Computational Approaches to Cameras

11/30/10

Magritte , *The False Mirror* (1935)

Computational Photography

Derek Hoiem, University of Illinois

Desiderata

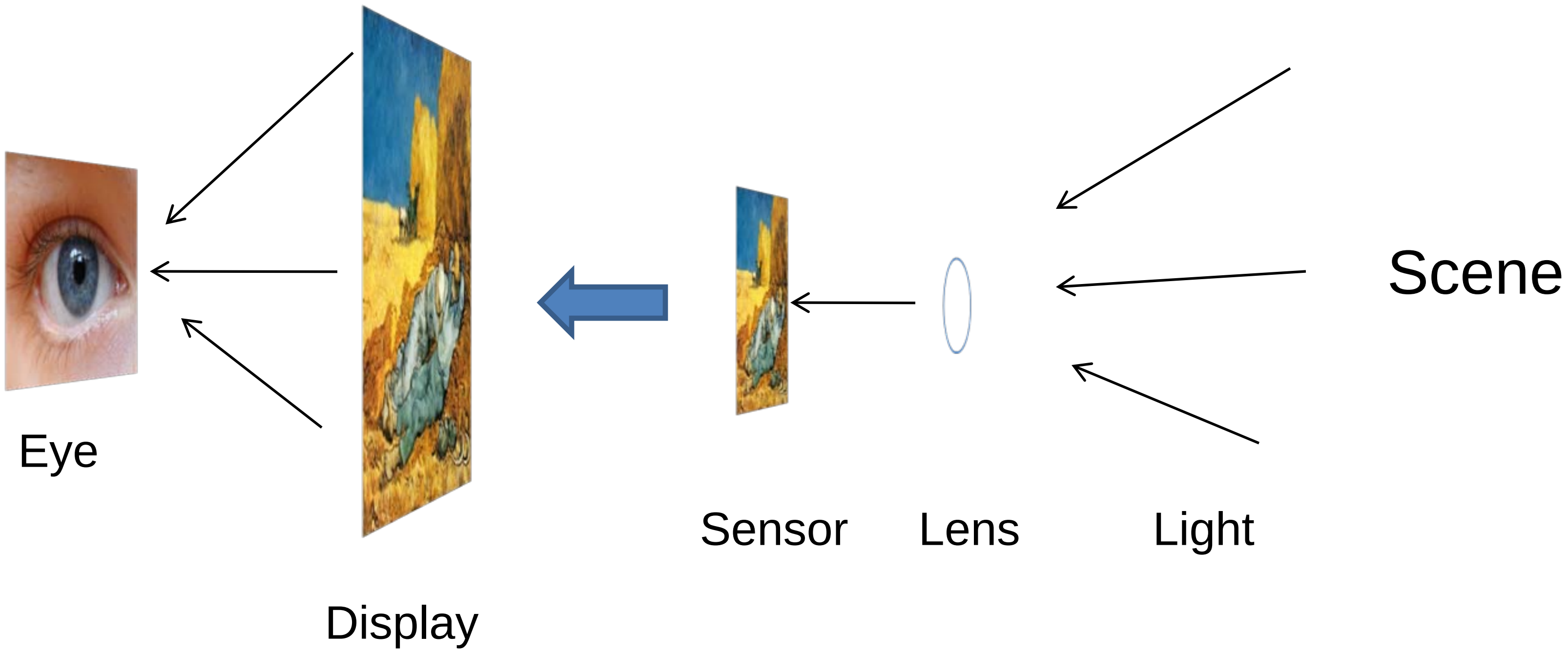
- Vote for Project 5 favorites by Wed night

- Final projects
  - Email me what you're doing if you haven't
  - Start thinking about it early
  - Meet with me if helpful

- What people are doing so far
  - Texture synthesis/transfer: Alex, Steve D., Guenther
  - Non-photorealistic rendering (inc. image analogies): Doheum, Brian, Arash, RJ
  - Relighting: Charles
  - Projector display: Raj, Brett
  - Unspecified: everyone else

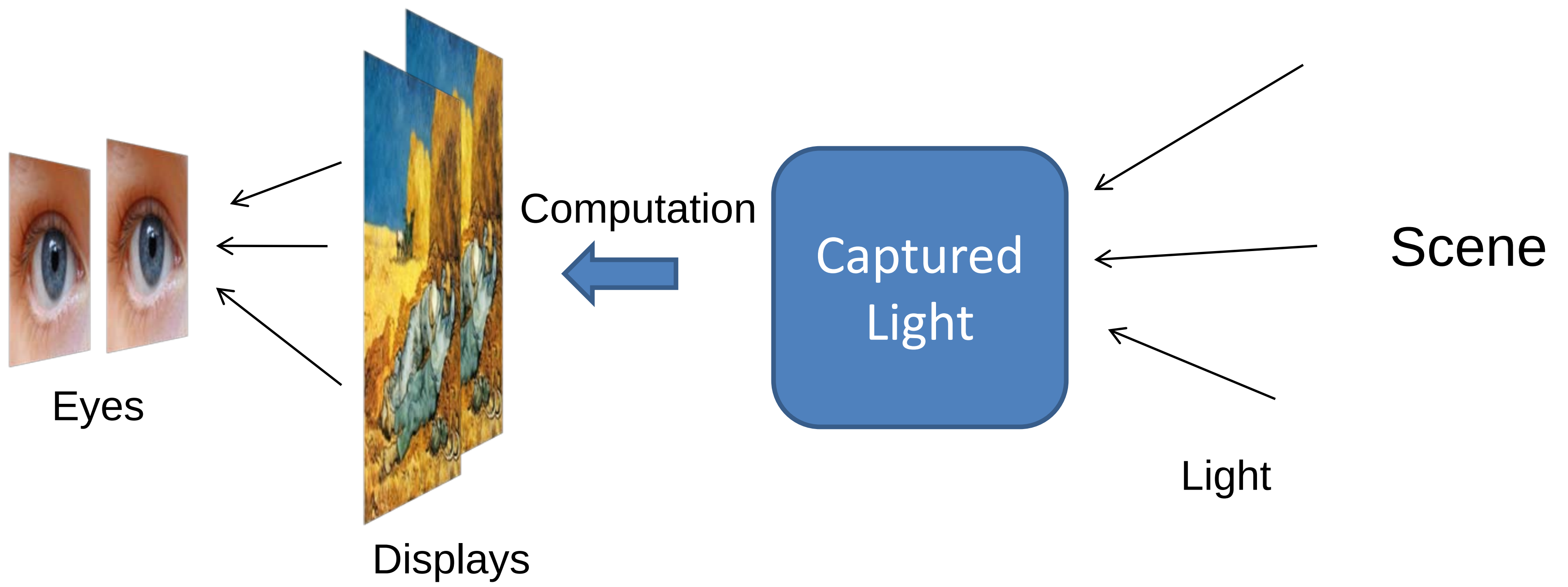
Conventional cameras

- Conventional cameras are designed to capture light in a medium that is directly viewable



Computational cameras

- With a computational approach, we can capture light and then figure out what to do with it



Questions for today

- How can we represent all of the information contained in light?

- What are the fundamental limitations of cameras?

- What sacrifices have we made in conventional cameras? For what benefits?

- How else can we design cameras for better focus, deblurring, multiple views, depth, etc.?

Representing Light: The Plenoptic Function

Figure by Leonard McMillan

Q: What is the set of all things that we can ever see?

A: The Plenoptic Function (Adelson & Bergen)

Let’s start with a stationary person and try to parameterize <u>everything</u> that he can see…

Slides from Efros

Grayscale snapshot

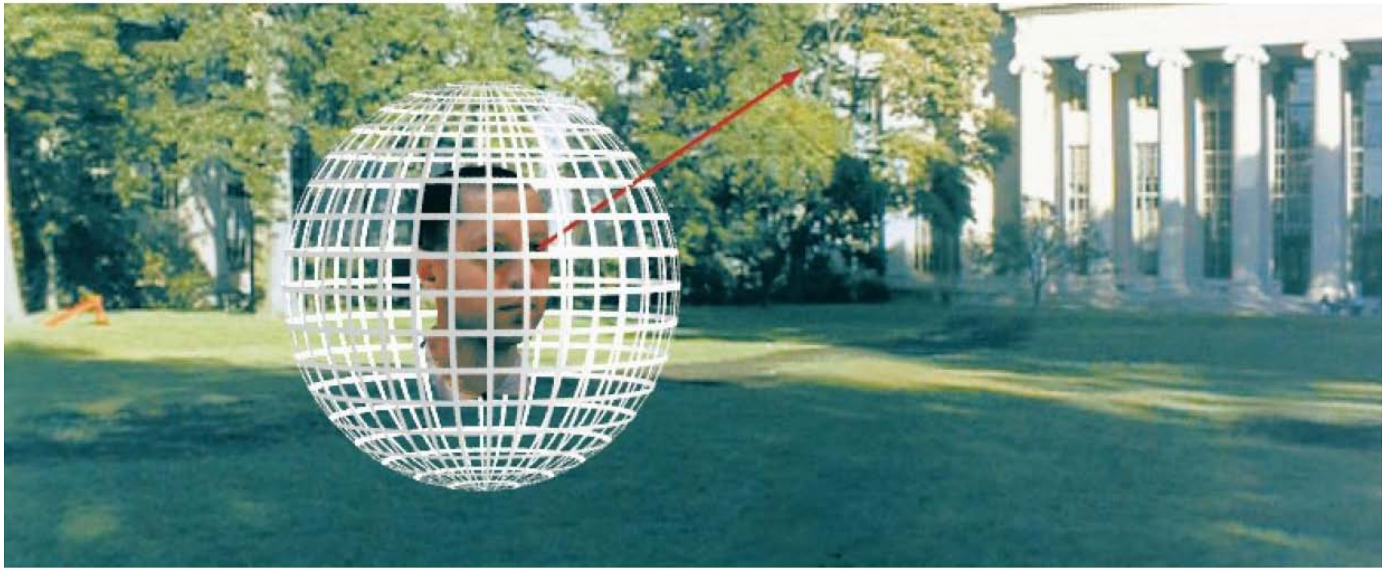
$$P(\theta,\phi)$$

is intensity of light

- Seen from a single view point
- At a single time
- Averaged over the wavelengths of the visible spectrum

(can also do *P(x,y),* but spherical coordinate are nicer)

Color snapshot

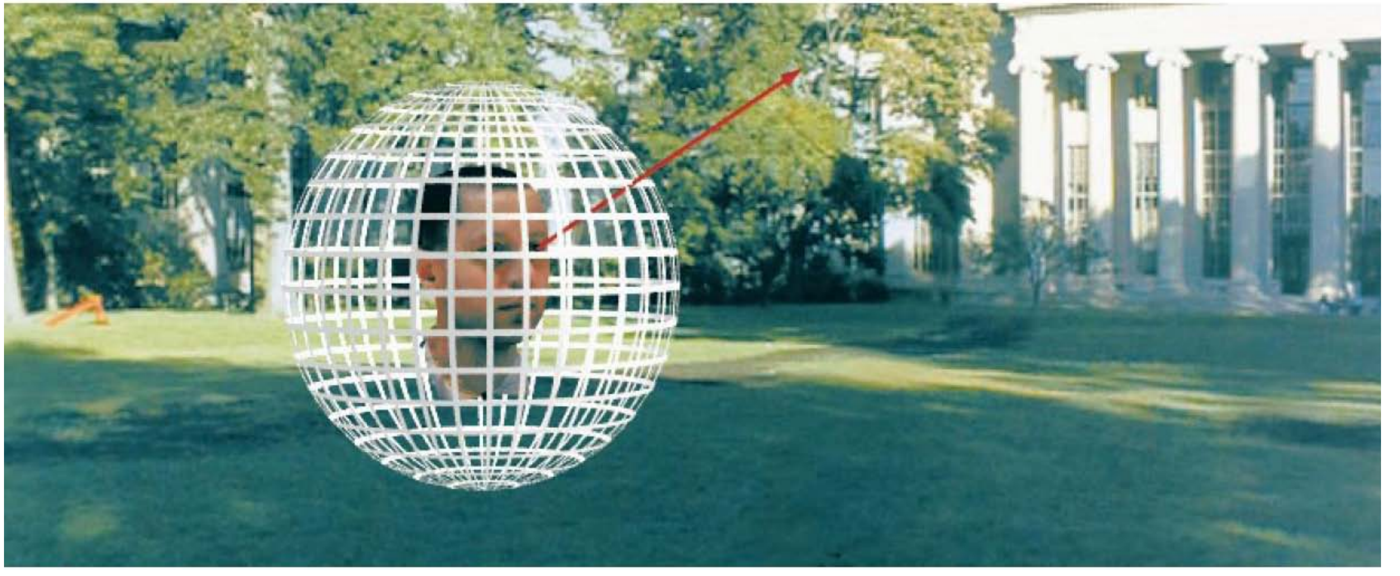


$$P(\theta,\phi,\lambda)$$

is intensity of light

- Seen from a single view point
- At a single time
- As a function of wavelength

A movie

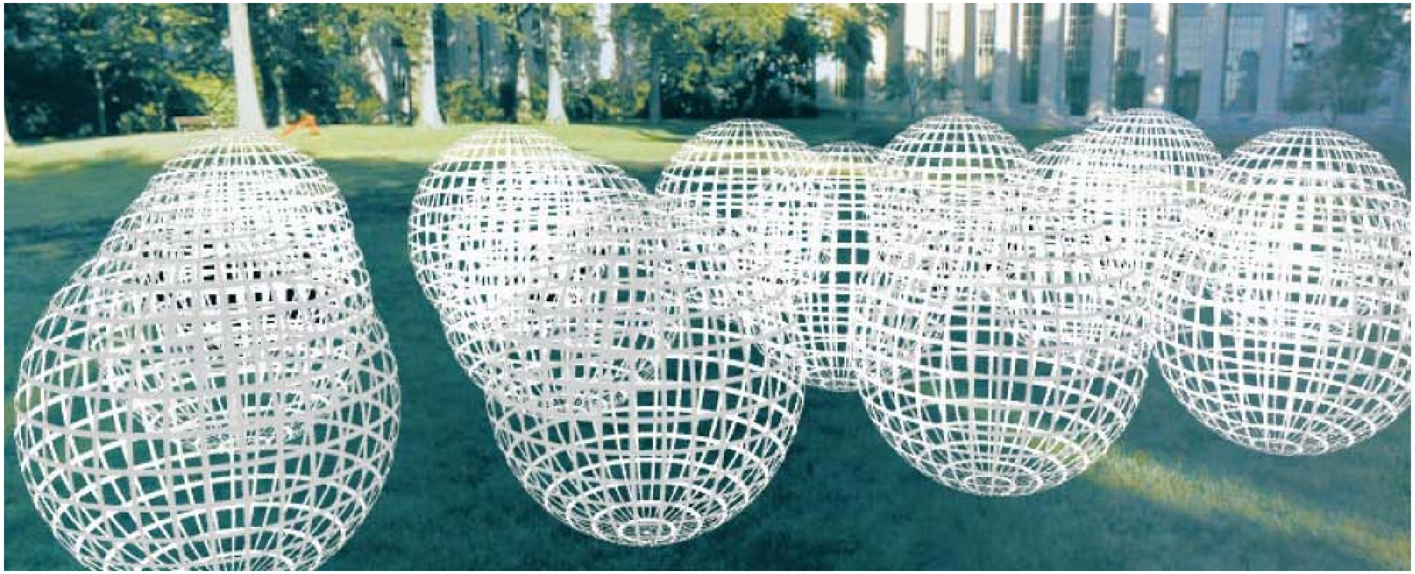


$$P(\theta,\phi,\lambda,t)$$

is intensity of light

- Seen from a single view point
- Over time
- As a function of wavelength

Holographic movie

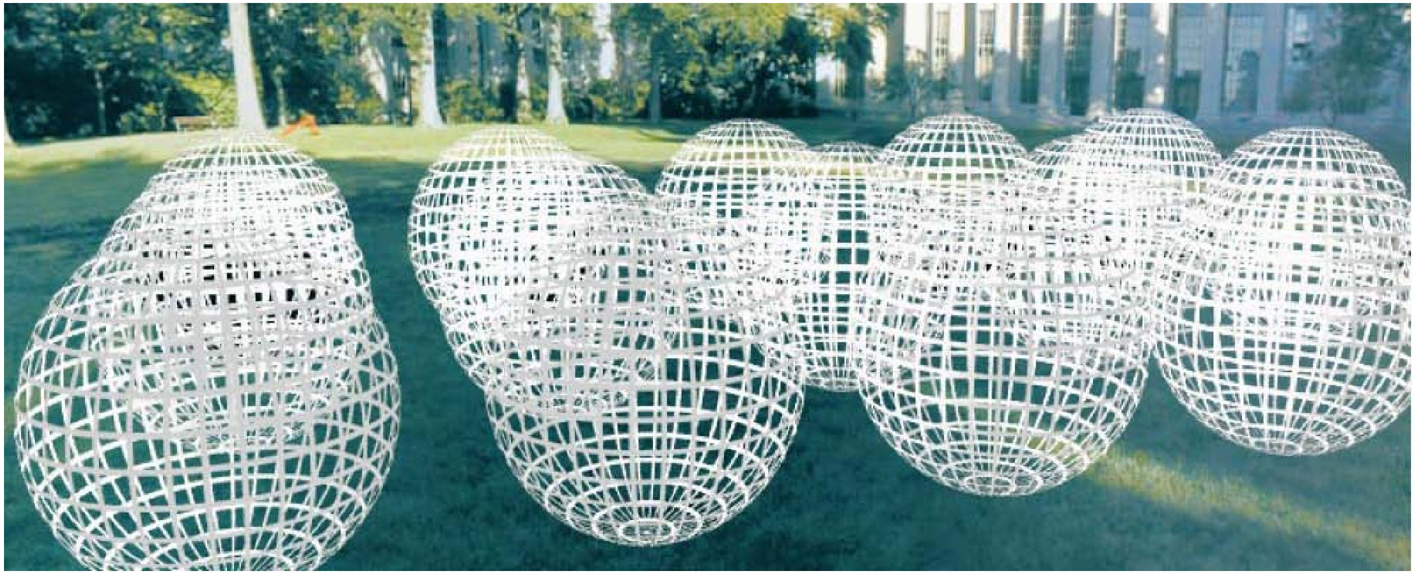


$$P(\theta,\phi,\lambda,t,V_X,V_Y,V_Z)$$

is intensity of light

- Seen from ANY viewpoint
- Over time
- As a function of wavelength

The Plenoptic Function



$$P(\theta,\phi,\lambda,t,V_X,V_Y,V_Z)$$

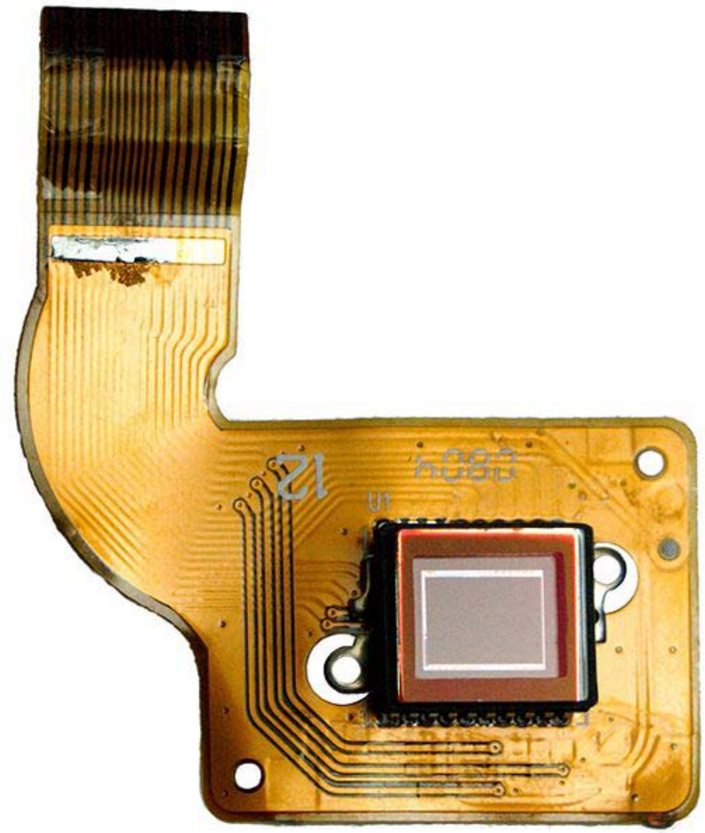
- Can reconstruct every possible view, at every moment, from every position, at every wavelength
- Contains every photograph, every movie, everything that anyone has ever seen!

Representing light

The atomic element of light: ~~a pixel~~ **a ray**

Fundamental limitations and trade-offs

- Only so much light in a given area to capture
- Basic sensor accumulates light at a set of positions from all orientations, over all time
- We want **intensity** of light at **a given time** at **one position** for a **set of orientations**
- Solutions:
  - funnel, constrain, redirect light
  - change the sensor



CCD inside camera

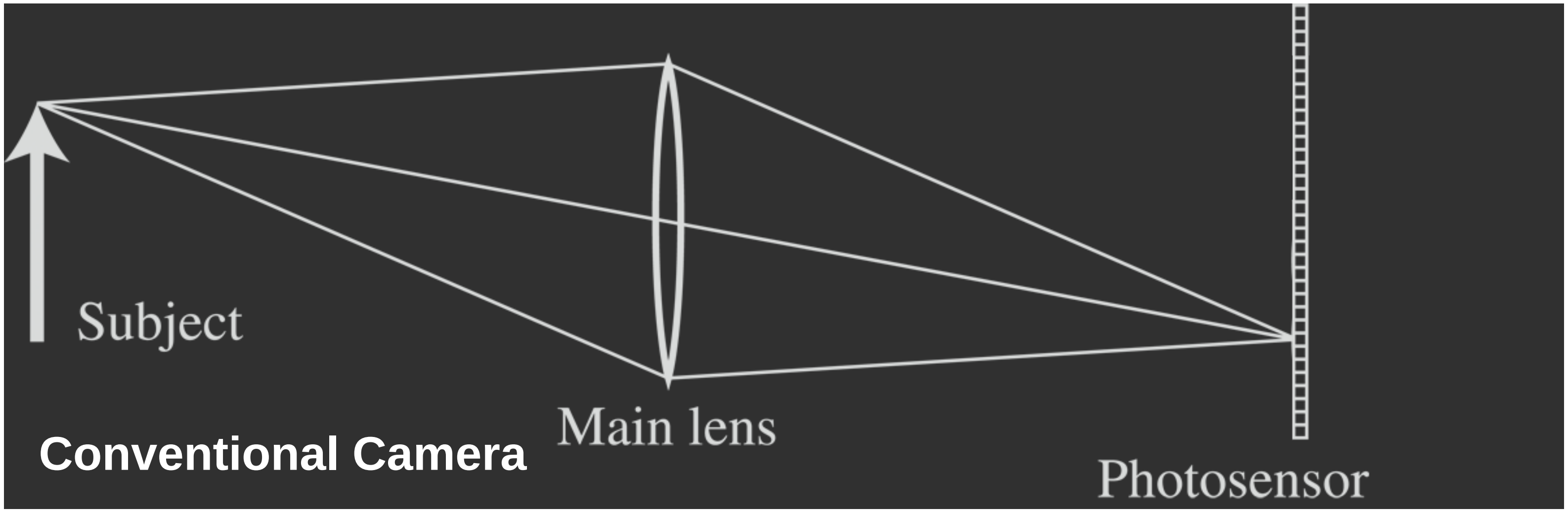
Trade-offs of conventional camera

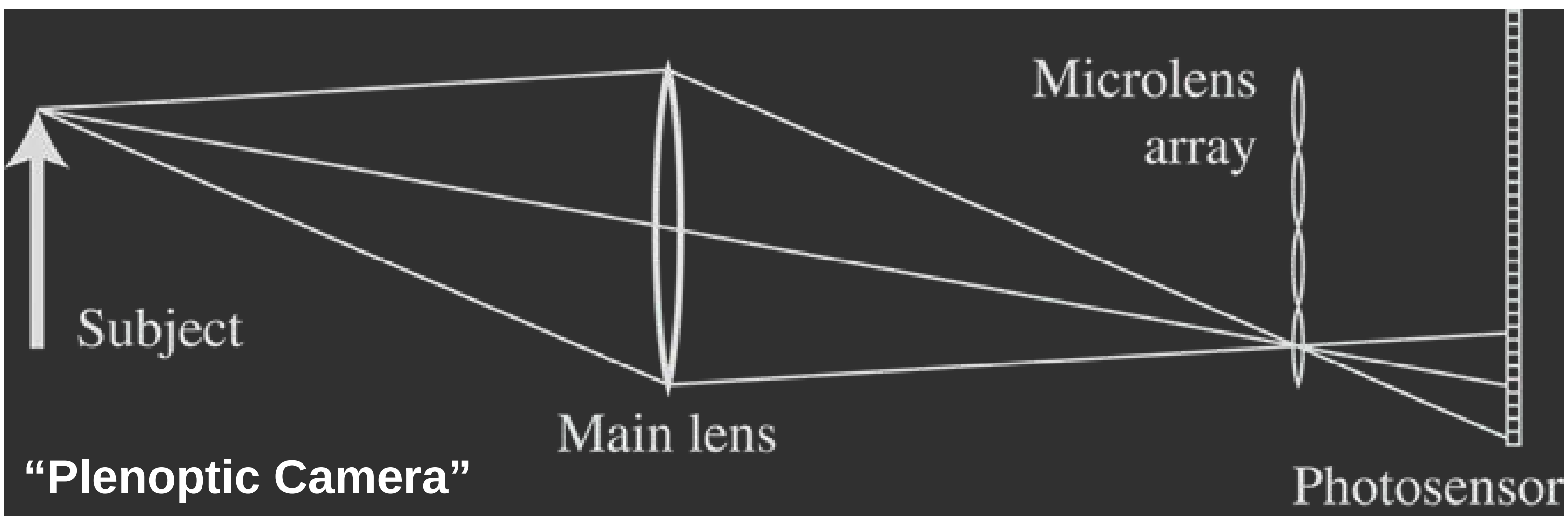
- Add a pinhole
  - ✓ Pixels correspond to small range of orientations at the camera center, instead of all gathered light at one position
  - ✗ Much less light hits sensor
- Add a lens
  - ✓ More light hits sensor
  - ✗ Limited depth of field
  - ✗ Chromatic aberration
- Add a shutter
  - Capture average intensity at a particular range of times
- Increase sensor resolution
  - ✓ Each pixel represents a smaller range of orientations
  - ✗ Less light per pixel
- Controls: aperture size, focal length, shutter time

How else can we design cameras?

What do they sacrifice/gain?

1. Light Field Photography with “Plenoptic Camera”



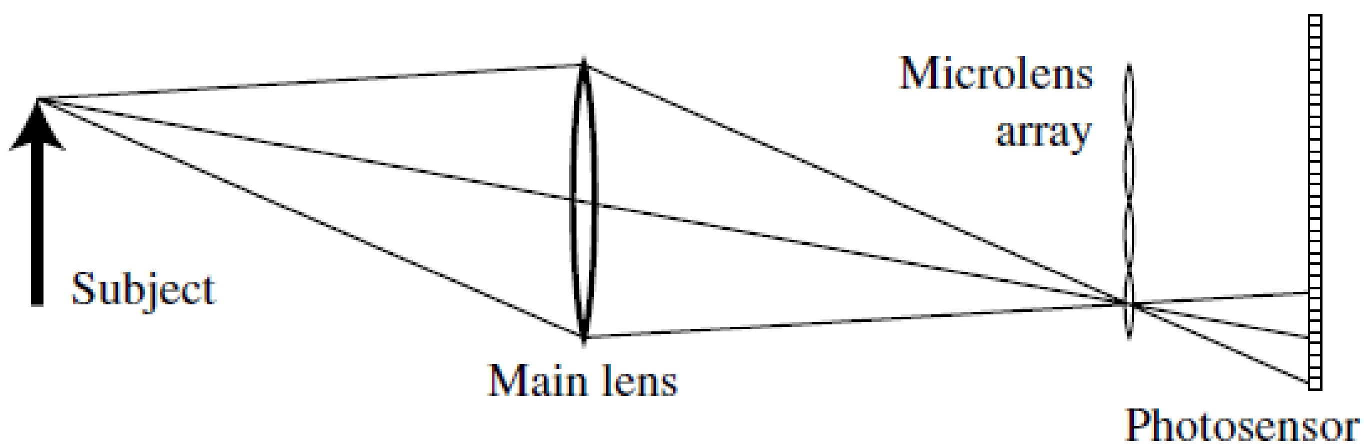


Adelson and Wang 1992

Ng et al. Stanford TR, 2005

Light field photography

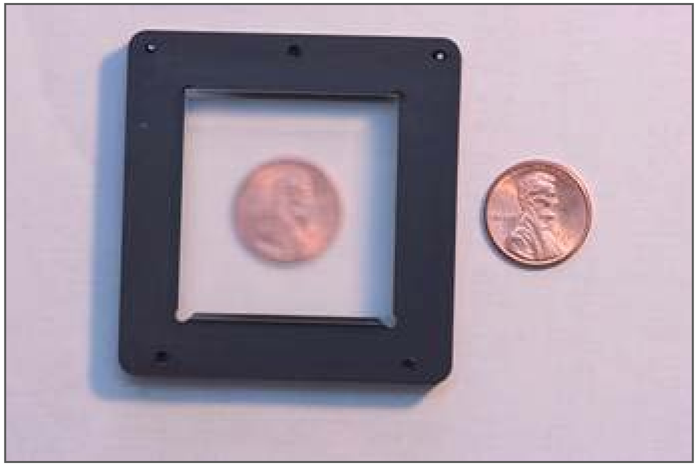
- Like replacing the human retina with an insect compound eye
- Records where light ray hits the lens



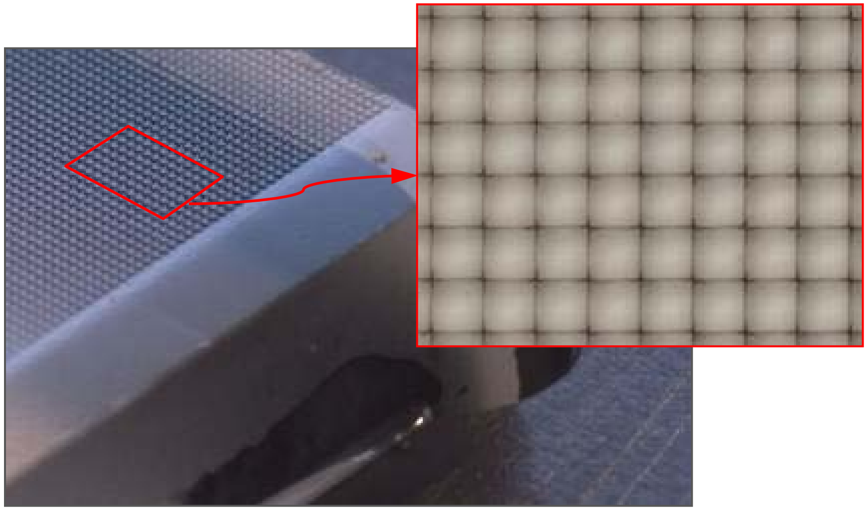
Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor



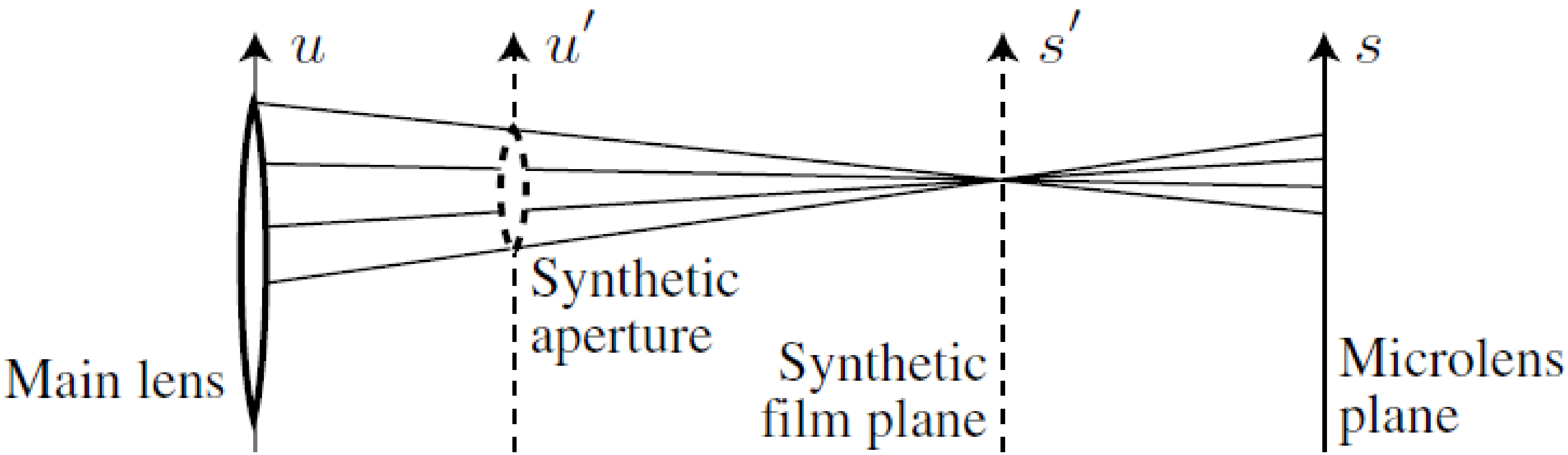
Adaptive Optics microlens array



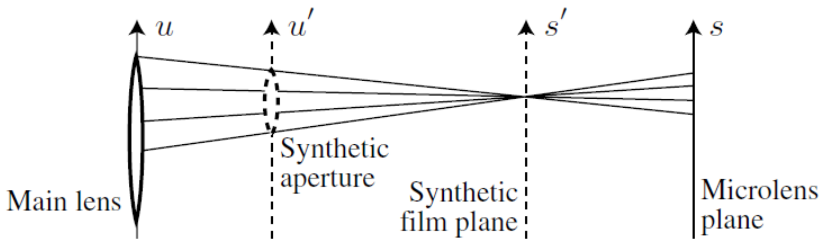
125μ square-sided microlenses

4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens

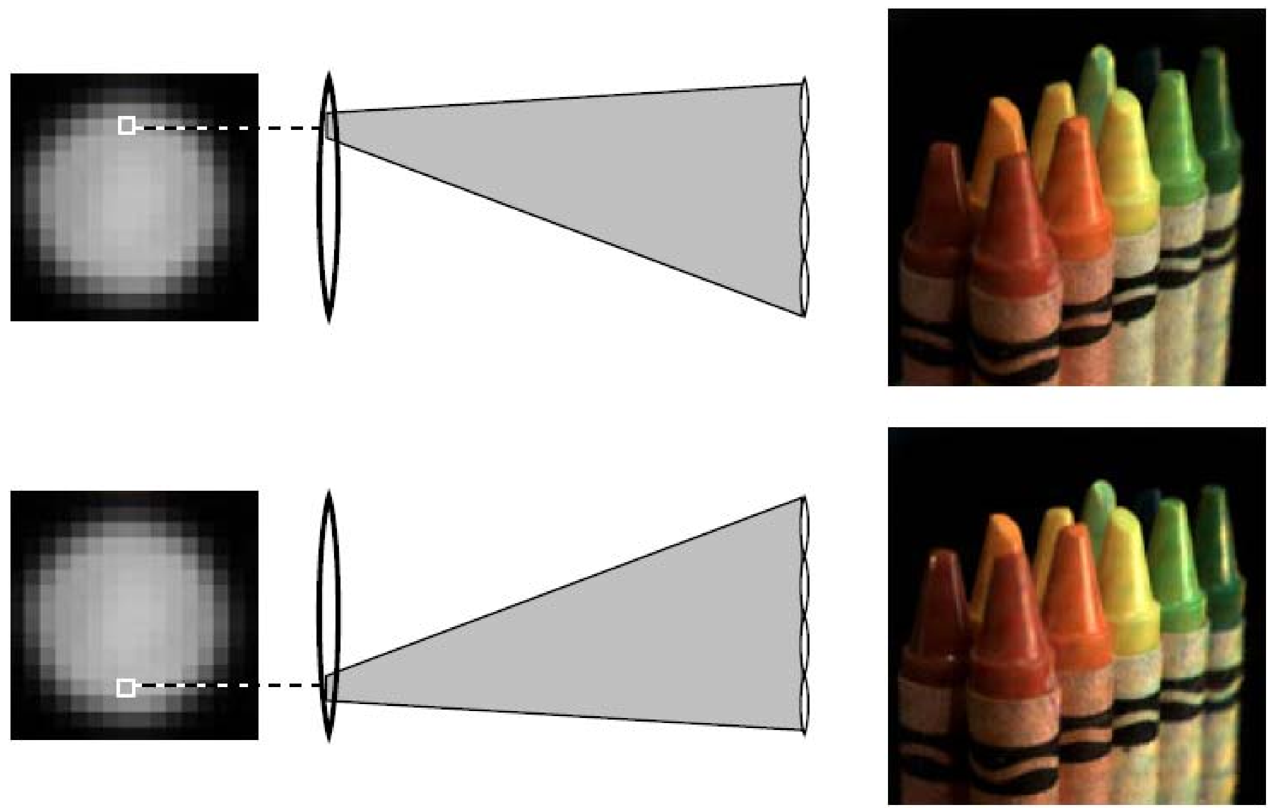
Light field photography: applications



Light field photography: applications



Change in viewpoint



Digital Refocusing

Light field photography w/ microlenses

- We gain
  - Ability to refocus or increase depth of field
  - Ability for small viewpoint shifts

- What do we lose (vs. conventional camera)?

2. Coded apertures

Image and Depth from a Conventional Camera with a Coded Aperture

Anat Levin, Rob Fergus,
Frédo Durand, William Freeman

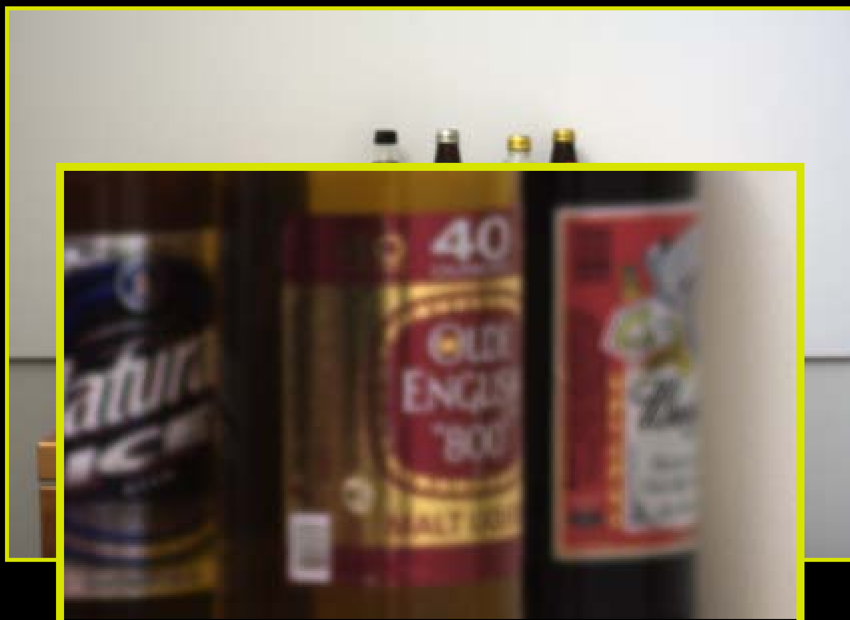
MIT CSAIL

Sliides from SIGGRAPH Presentation

Single input image:

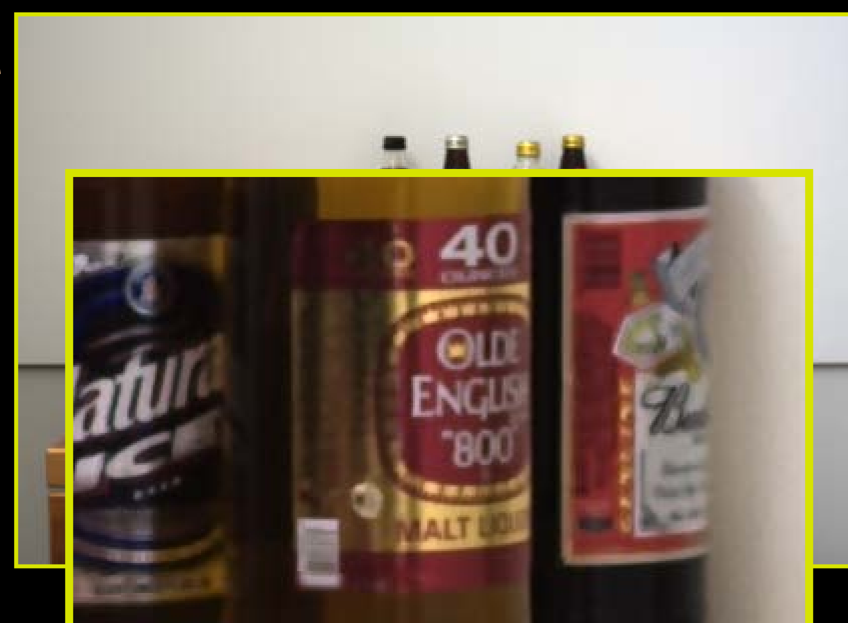
Output #1: Depth map

Single input image:



Output #1: Depth map

Output #2: All-focused image



Lens and defocus

Lens’ aperture

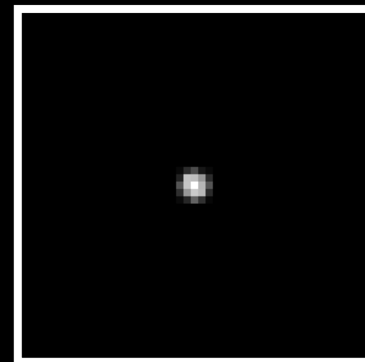
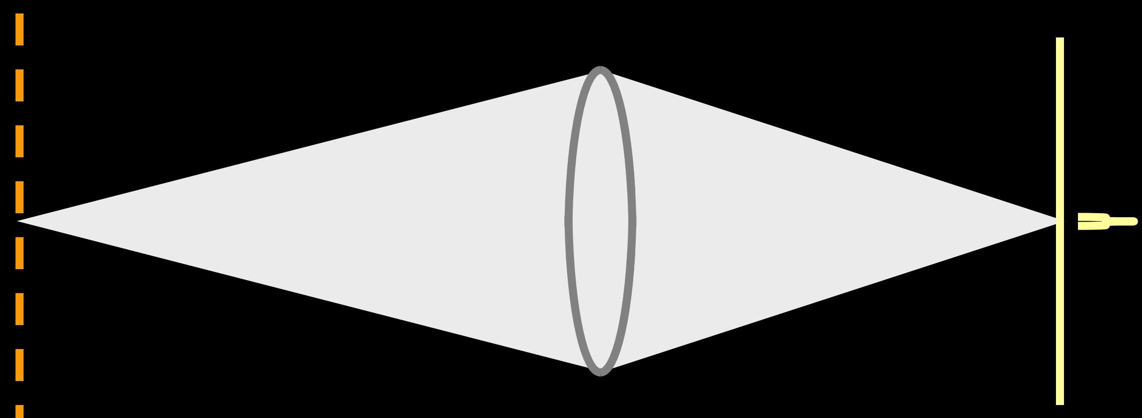


Image of a point light source



Lens and defocus

Lens’ aperture

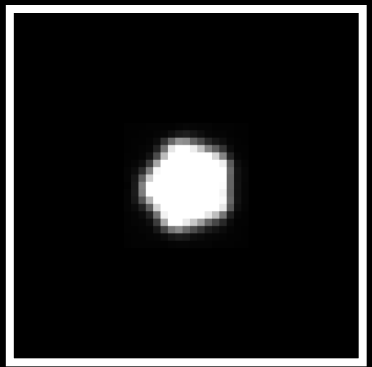
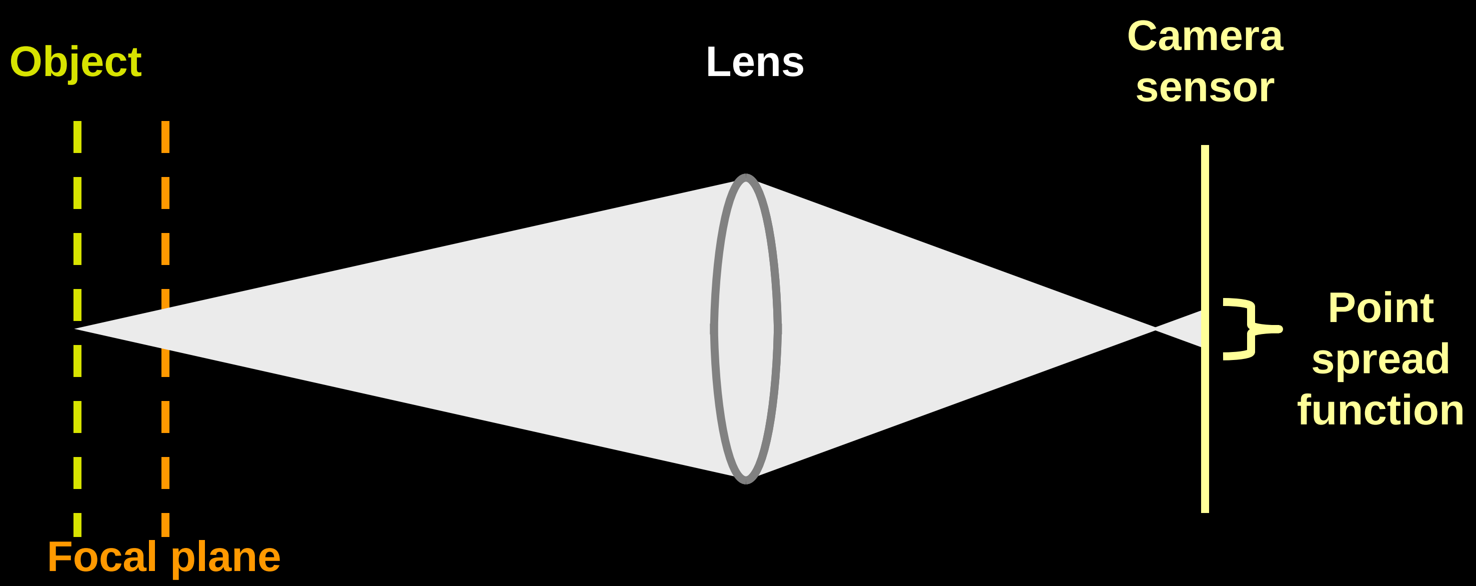


Image of a defocused point light source



Lens and defocus

Lens’ aperture

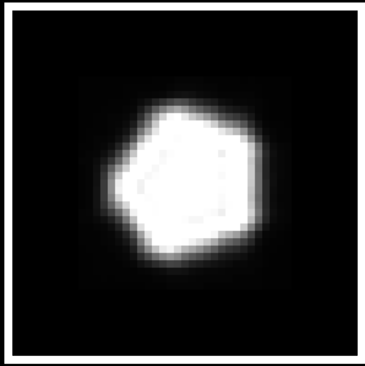
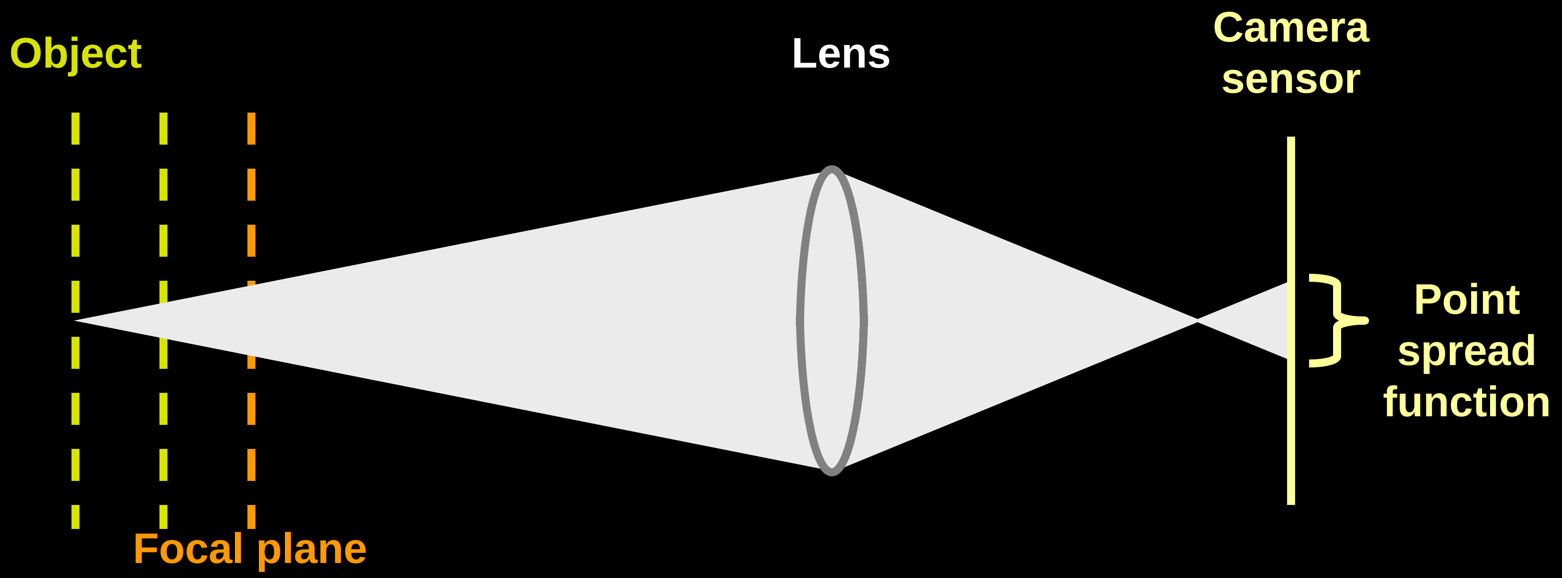


Image of a defocused point light source



Lens and defocus

Lens' aperture

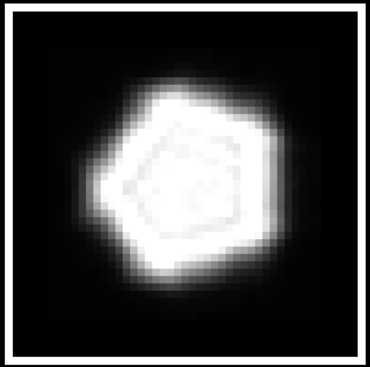
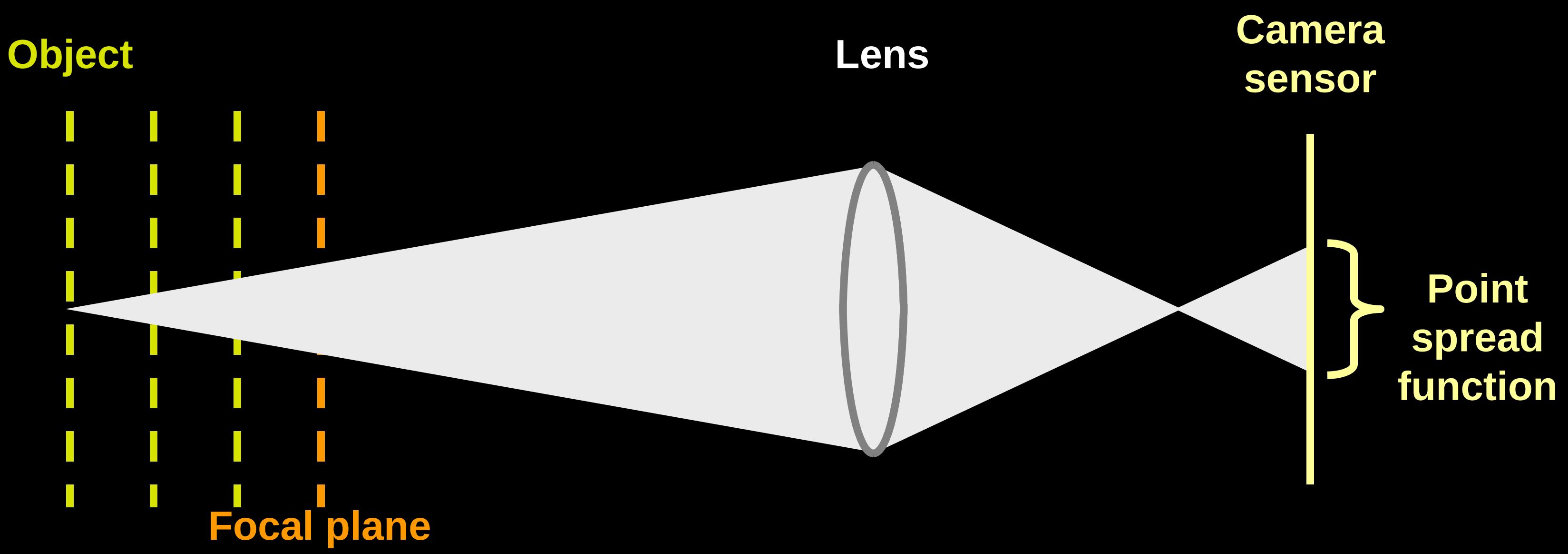


Image of a defocused point light source



Lens and defocus

Lens’ aperture

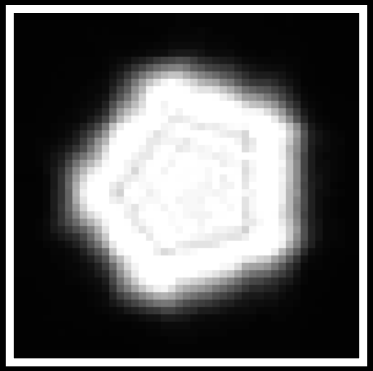
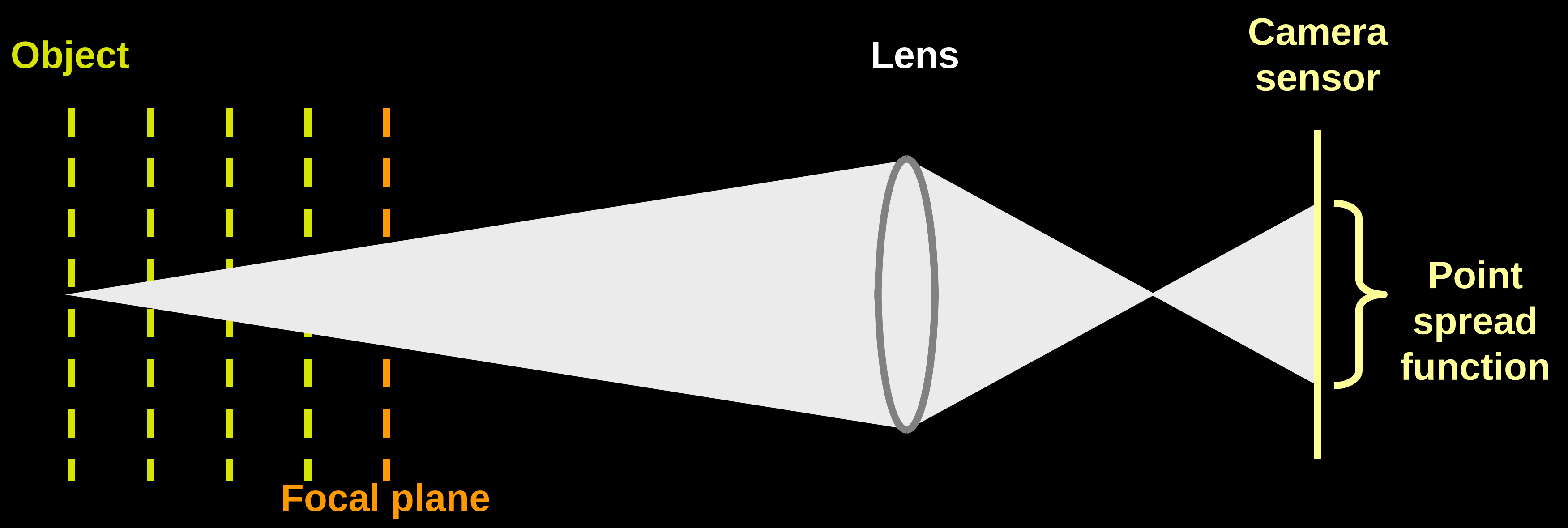


Image of a defocused point light source



Depth and defocus

Out of focus

In focus

ill posed

Depth from defocus:

Infer depth by analyzing local scale of defocus blur

Challenges

- Hard to discriminate a smooth scene from defocus blur

?

Out of focus

- Hard to undo defocus blur

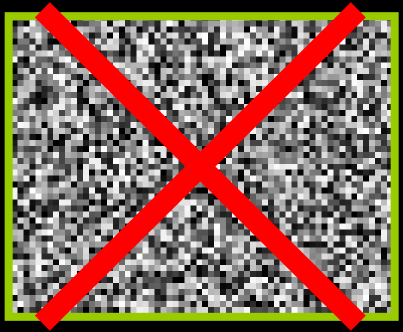
Input

Ringing with conventional deblurring algorithm

Key ideas

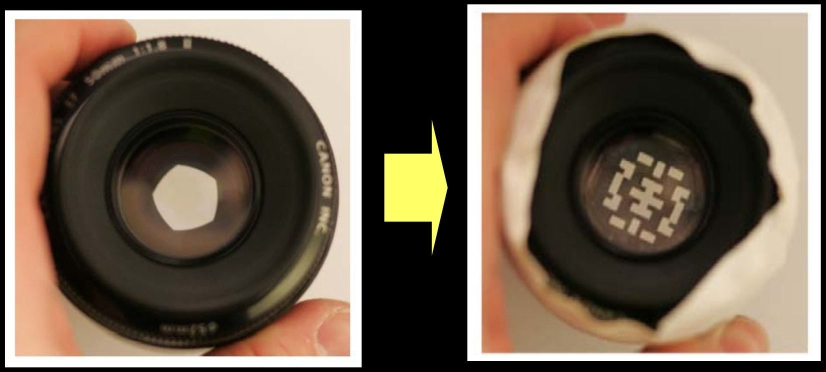
- **Exploit prior on natural images**
  - Improve deconvolution
  - Improve depth discrimination

Natural



Unnatural

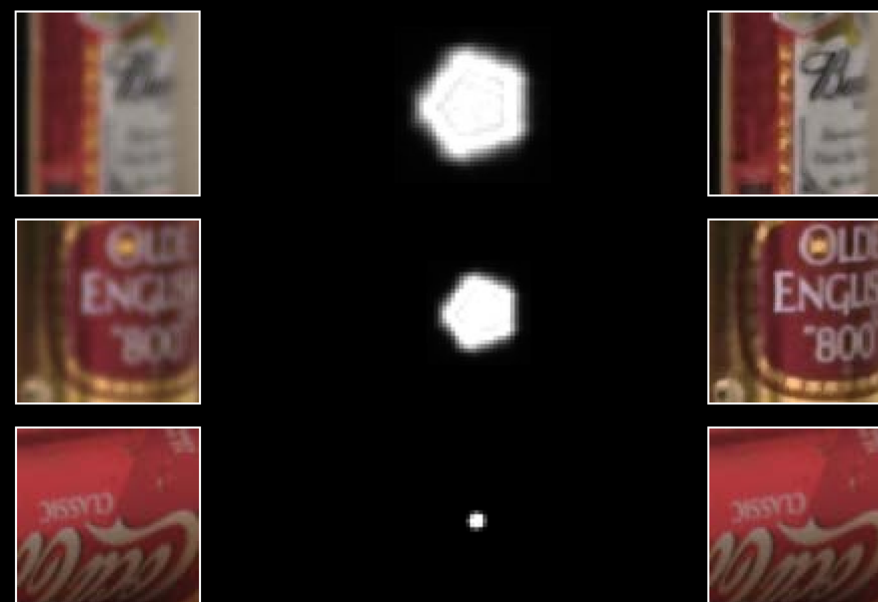
- **Coded aperture (mask inside lens)**
  - make defocus patterns different from natural images and easier to discriminate



Defocus as local convolution

Input defocused image

	Local sub-window	Calibrated blur kernels at depth	Sharp sub-window



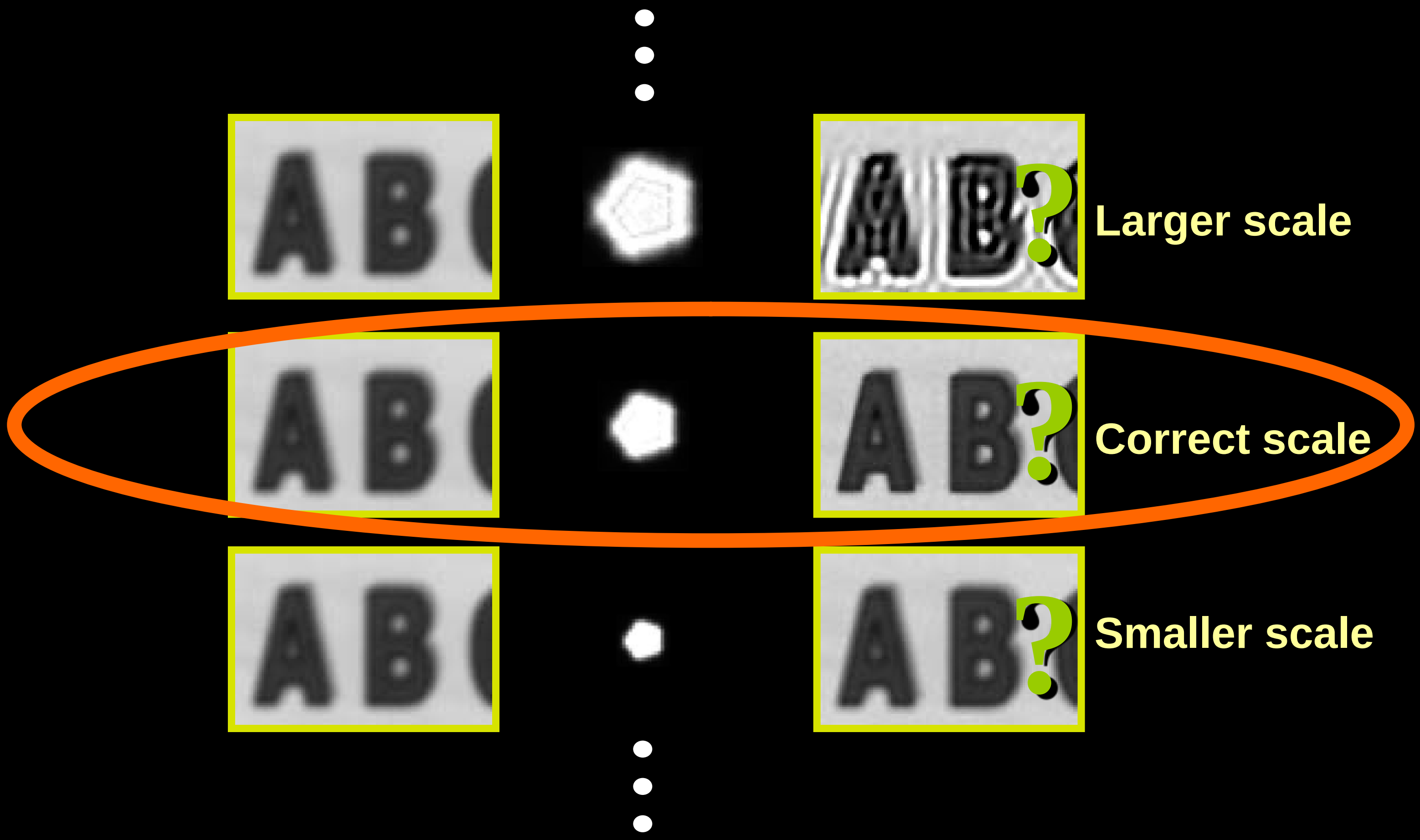
Depth k=1:

Depth k=2:

Depth k=3:

Overview

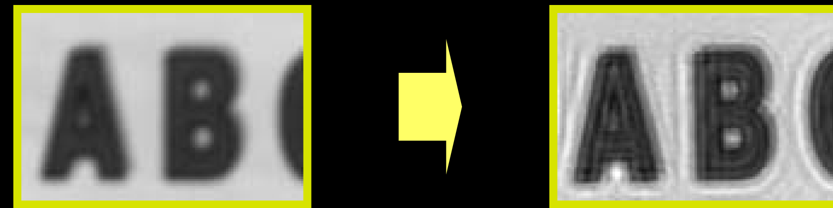
Try deconvolving local input windows with different scaled filters:



Somehow: select best scale.

Challenges

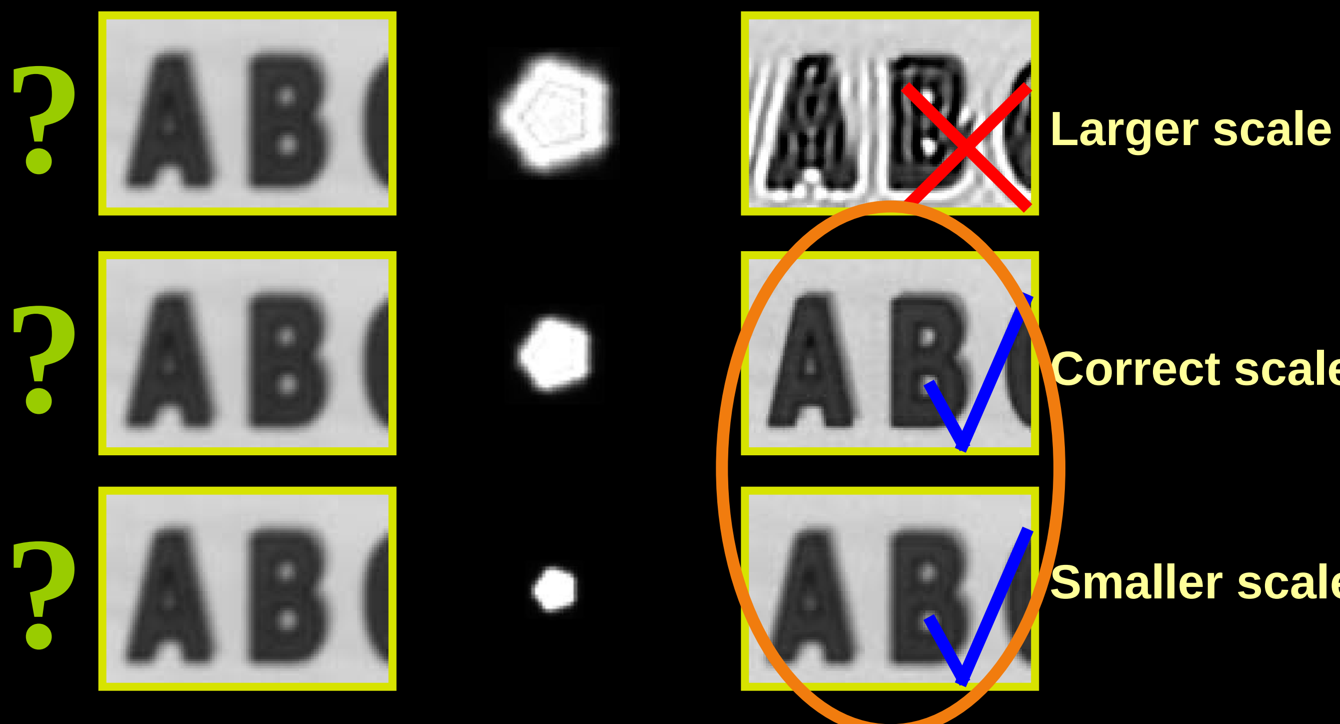
- Hard to deconvolve even when kernel is known



Input

Ringing with the traditional Richardson-Lucy deconvolution algorithm

- Hard to identify correct scale:



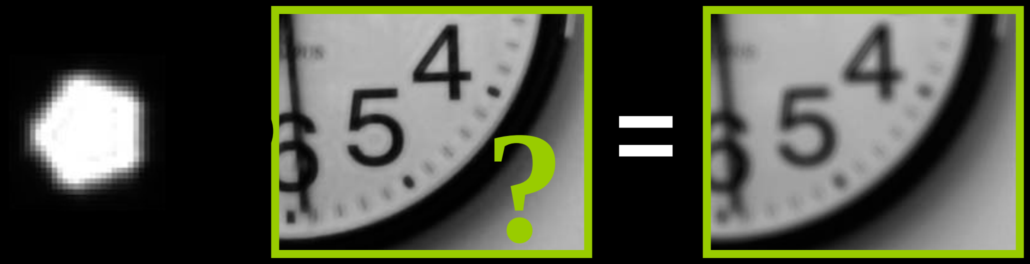
Deconvolution is ill posed

?

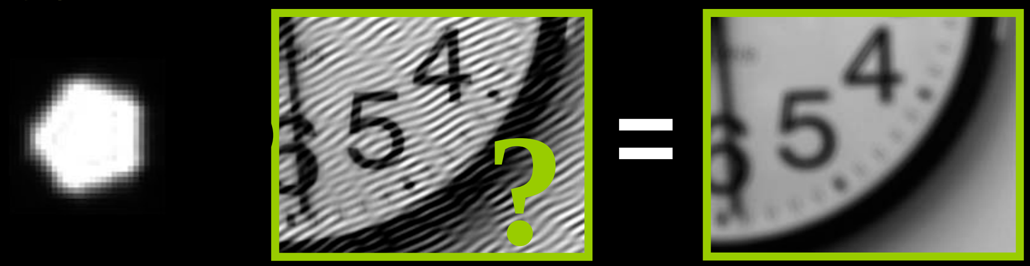
=

Deconvolution is ill posed

Solution 1:



Solution 2:



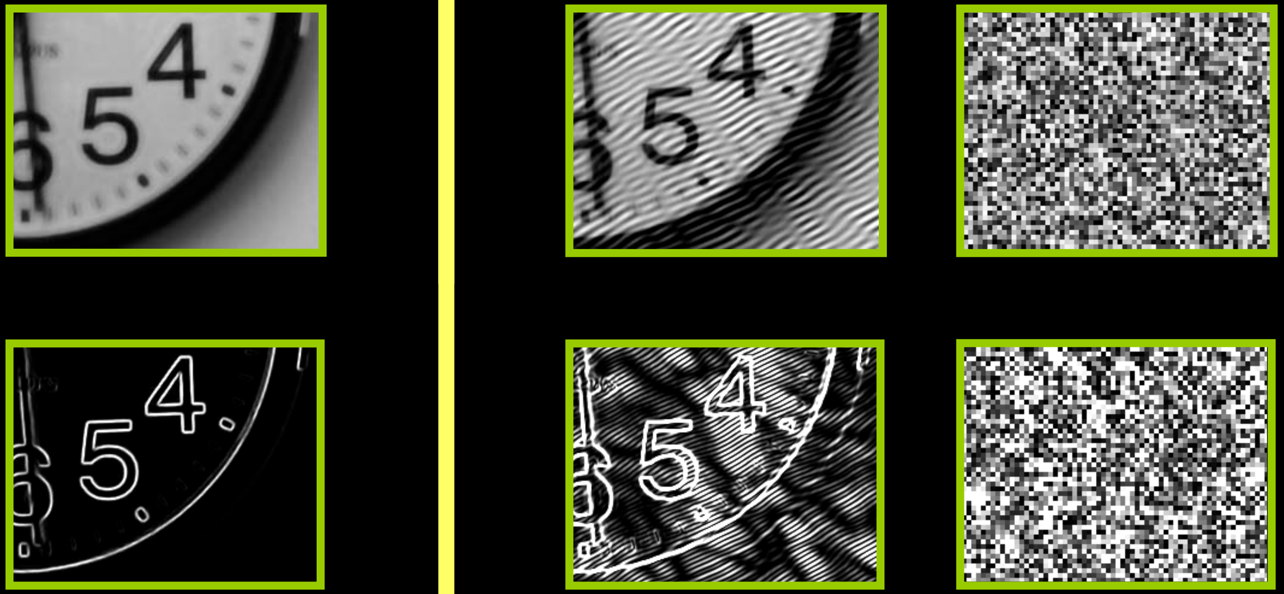
Idea 1: Natural images prior

What makes images special?

Natural | **Unnatural**

Image

gradient

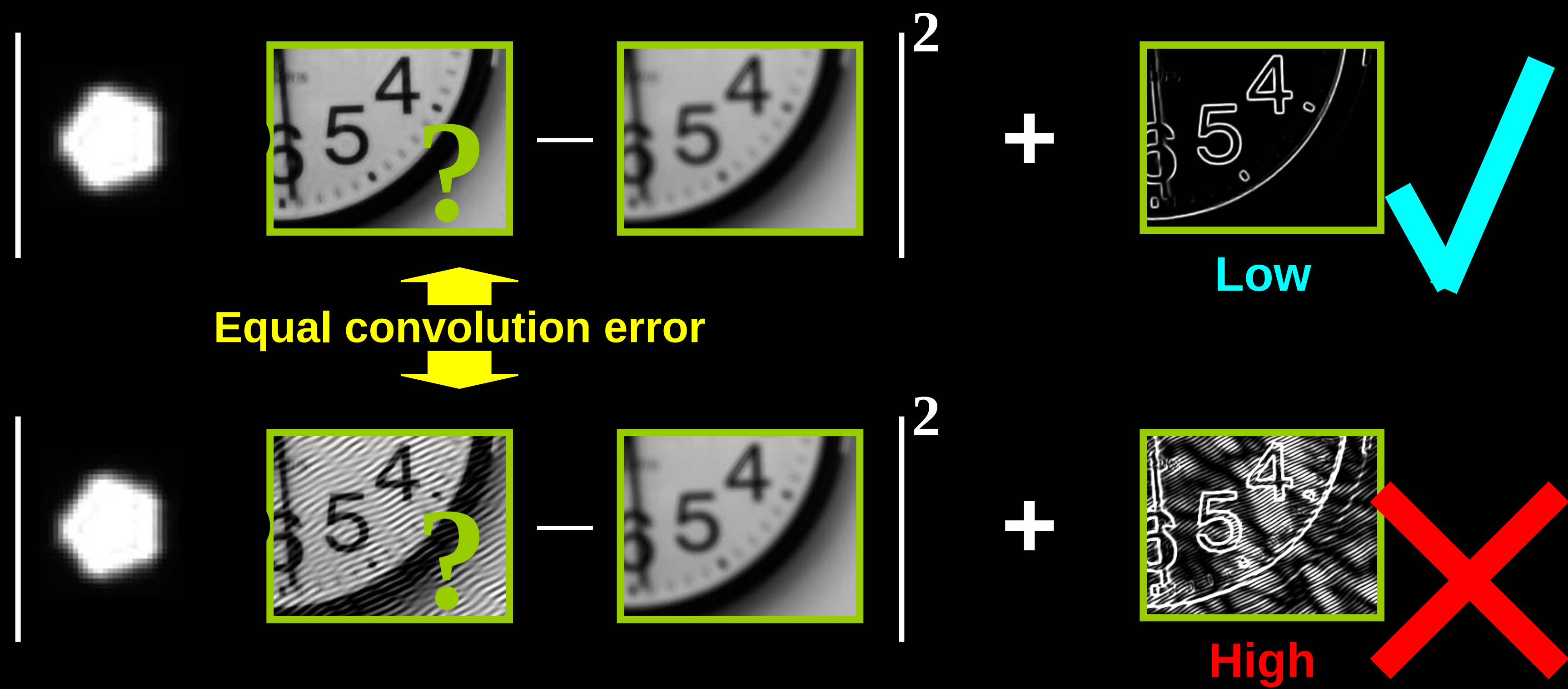


Natural images have sparse gradients

➡ **put a penalty on gradients**

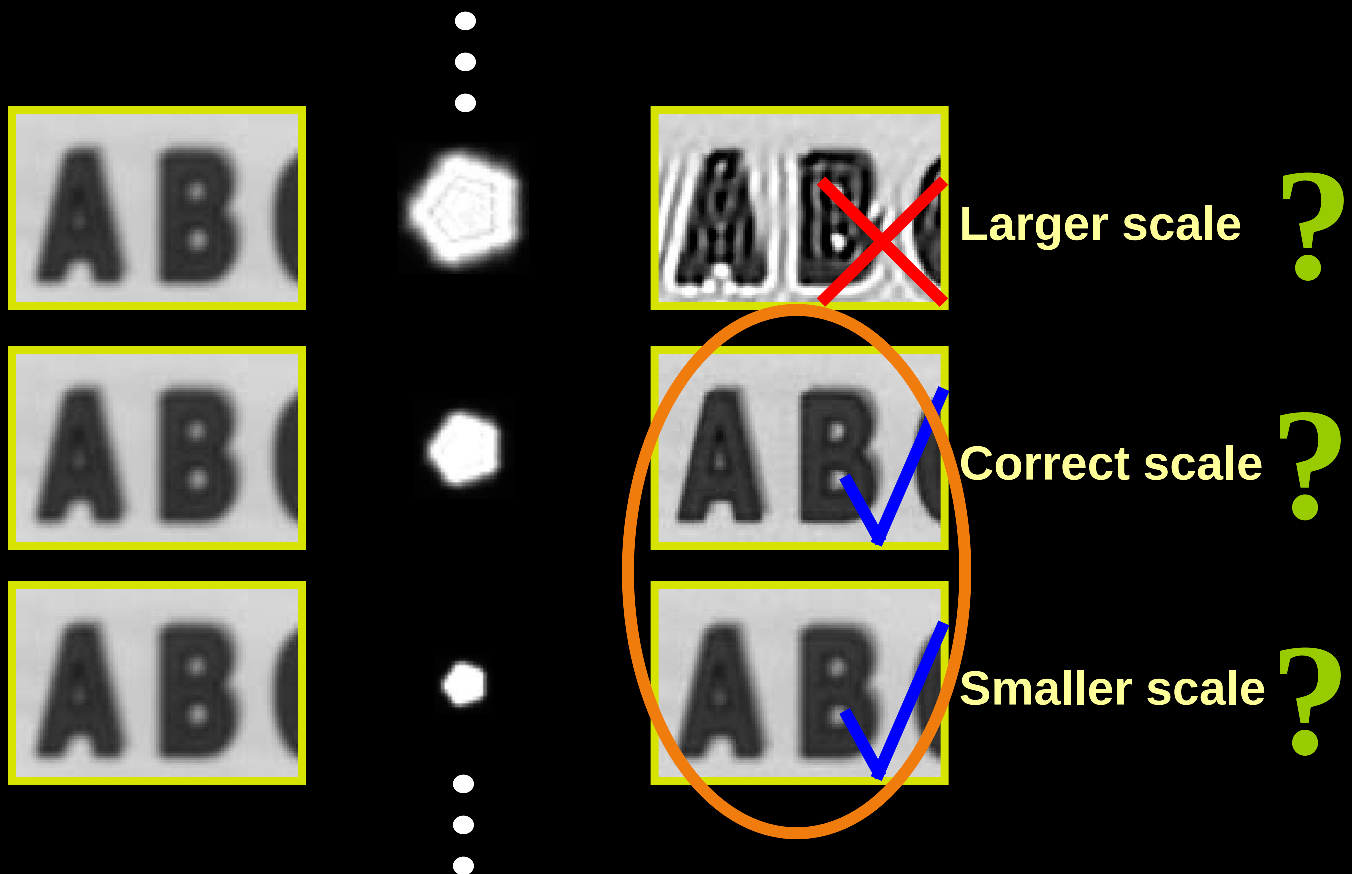
Deconvolution with prior

$$x = \arg\min \underbrace{|f \otimes x - y|^2}_{\text{Convolution error}} + \lambda \underbrace{\sum_i \rho(\nabla x_i)}_{\text{Derivatives prior}}$$



Recall: Overview

Try deconvolving local input windows with different scaled filters:



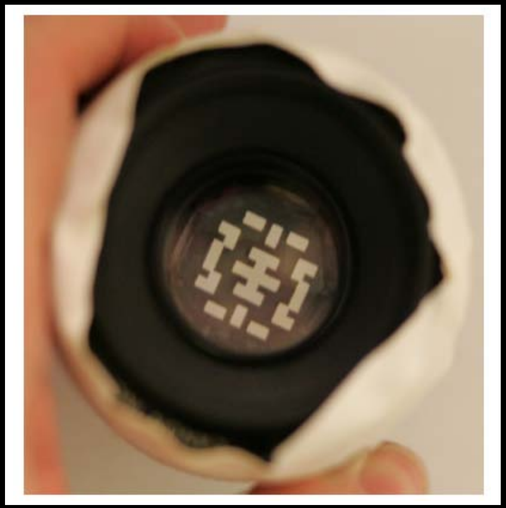
Somehow: select best scale.

Challenge: smaller scale not so different than correct

Idea 2: Coded Aperture

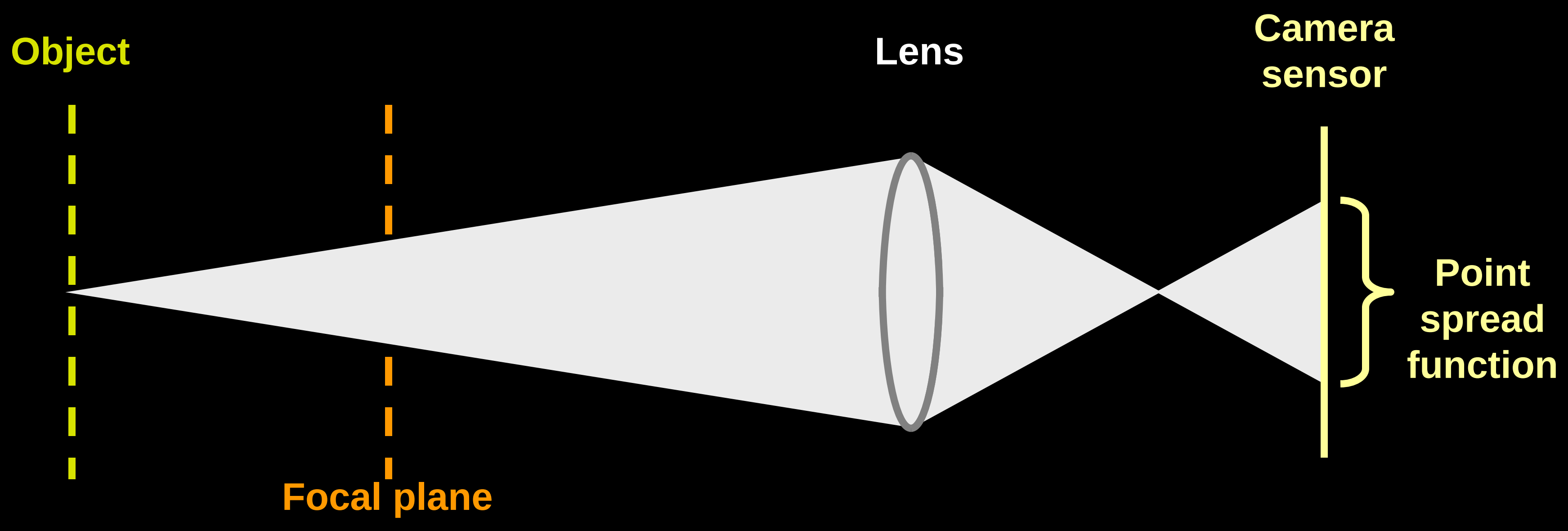
- Mask (code) in aperture plane
  - make defocus patterns different from natural images and easier to discriminate

Conventional aperture



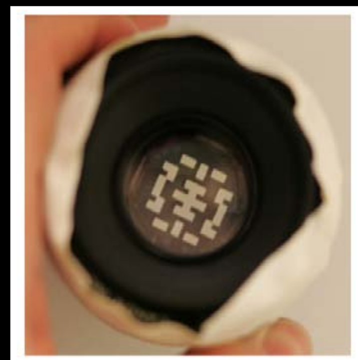
Our coded aperture

Solution: lens with occluder



Solution: lens with occluder

Aperture pattern



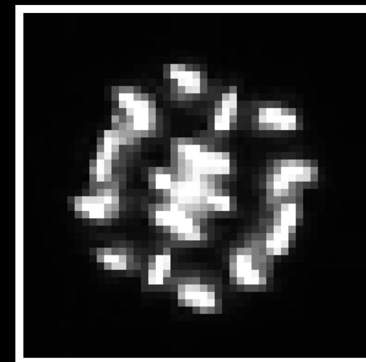
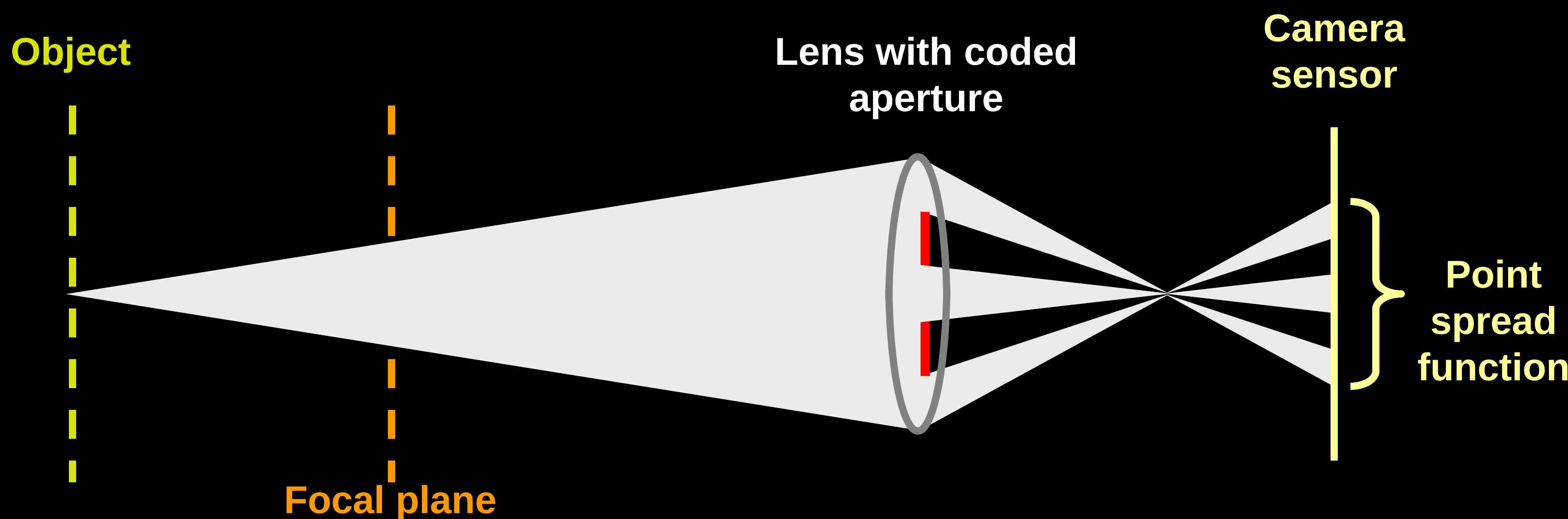
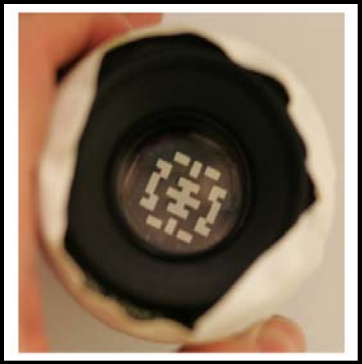


Image of a defocused point light source



Solution: lens with occluder

Aperture pattern



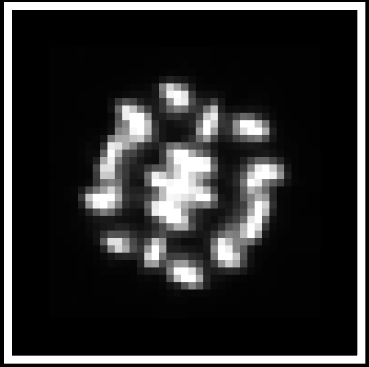
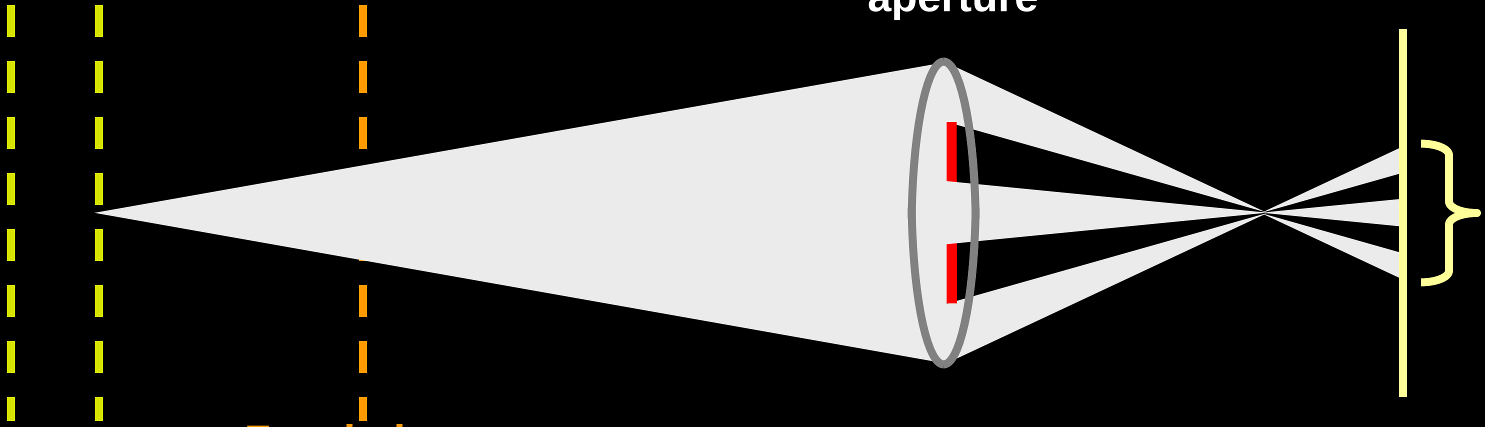
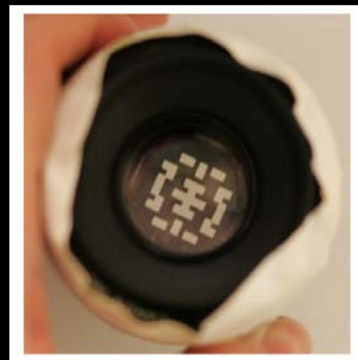


Image of a defocused point light source



Solution: lens with occluder

Aperture pattern



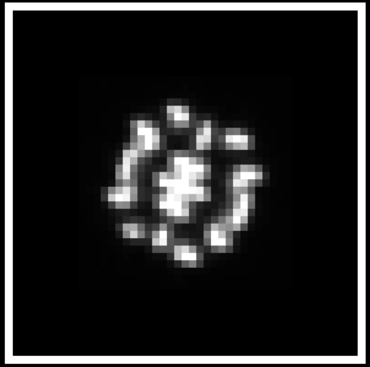
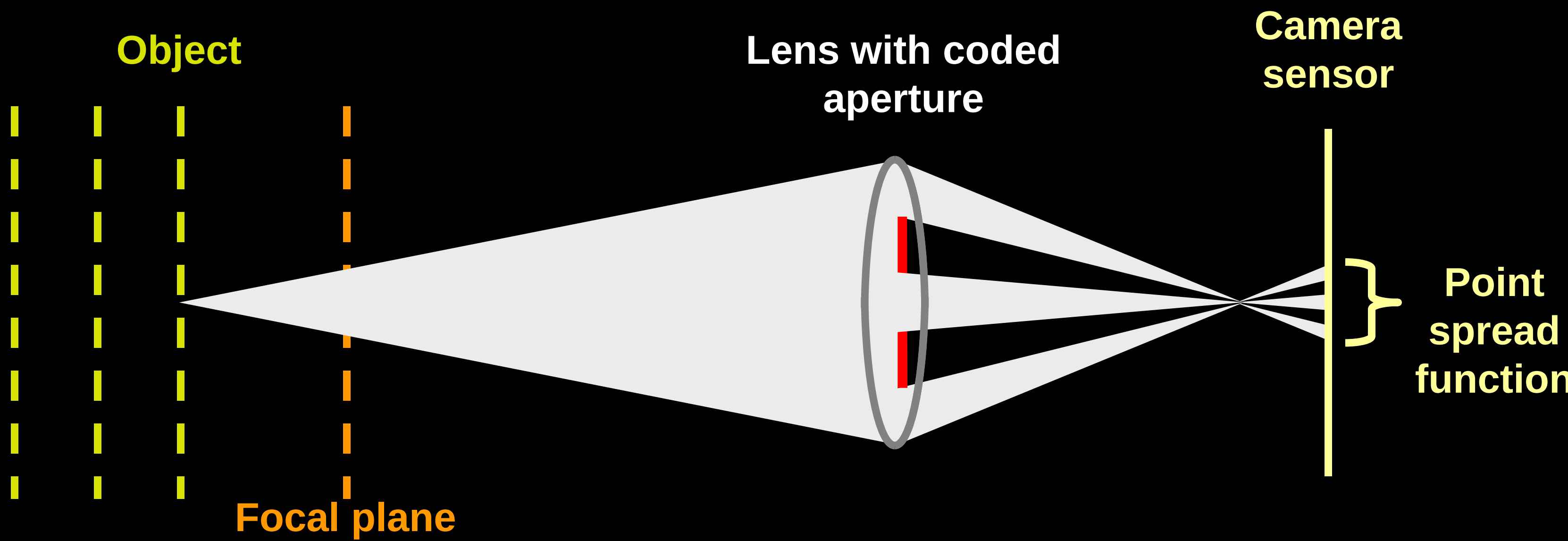
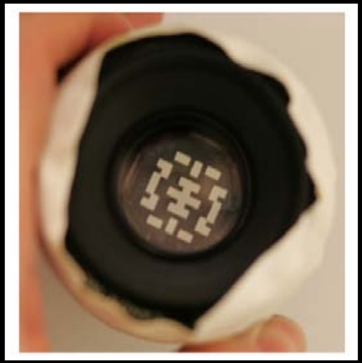


Image of a defocused point light source



Solution: lens with occluder

Aperture pattern



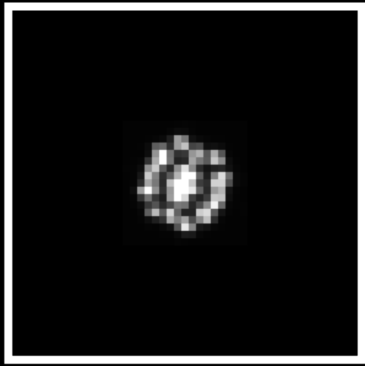
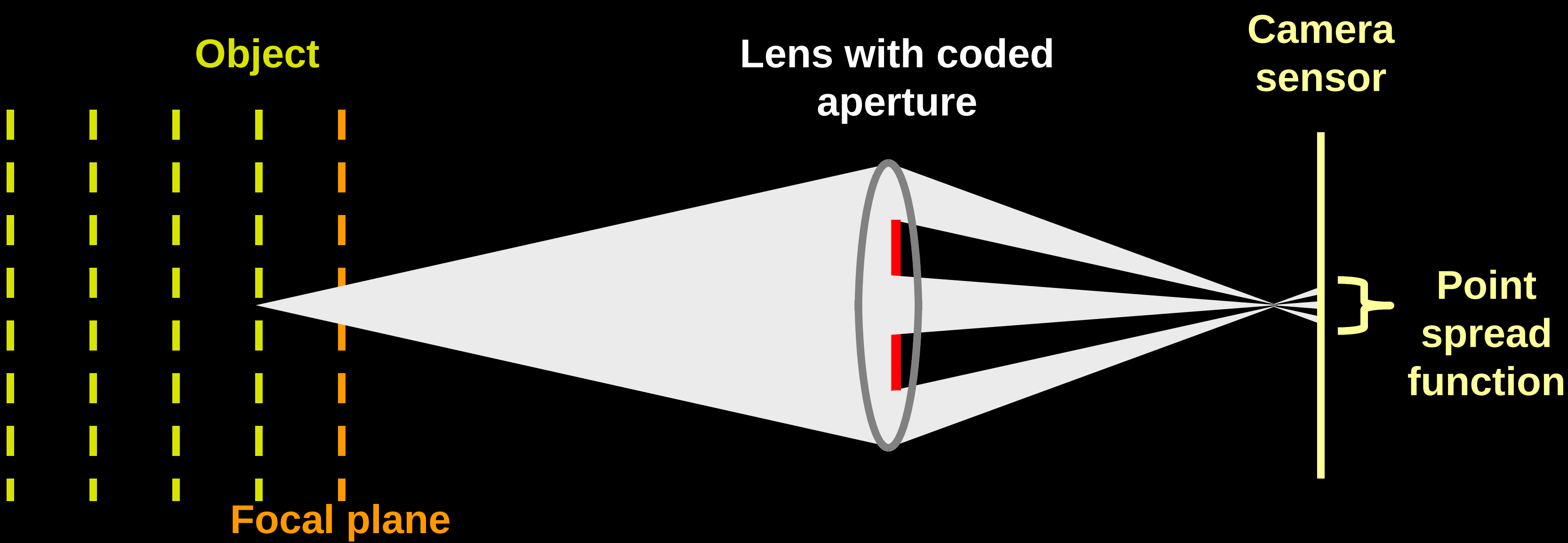
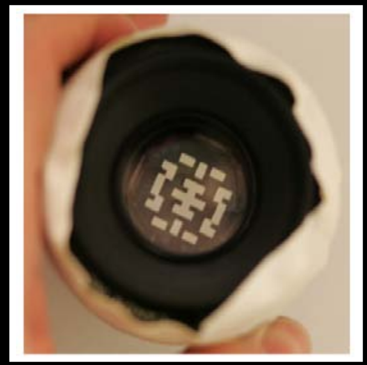


Image of a defocused point light source



Solution: lens with occluder

Aperture pattern



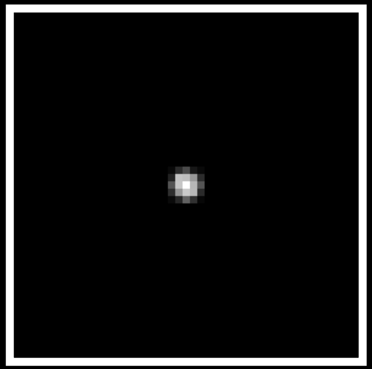
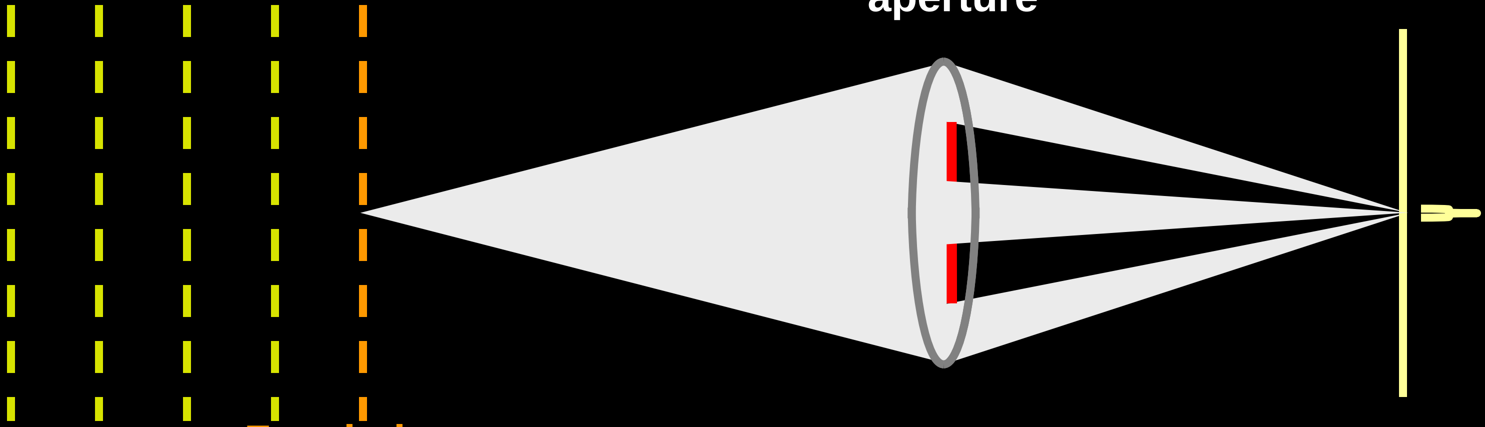
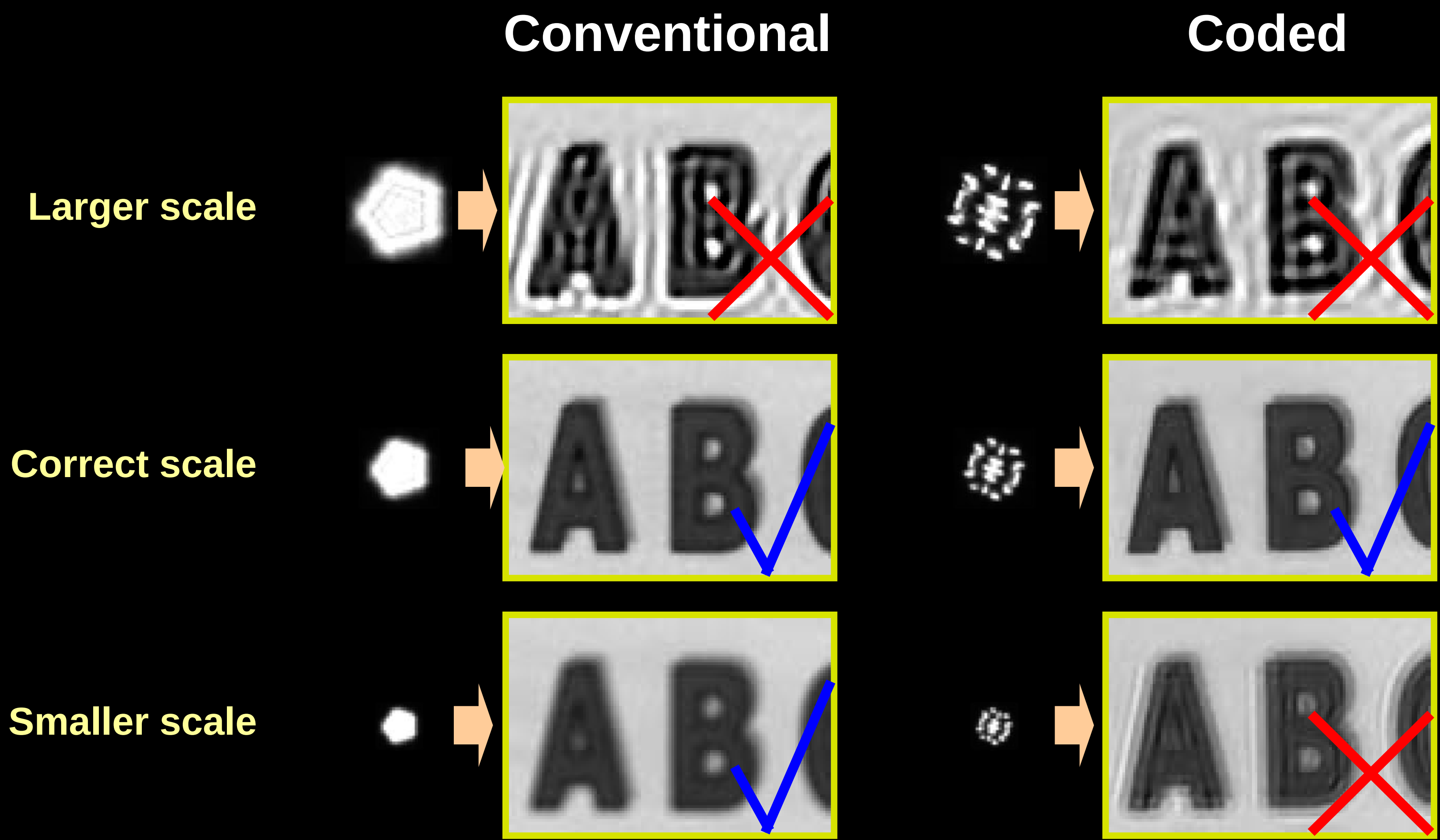


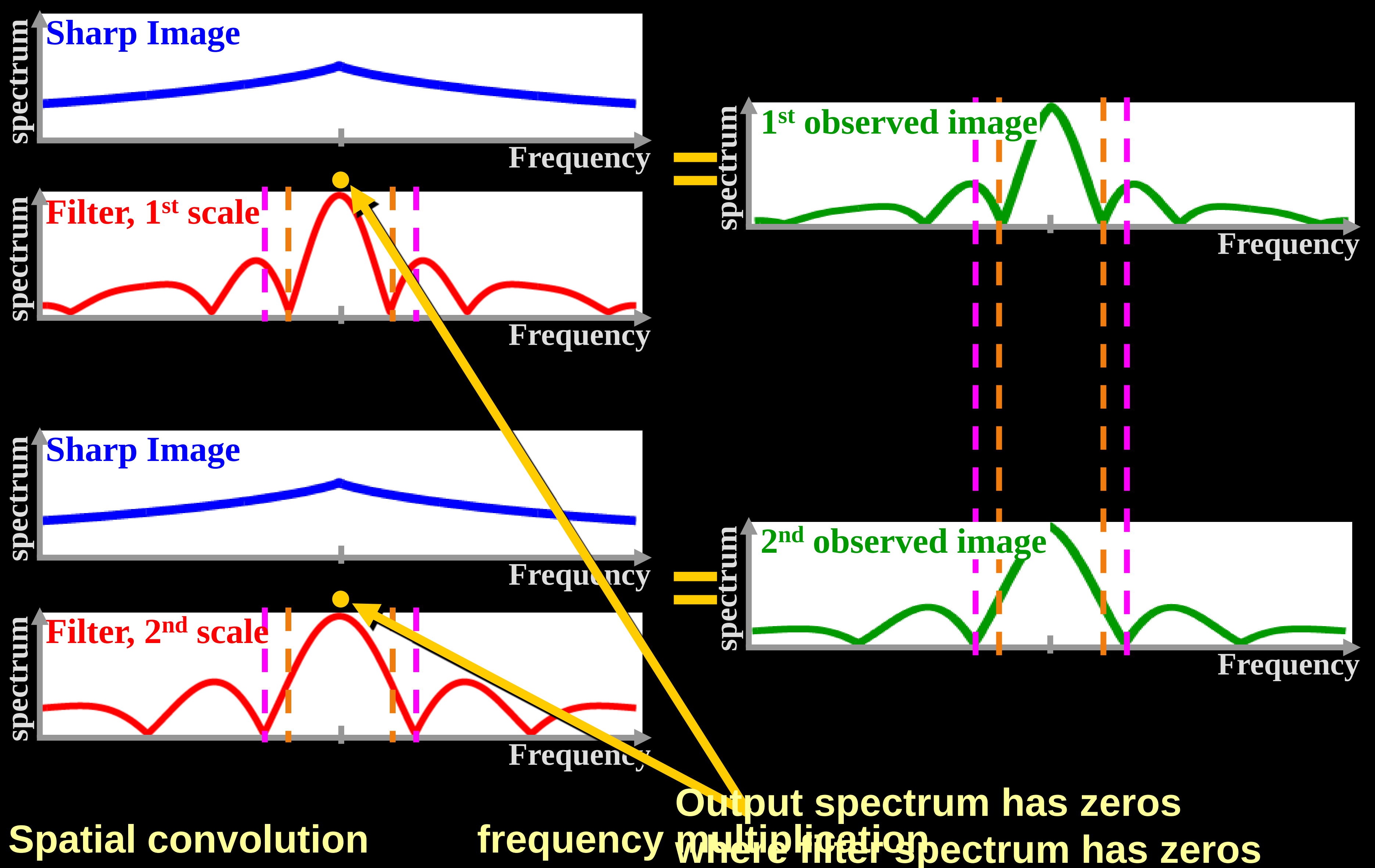
Image of a defocused point light source



Coded aperture reduces uncertainty in scale identification



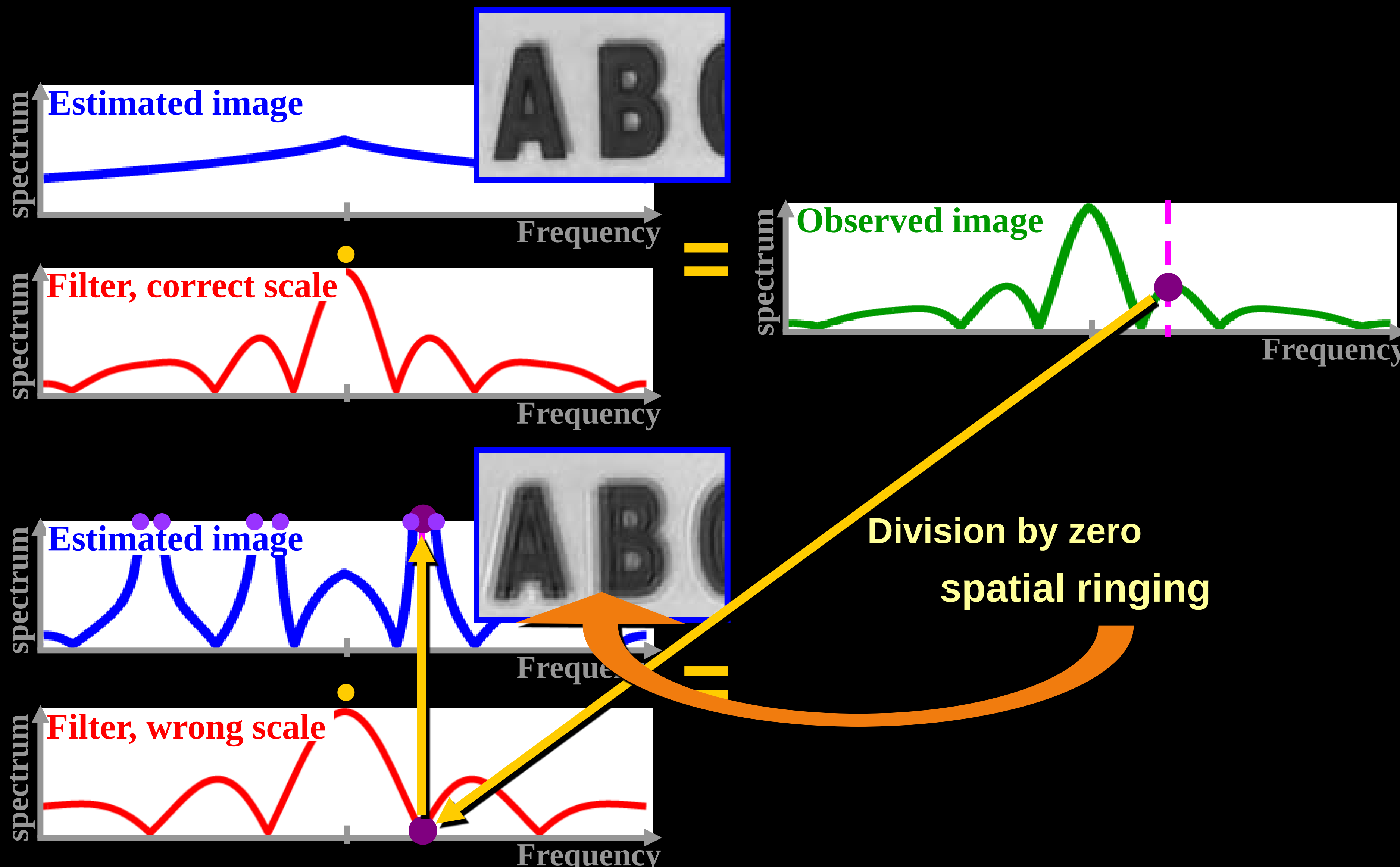
Convolution- frequency domain representation



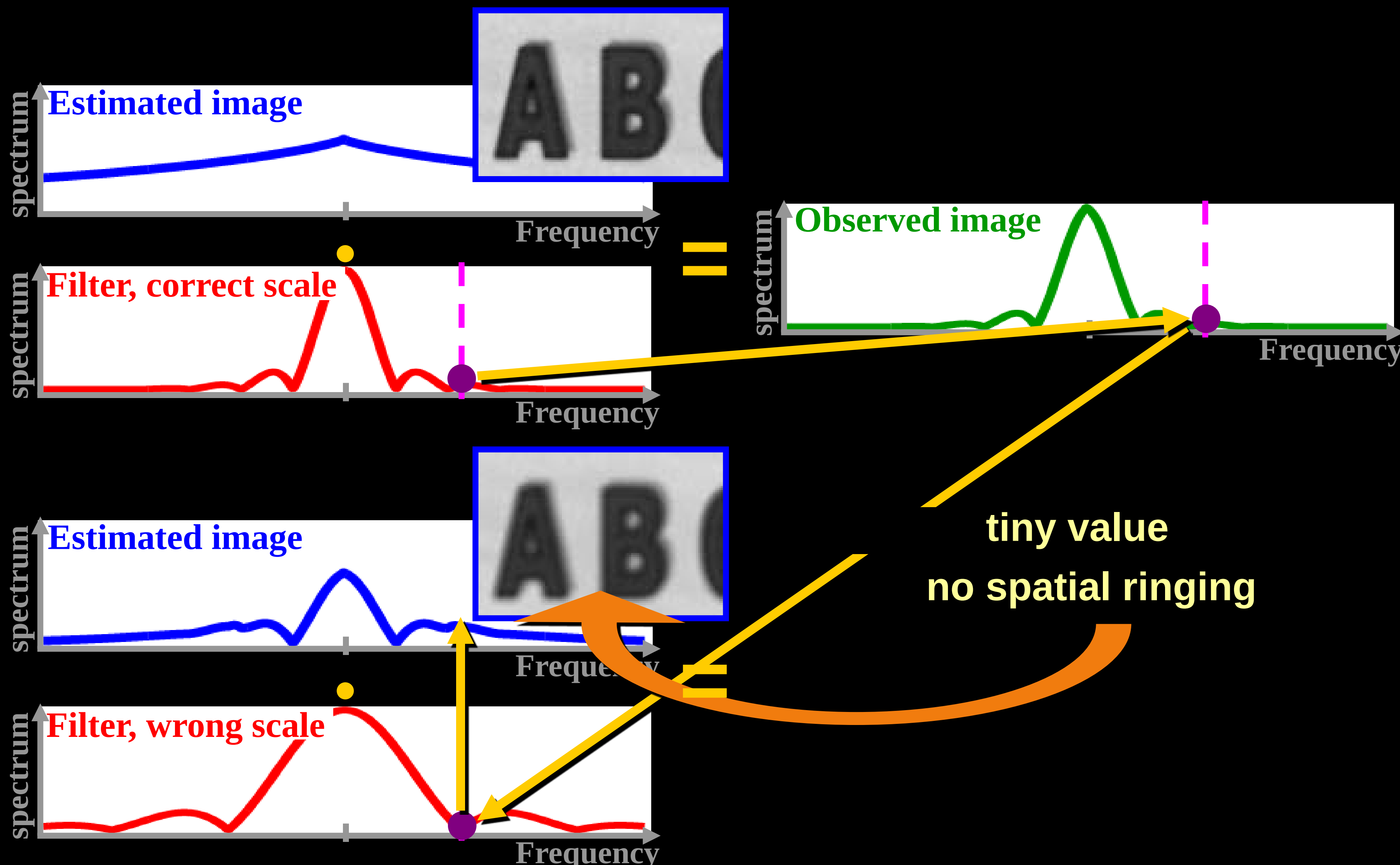
Spatial convolution

frequency multiplication

Coded aperture: Scale estimation and division by zero



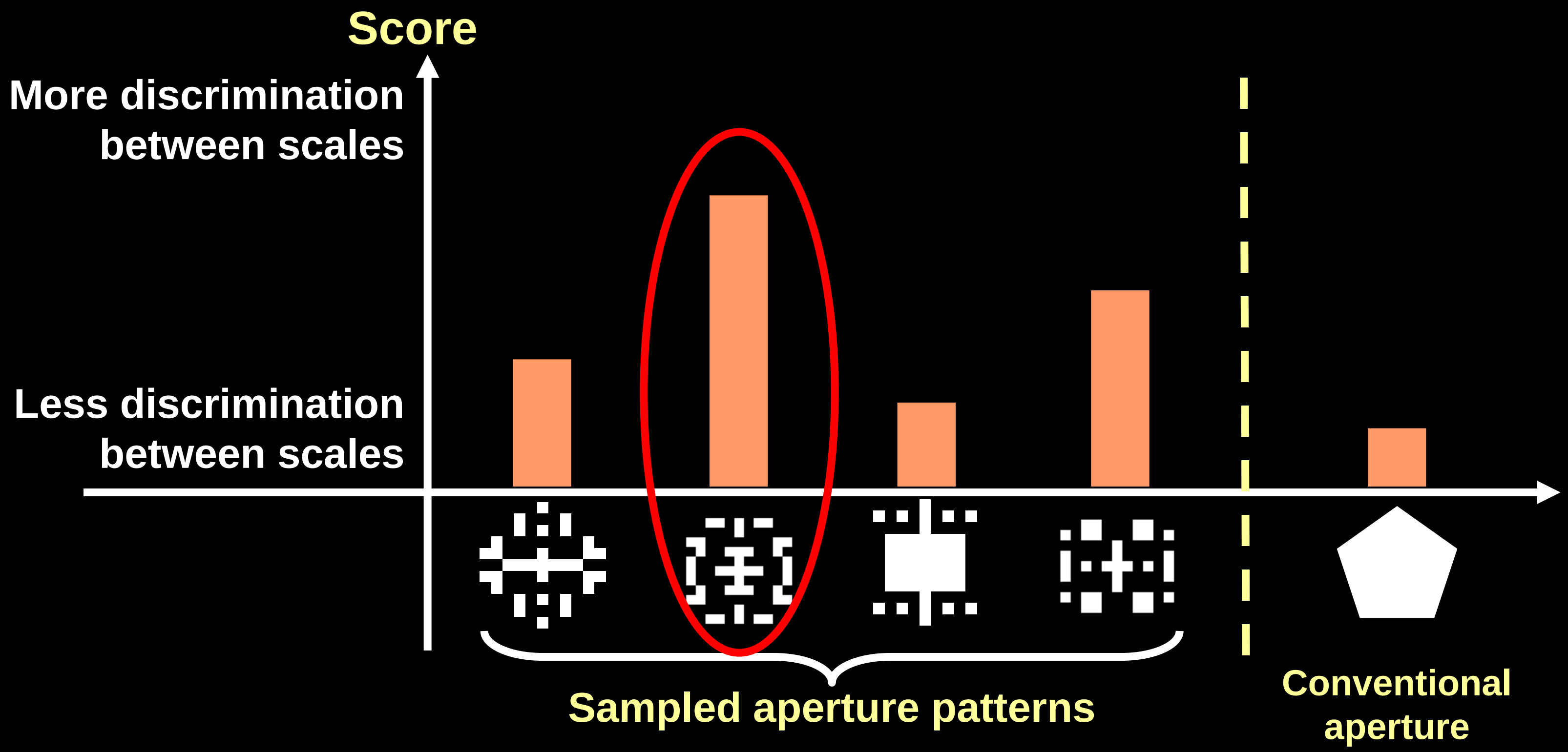
Division by zero with a conventional aperture?



Filter Design

Analytically search for a pattern maximizing discrimination between images at different defocus scales (*KL-divergence*)

Account for image prior and physical constraints

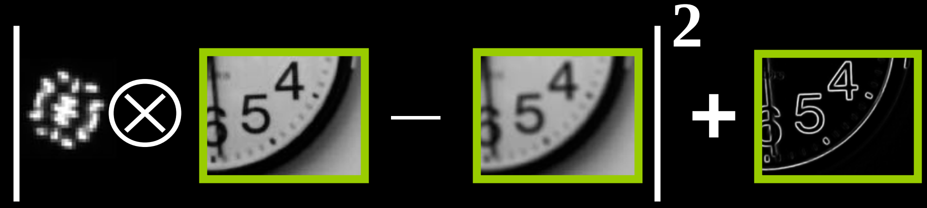


Depth results

Regularizing depth estimation

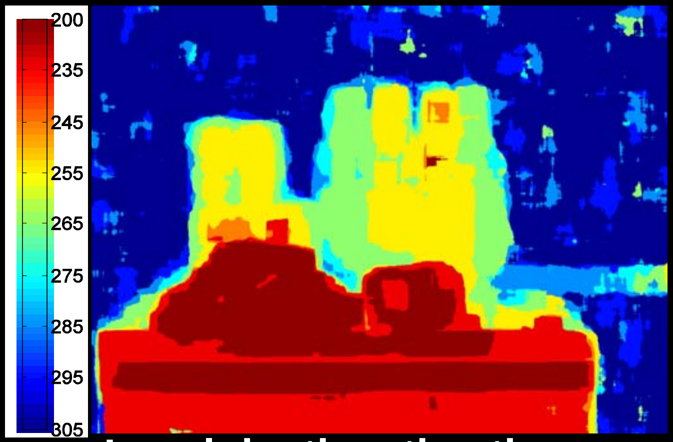
Try deblurring with 10 different aperture scales

$$x = \arg\min \underbrace{|f \otimes x - y|^2}_{\text{Convolution error}} + \underbrace{\lambda \sum_i \rho(\nabla x_i)}_{\text{Derivatives prior}}$$



Keep minimal error scale in each local window + regularization

Input

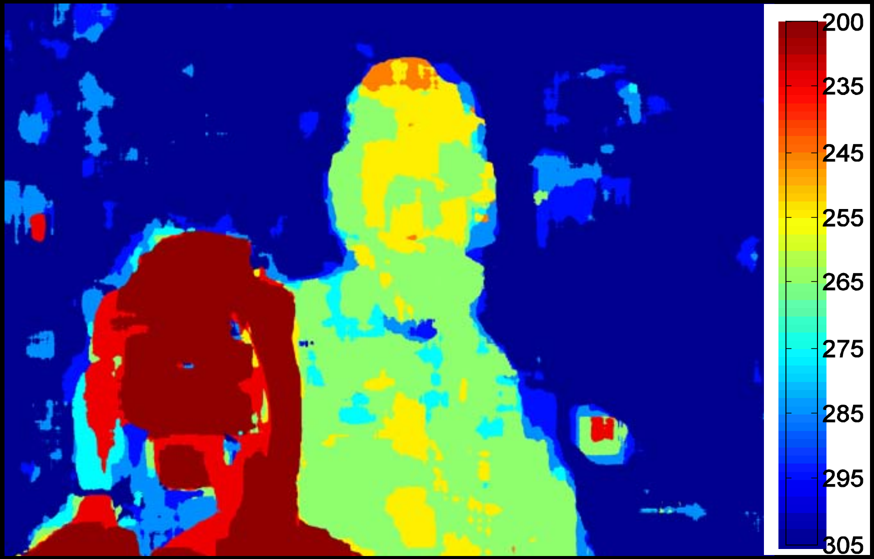


Local depth estimation

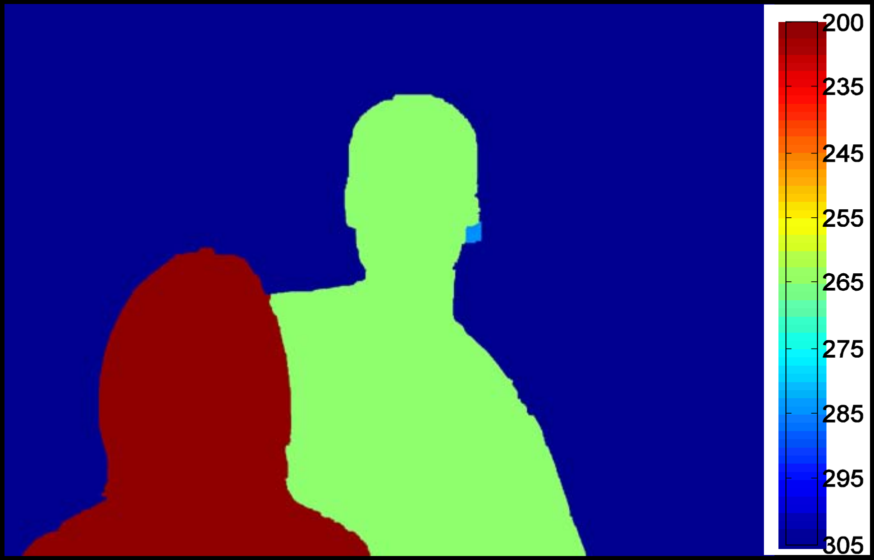
Regularized depth

Regularizing depth estimation

Input



Local depth estimation



Regularized depth

All focused results

Input

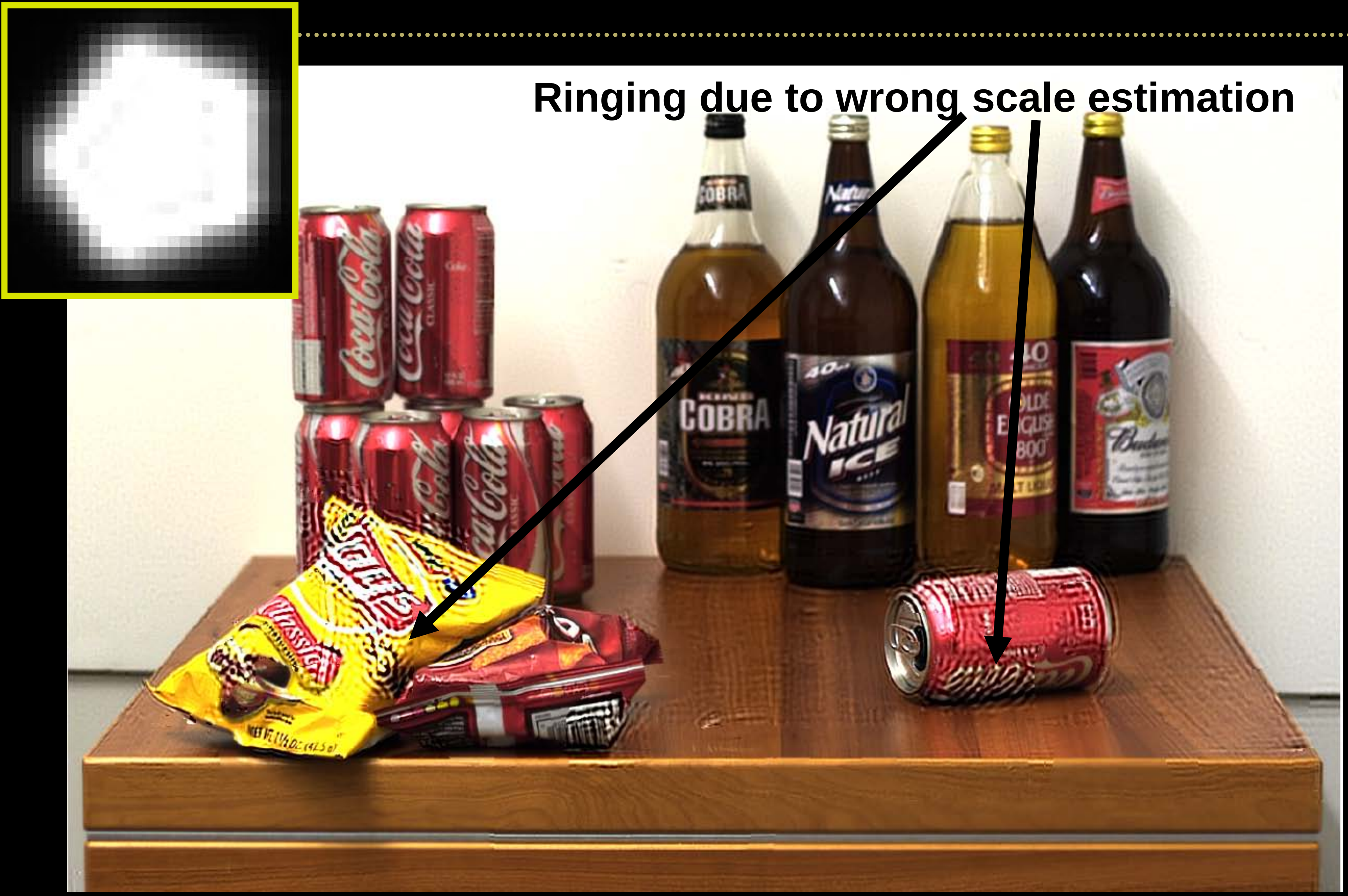
All-focused (deconvolved)

Close-up

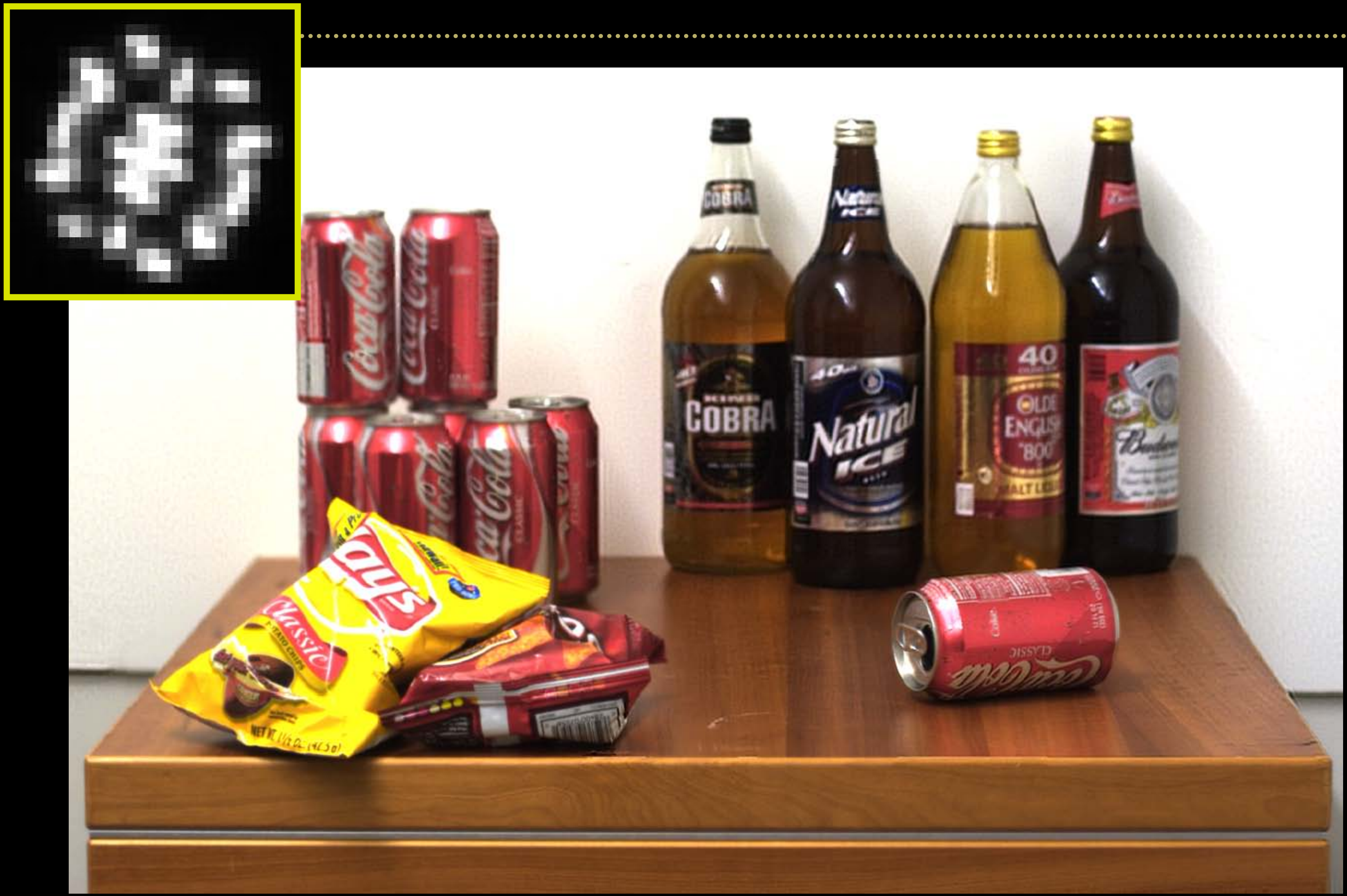
Original image

All-focus image

Comparison- conventional aperture result



Comparison- coded aperture result




Input


All-focused
(deconvolved)

Close-up

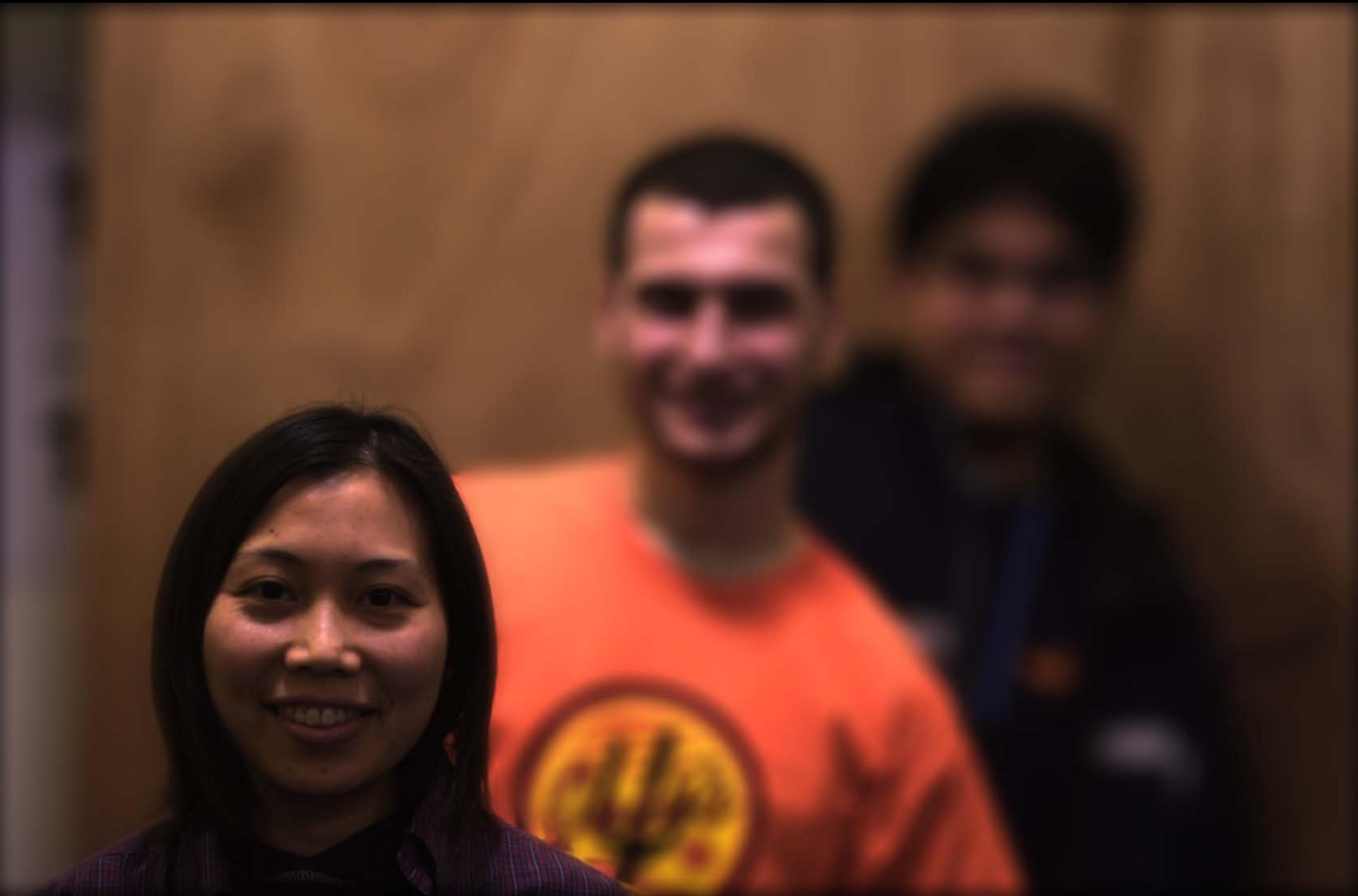
Original image

All-focus image

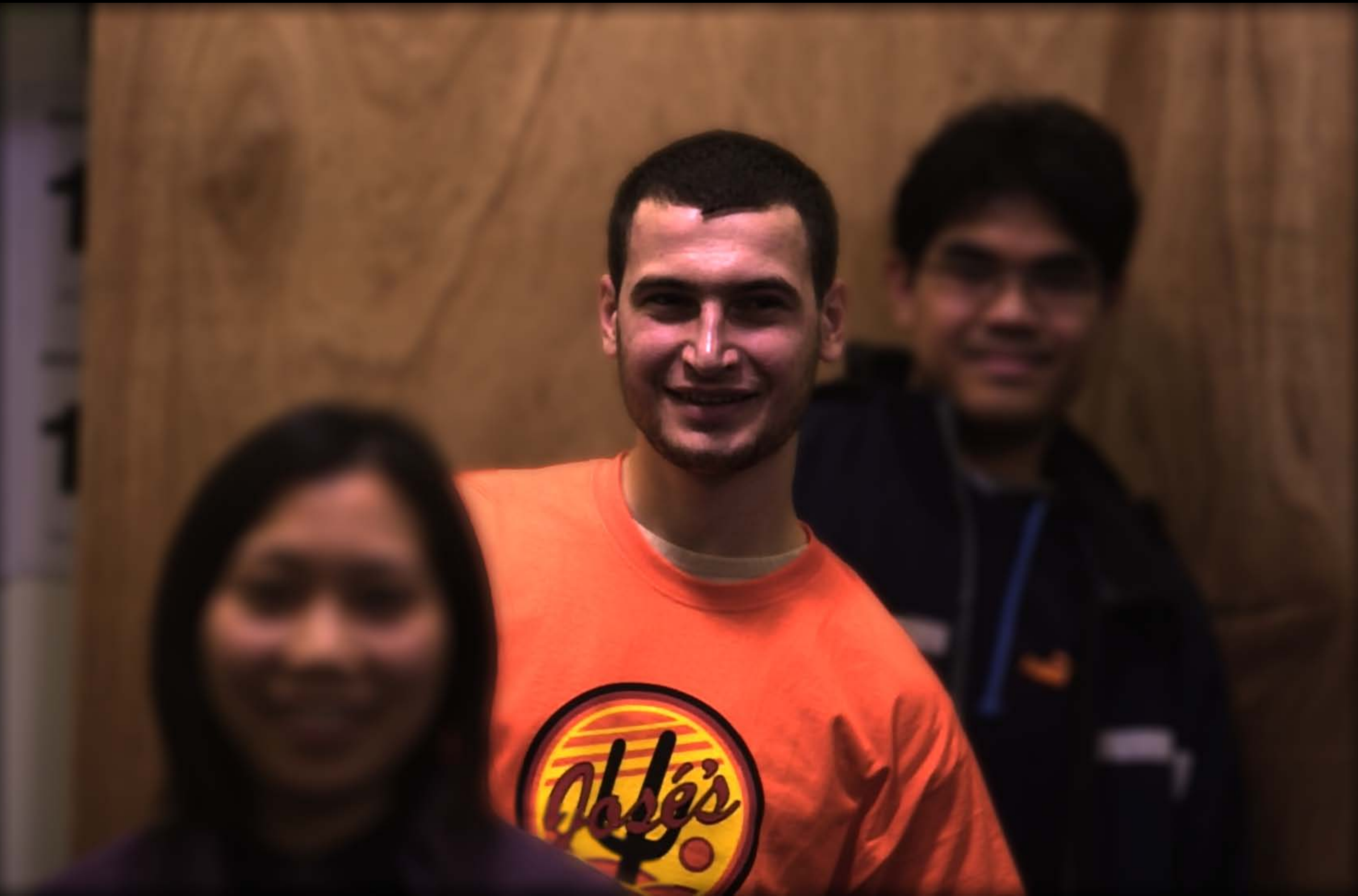
Naïve sharpening

Application: Digital refocusing from a single image

Application: Digital refocusing from a single image



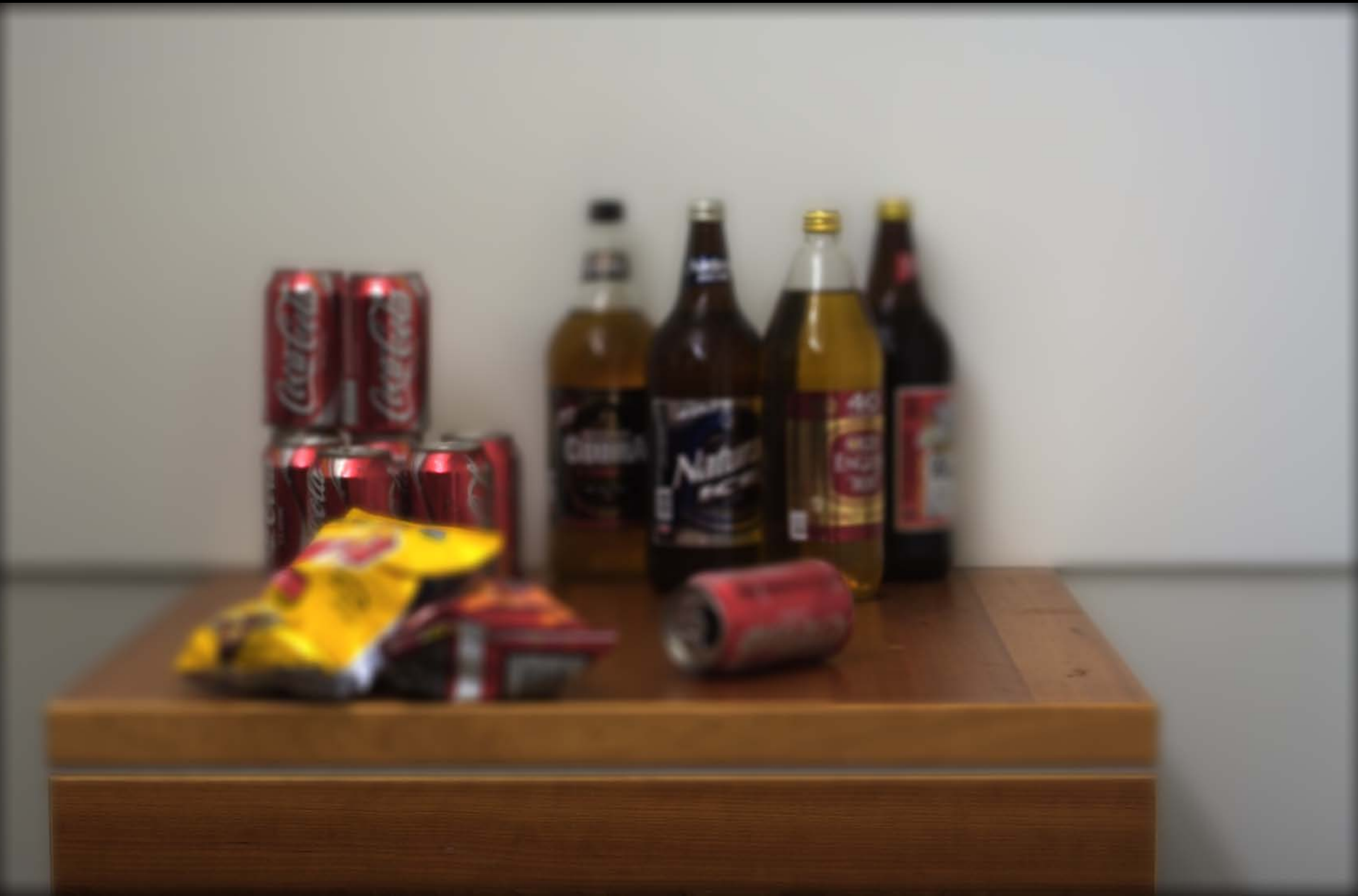
Application: Digital refocusing from a single image



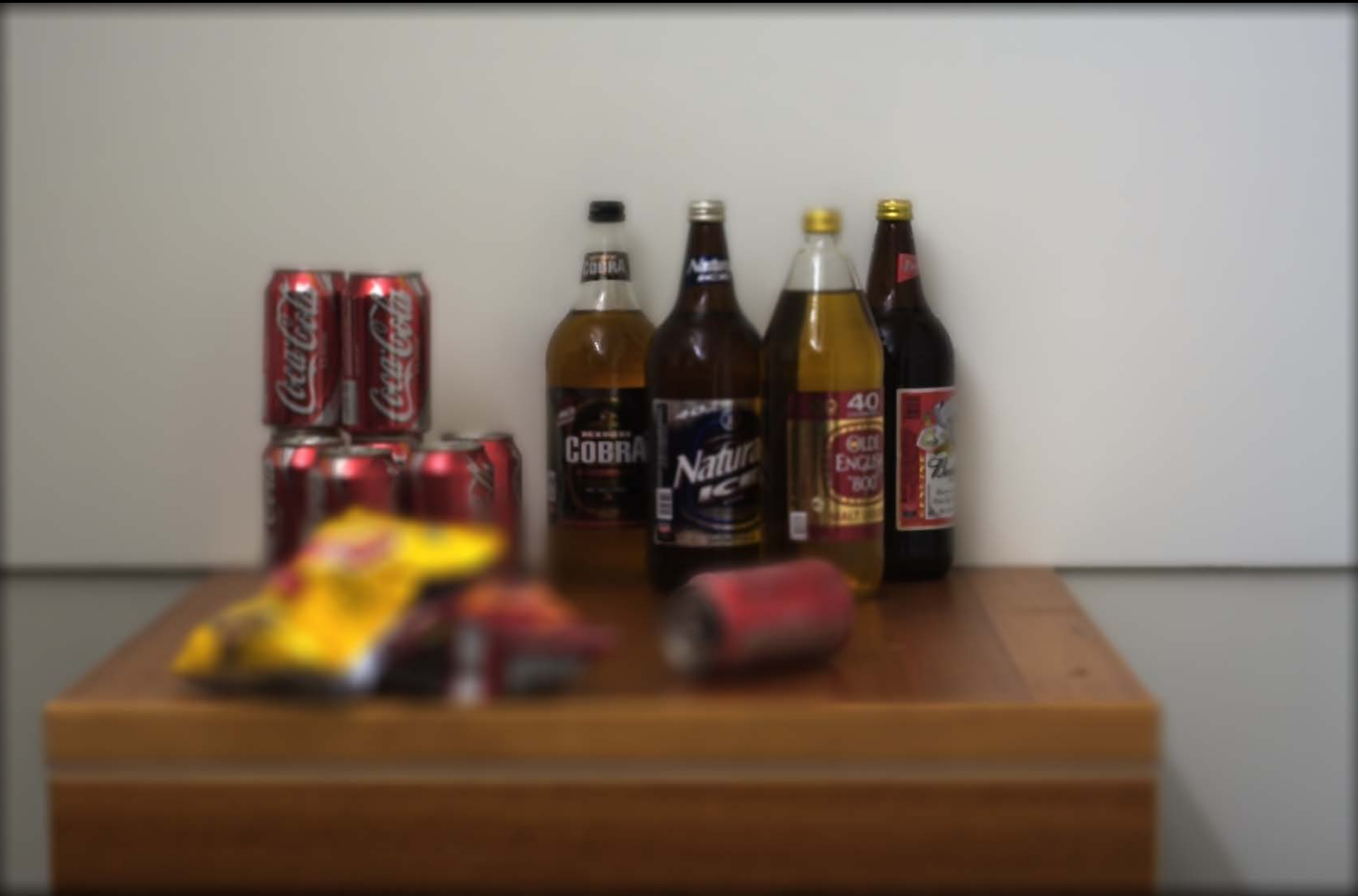
Application: Digital refocusing from a single image

Application: Digital refocusing from a single image

Application: Digital refocusing from a single image



Application: Digital refocusing from a single image



Coded aperture: pros and cons

+ Image AND depth at a single shot
+ No loss of image resolution
+ Simple modification to lens

– Depth is coarse

  unable to get depth at untextured areas,
  might need manual corrections.

+ But depth is a pure bonus

– Lose some light

+ But deconvolution increases depth of field

50mm f/1.8:	**$79.95**
Cardboard:	**$1**
Tape:	**$1**
Depth acquisition:	**priceless**

CodedAperture

Some more quick examples

Motion-Invariant Photography

Anat Levin   Peter Sand   Taeg Sang Cho   Frédo Durand   William T. Freeman
Massachusetts Institute of Technology, Computer Science and Artificial Intelligence Laboratory

- Quickly move camera in a parabola when taking a picture
- A motion at any speed in the direction of the parabola will give the same blur kernel

Results

Static Camera

Parabolic Camera

Results

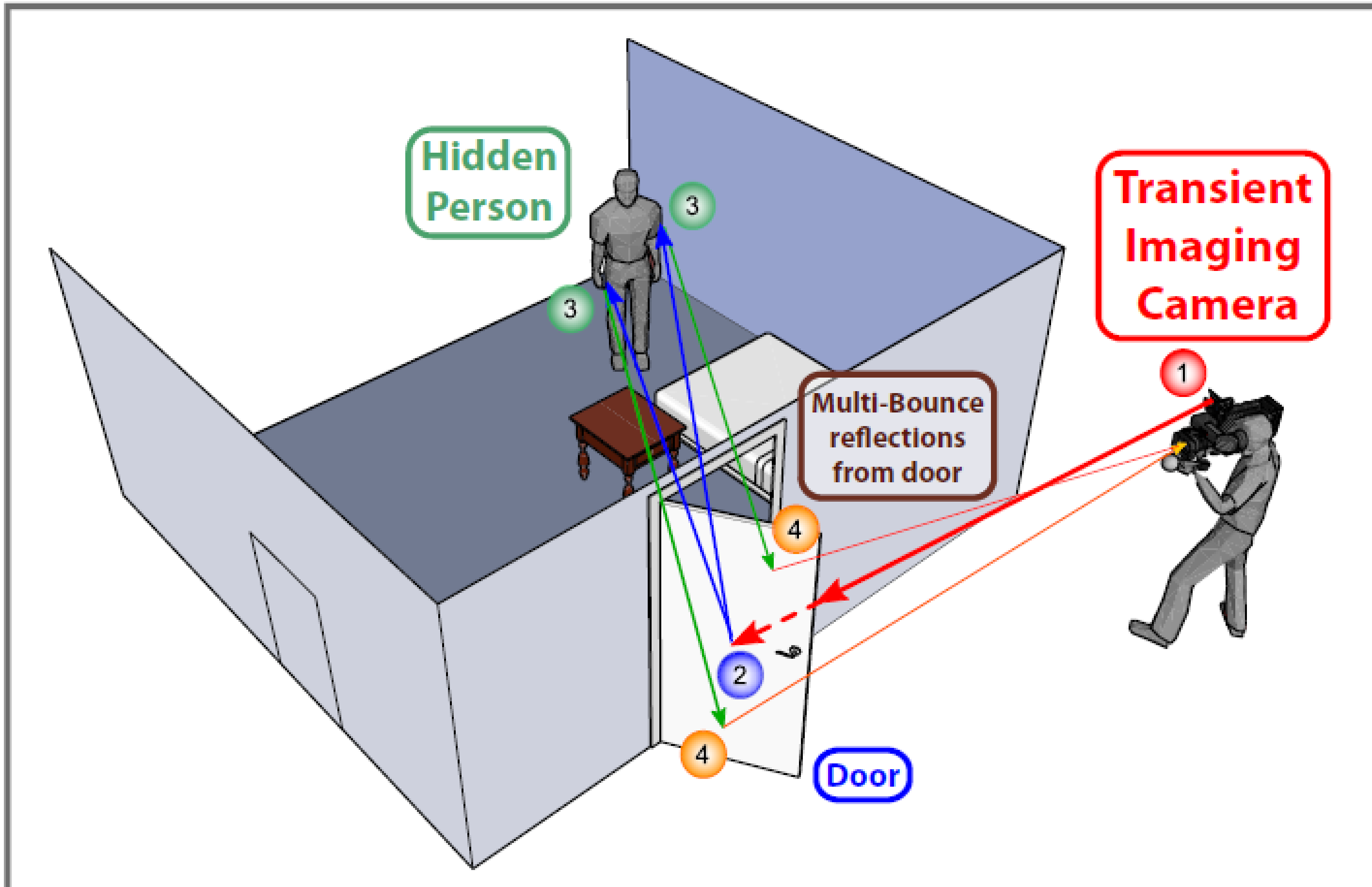
Static Camera

Parabolic Camera

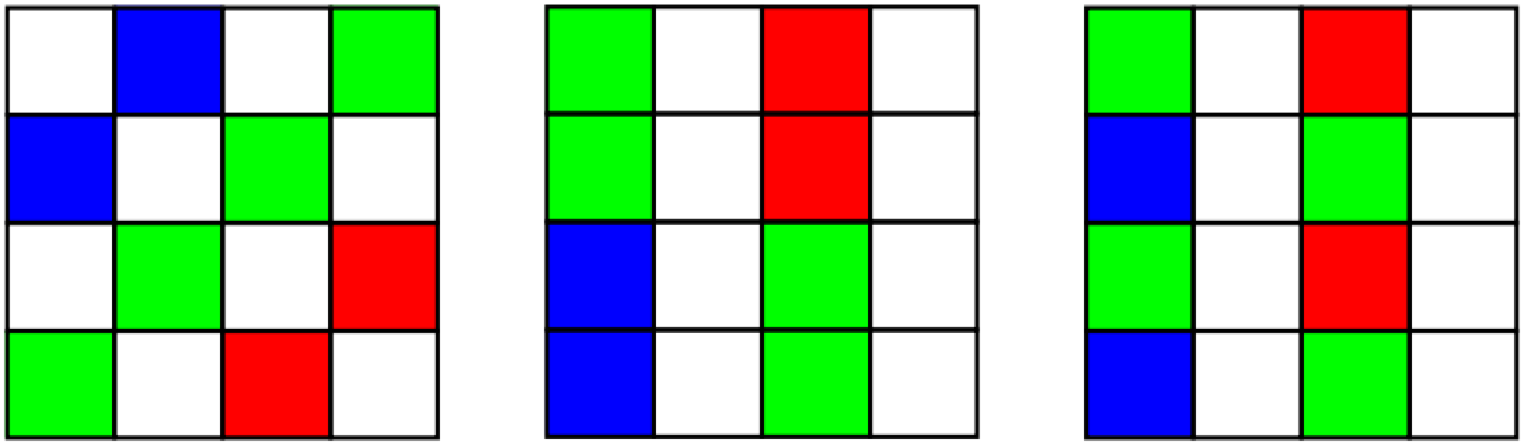
Motion in wrong direction

Looking Around the Corner using Transient Imaging

Ahmed Kirmani *[1], Tyler Hutchison[1], James Davis †[2], and Ramesh Raskar‡[1]
[1]MIT Media Laboratory [2] UC Santa Cruz



RGBW Sensors



- 2007: Kodak ‘Panchromatic’ Pixels
- Outperforms Bayer Grid
  - 2X-4X sensitivity (W: no filter loss)
  - May improve dynamic range (W >> RGB sensitivity)
  - Colorimetry: Direct luminance, not computed

Computational Approaches to Display

- 3D TV without glasses
  - 20", $2900, available in Japan soon
  - You see different images from different angles

Toshiba

http://news.cnet.com/8301-13506_3-20018421-17.html

Recap of questions

- How can we represent all of the information contained in light?
- What are the fundamental limitations of cameras?
- What sacrifices have we made in conventional cameras? For what benefits?
- How else can we design cameras for better focus, deblurring, multiple views, depth, etc.?

Next class: detecting fakes

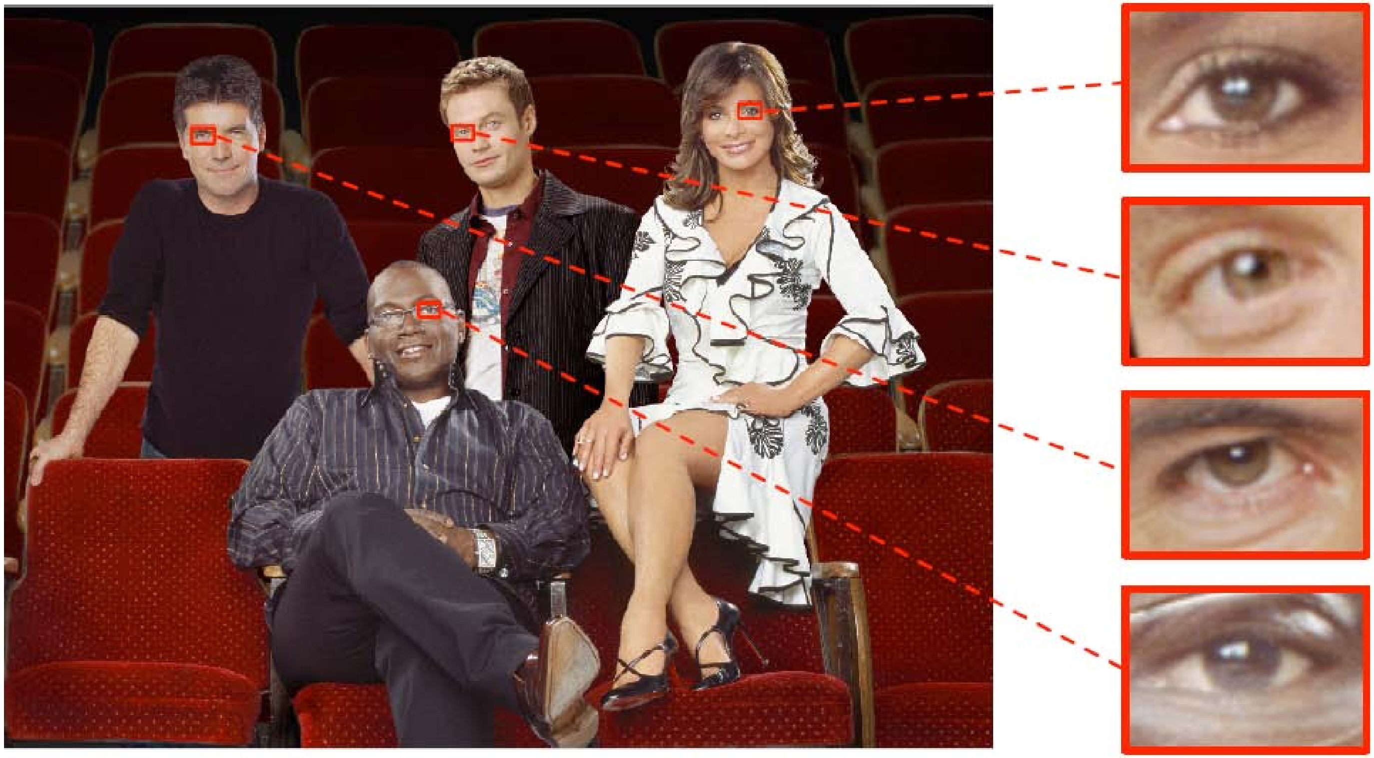


Fig. 1. This photograph of the *American Idol* host and judges is a digital composite of multiple photographs. The inconsistencies in the shape and position of the specular highlight on the eyes suggest that these people were originally photographed under different lighting conditions. Photo courtesy of Fox News and the Associated Press.