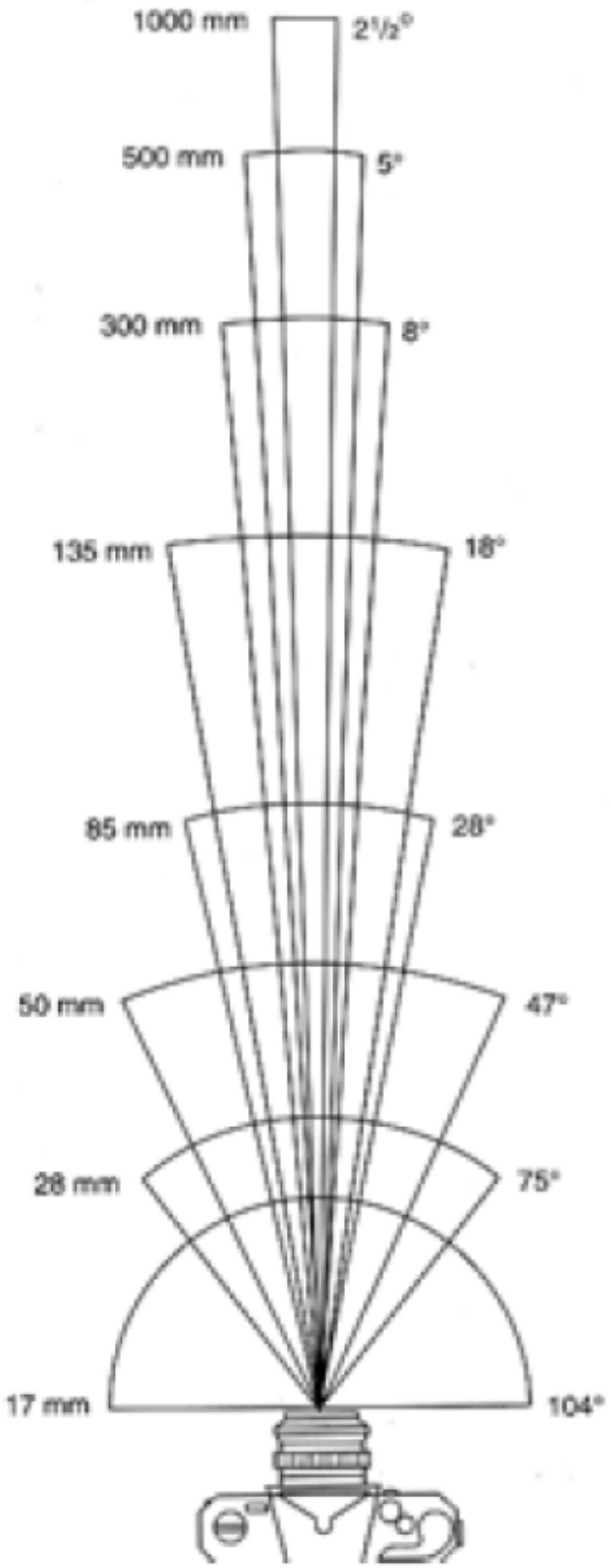
Changing FOV—viewpoint constant

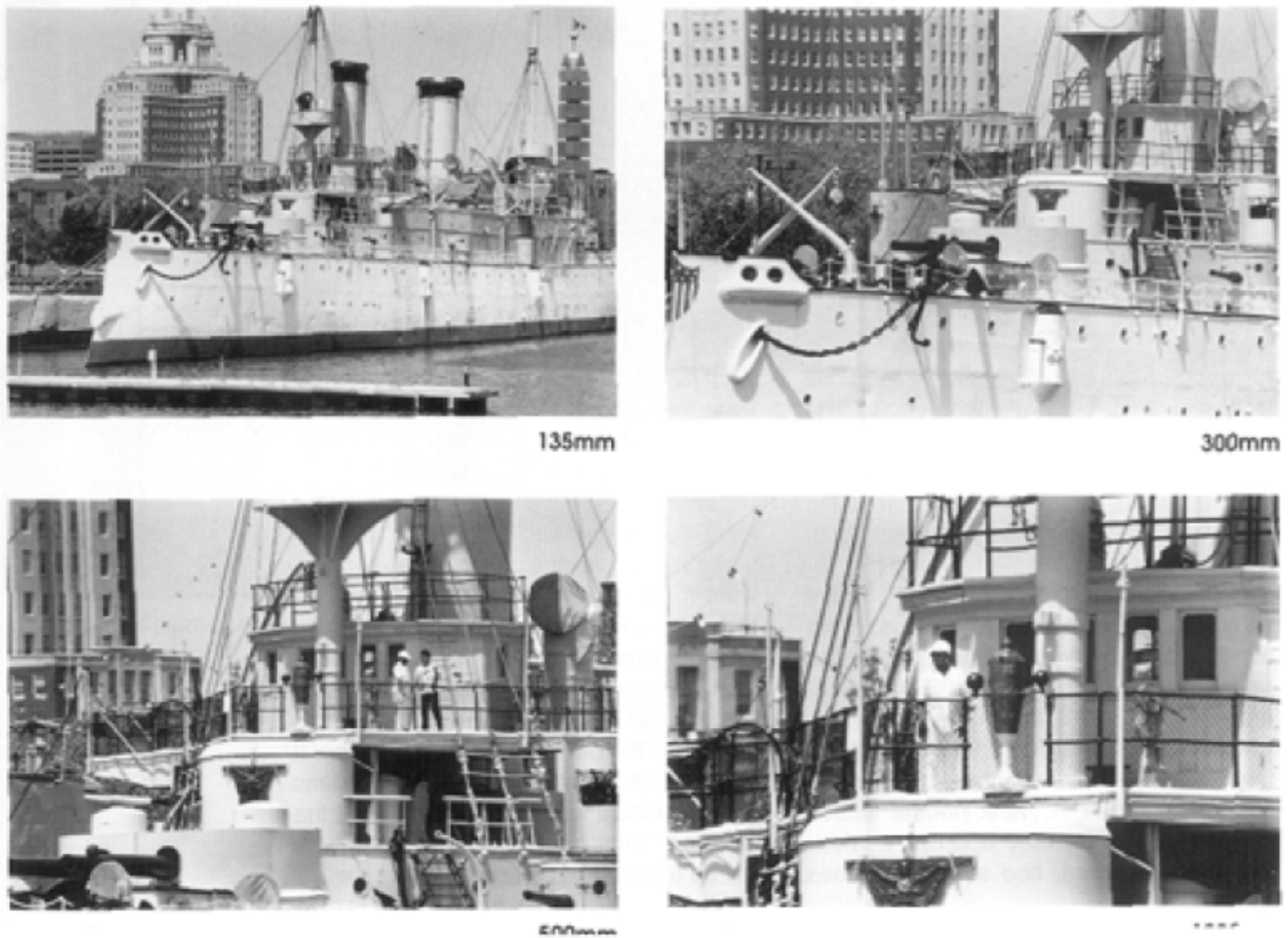


From London and Upton

slide by Alyosha Efros, CMU

Changing FOV—viewpoint constant





slide by Alyosha Efros, CMU

From London and Upton

Changing FOV—magnification constant

Photos: Micaël Reynaud

Changing FOV — magnification constant

[Ansel Adams]

close viewpoint
wide angle
large scale differences

far viewpoint
narrow angle
small scale differences

Perspective vs. viewpoint

- **Portrait: distortion with wide angle**
- **Why?**

Wide angle

Standard

Telephoto

slide by Frédo Durand, MIT

Fields of view in a modern smartphone

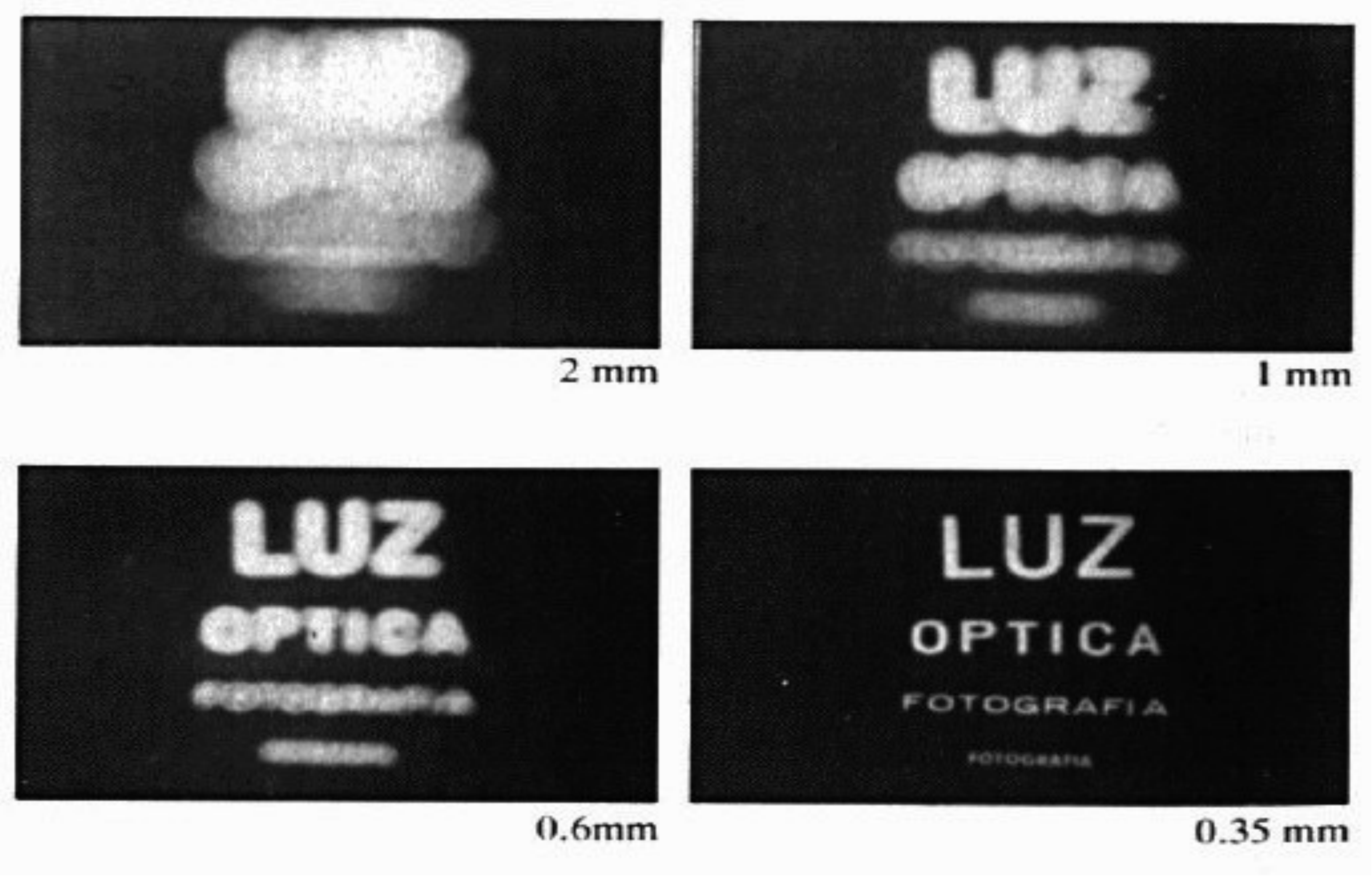
wide/normal
“1/1.28 type” 10x7.5mm sensor
“24mm equivalent” is 53°
f = ~7.5mm

ultra-wide
“1/2.55 type” 5.7x4.2mm sensor
“13mm equivalent” is 85°
f = ~2.3mm

telephoto
“1/2.55 type” 5.7x4.2mm sensor
“100mm equivalent” is 14°
f = ~17mm

iPhone 17 Pro camera module | Apple

Smaller pinhole is sharper …to a point



Slide after Steve Seitz, U. Washington

Camera, version 0: box with hole

- **Simple, distortion-free, charmingly analog, but:**
  Large pinholes produce blurry images
  Small pinholes produce dim images
  Diffraction limits sharpness for very small pinholes

Francesco Capponi
Blown egg transformed into a wide-angle pinhole camera

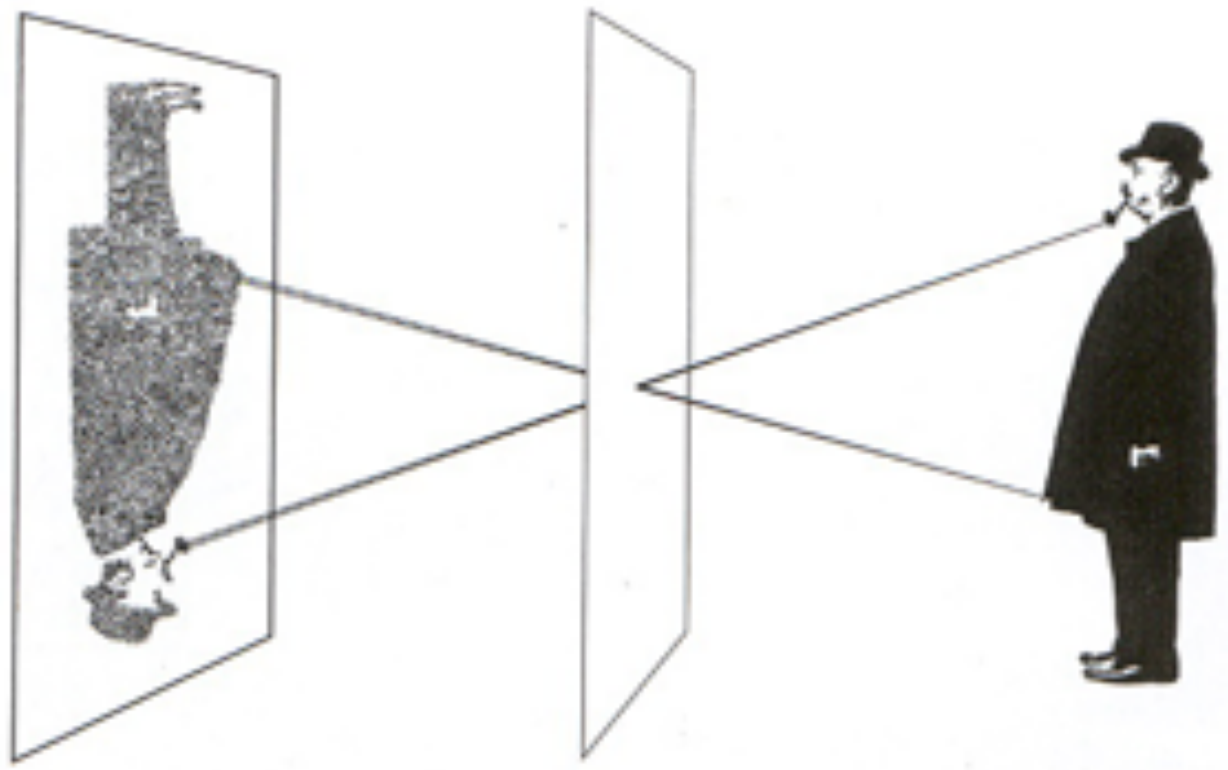
http://www.petapixel.com/2011/04/25/eggs-transformed-into-pinhole-cameras/

Forming images with lenses

Lenses

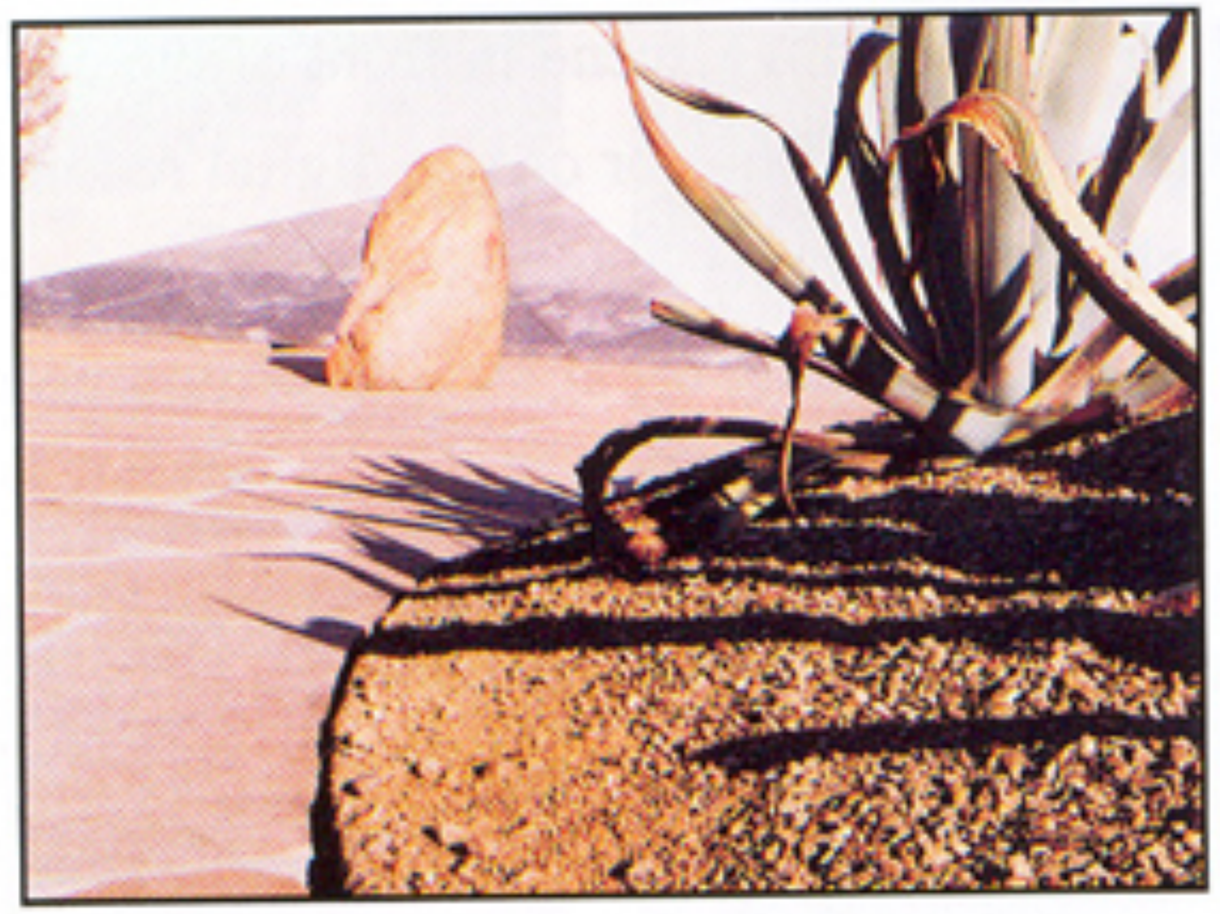
- Gather more light!
- But need to be focused

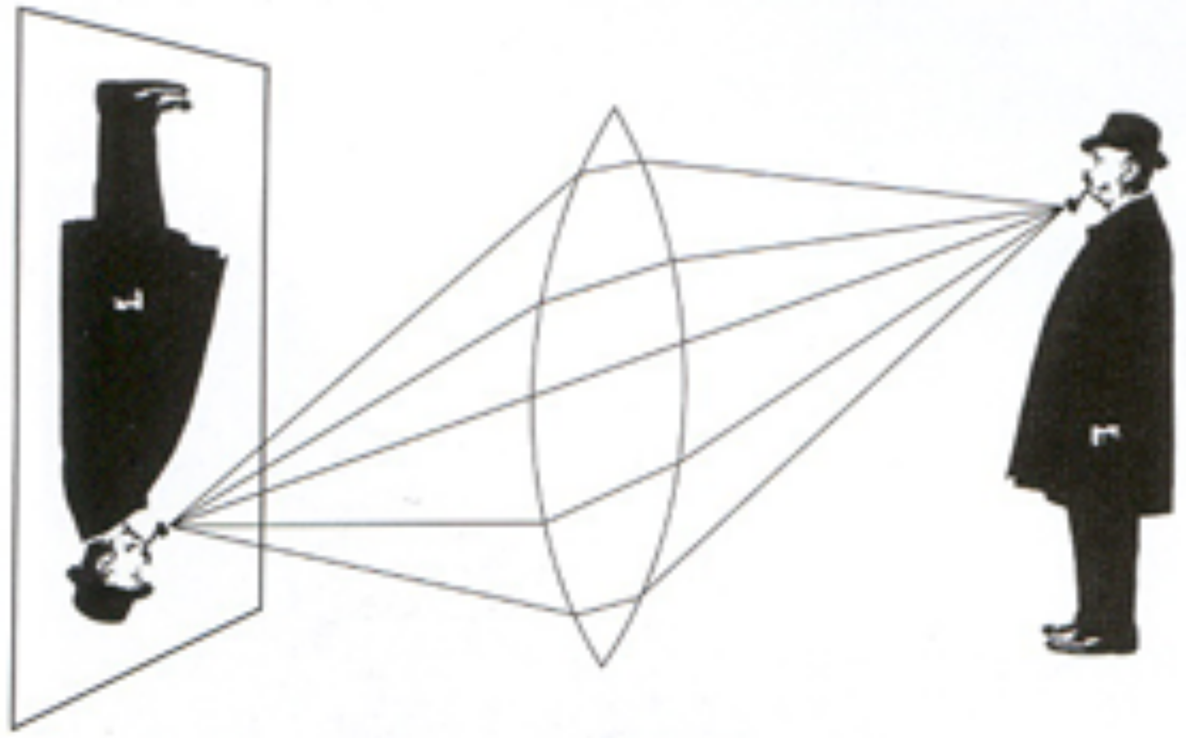
Photograph made with small pinhole



To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, *equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.*

Photograph made with lens





This time, using a simple convex lens with an f/16 aperture, *the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec.*

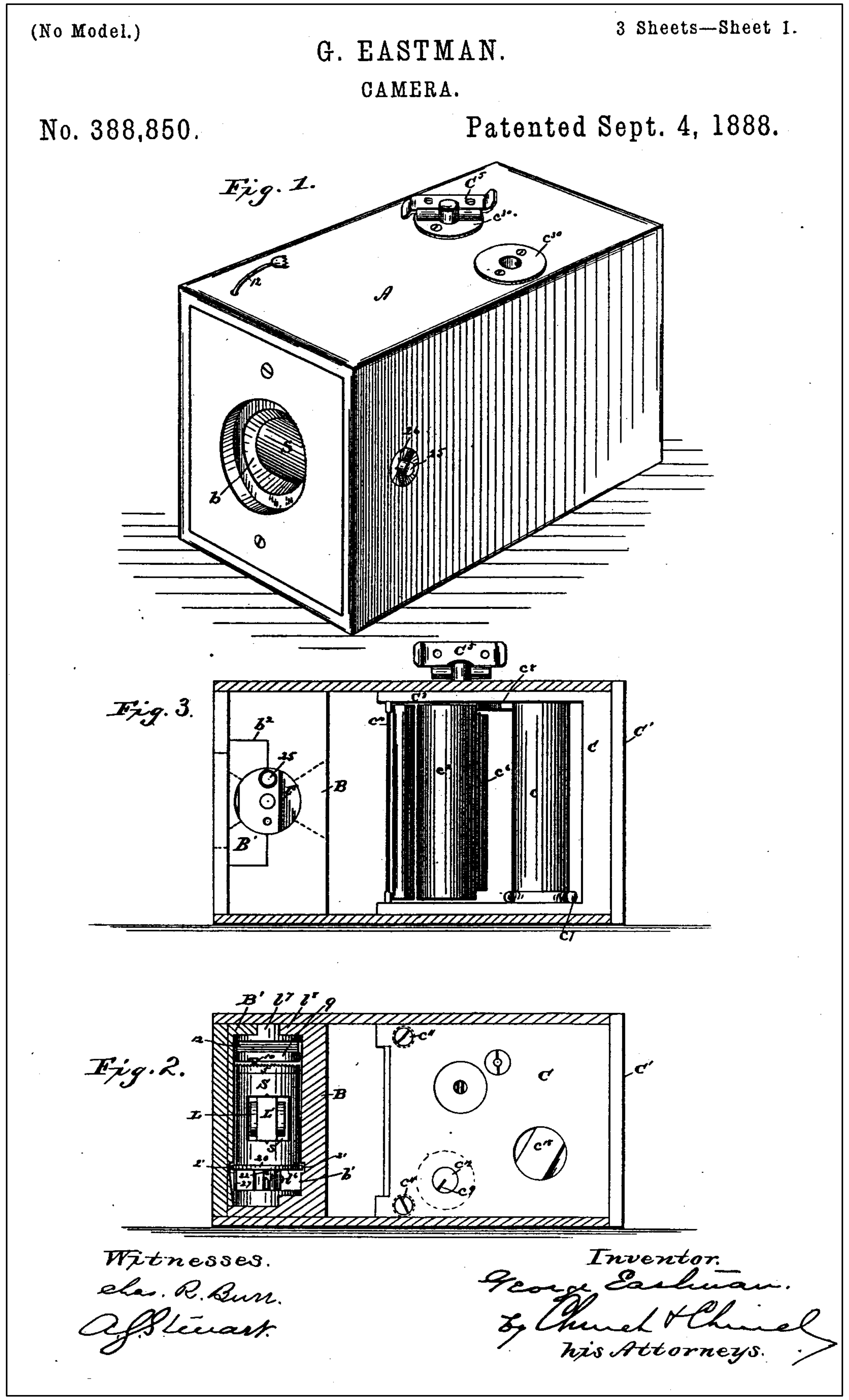
The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.

From Photography, London et al.

slide by Frédo Durand, MIT

Camera, v. 1: Box with lens & shutter

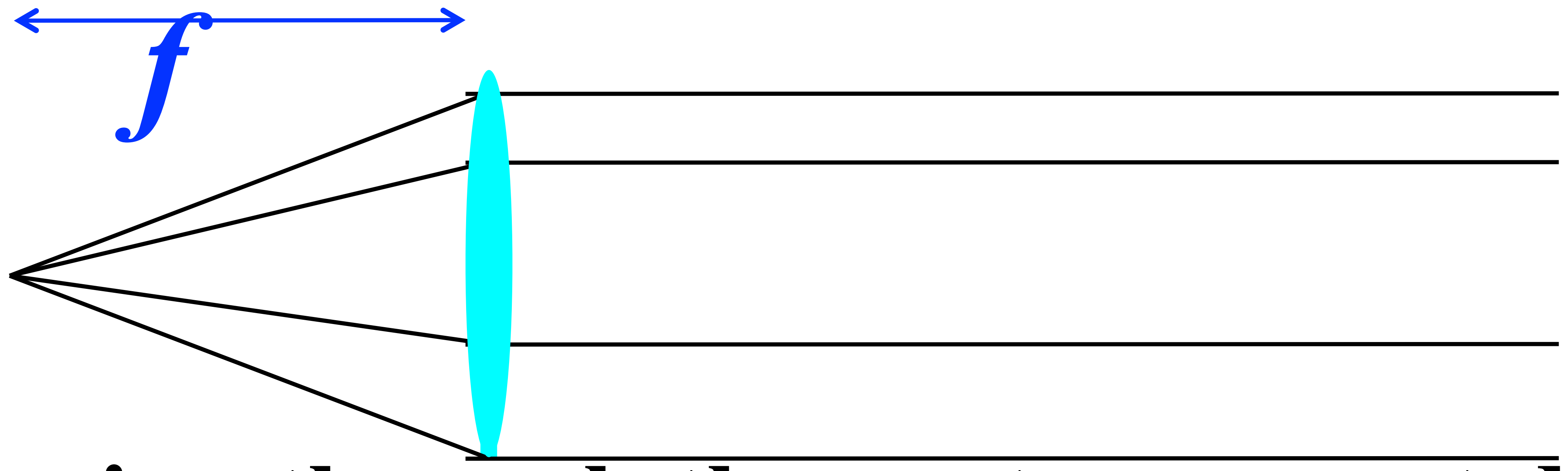
- **First practical cameras had**
  - film (roll film or glass plate)
  - lens (small aperture)
  - mechanism for winding film
  - mechanism for triggering shutter
- **Limitations**
  - cannot control exposure
  - focus is fixed (like an inexpensive cell phone camera today)
  - want to be outdoors in strong light



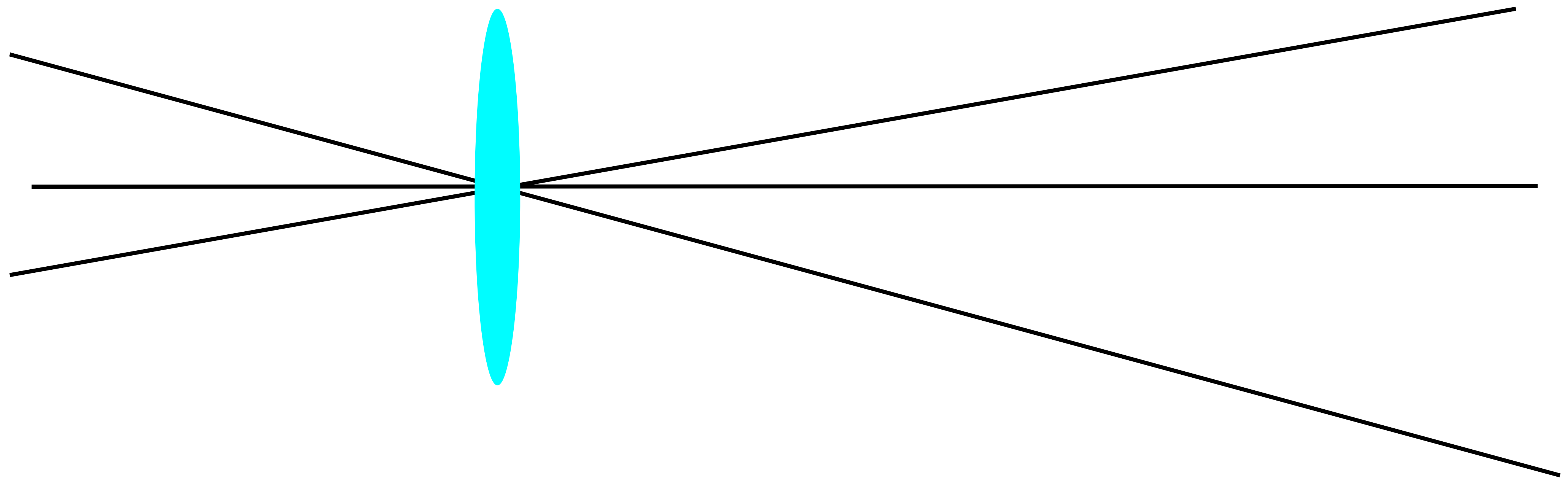
George Eastman
Kodak Camera
1888

Thin lens optics

- **Simplification of geometrical optics for well-behaved lenses**
- **All parallel rays converge to one point on a plane located at the focal length *f***



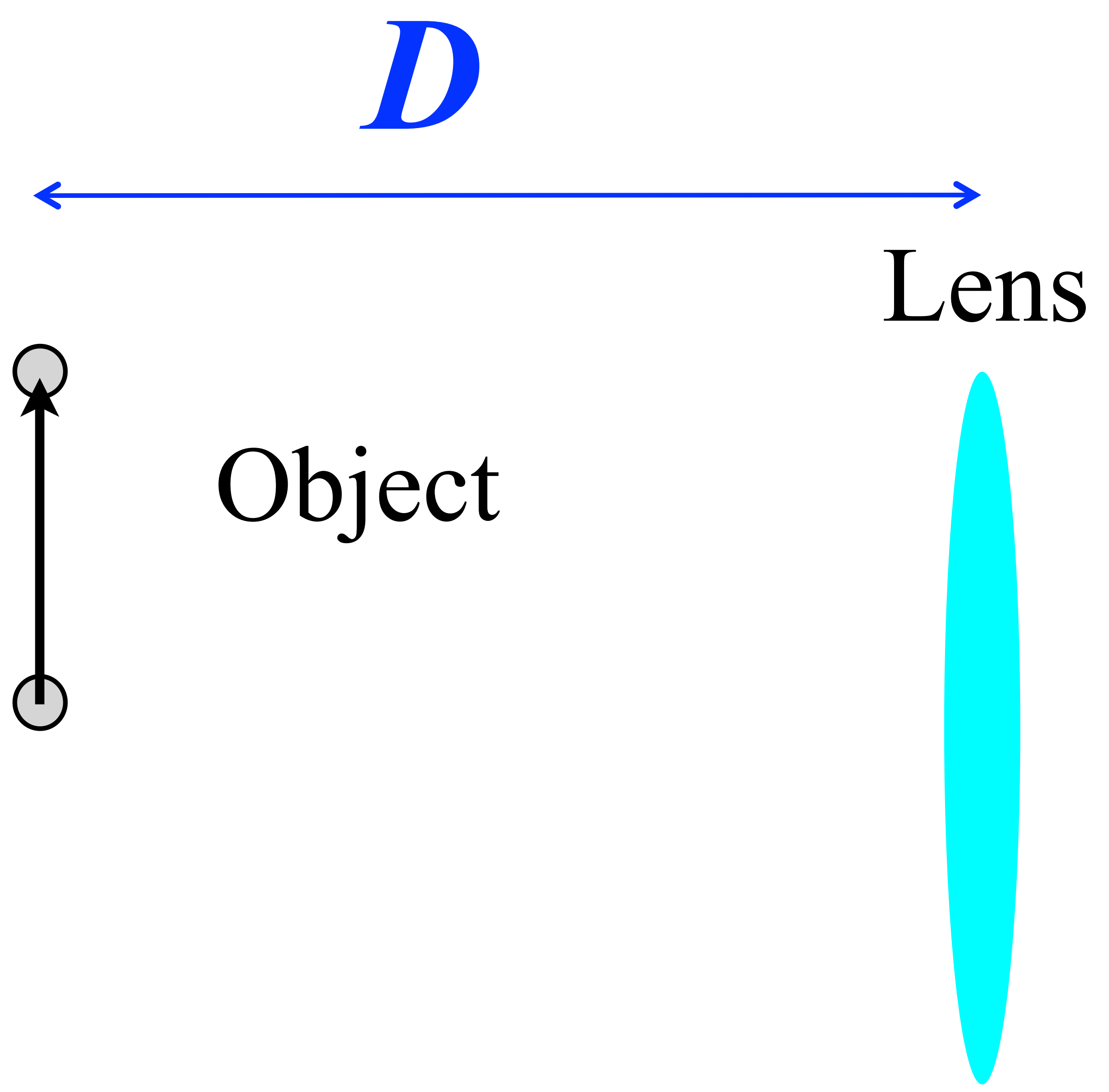
- **All rays going through the center are not deviated**
  - Hence same perspective as pinhole



slide by Frédo Durand, MIT

How lenses focus

- **Let's look at an object at distance D**



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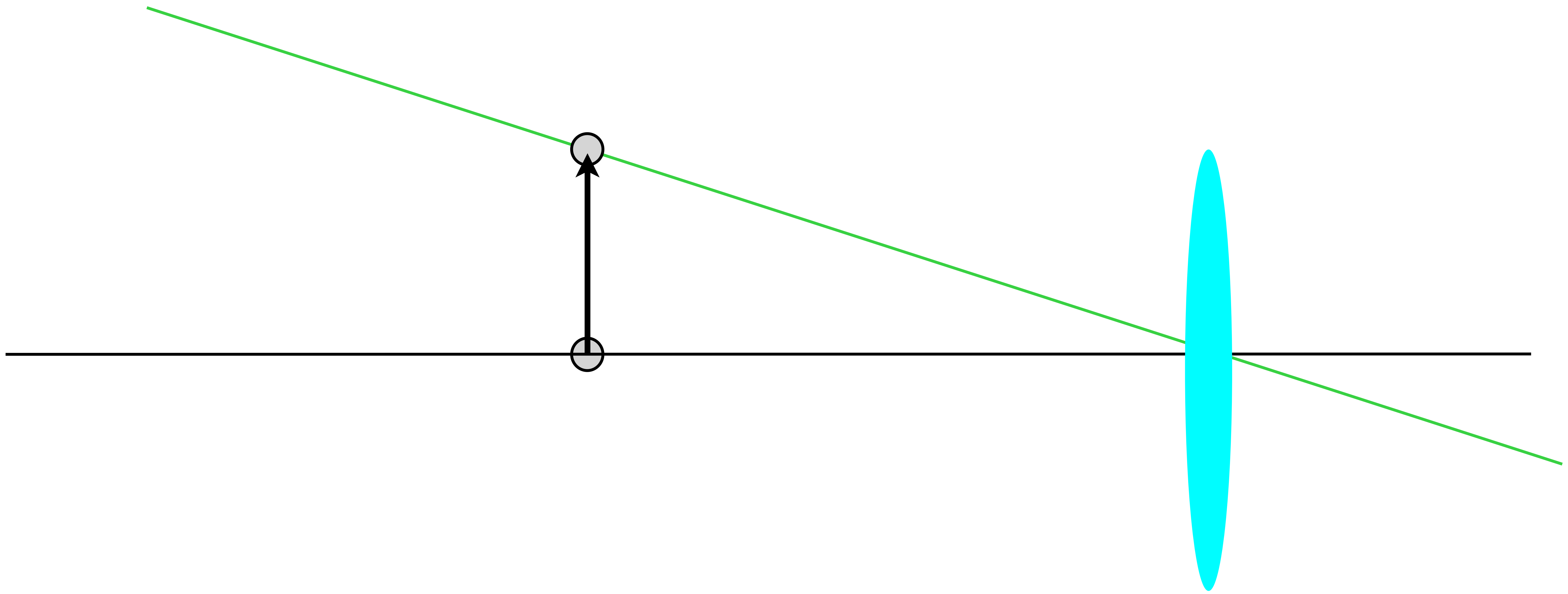
How to trace rays

- **Start by rays through the center**



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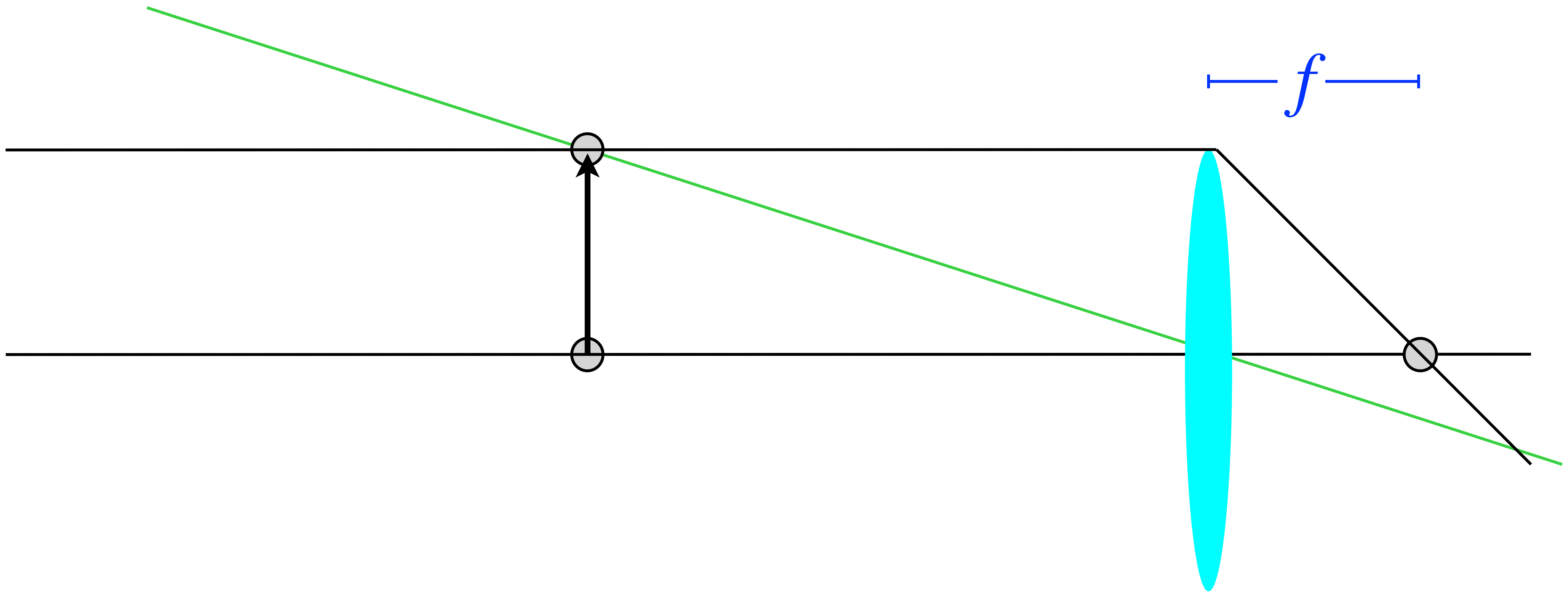
How to trace rays

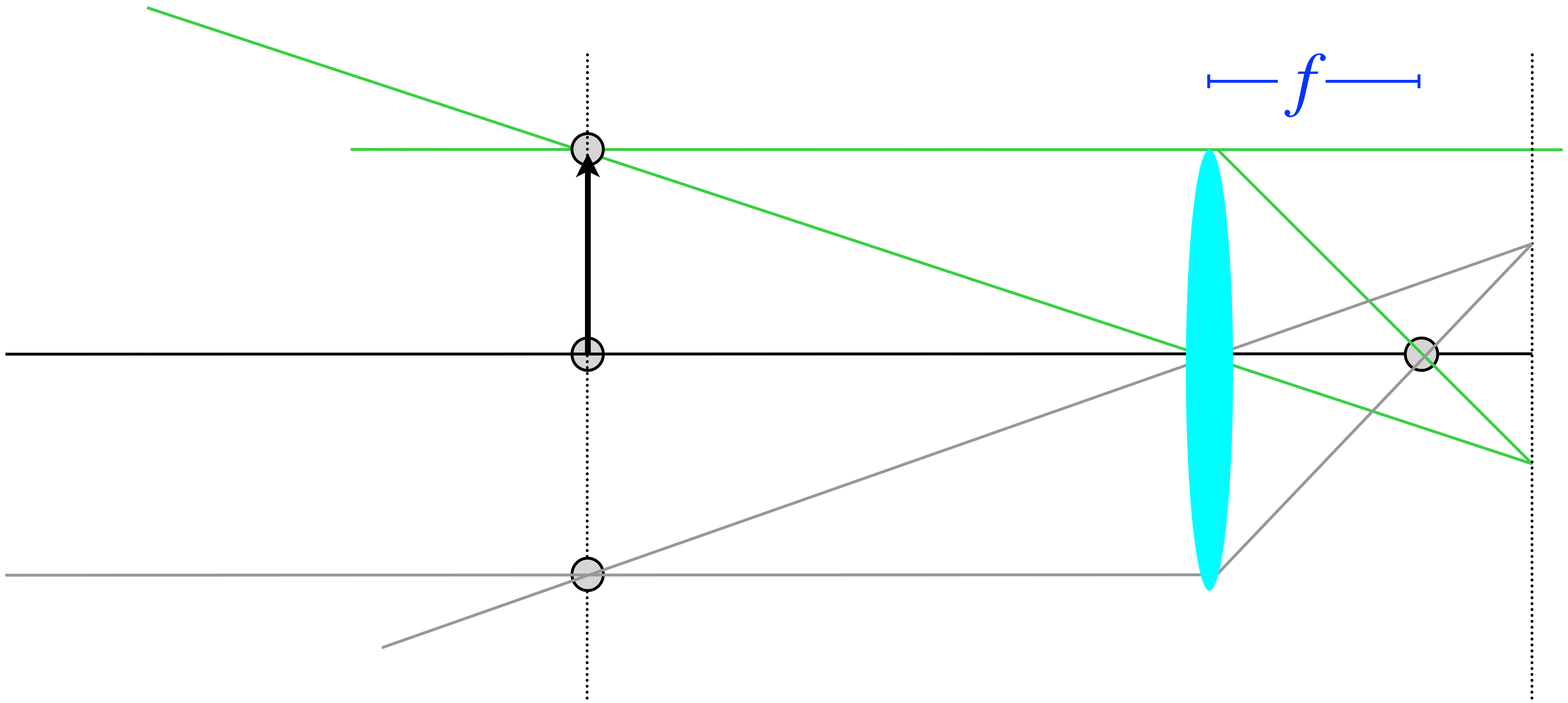
- **Start by rays through the center**
- **Choose focal length, trace parallels**



slide by Frédo Durand, MIT

How to trace rays

- **Start by rays through the center**
- **Choose focal length, trace parallels**
- **You get the focus plane for a given scene plane**
  - All rays coming from points on a plane parallel to the lens are focused on another plane parallel to the lens



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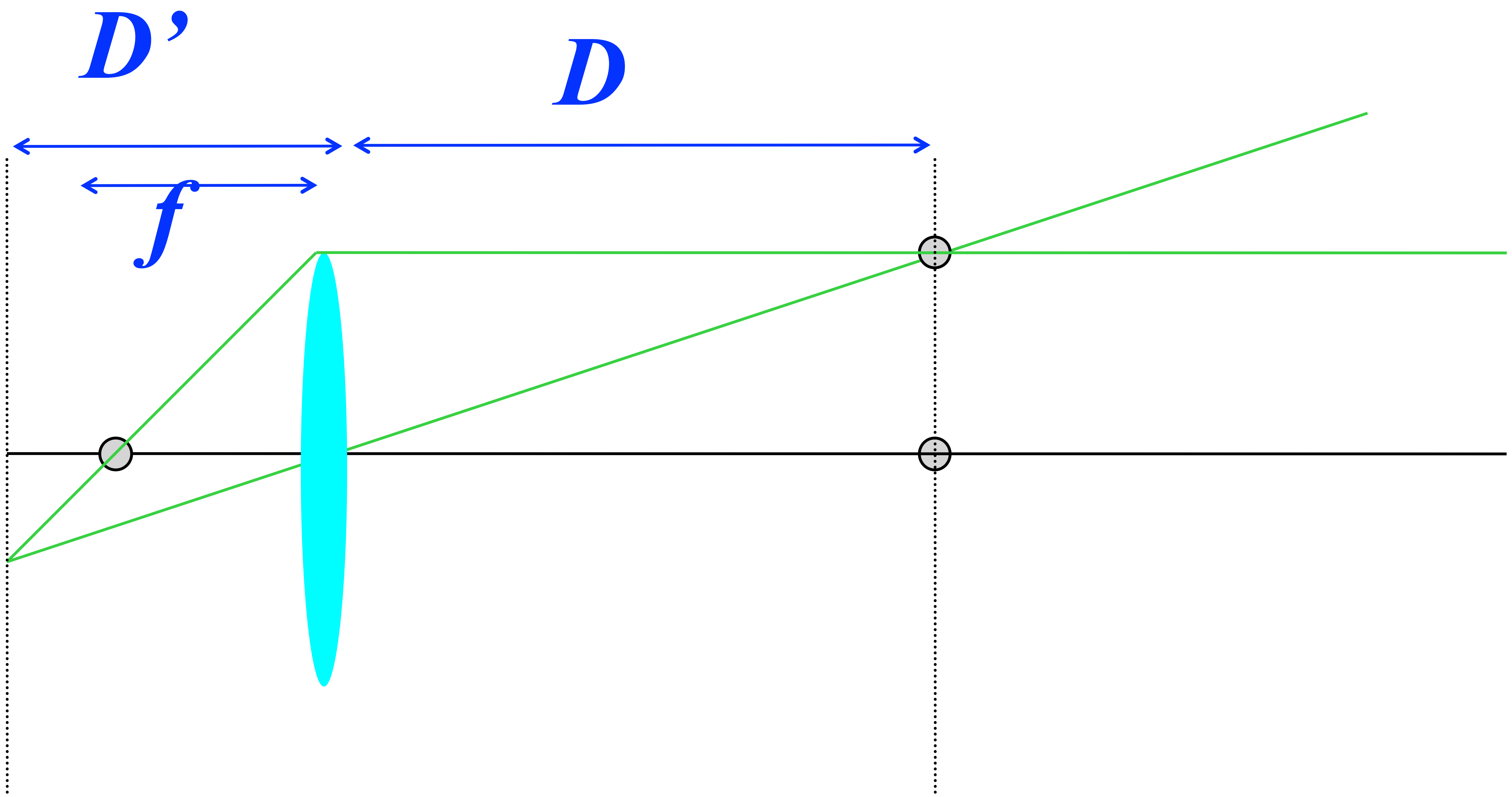
Thin lens formula



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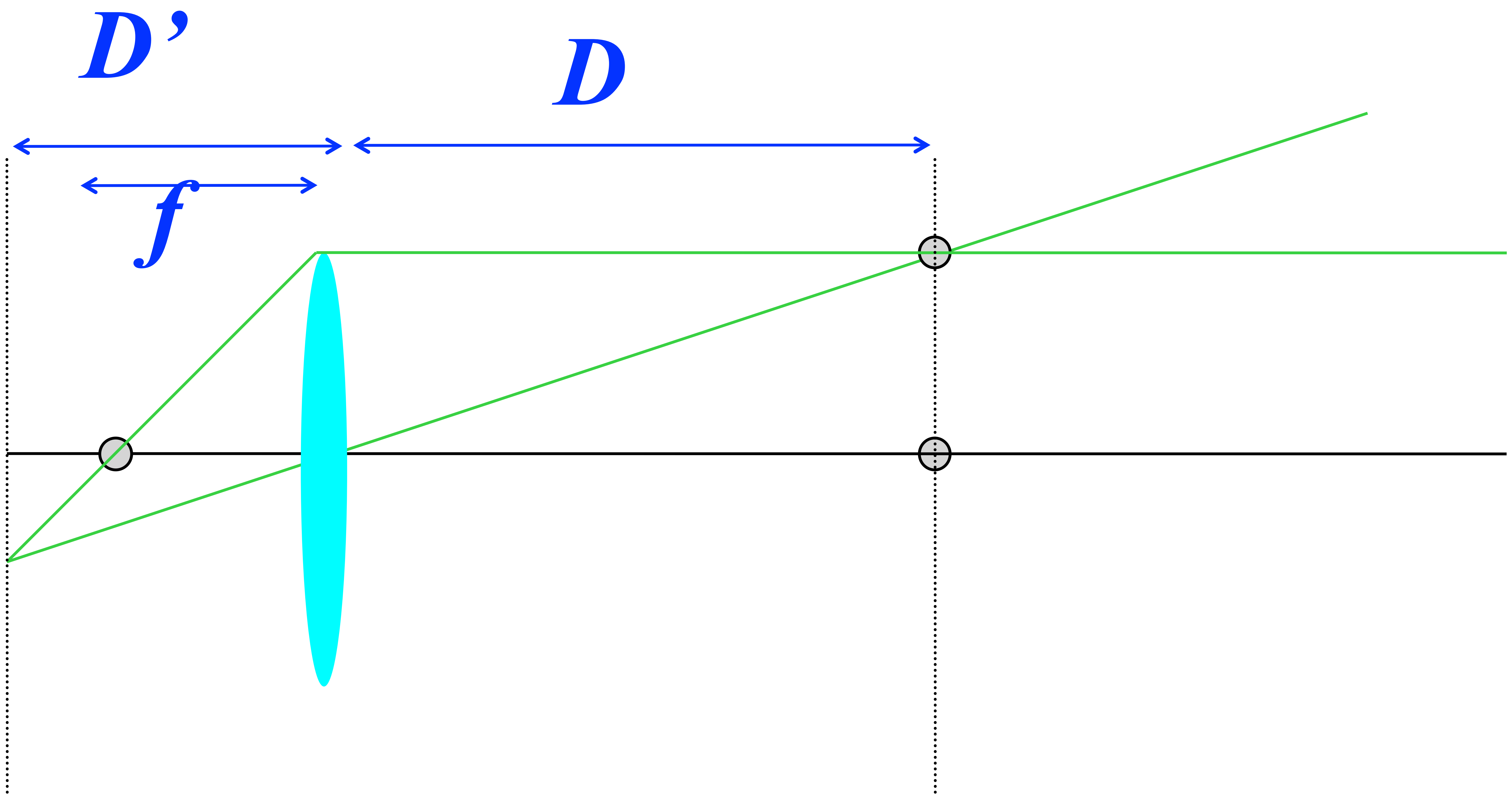
Thin lens formula

Similar triangles everywhere!



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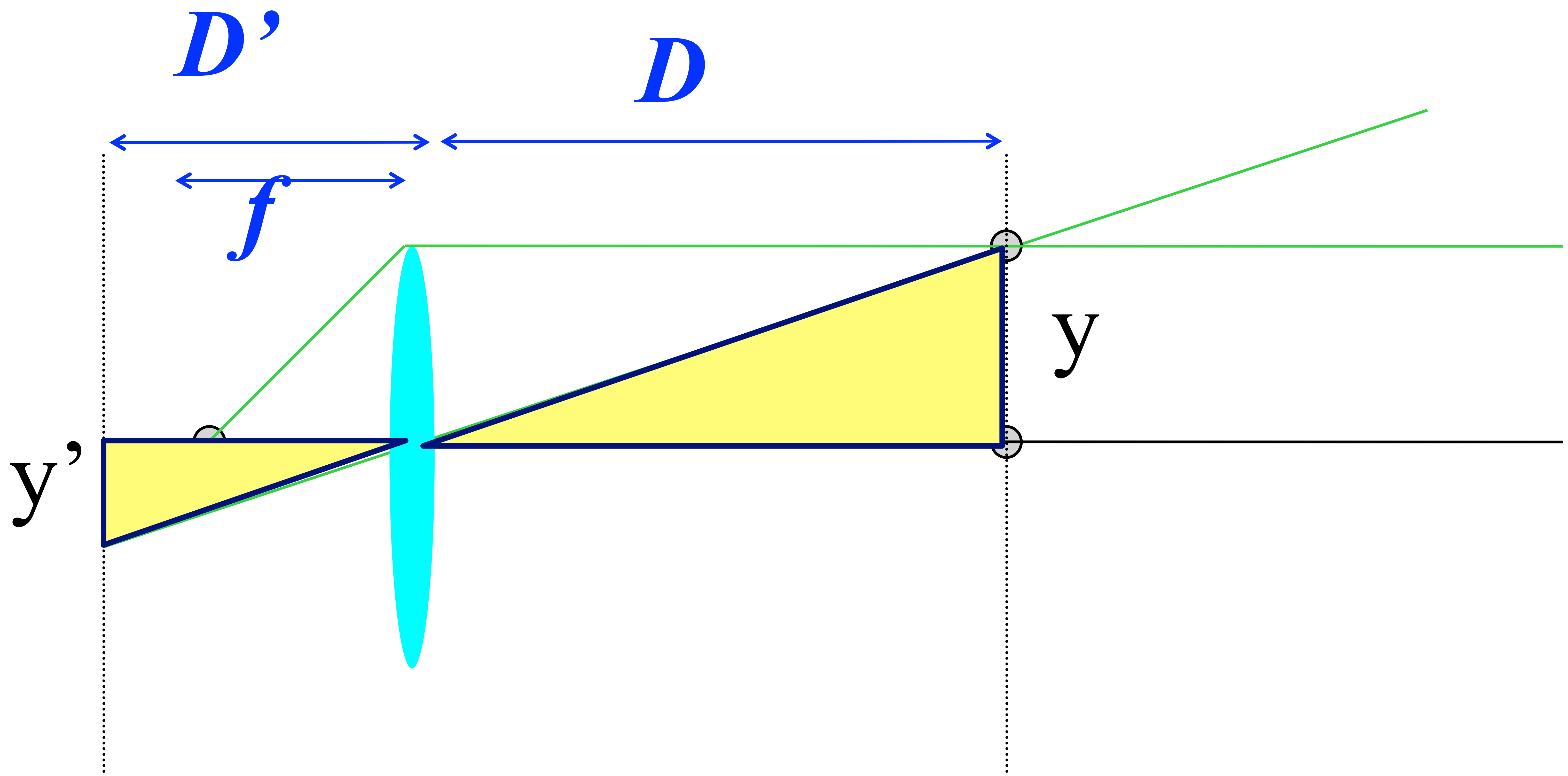
Thin lens formula

Similar triangles everywhere!

$y'/y = D'/D$



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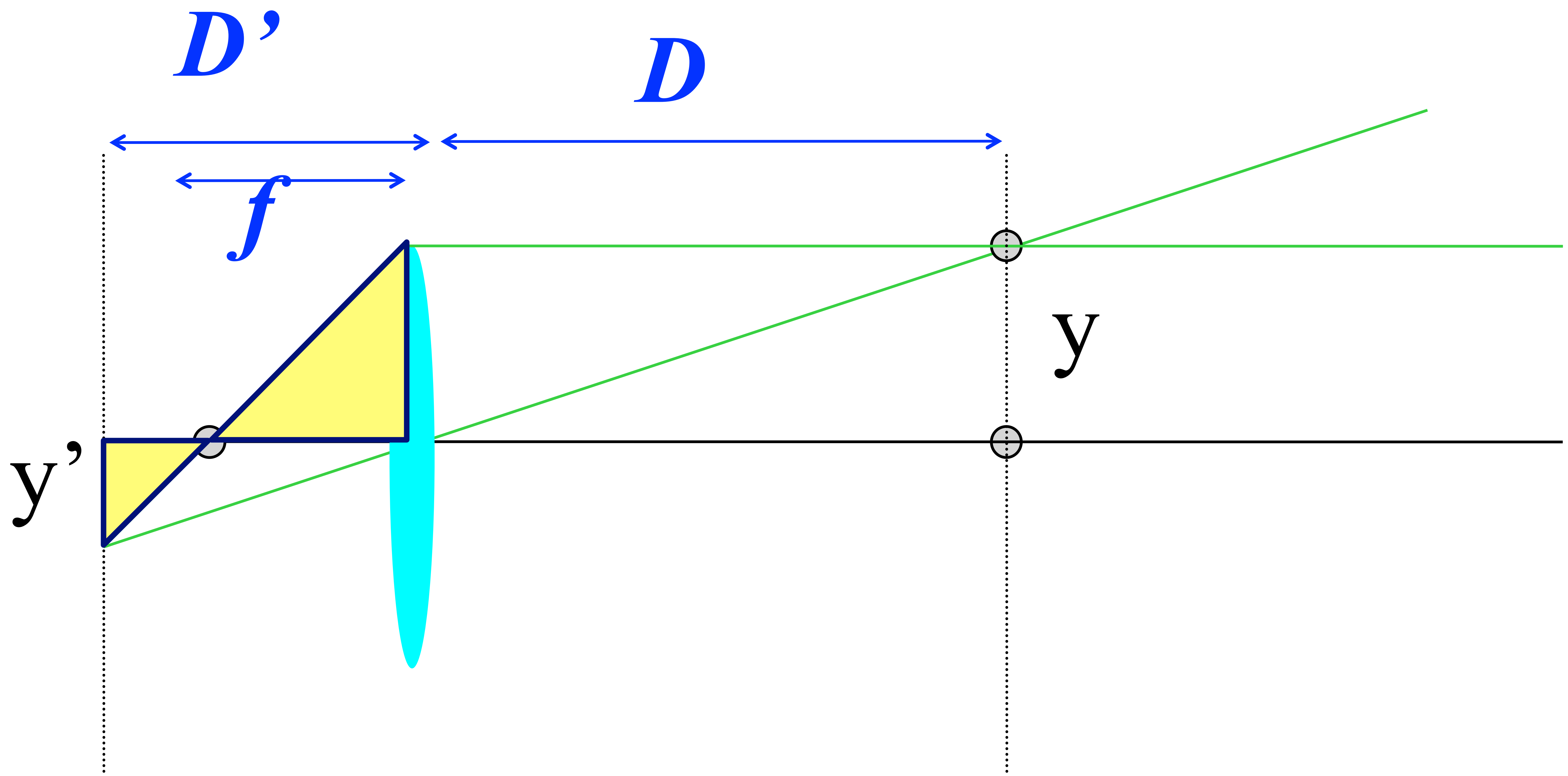
Thin lens formula

Similar triangles everywhere!

$$y'/y = D'/D$$

$$y'/y = (D'-f)/f$$



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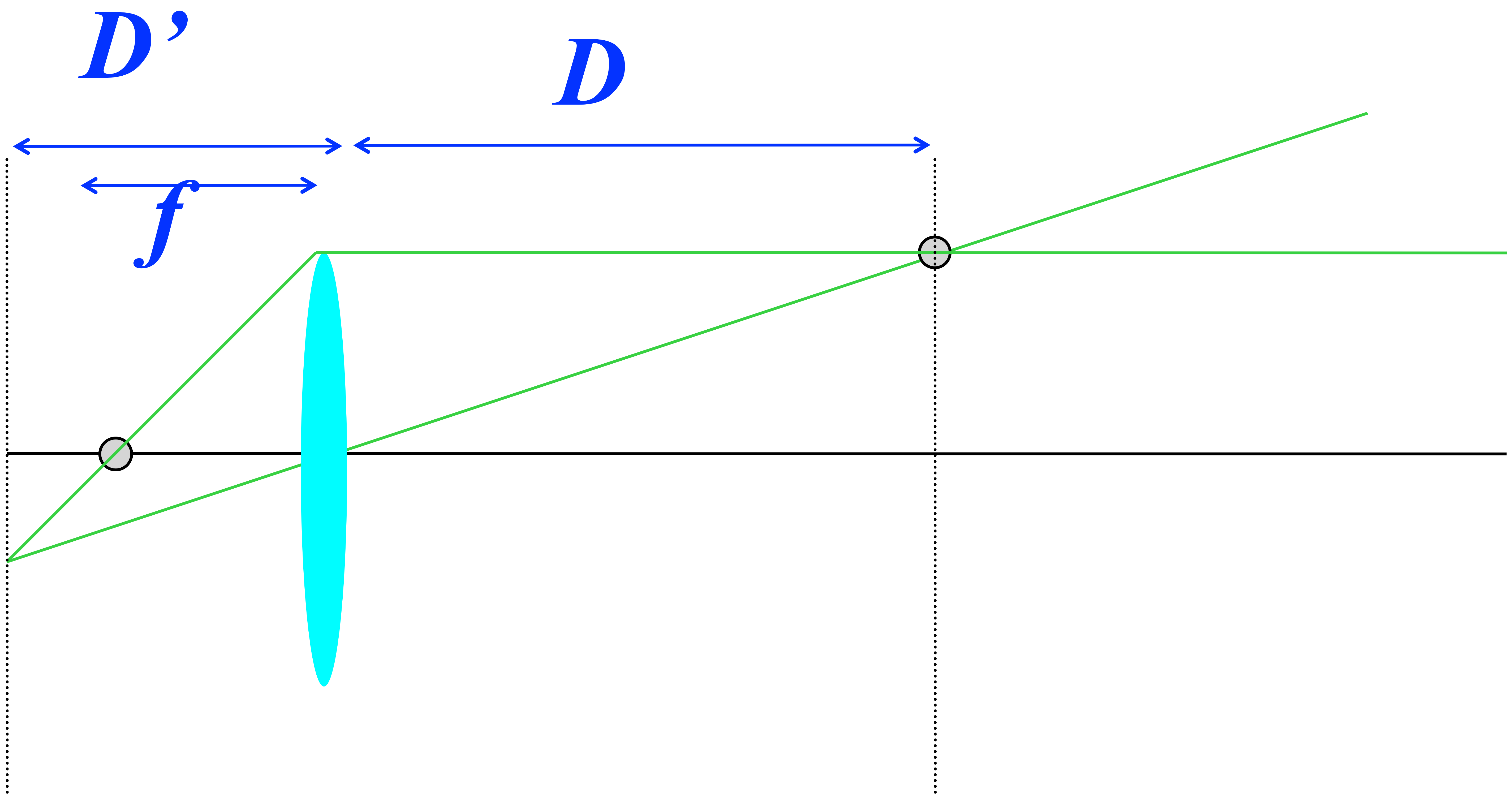
Thin lens formula

$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$



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Thin lens focusing

How to focus on things closer than infinity?

- move the lens farther from the image sensor

$$\frac{1}{f} = \frac{1}{D_{\text{obj}}} + \frac{1}{D_{\text{img}}}$$

- focus at infinity: $D_{\text{obj}} = 0$ and $D_{\text{img}} = f$
- symmetric focus ($4f$ optical system): $D_{\text{obj}} = D_{\text{img}} = 2f$
- can approach focusing at $D_{\text{obj}} \approx f$ by moving image sensor far away, but not so practical

So in a camera, make D_{img} adjustable

- put the lens on a fine-thread screw
- user adjusts to focus on desired subject

More ingredients

- **Timed shutter**

  with a UI for setting the duration of the exposure (“**exposure time**”)

- **Variable aperture**

  effective size of the hole through which light enters can be changed
  with a UI for setting the size (“**aperture**”)

- **Viewfinder**

  some way better than guessing
  to tell what you are photographing

photo: Ken Rockwell

Camera, v. 2: 3 variables, 5 controls

turn to focus

turn to adjust aperture

turn to adjust shutter speed

press to take picture

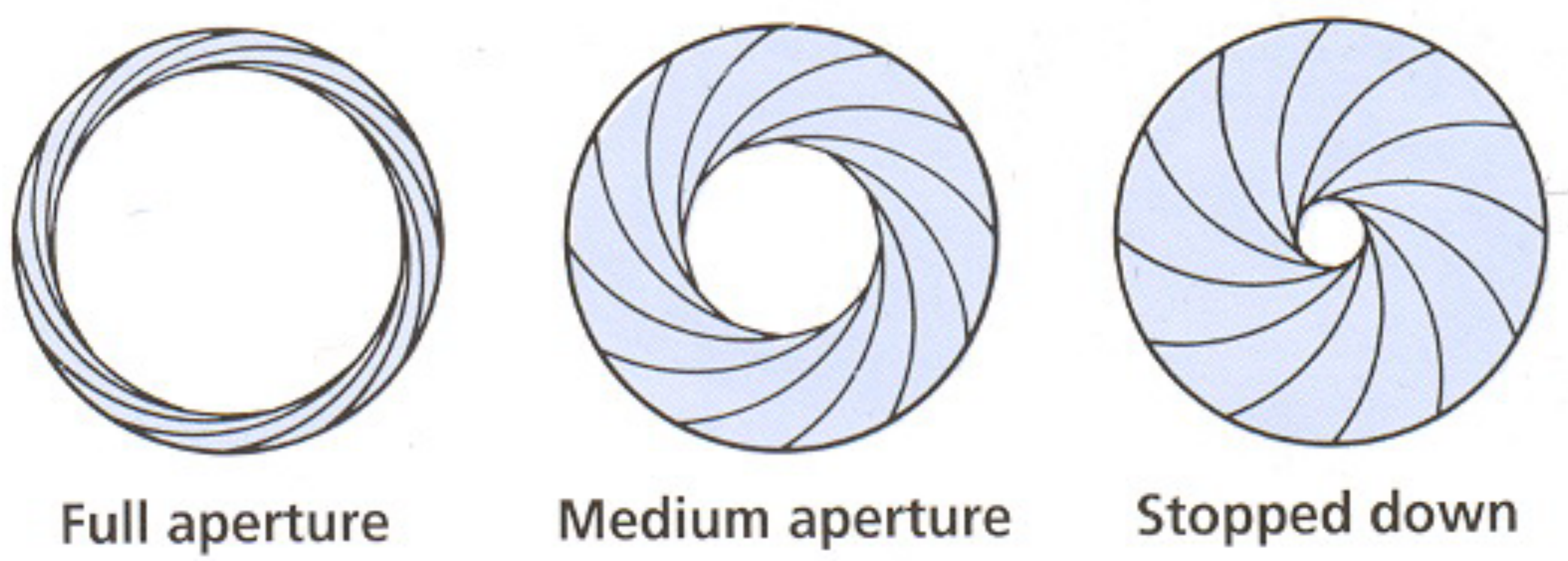
pull to wind film

photo: Ken Rockwell

Aperture

- **Diameter of the lens opening (controlled by diaphragm)**
- **Expressed as a fraction of focal length, in f-number**
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is 50mm
- **Disconcerting: small f number = big aperture**
- **What happens to the area of the aperture when going from f/2.0 to f/4.0?** divided by 4 (square of f number ratio)
- **Typical f numbers are**
  f/2.0, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32
  - See the pattern?

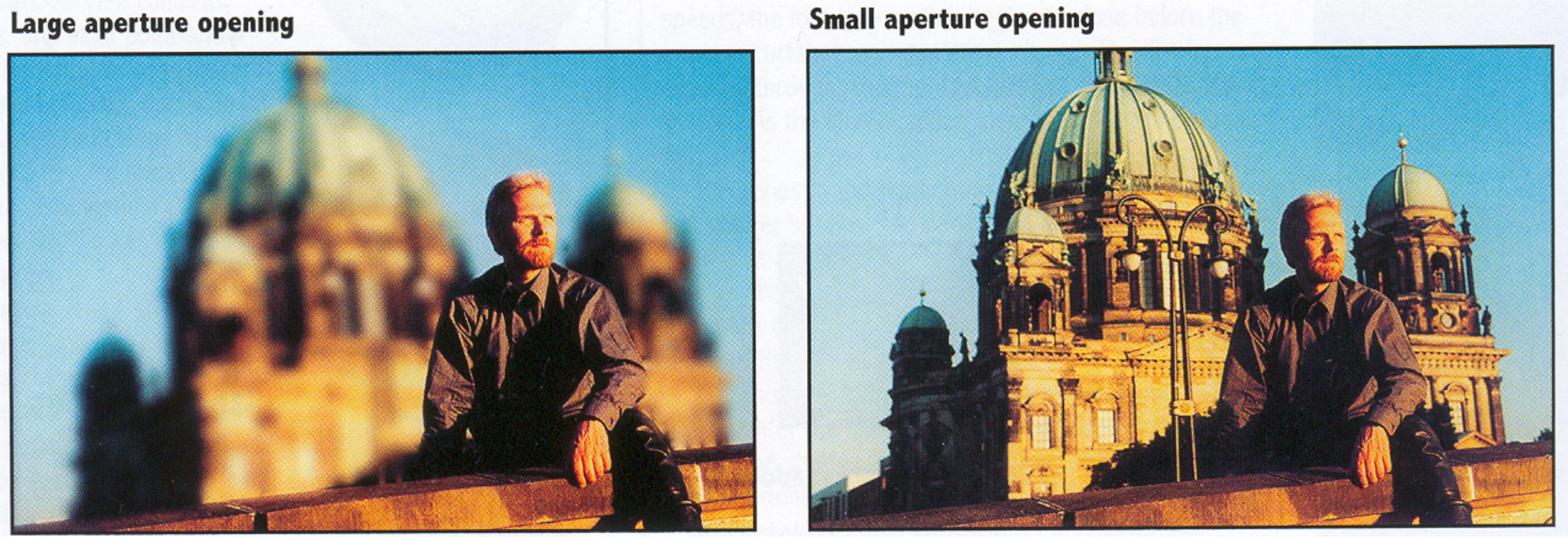
slide by Frédo Durand, MIT



Worth a look:
www.youtube.com/watch?v=KmNIouLByJQ

Main effect of aperture

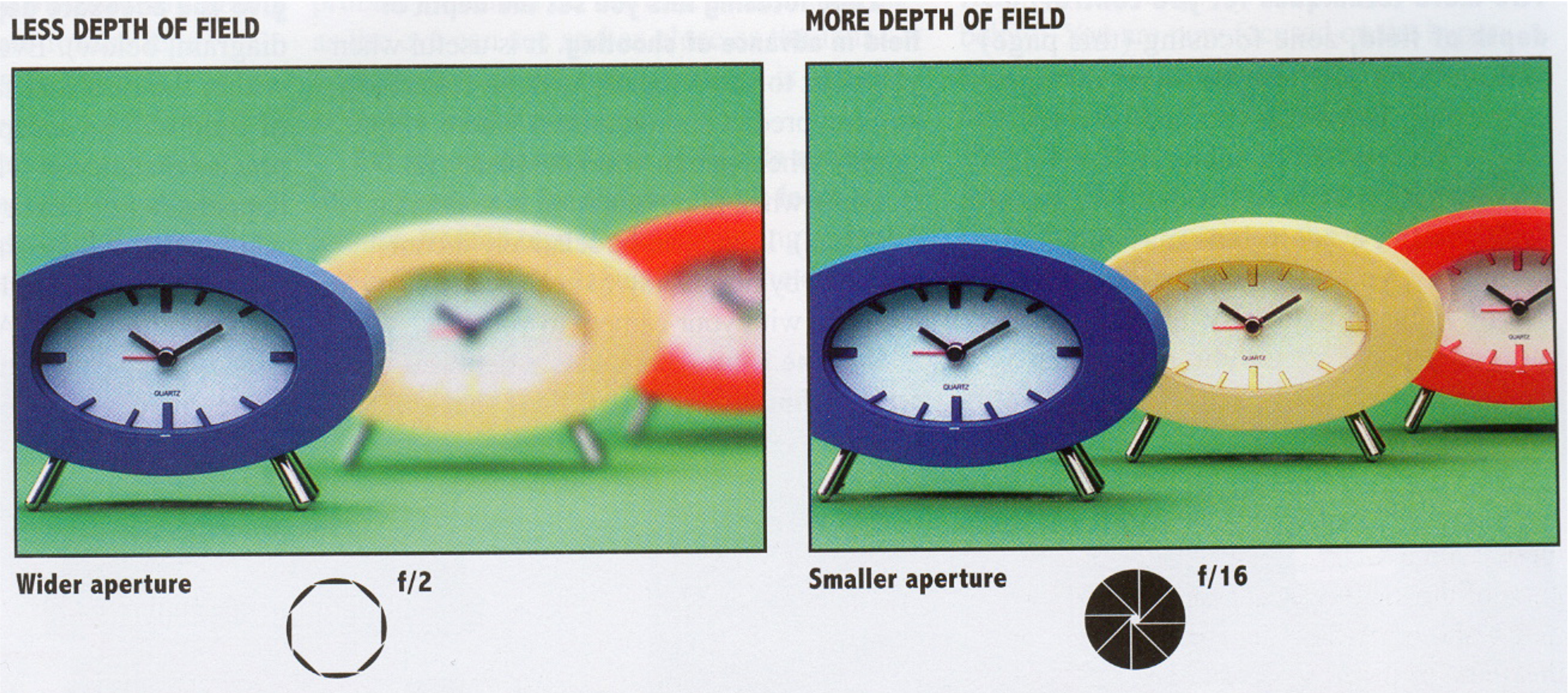
- **Depth of field**



slide by Frédo Durand, MIT

From Photography, London et al.

Depth of field



From Photography, London et al.

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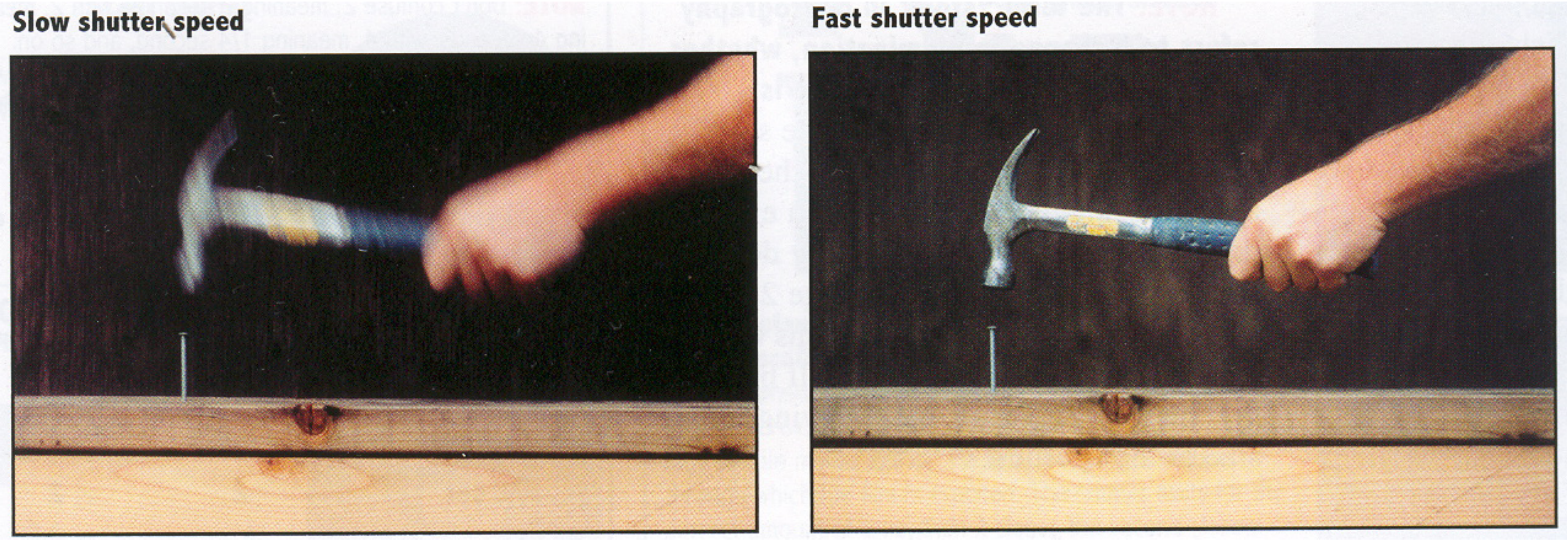
Main effect of shutter speed

- **Motion blur**



From Photography, London et al.

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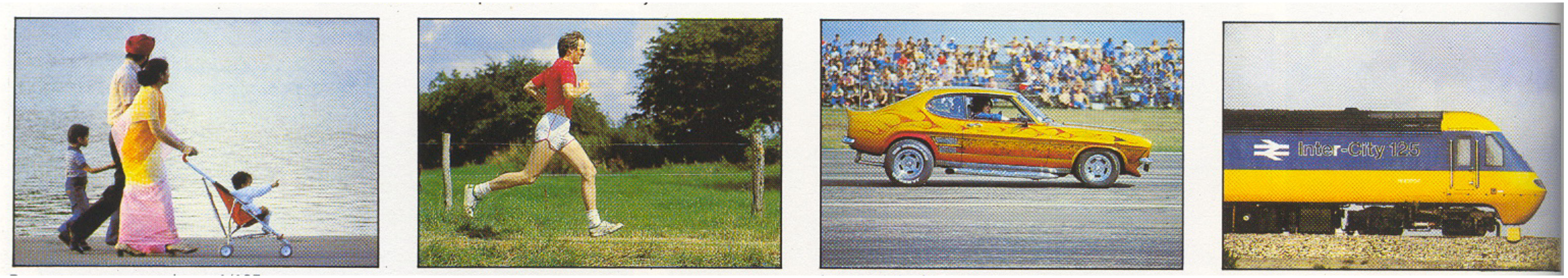
Effect of shutter speed

- **Freezing motion**

Walking people | Running people | Car | Fast train



1/125 | 1/250 | 1/500 | 1/1000

slide by Frédo Durand, MIT

Note: it doesn't mean that shutter speed is proportional to the absolute speed of the object. Object distance is very important, and a photographer often tracks the subject.

Variables in photogaphy

Camera pose

- 6 degrees of freedom
  - where is the camera
  - how is it oriented
- in renderers, specified by associating a rigid transformation with the camera

Field of view

- determined by lens-sensor distance (≈ focal length when not focused super close)

Lens aperture and focus distance

- determines what appears in and out of focus

Exposure time

- determines appearance of moving objects

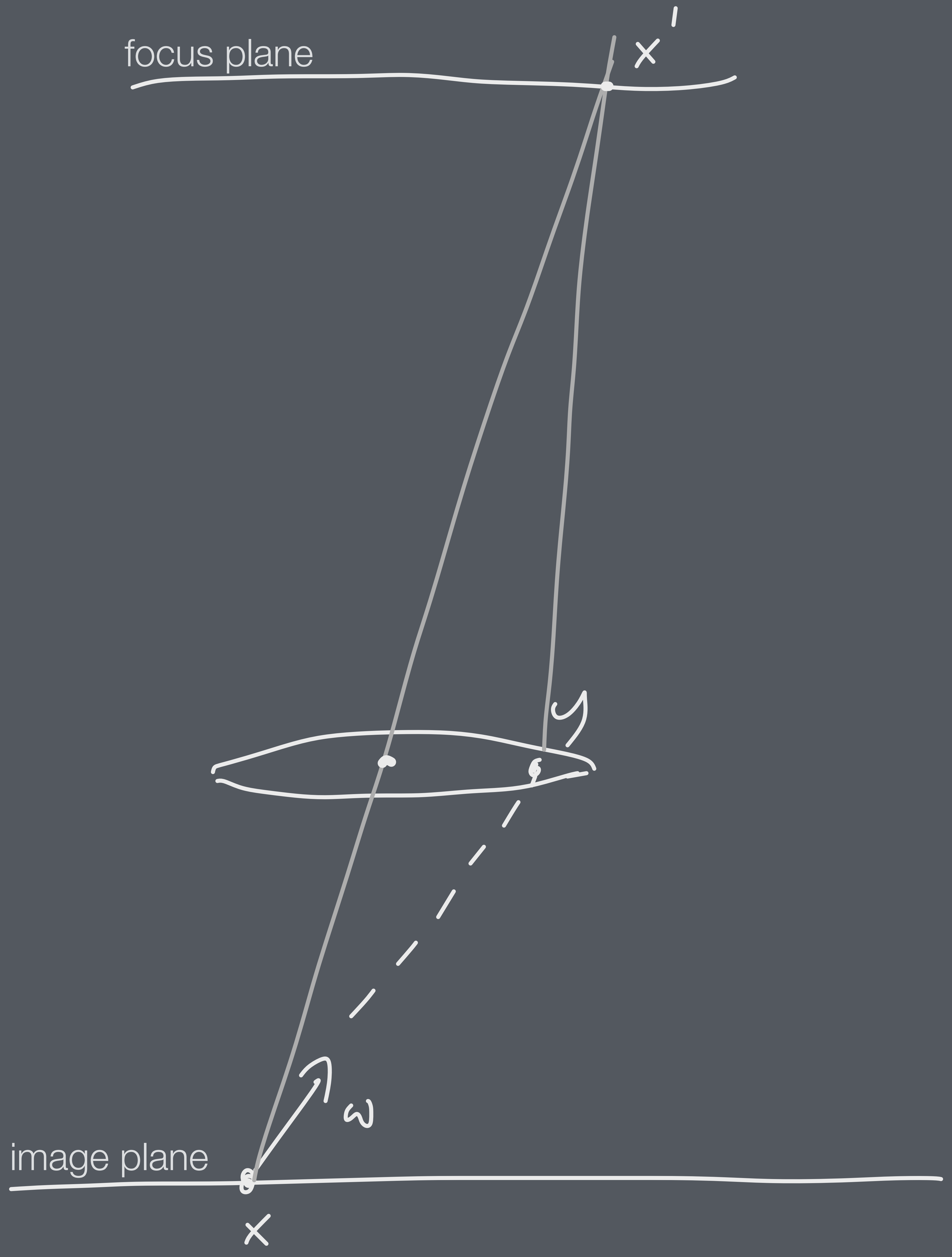
Modeling cameras for rendering

One point on the sensor plane is illuminated by whole aperture

- irradiance on sensor is an integral over the aperture

$$
\begin{aligned}
E(\mathbf{x}) &= \int_{\Omega_A} L_i(\mathbf{x}, \omega)\, \cos\theta_{\mathbf{x}}\, d\omega \\
&= \int_A L(\mathbf{y}, \overrightarrow{\mathbf{yx}}) \frac{\cos\theta_{\mathbf{x}} \cos\theta_{\mathbf{y}}}{\|\mathbf{x}-\mathbf{y}\|^2} d\mathbf{y} \\
&= \frac{1}{f^2} \int_A L(\mathbf{y}, \overrightarrow{\mathbf{yx}})\, \cos^4\theta\, d\mathbf{y} \\
&= \frac{1}{f^2} \int_A L_i(\mathbf{y}, \overrightarrow{\mathbf{yx}'})\, \cos^4\theta\, d\mathbf{y}
\end{aligned}
$$

- simple camera omit the $\cos^4$



Time integration

If the shutter time is nonzero, the scene can move

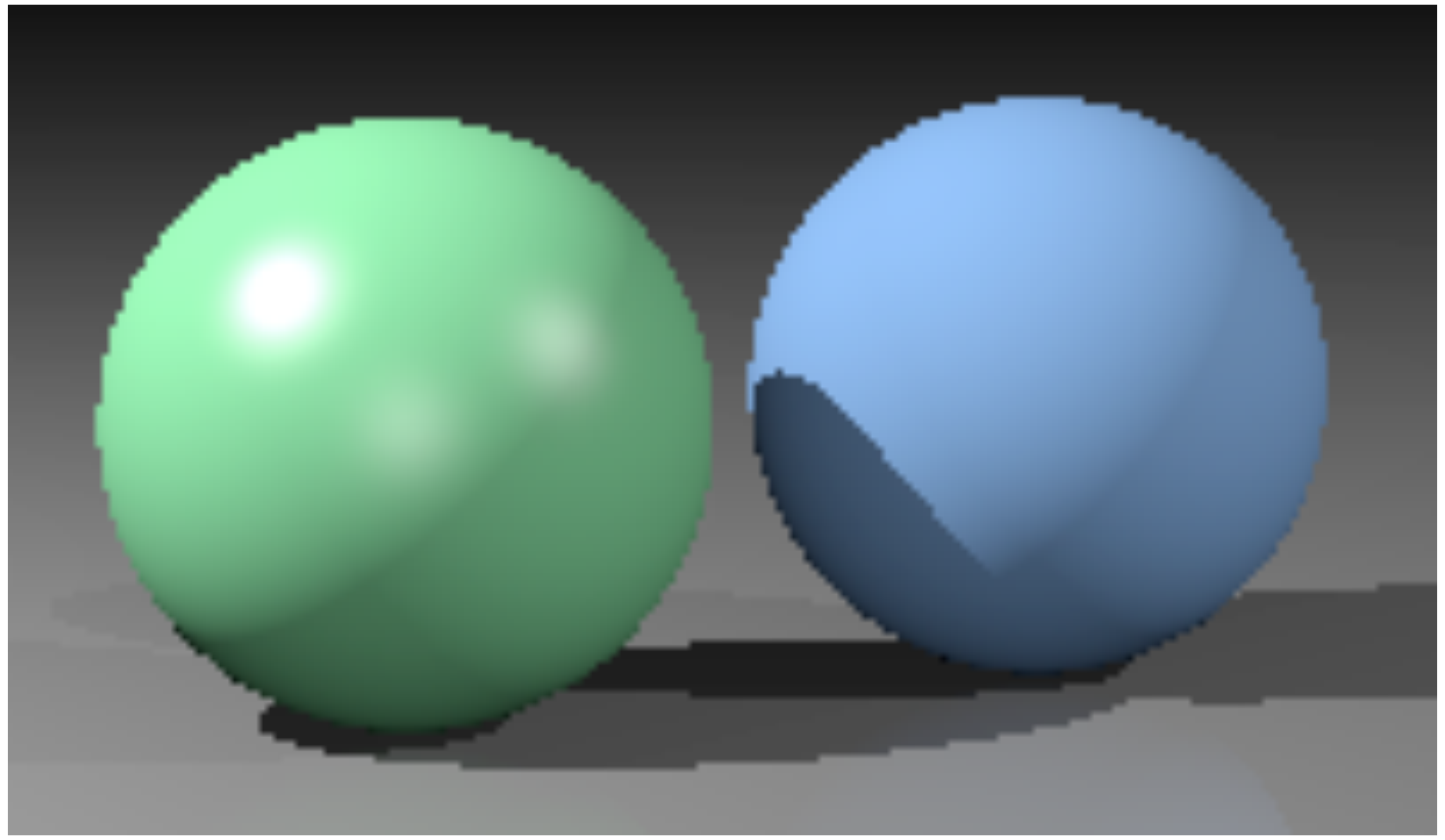
This is simple to model with two extensions

- each ray probing the scene from the camera is tagged with a time
- each moving object pays attention to the time when computing ray intersections

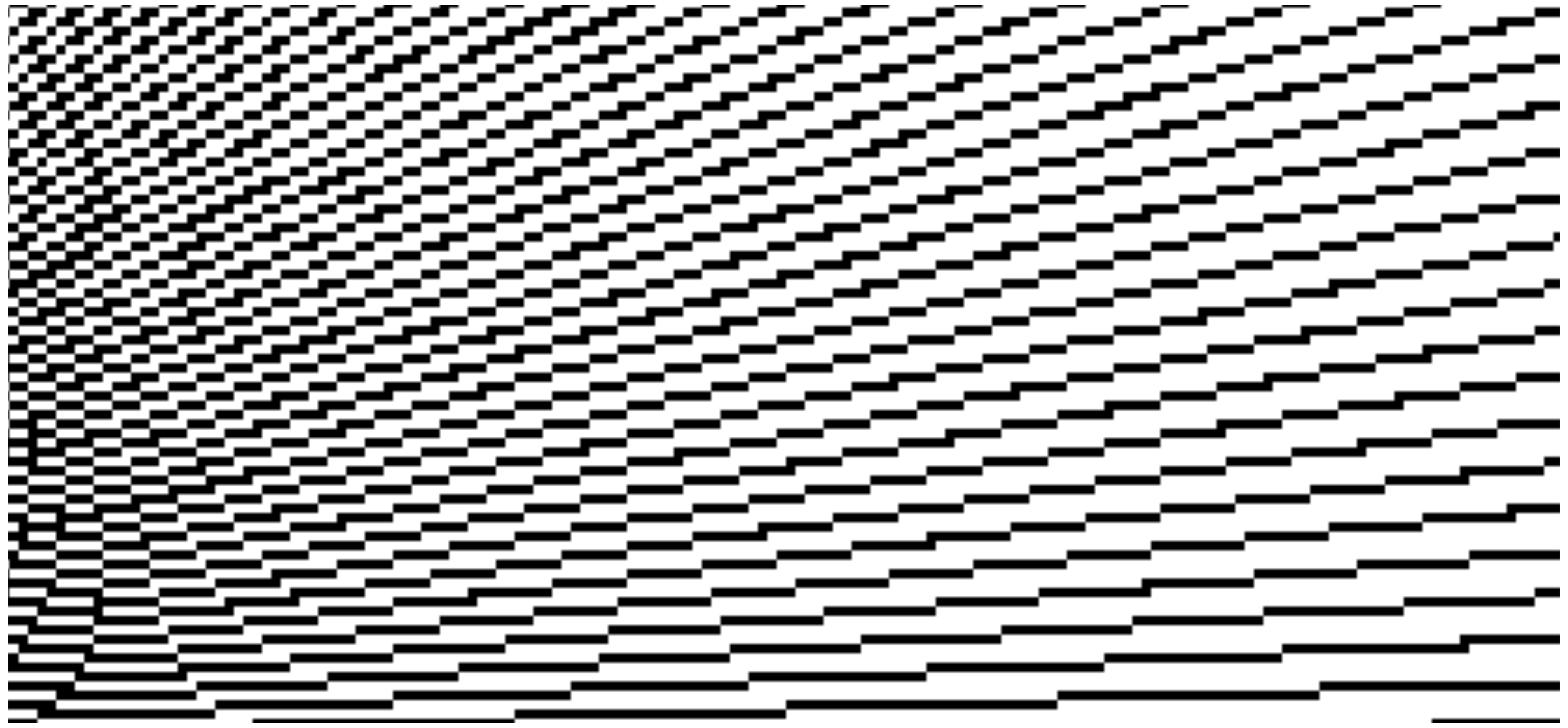
Aliasing

point sampling a
continuous image:

continuous image defined
by ray tracing procedure

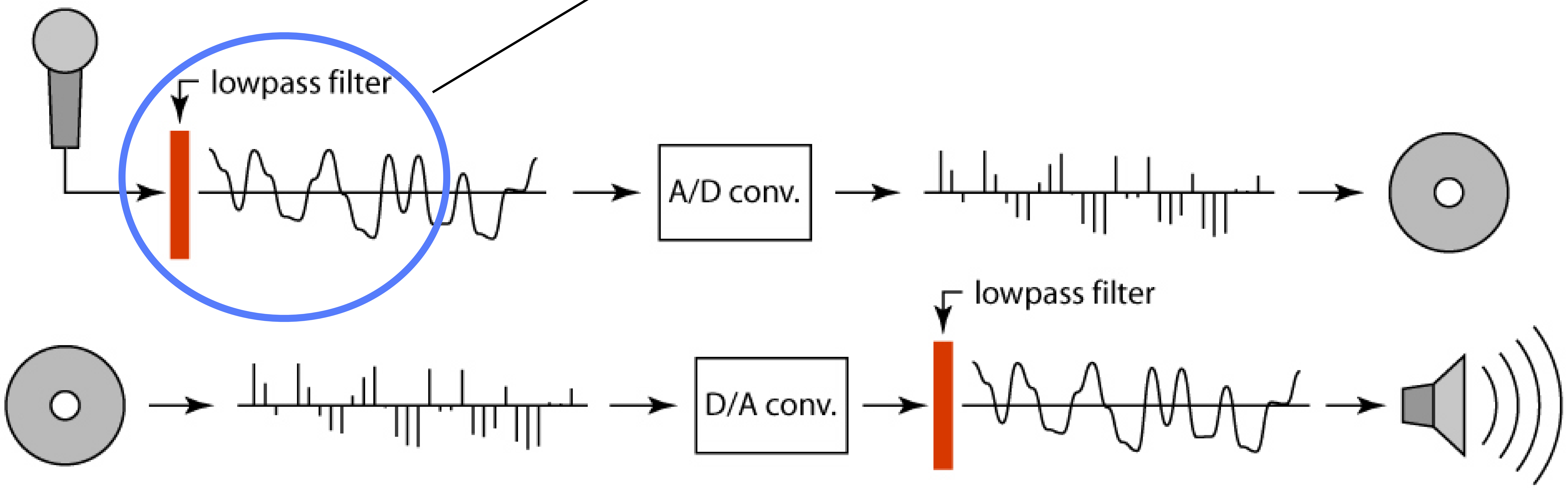


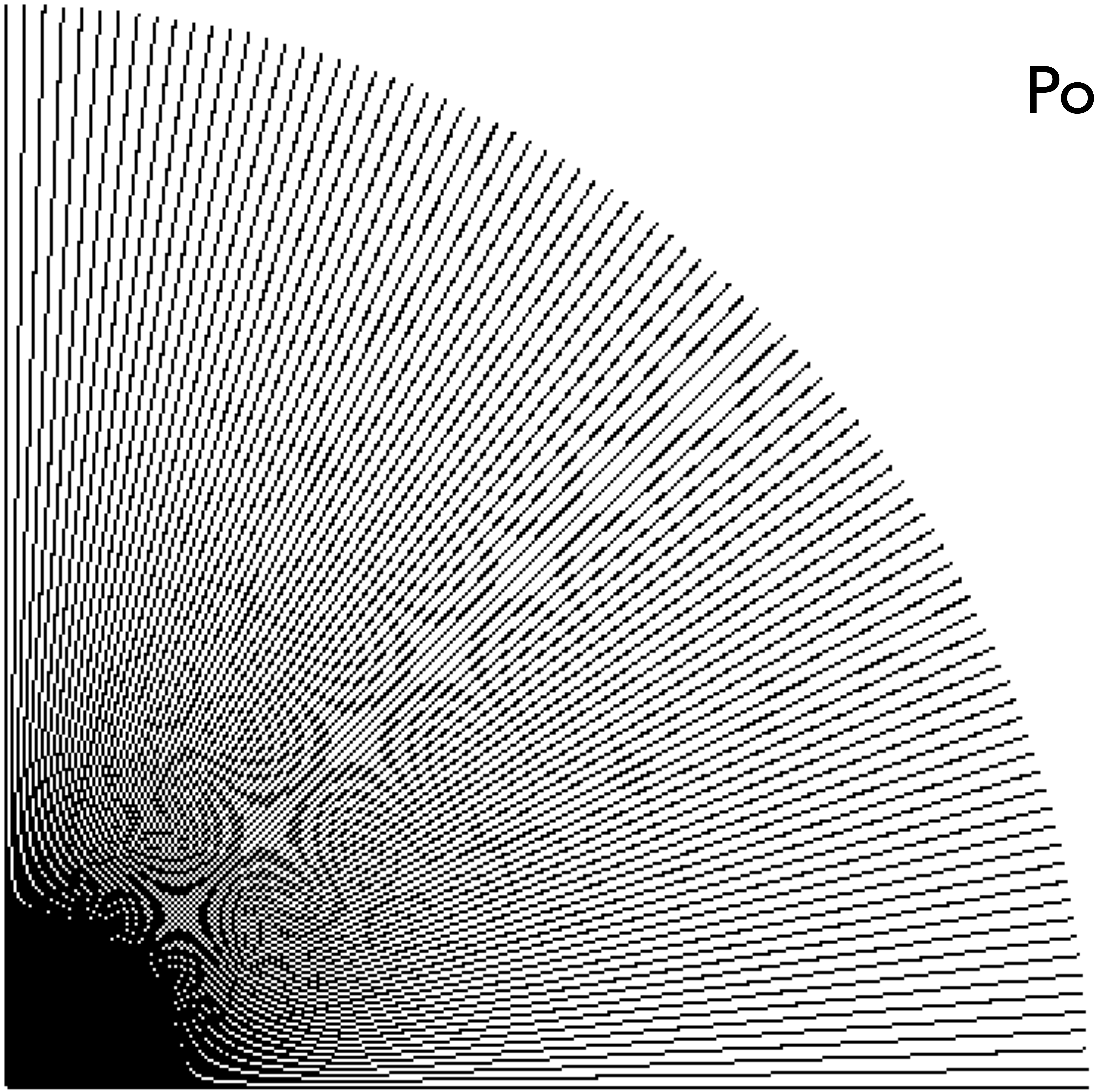
continuous image defined
by a bunch of black rectangles



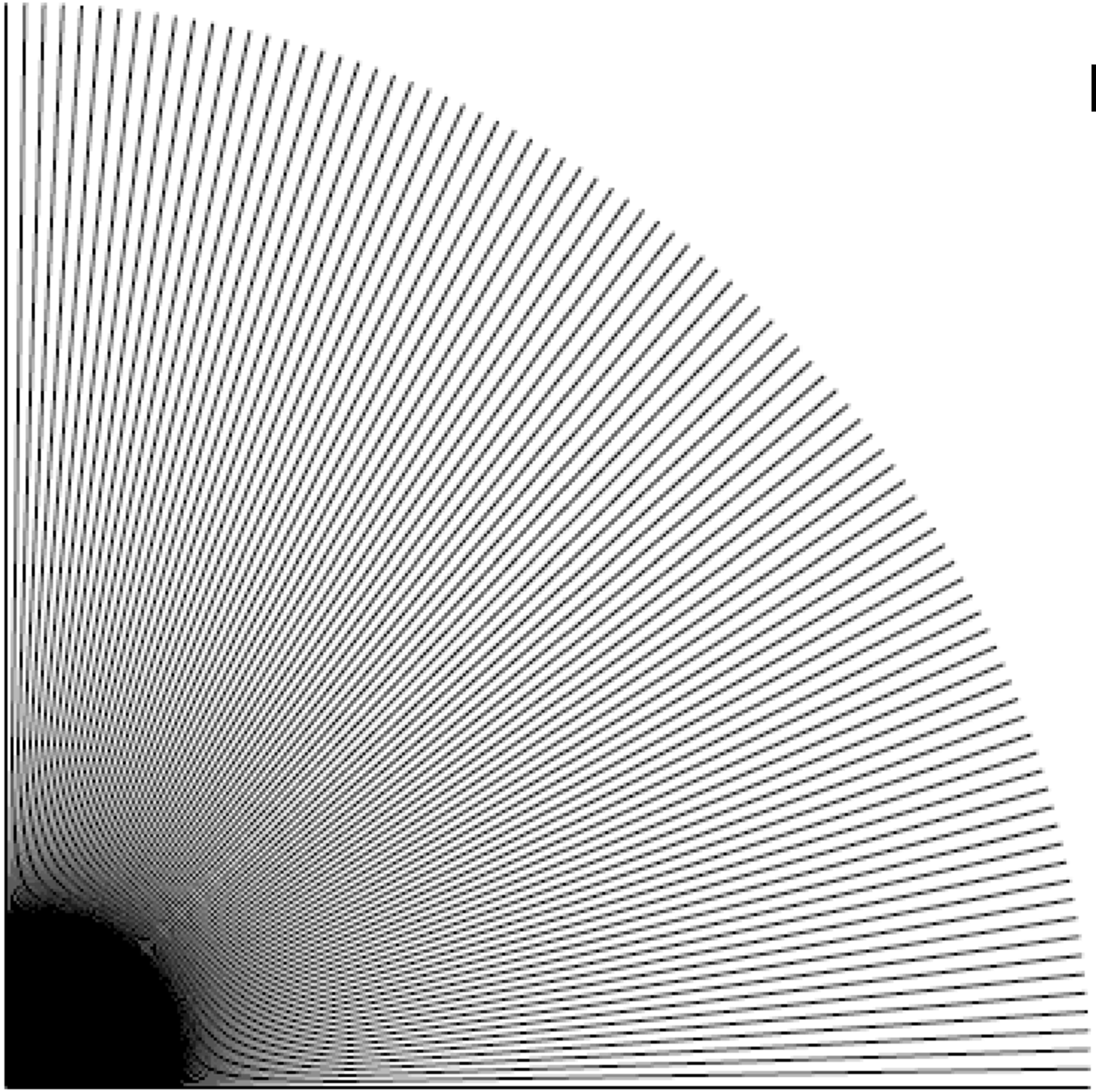
Signal processing view

we need to remember this step





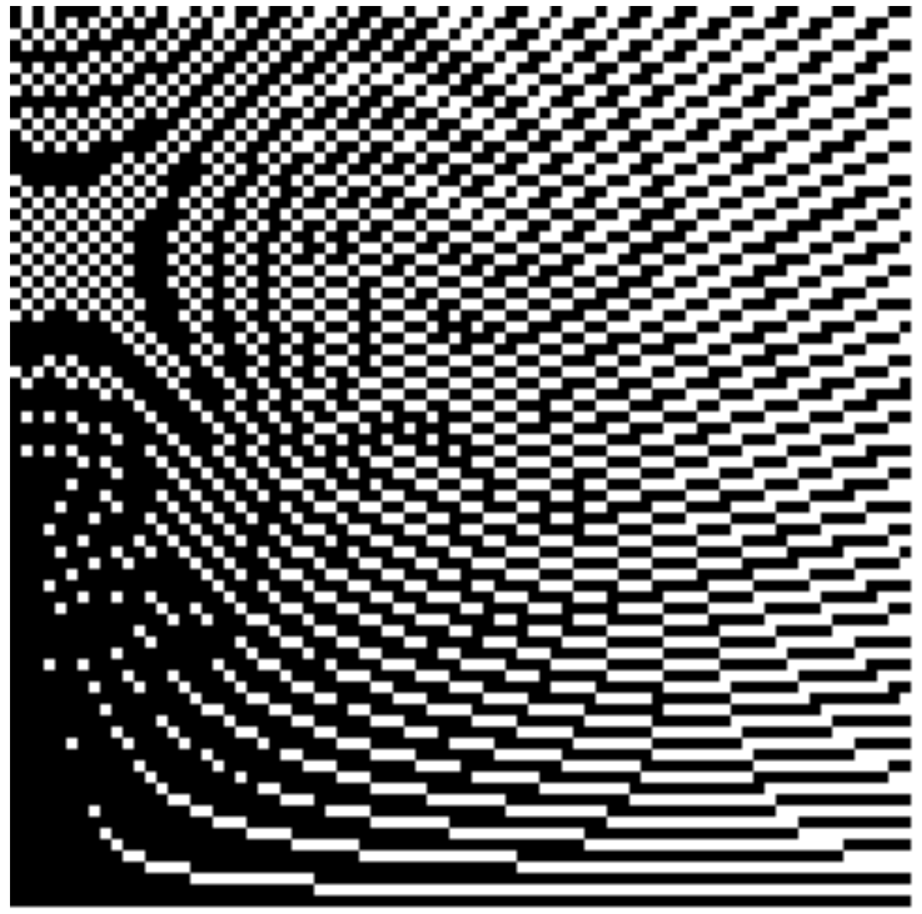
Point sampling in action



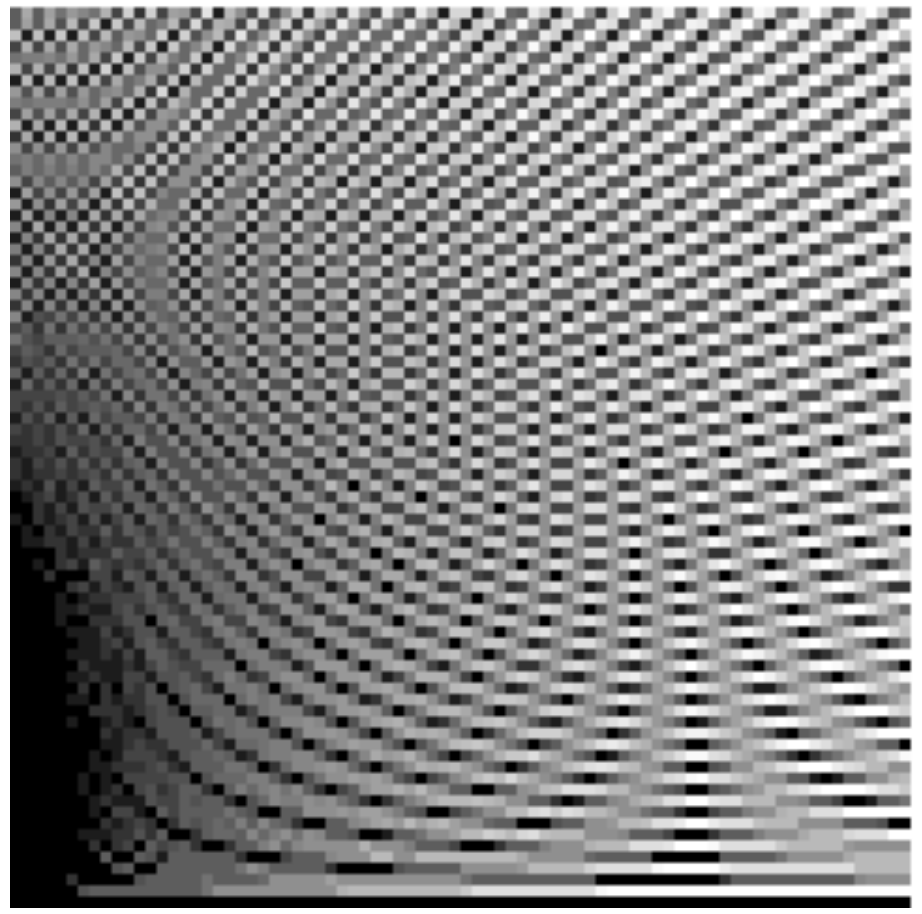
Box filtering in action

Gaussian filtering in action

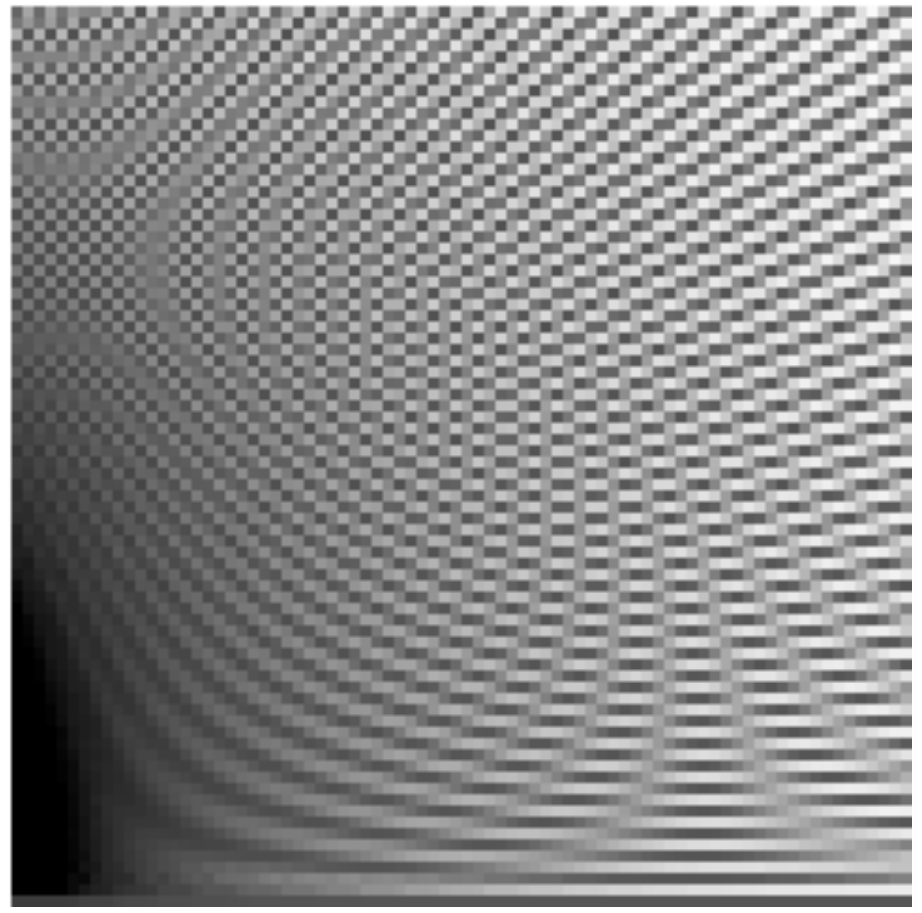
Filter comparison



Point sampling



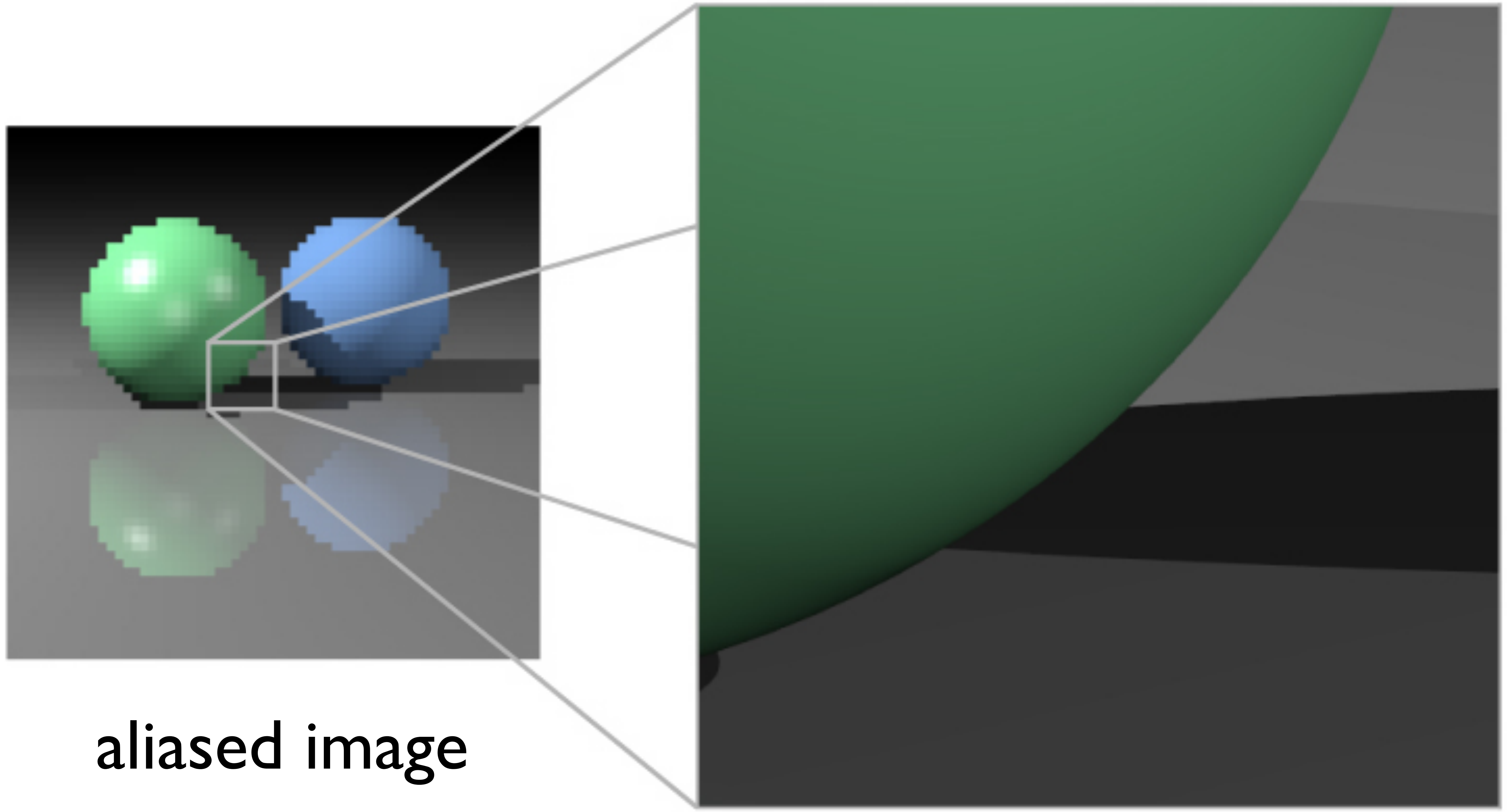
Box filtering



Gaussian filtering

(with previous instructors James/Bala, and some slides borrowed from Kurt Akeley)

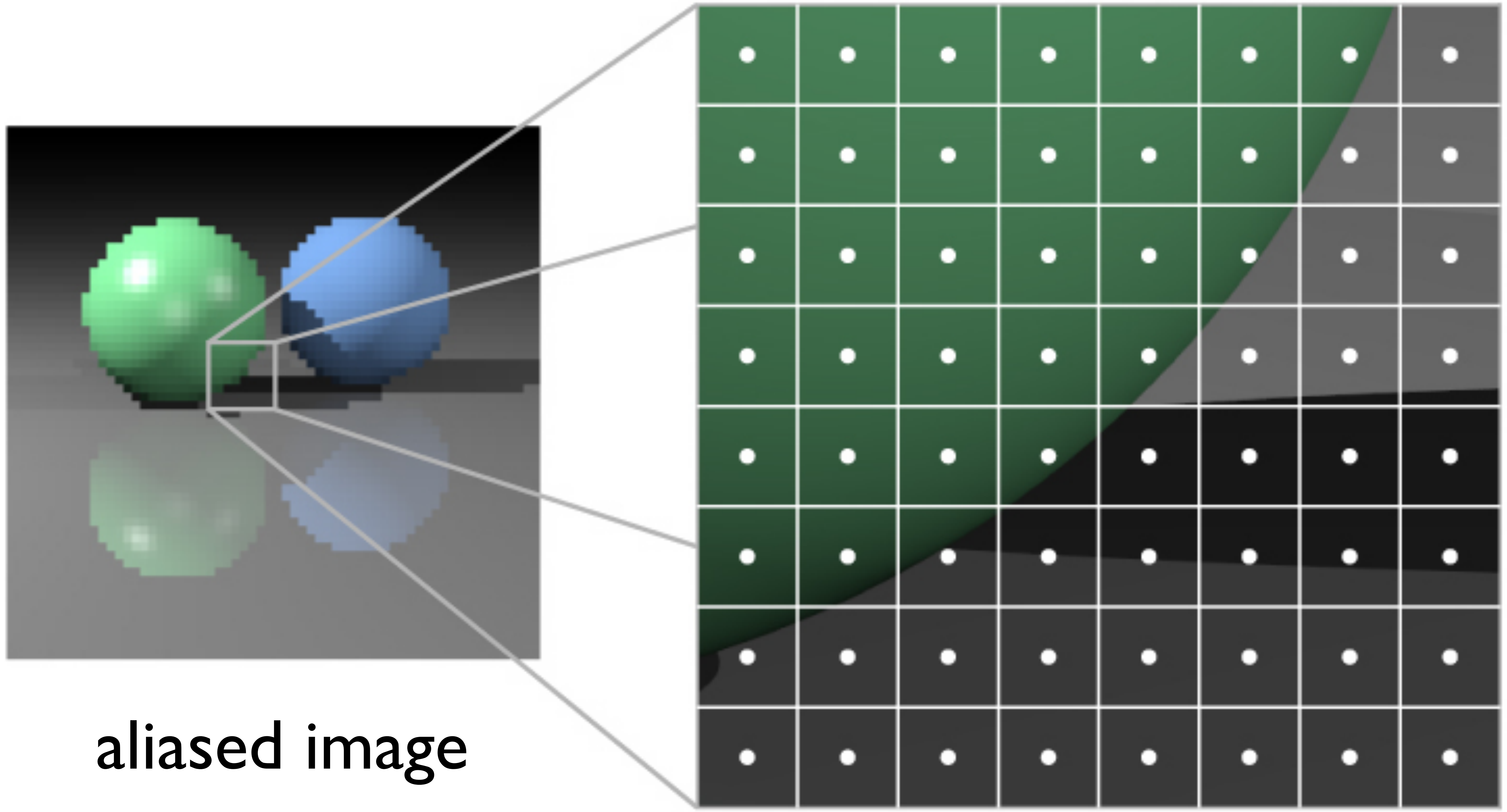
Antialiasing in ray tracing



aliased image

(with previous instructors James/Bala, and some slides borrowed from Kurt Akeley)

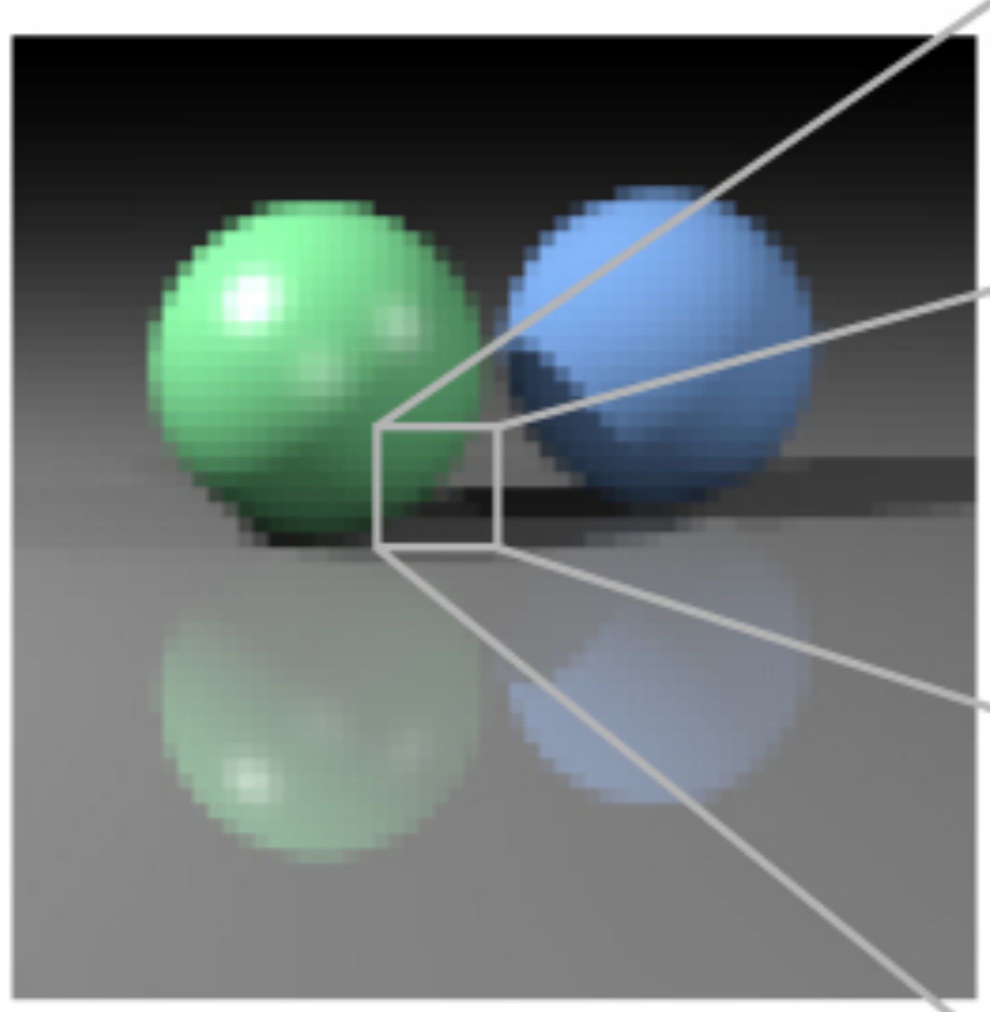
Antialiasing in ray tracing



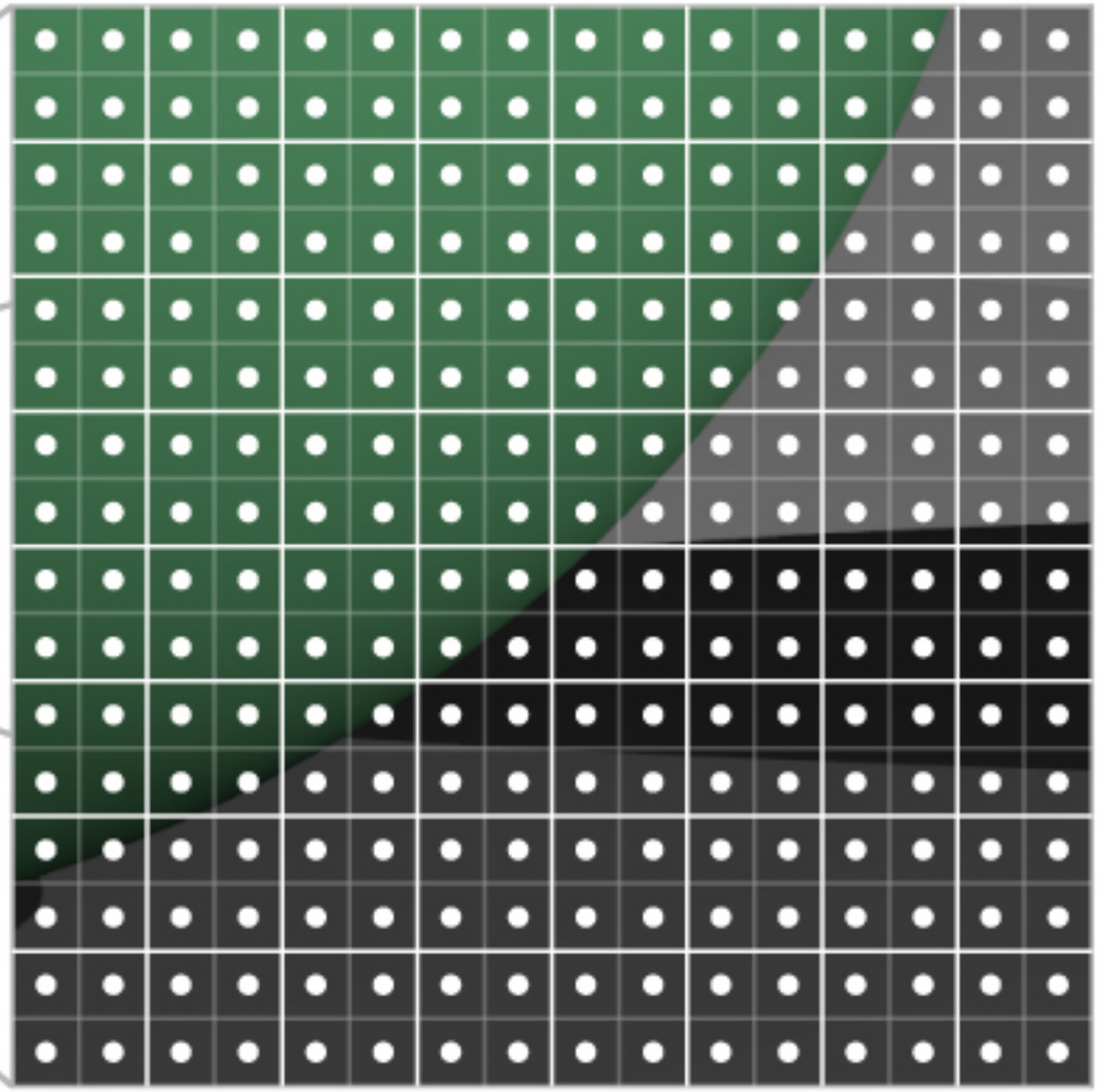
aliased image

one sample per pixel

Antialiasing in ray tracing

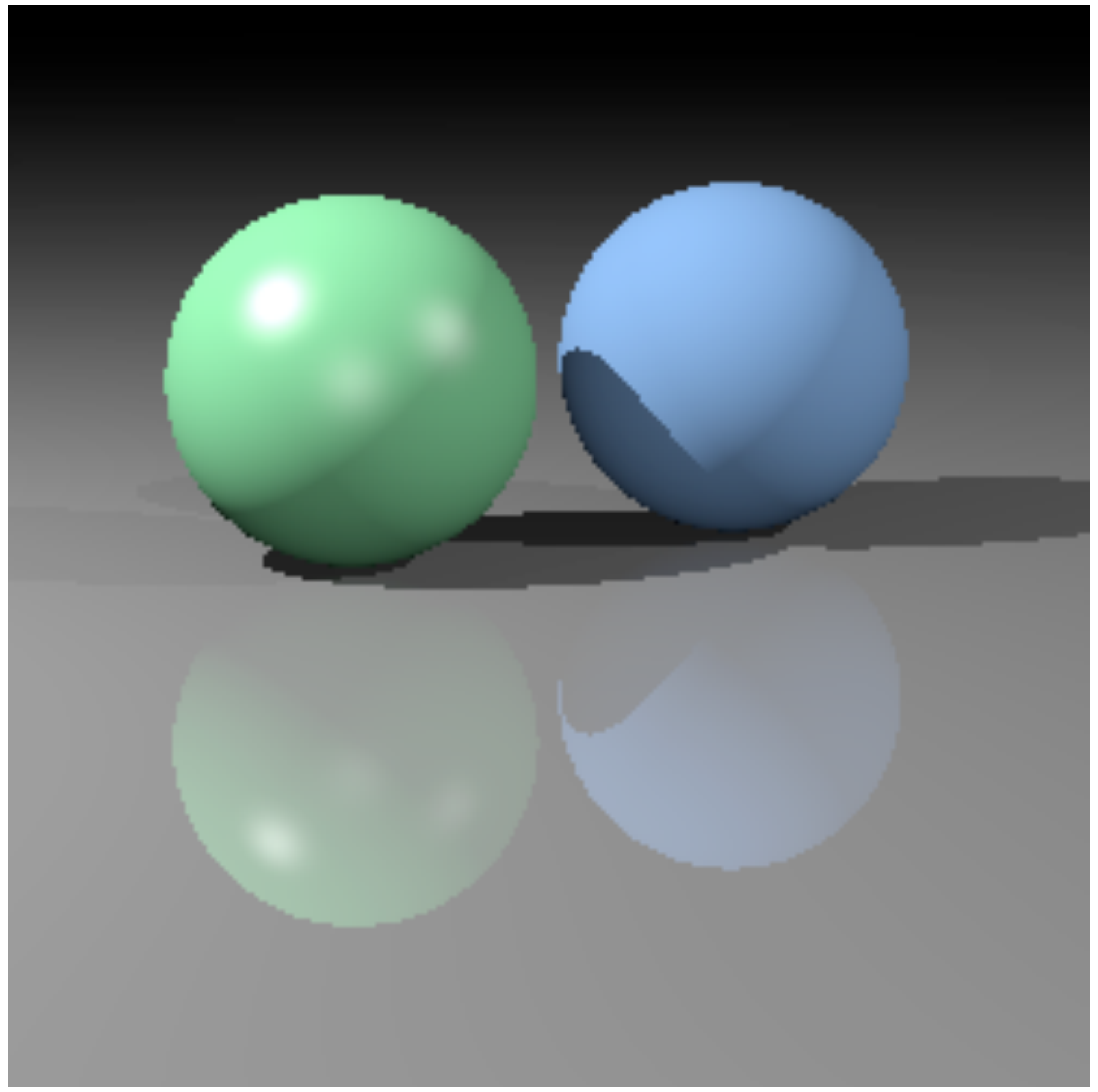


antialiased image

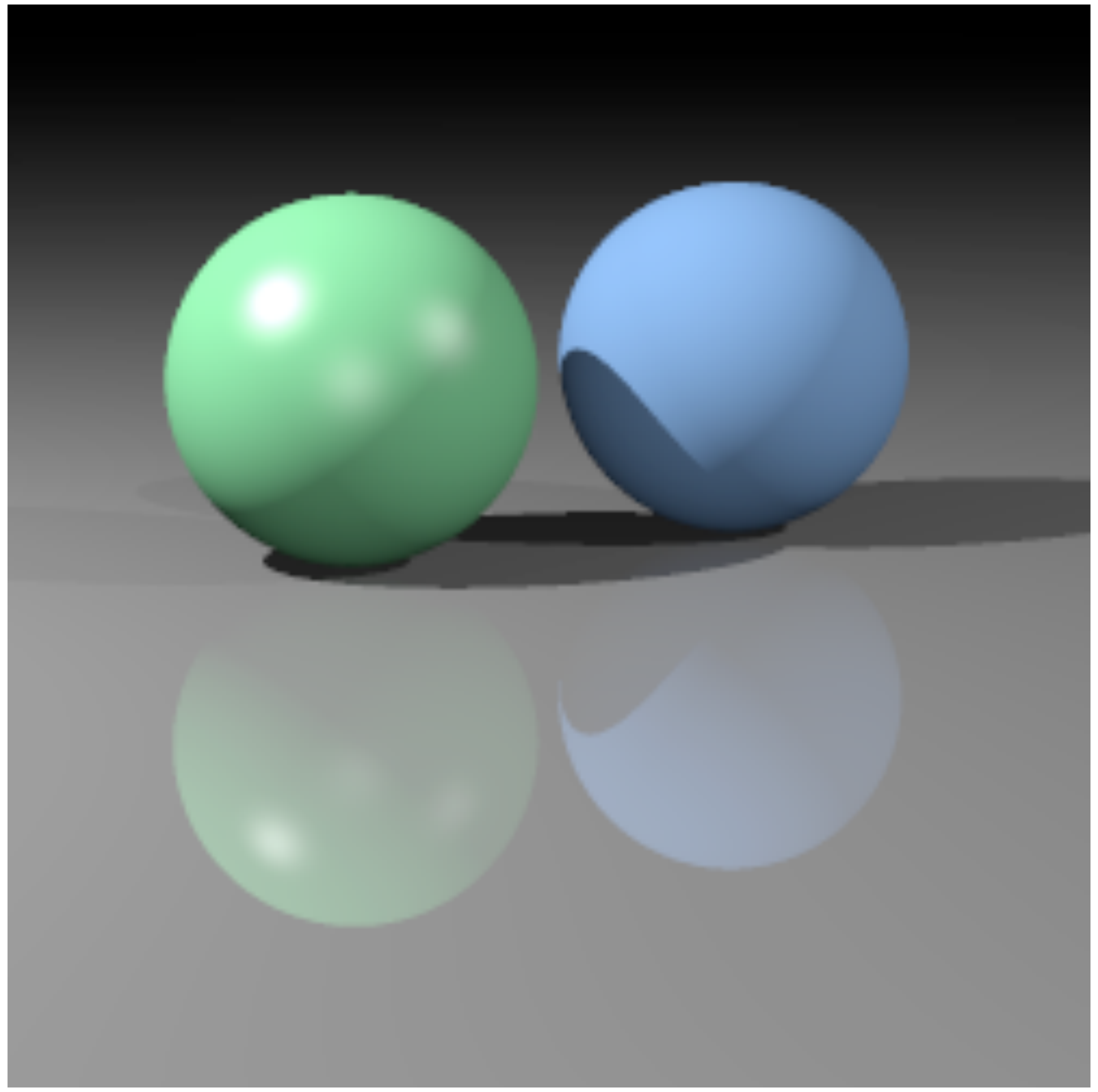


four samples per pixel

Antialiasing in ray tracing



one sample/pixel



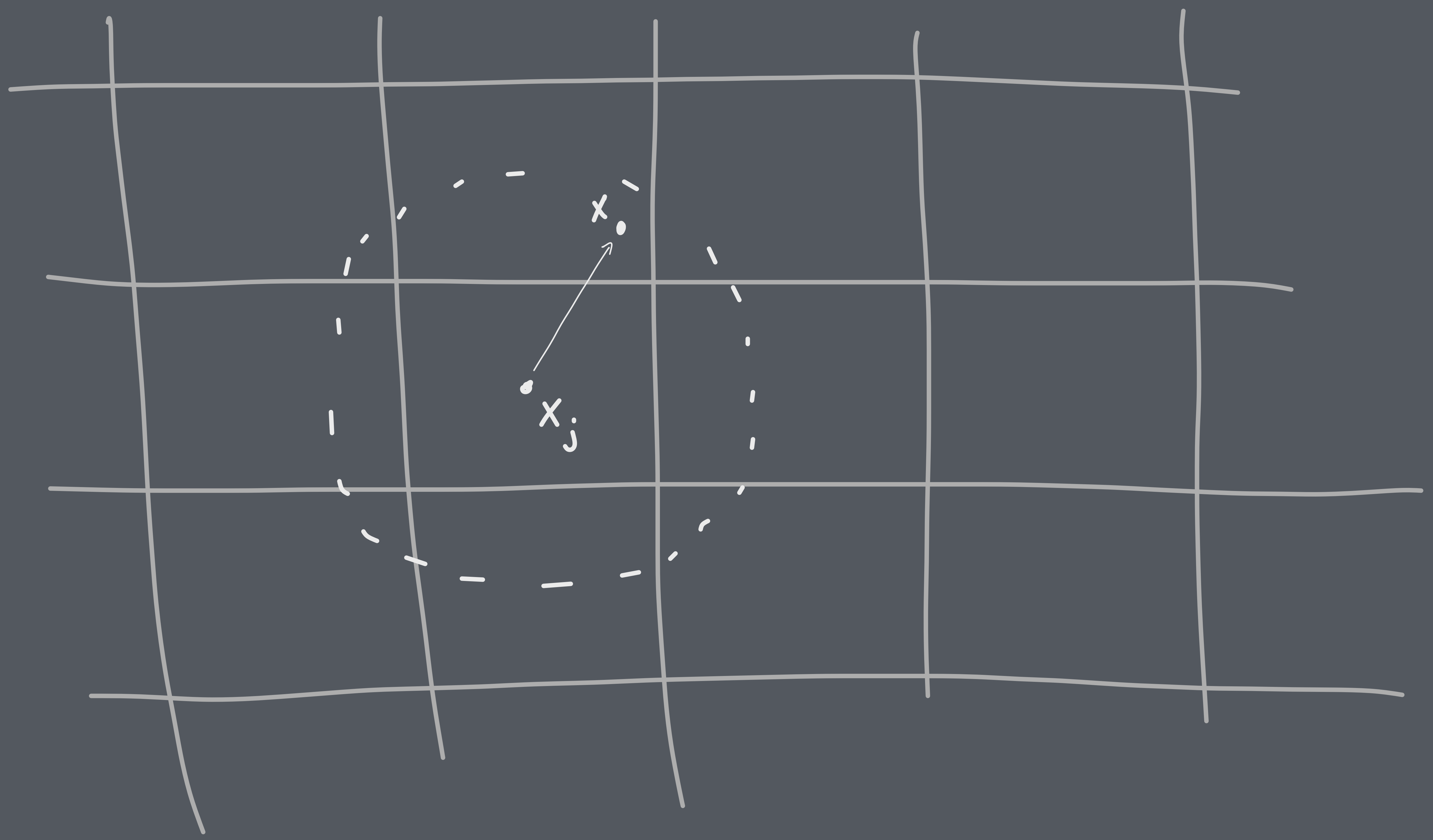
9 samples/pixel

(with previous instructors James/Bala, and some slides borrowed from Kurt Akeley)

Pixel filtering

For antialiasing, each pixel is a weighted integral

- $\Phi_j = \int E(\mathbf{x}) h(\mathbf{x} - \mathbf{x_j})\, d\mathbf{x}$



The Measurement Equation

Pixel value is a measurement of energy

- integrate radiance over aperture solid angle: irradiance
- integrate irradiance over pixel area: power
- integrate power over shutter time: energy
- $$J_j = \int_{\Delta t} \int_{R^2} \int_{\Omega_A} L_i(\mathbf{x}, \omega_i)\, h(\mathbf{x} - \mathbf{x}_j)\ \cos\theta\, d\omega\, d\mathbf{x}\, dt$$
- change variable to aperture to integrate over scene rays
- $$J_j = \frac{1}{f^2} \int_{\Delta t} \int_{R^2} \int_{A} L_i(\mathbf{y}, \omega(\mathbf{x}, \mathbf{y}))\, h(\mathbf{x} - \mathbf{x}_j)\ \cos^4\theta\, d\omega\, d\mathbf{y}\, dt$$
- follow rays to surface to connect to rendering equation
- $$J_j = \frac{1}{f^2} \int_{\Delta t} \int_{R^2} \int_{A} L(\psi(\mathbf{y}, \omega), -\omega)\, h(\mathbf{x} - \mathbf{x}_j)\ \cos^4\theta\, d\omega\, d\mathbf{y}\, dt$$