Computational Approaches to Cameras

11/12/15

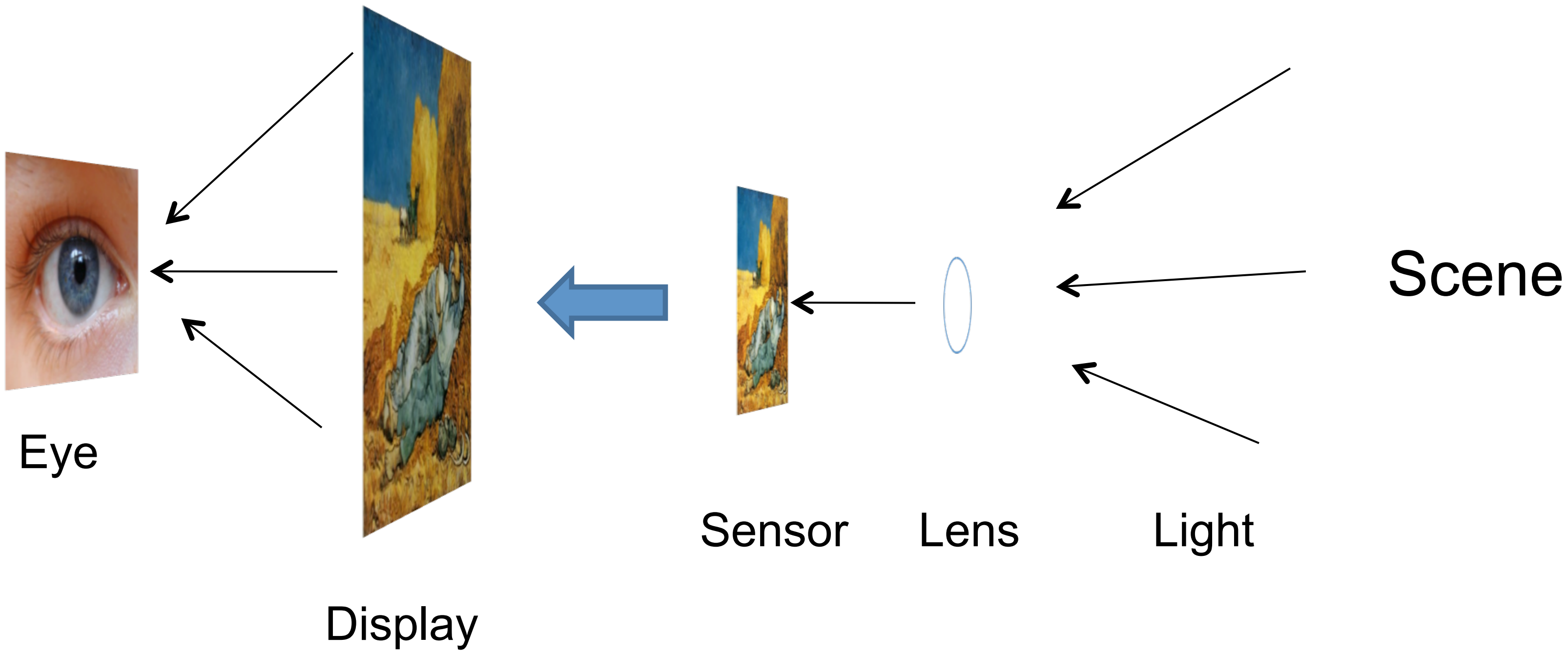
Magritte , *The False Mirror* (1935)

Computational Photography

Derek Hoiem, University of Illinois

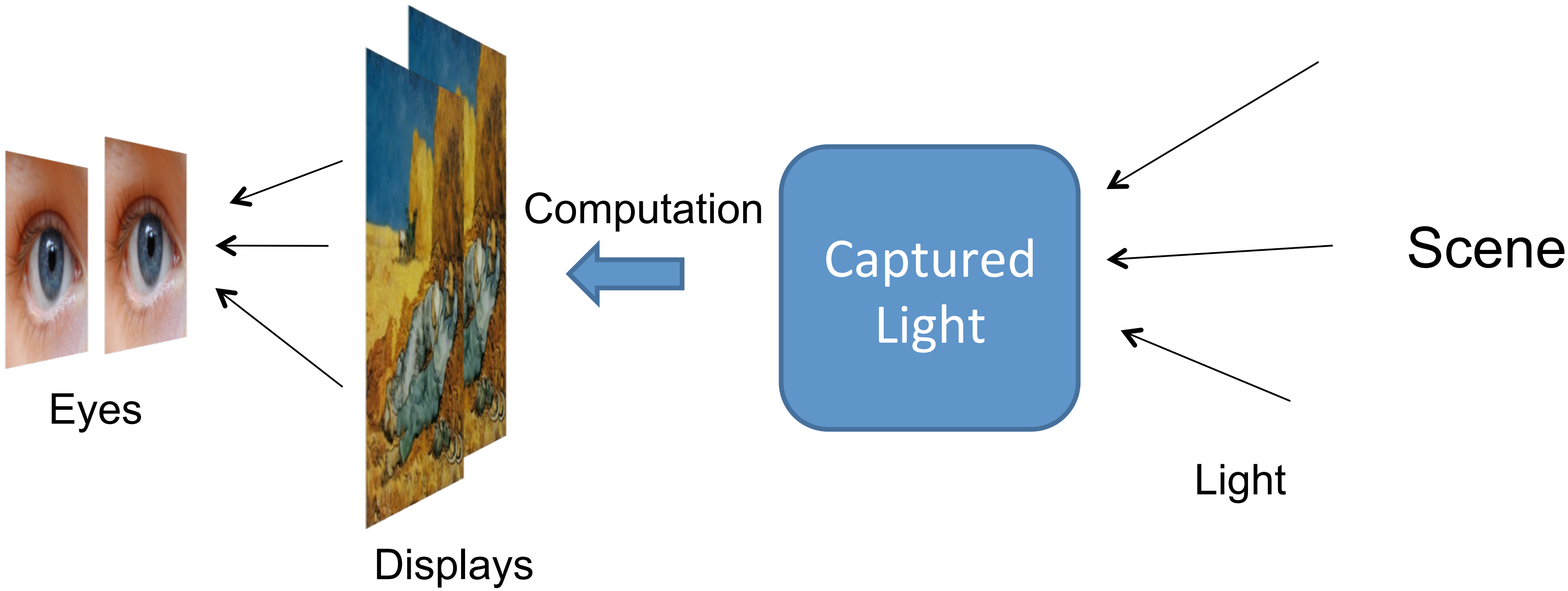
Conventional cameras

- 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.?

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

Representing Light: The Plenoptic Function

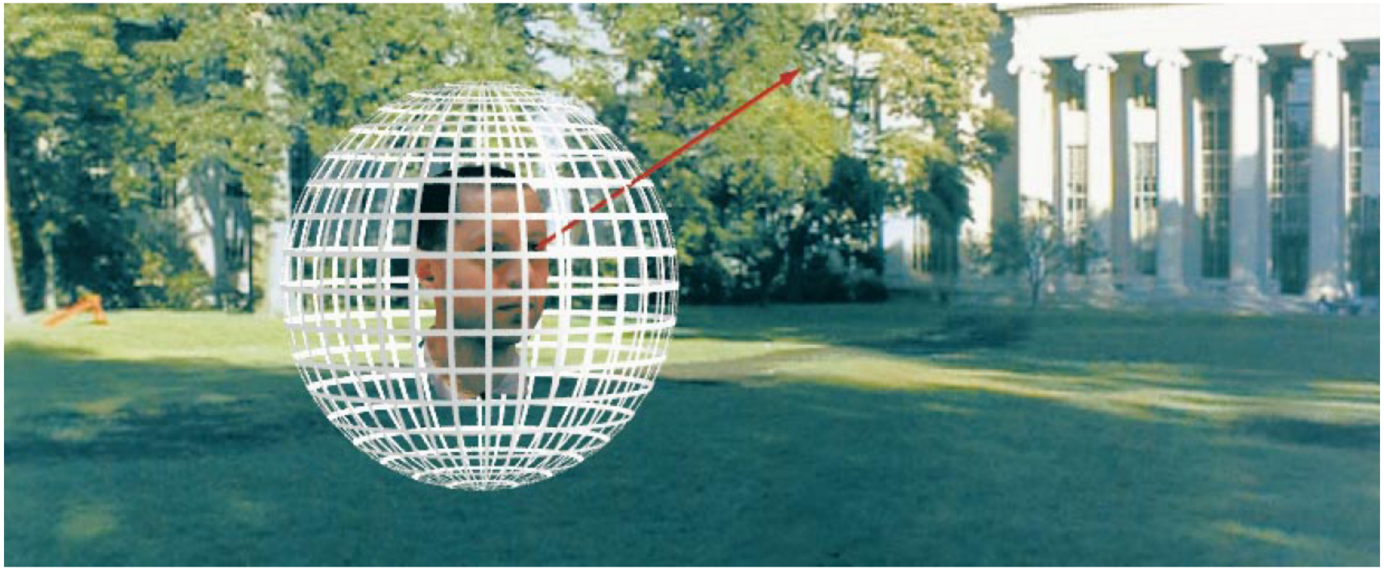


Figure by Leonard McMillan

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 everything that he can see…

Slides from Efros

Grayscale snapshot

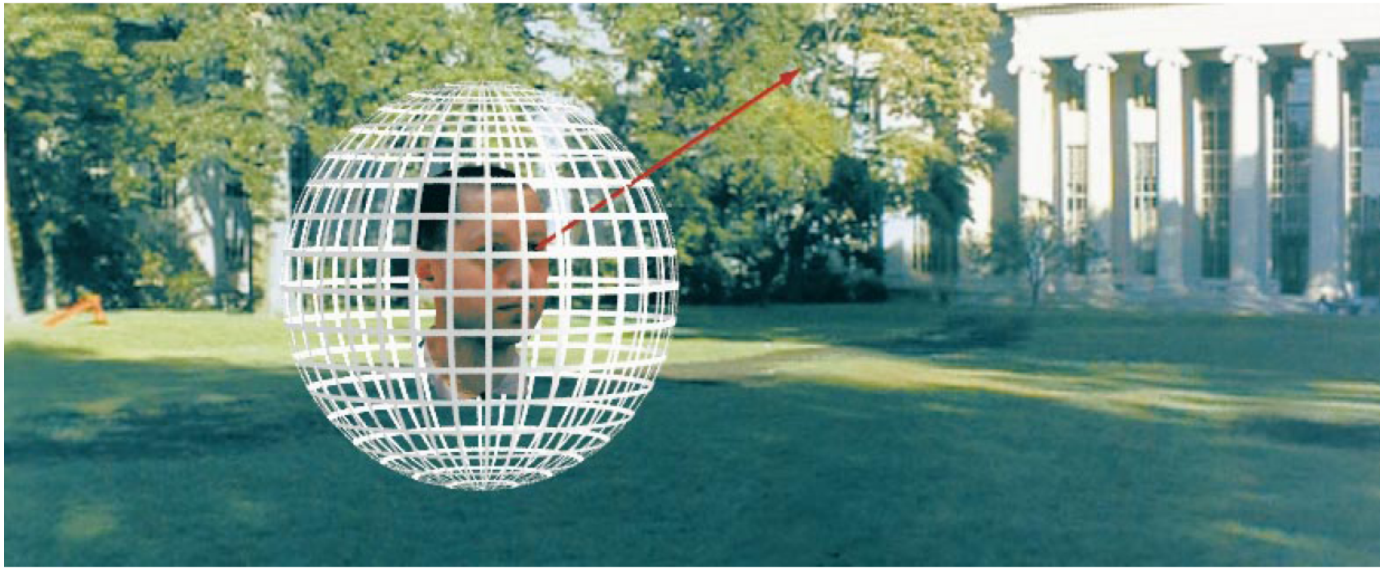
$$P(\theta,\phi)$$

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

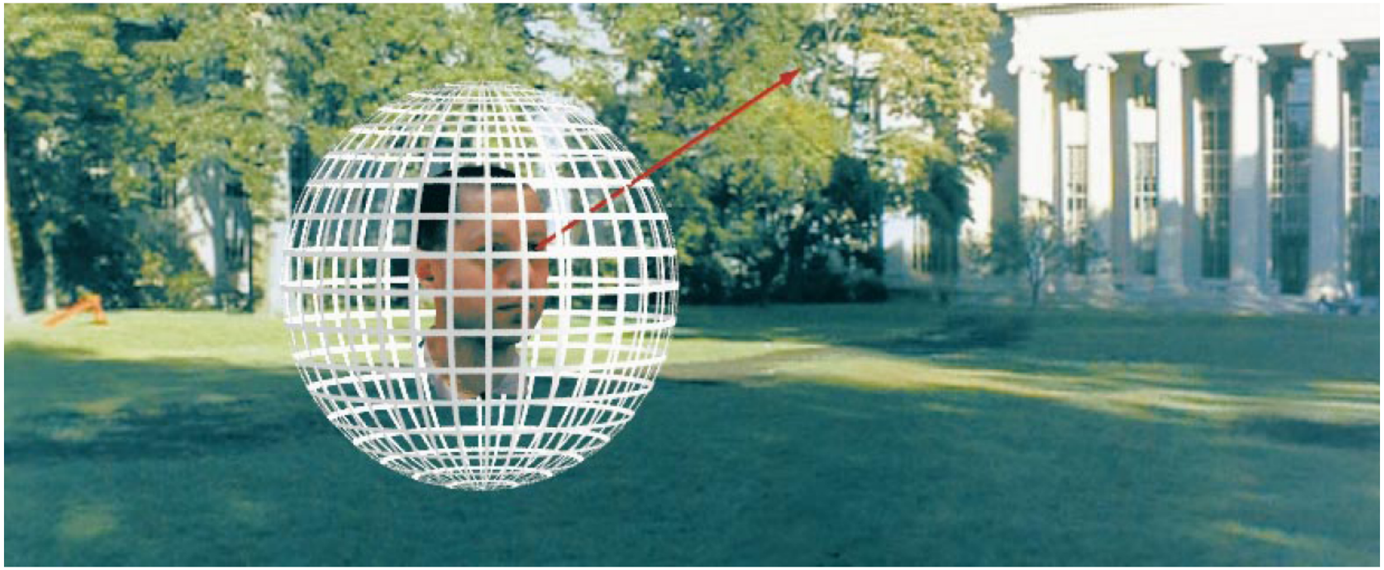


$$P(\theta,\phi,\lambda)$$

is intensity of light

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

A movie

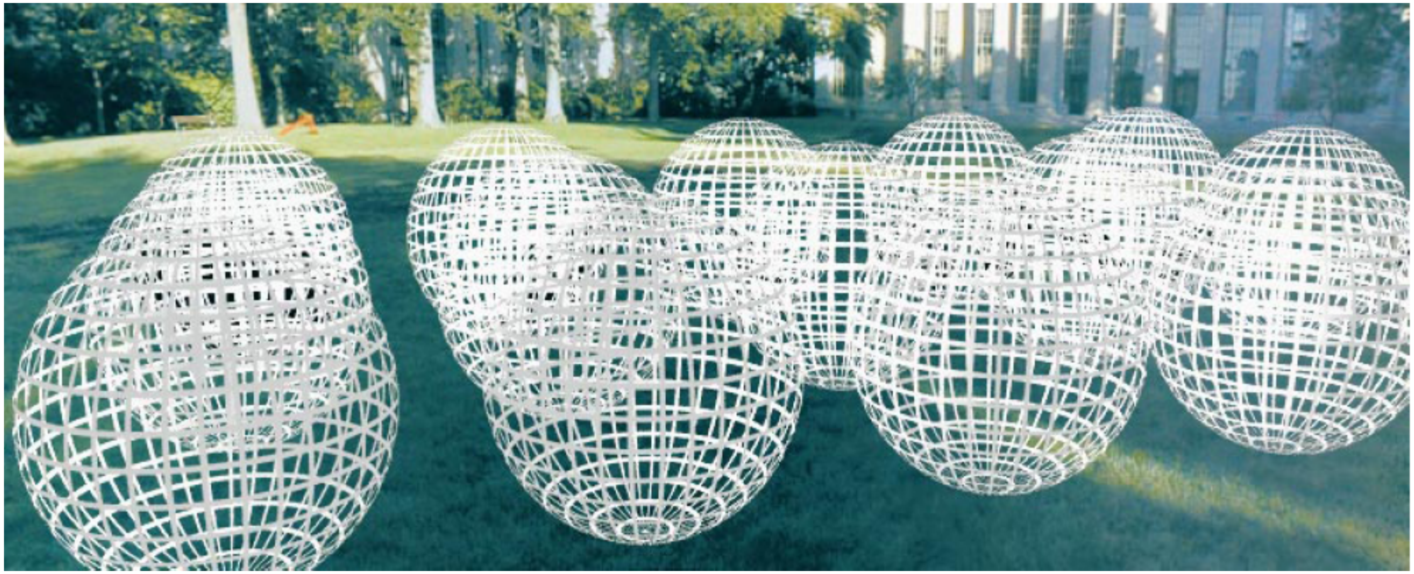


$$P(\theta,\phi,\lambda,t)$$

is intensity of light

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

Holographic movie

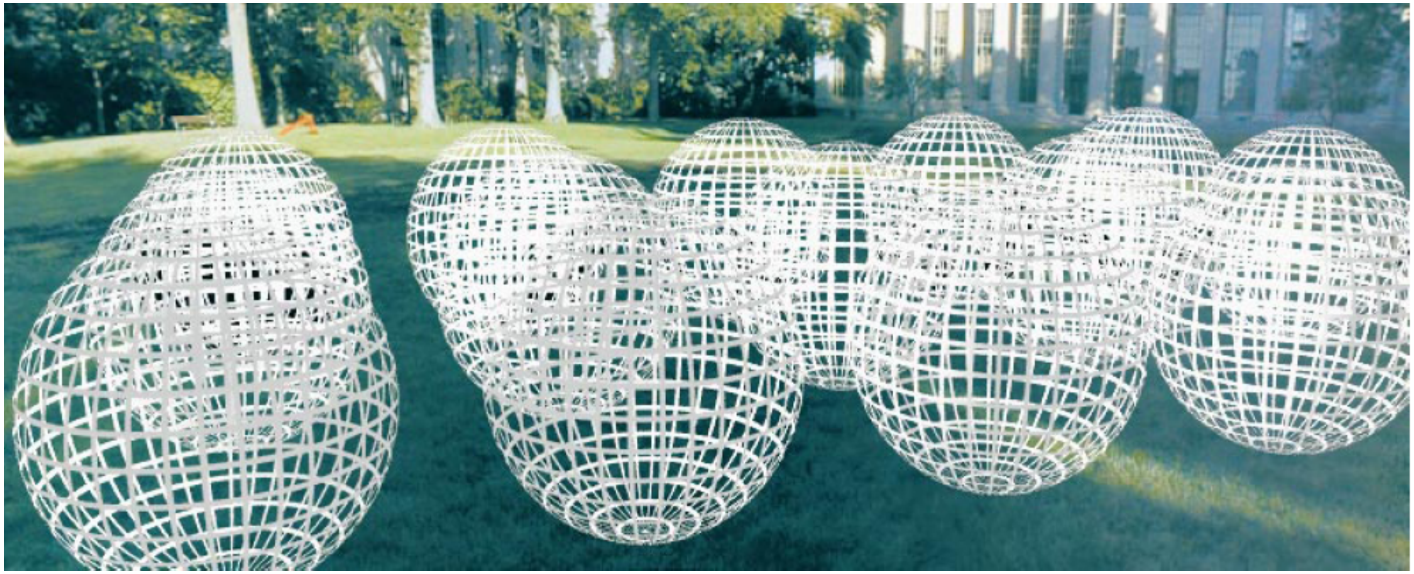


$$P(\theta,\phi,\lambda,t,V_X,V_Y,V_Z)$$

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!

Full Plenoptic Camera

Records position and orientation of each ray at each time and wavelength

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

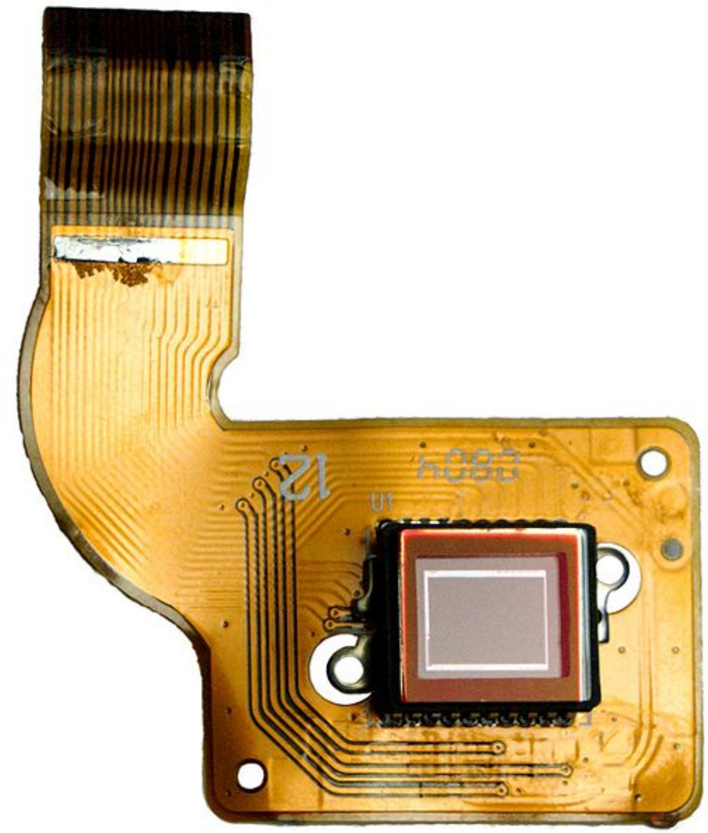
What fundamentally limits cameras?

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

What sacrifices does the conventional camera make? For what gains?

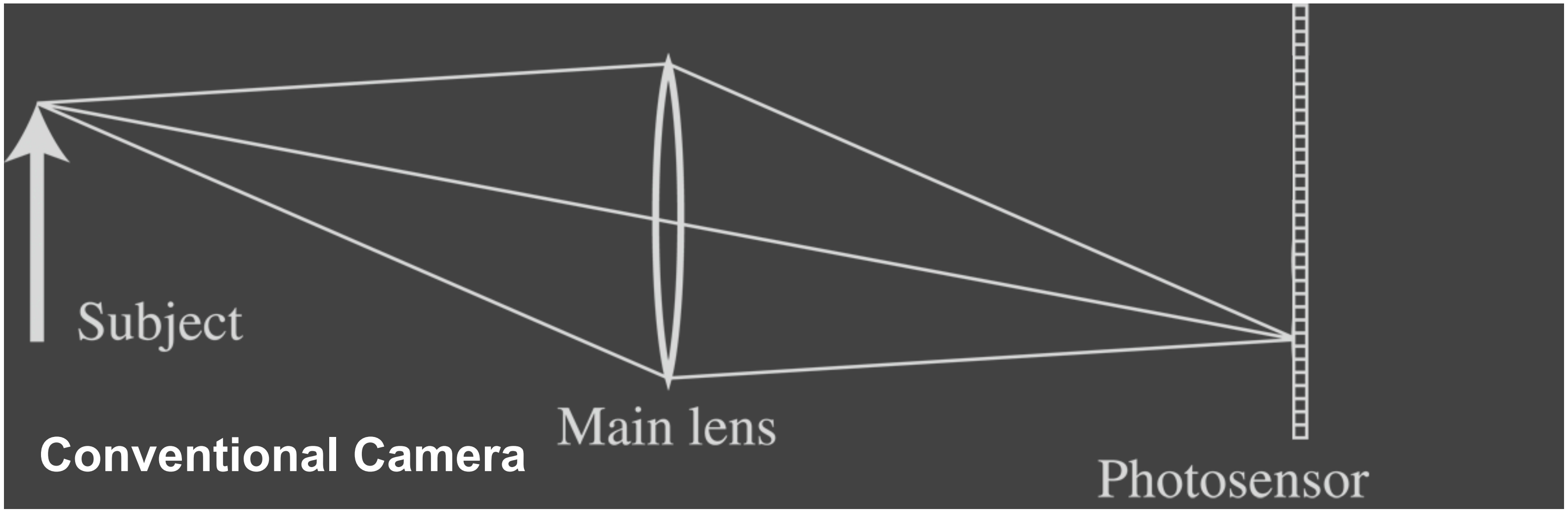
Trade-offs of conventional camera

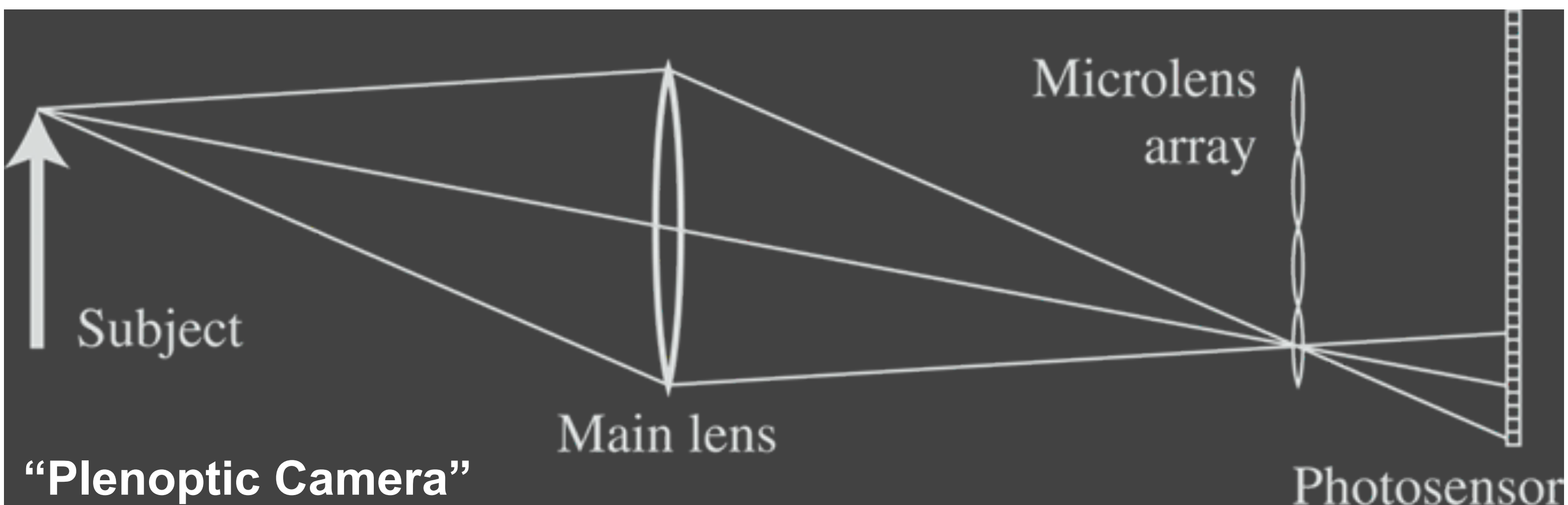
- Add a pinhole
  - ✓ Pixels correspond to small range of orientations at the camera center, instead of all gathered light at one position
  - ✗ Much less light hits sensor
- Add a lens
  - ✓ More light hits sensor
  - ✗ Limited depth of field
  - ✗ Chromatic aberration
- Add a shutter
  - Capture average 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”



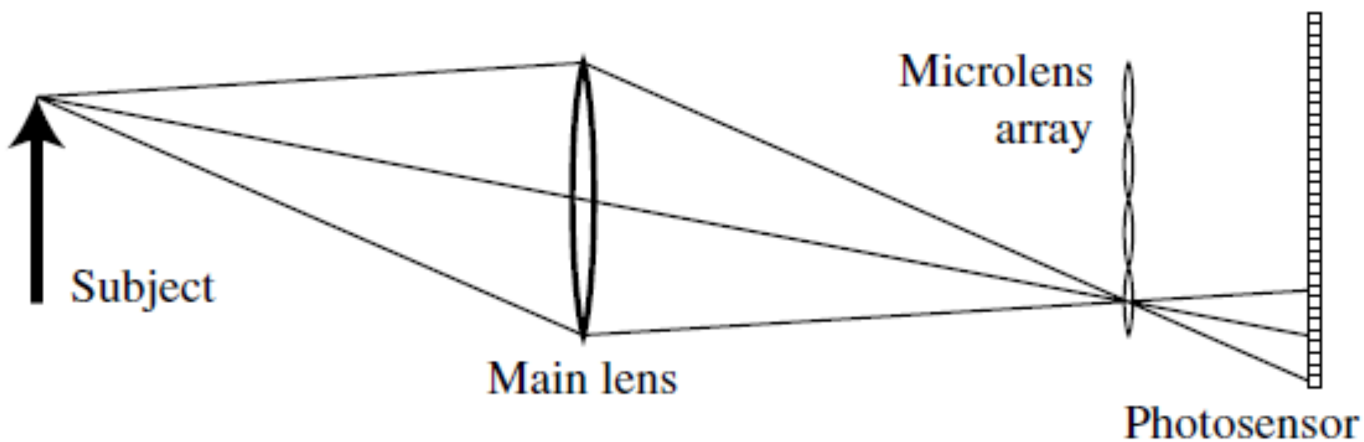


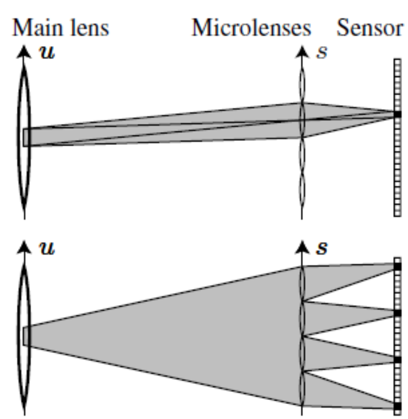
Adelson and Wang 1992

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

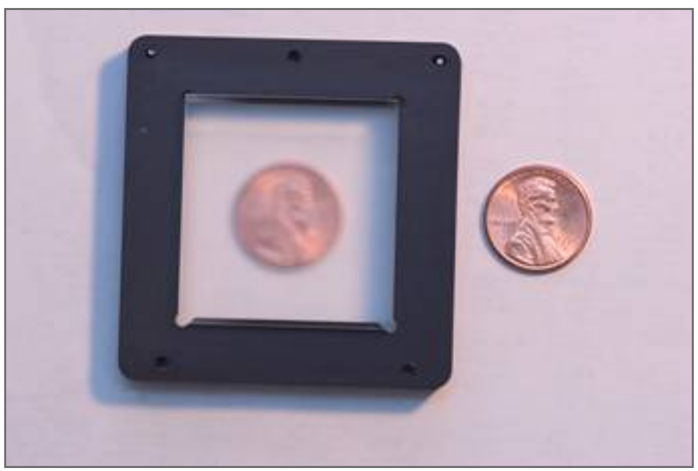




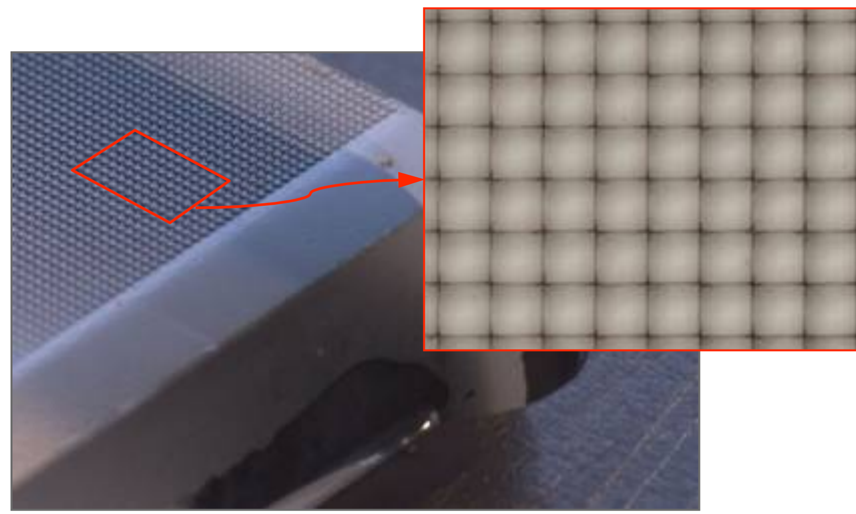
Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor



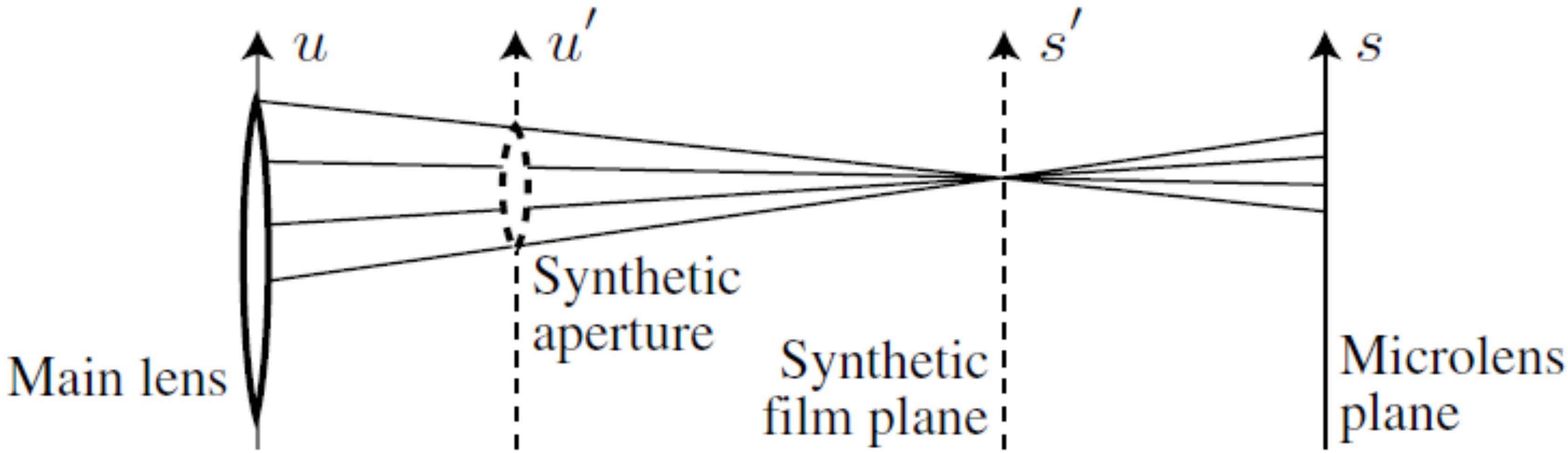
Adaptive Optics microlens array



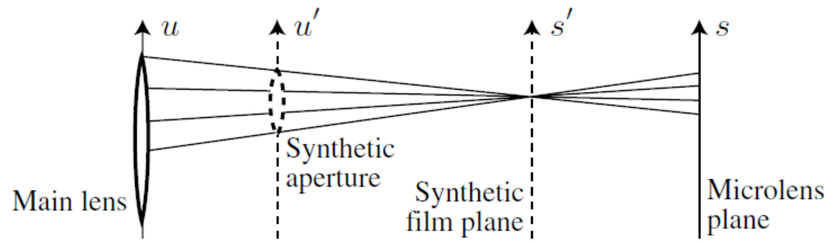
125μ square-sided microlenses

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

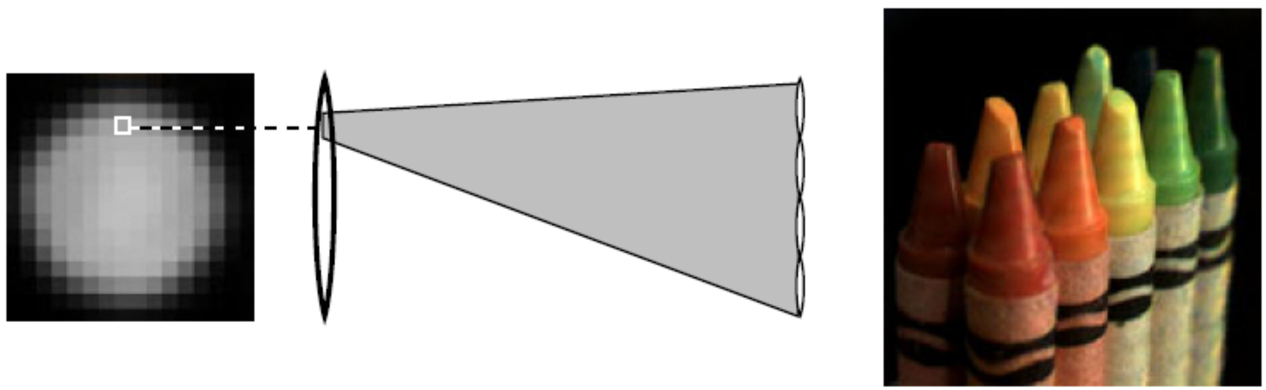
Light field photography: applications

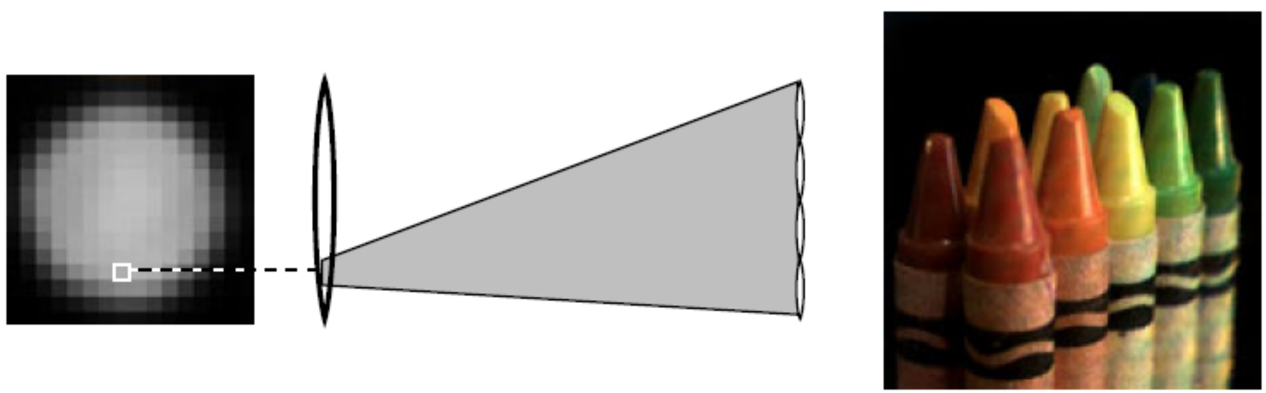


Light field photography: applications



Change in viewpoint



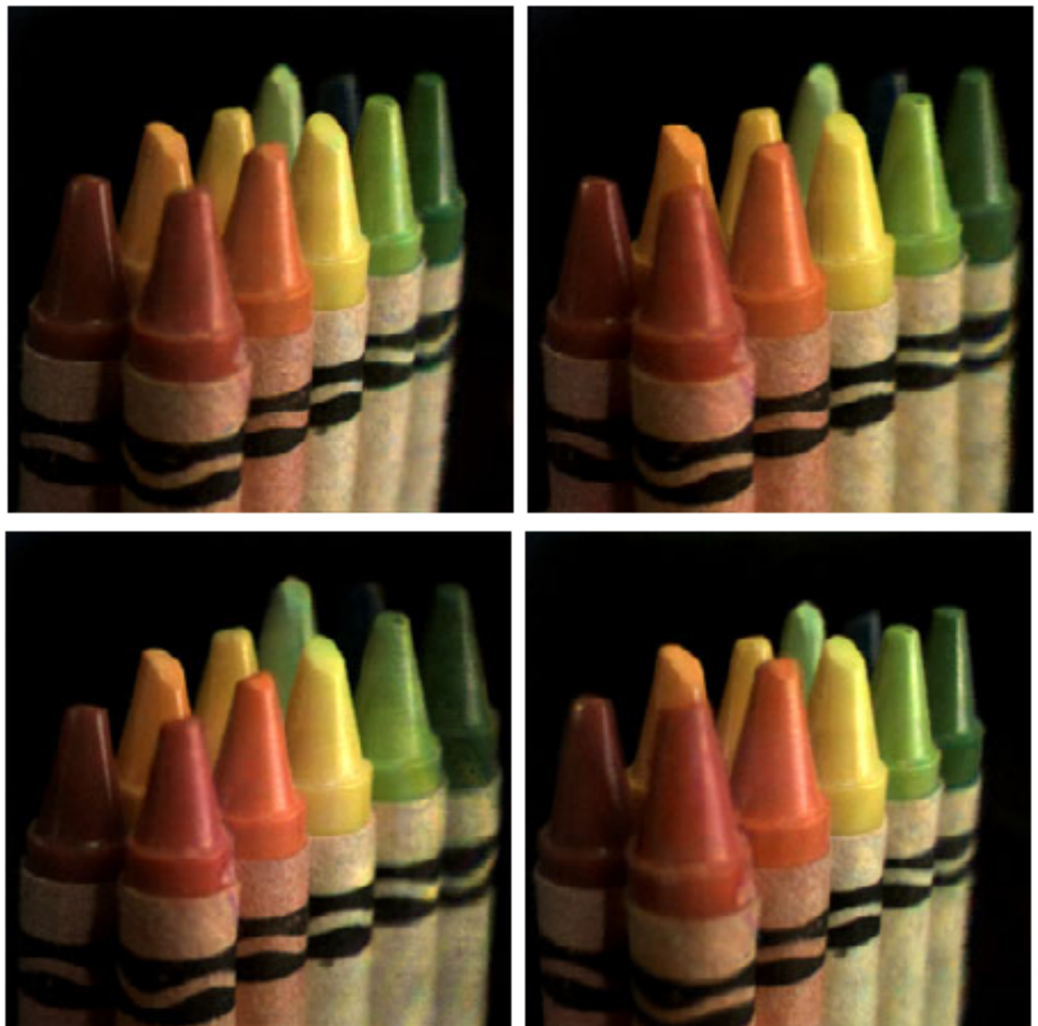


Light field photography: applications

Change in viewpoint

Lateral

Along Optical Axis



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

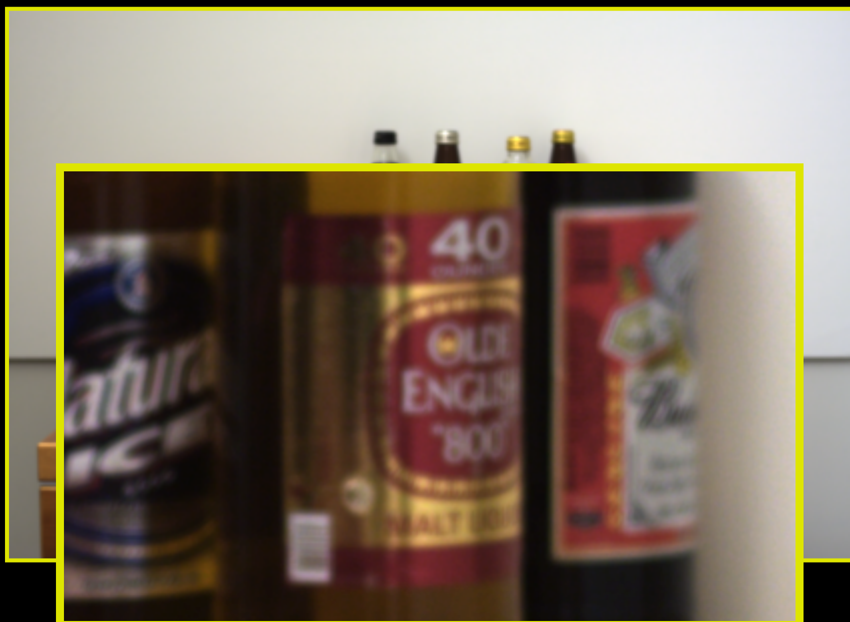
MIT CSAIL

Slides from SIGGRAPH Presentation

Output #1: Depth map

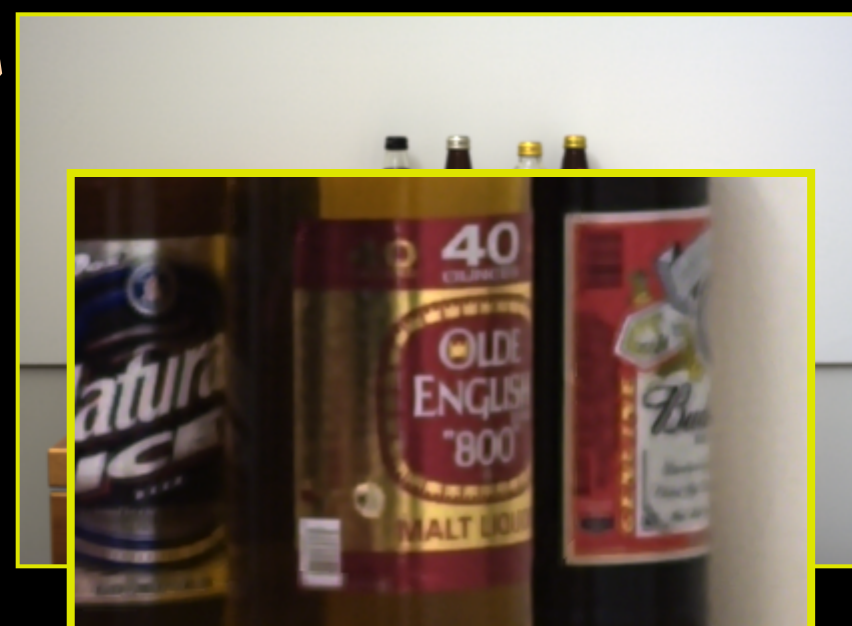
Single input image:

Single input image:



Output #1: Depth map

Output #2: All-focused image



Lens and defocus

Lens' aperture

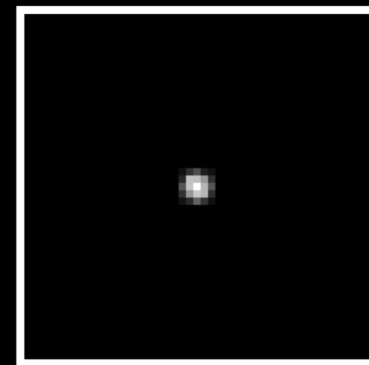
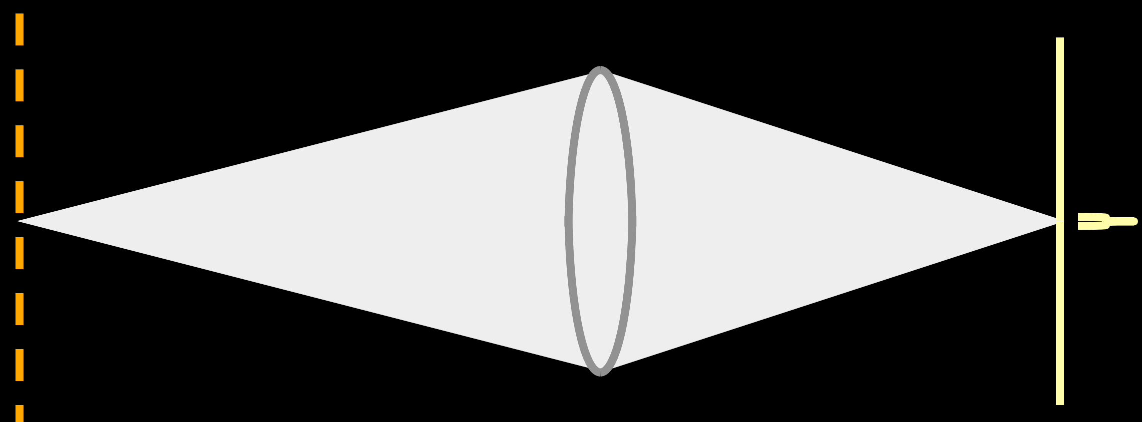
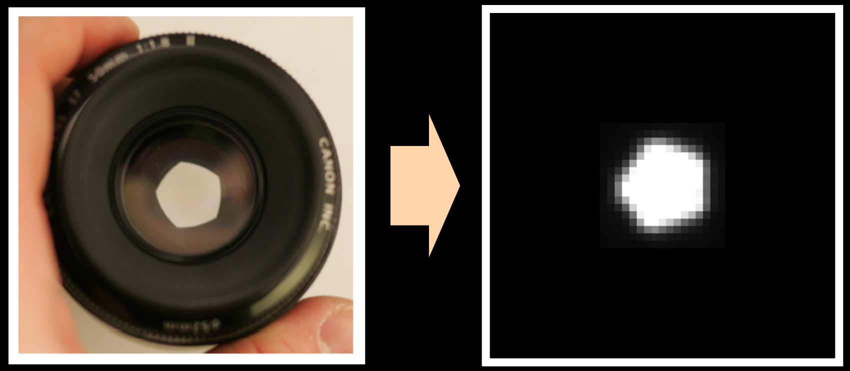
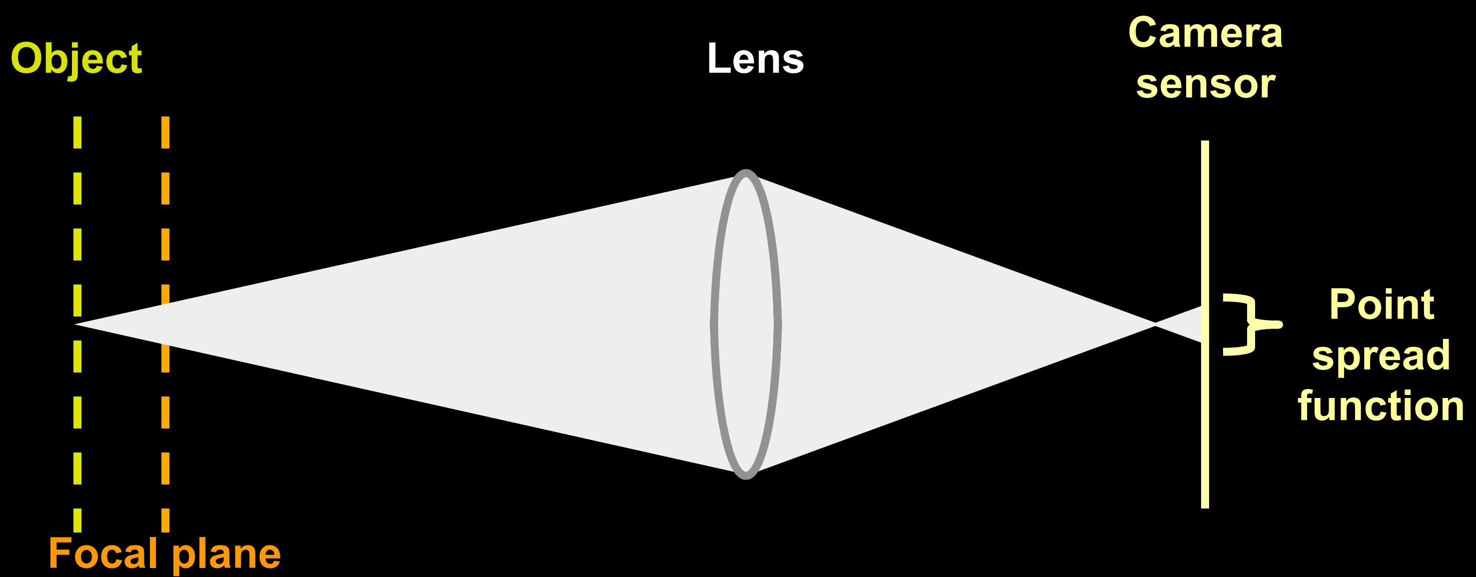


Image of a point light source



Lens and defocus





Lens and defocus

Lens' aperture

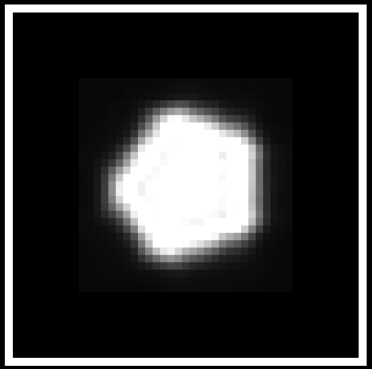
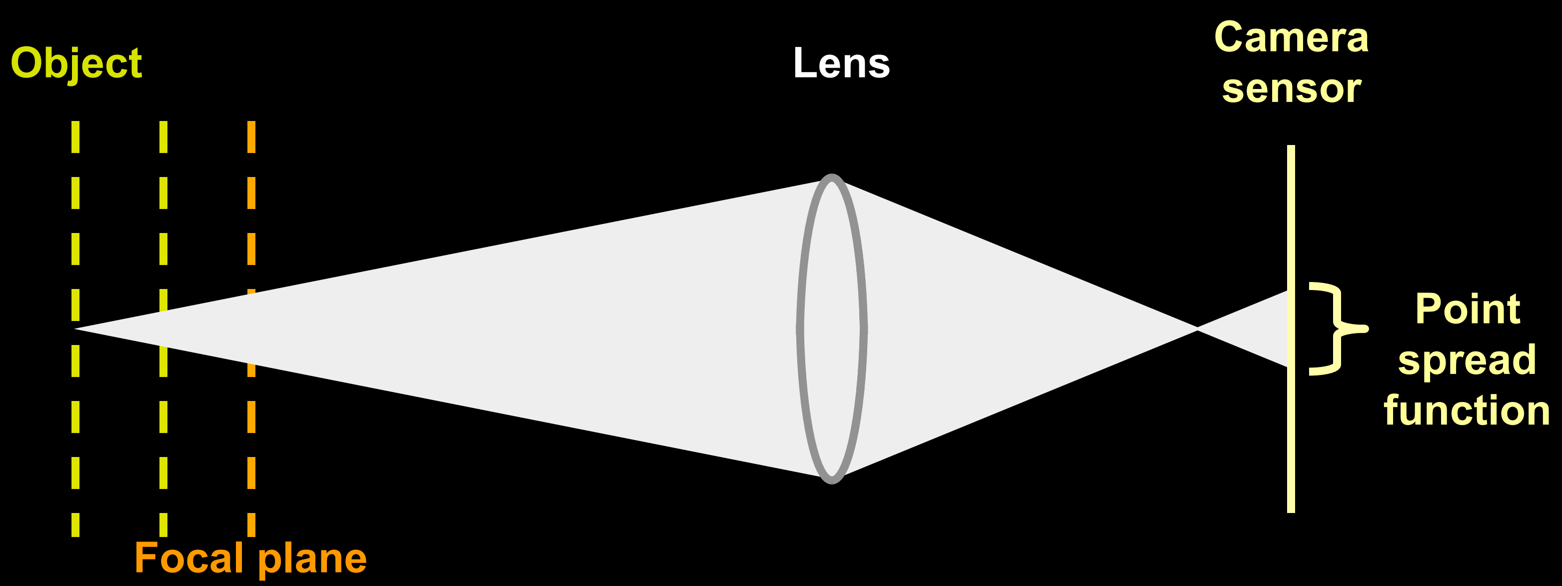


Image of a defocused point light source



Lens and defocus

Lens' aperture

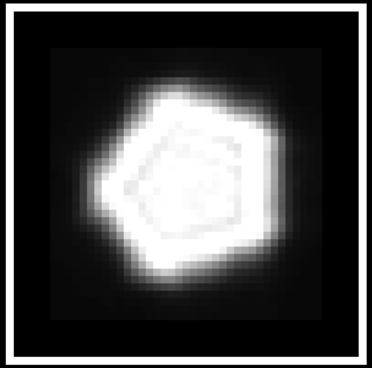
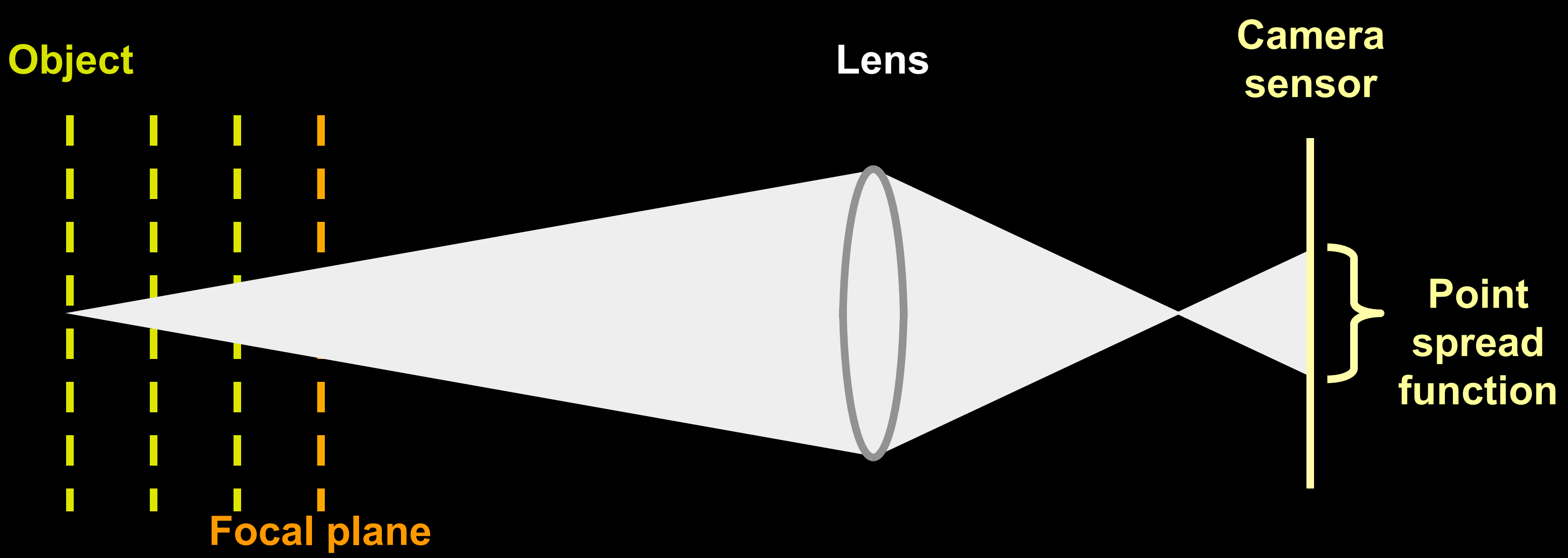
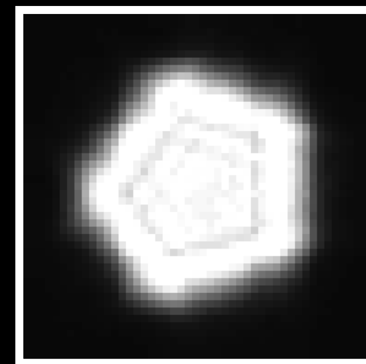


Image of a defocused point light source



Lens and defocus

Lens' aperture



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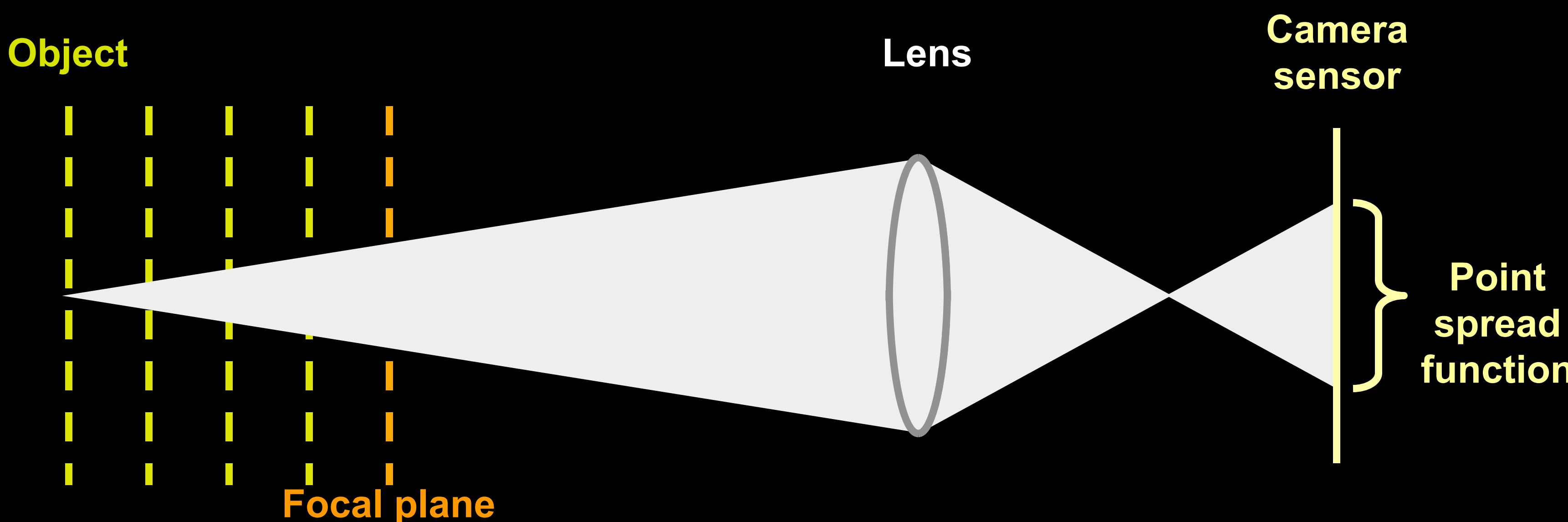


Depth and defocus

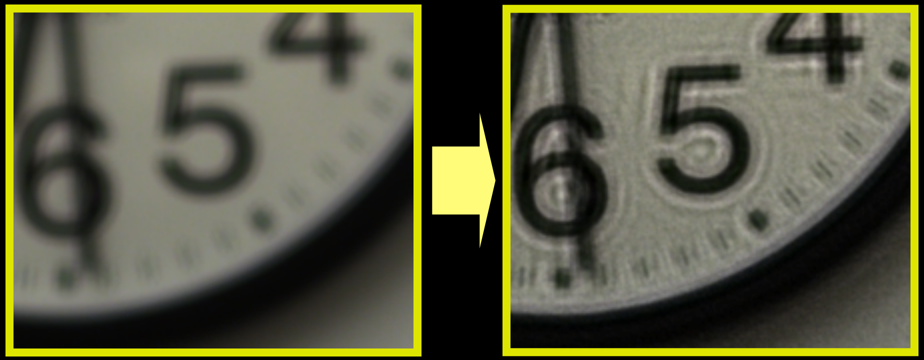
Depth from defocus:

Infer depth by analyzing local scale of defocus blur

Challenges

- Hard to discriminate a smooth scene from defocus blur

- Hard to undo defocus blur



Input

Ringing with conventional deblurring algorithm

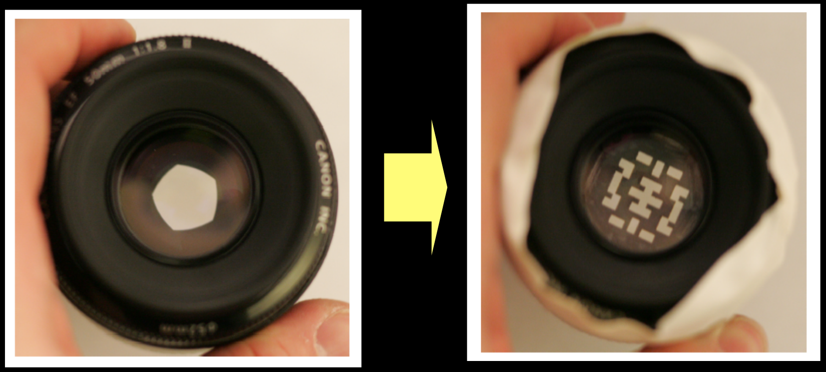
Key ideas

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

Natural

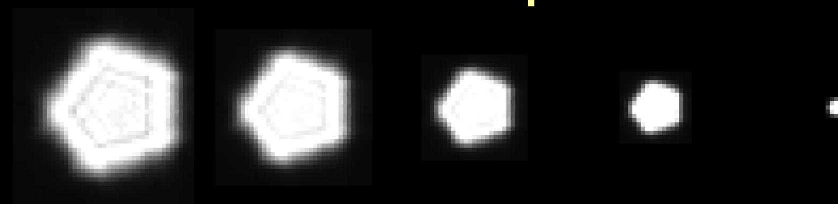
Unnatural

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



Defocus as local convolution

Calibrated blur kernels at different depths



Defocus as local convolution

$$y = f_k \otimes x$$

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

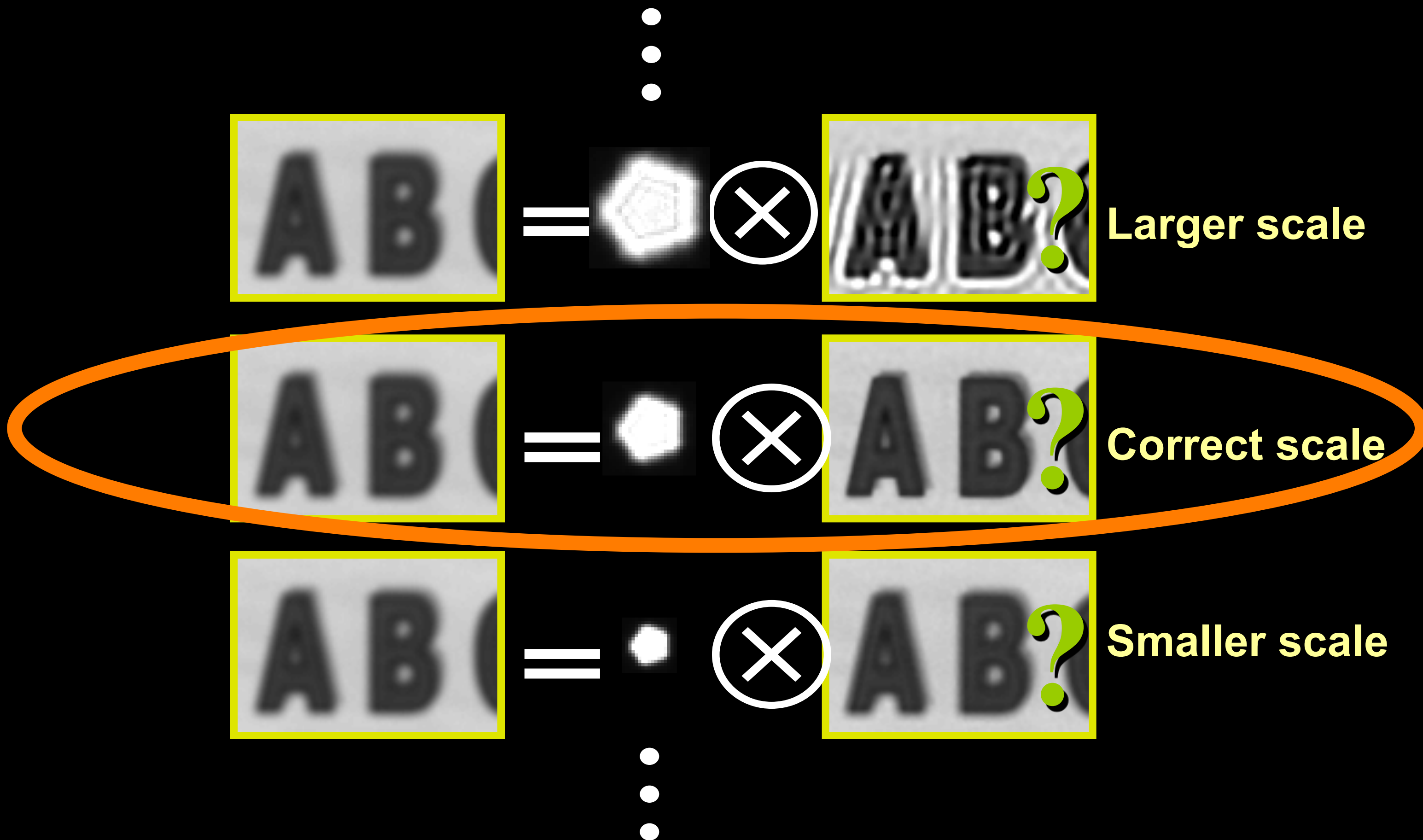
Depth k=1:

Depth k=2:

Depth k=3:

Overview

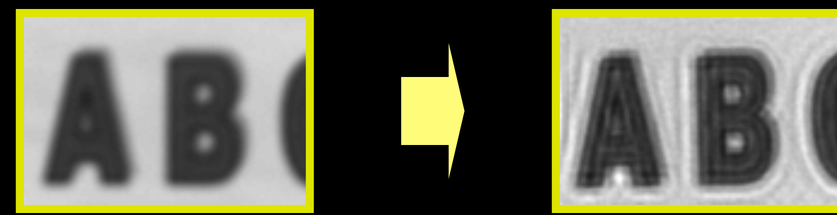
Try deconvolving local input windows with different scaled filters:



Somehow: select best scale.

Challenges

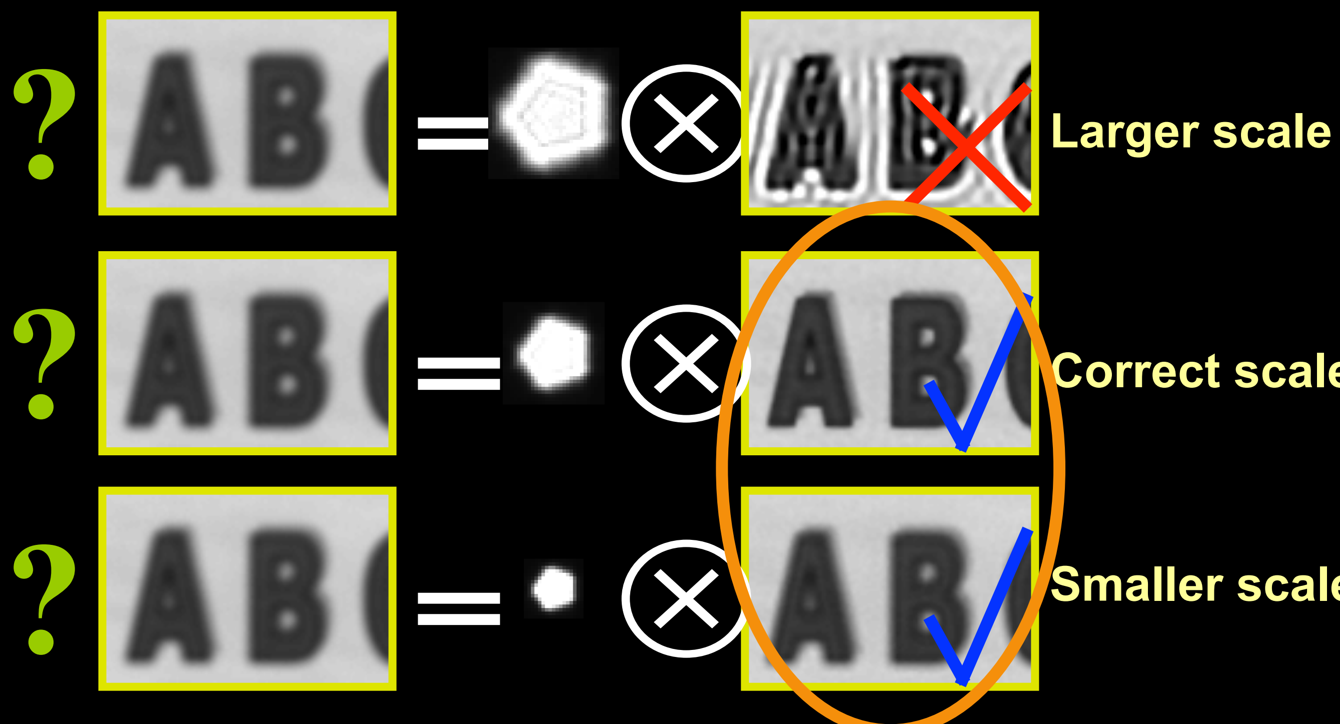
- **Hard to deconvolve even when kernel is known**



Input

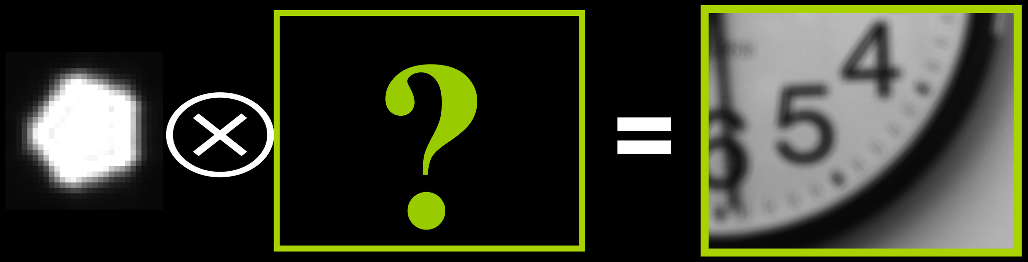
Ringing with the traditional Richardson-Lucy deconvolution algorithm

- **Hard to identify correct scale:**



Deconvolution is ill posed

$$f \otimes x = y$$



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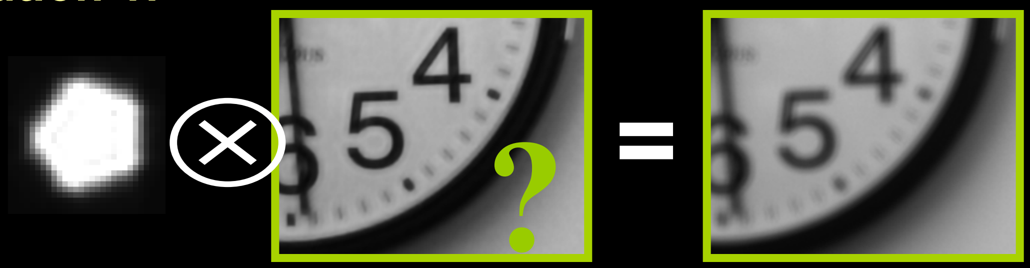
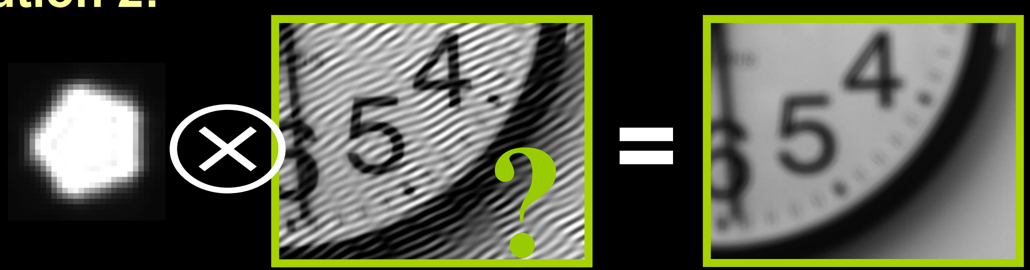
Solution 1:

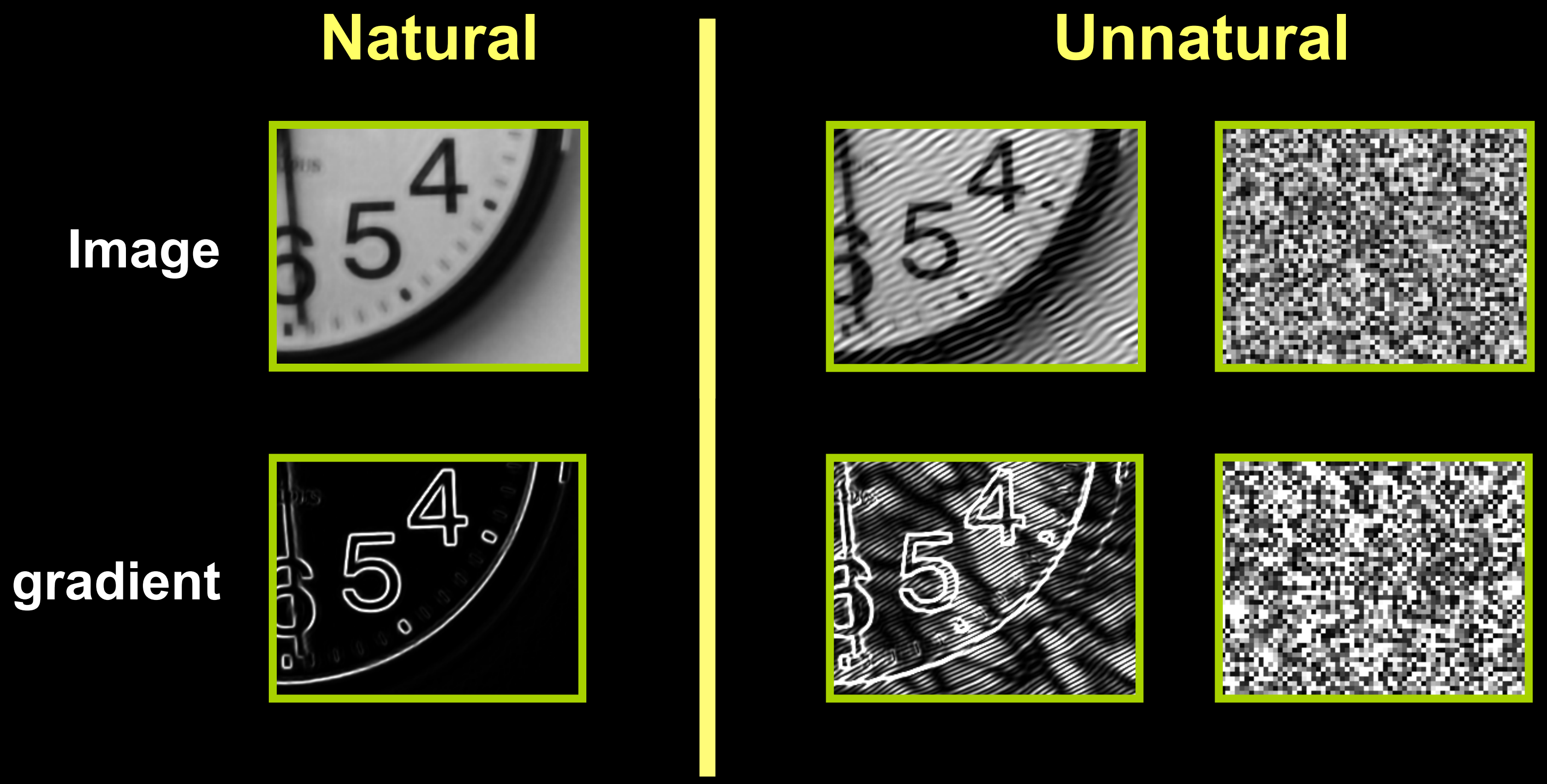


Solution 2:



Idea 1: Natural images prior

What makes images special?

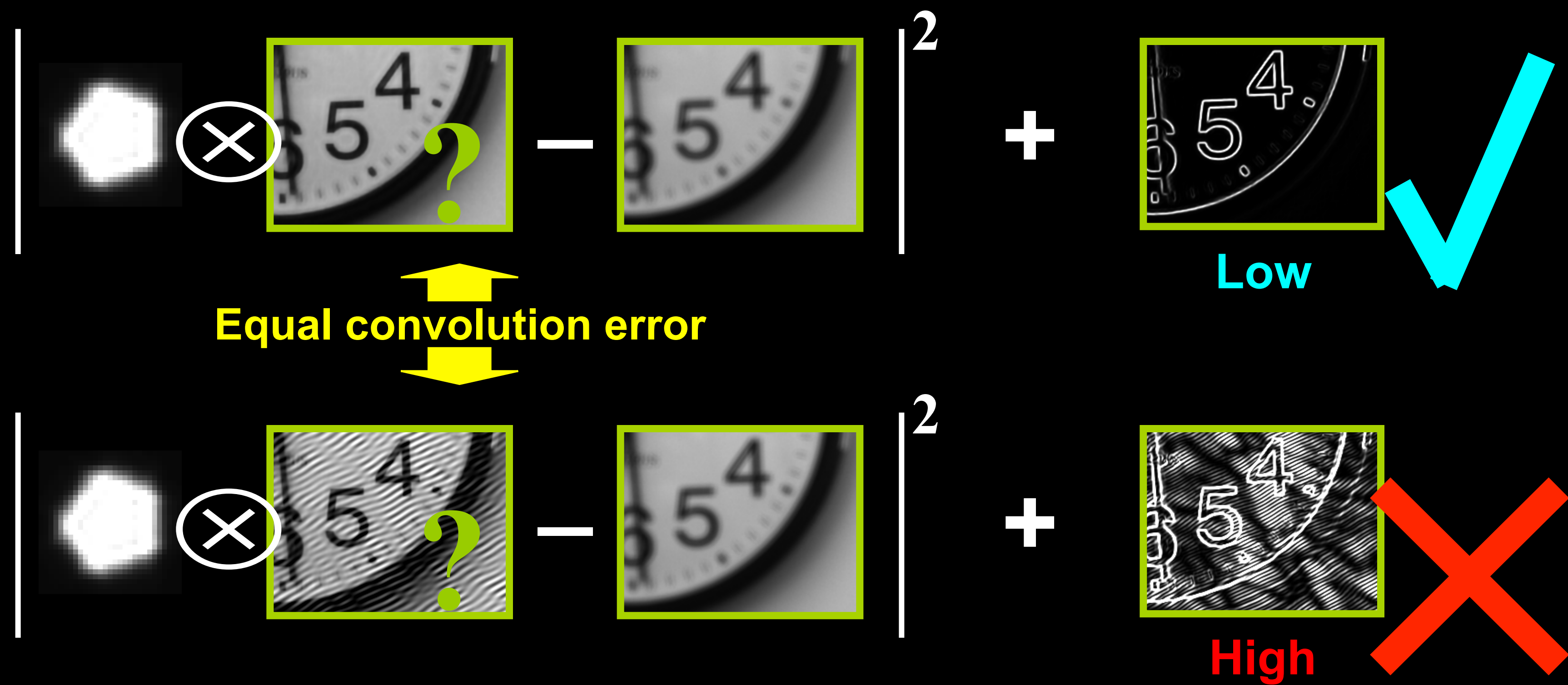


Natural images have sparse gradients

➡ **put a penalty on gradients**

Deconvolution with prior

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



Comparing deconvolution algorithms

Input

(Non blind) deconvolution code available online: http://groups.csail.mit.edu/graphics/CodedAperture/

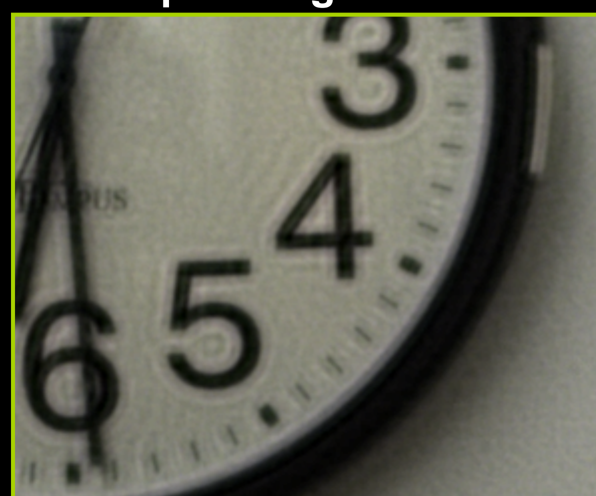
$$\rho(\nabla x) = \|\nabla x\|^2$$

"spread" gradients

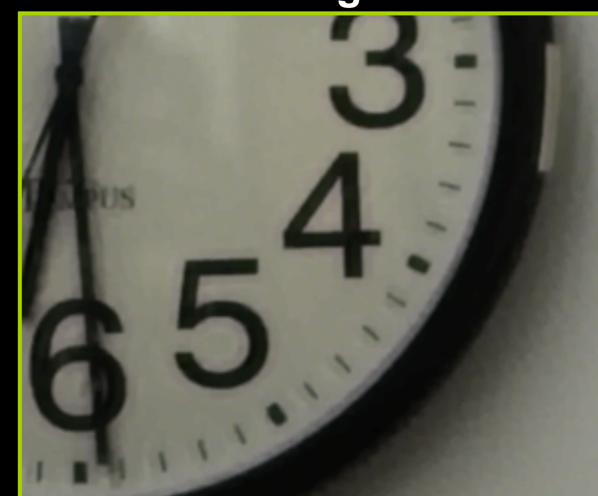
$$\rho(\nabla x) = \|\nabla x\|^{0.8}$$

"localizes" gradients

Richardson-Lucy



Gaussian prior



Sparse prior

Comparing deconvolution algorithms

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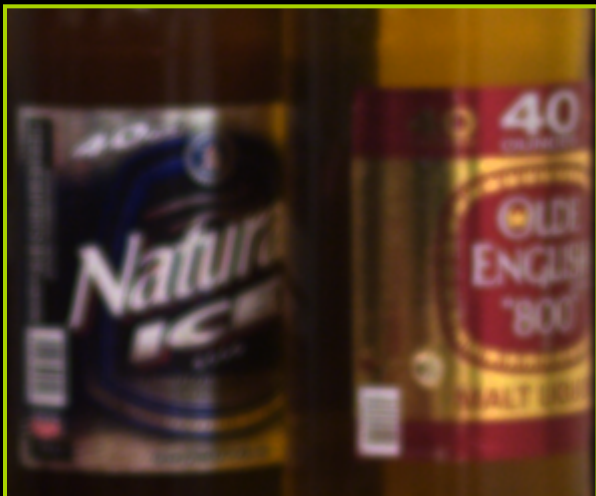

Input

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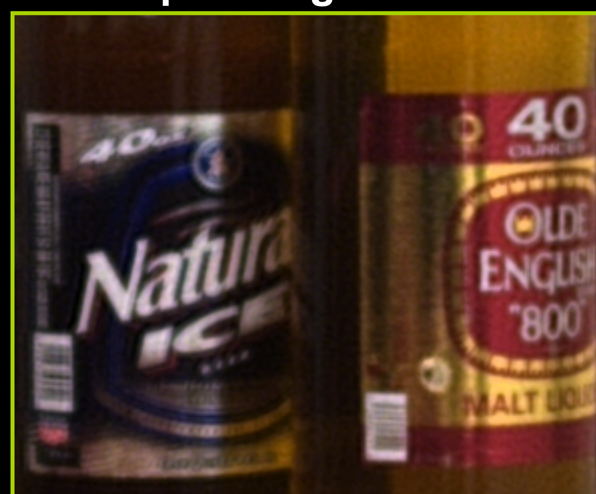
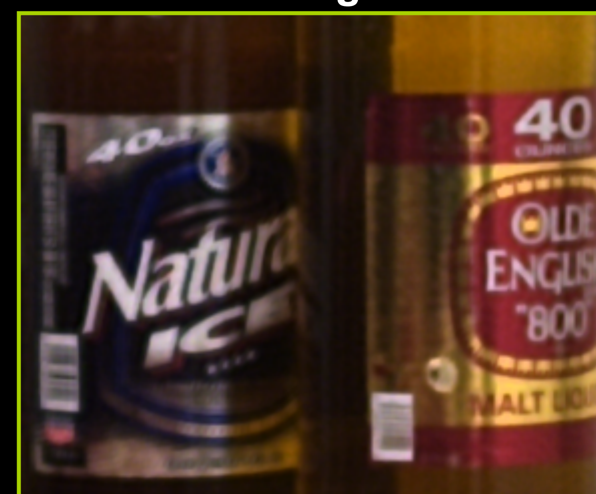
Richardson-Lucy



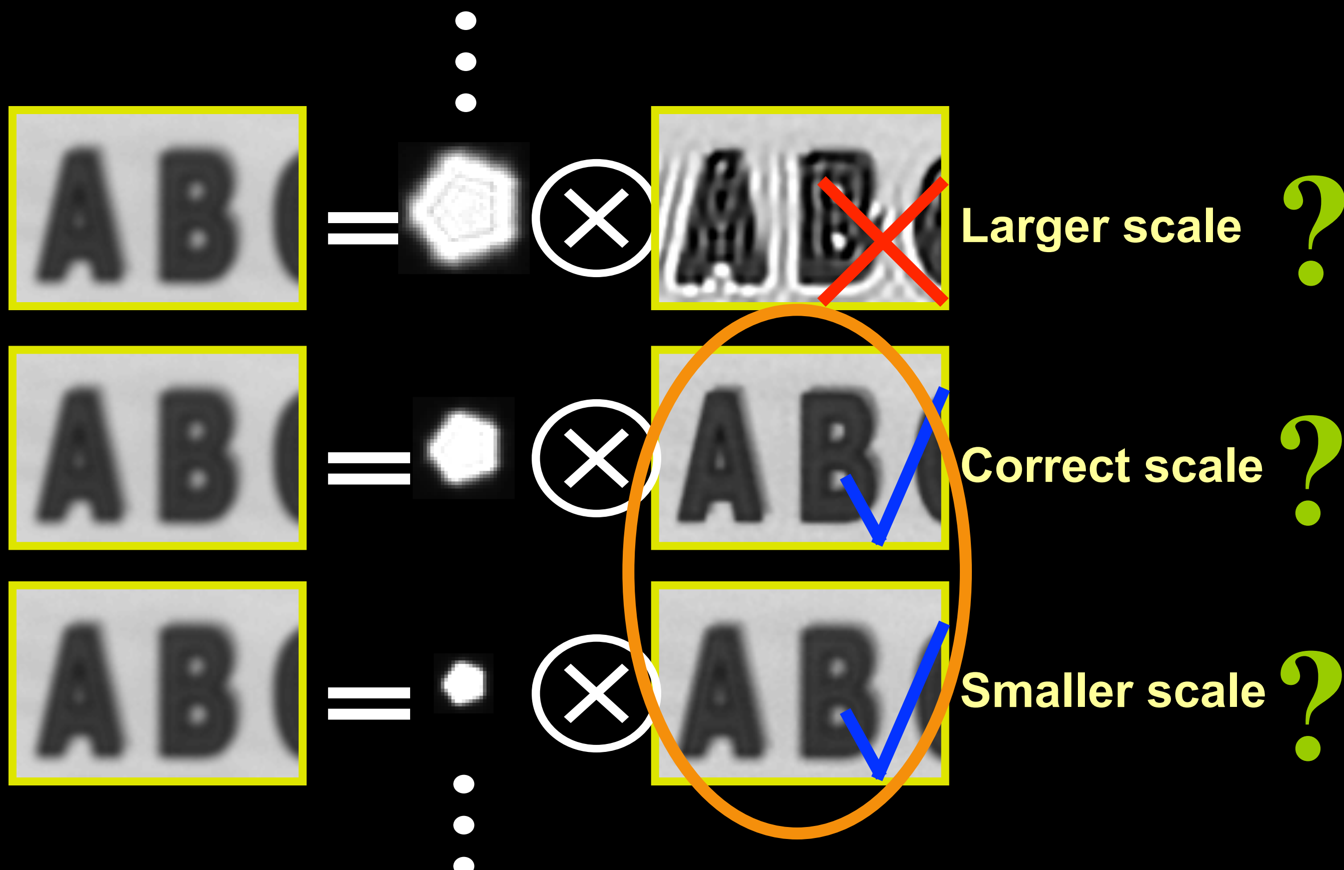
Gaussian prior



Sparse prior

Recall: Overview

Try deconvolving local input windows with different scaled filters:



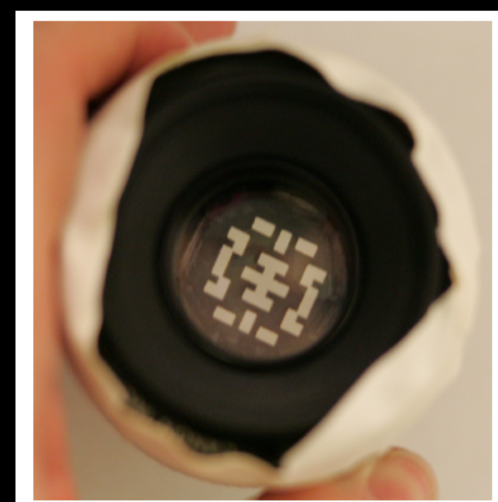
Somehow: select best scale.

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

Idea 2: Coded Aperture

- **Mask (code) in aperture plane**
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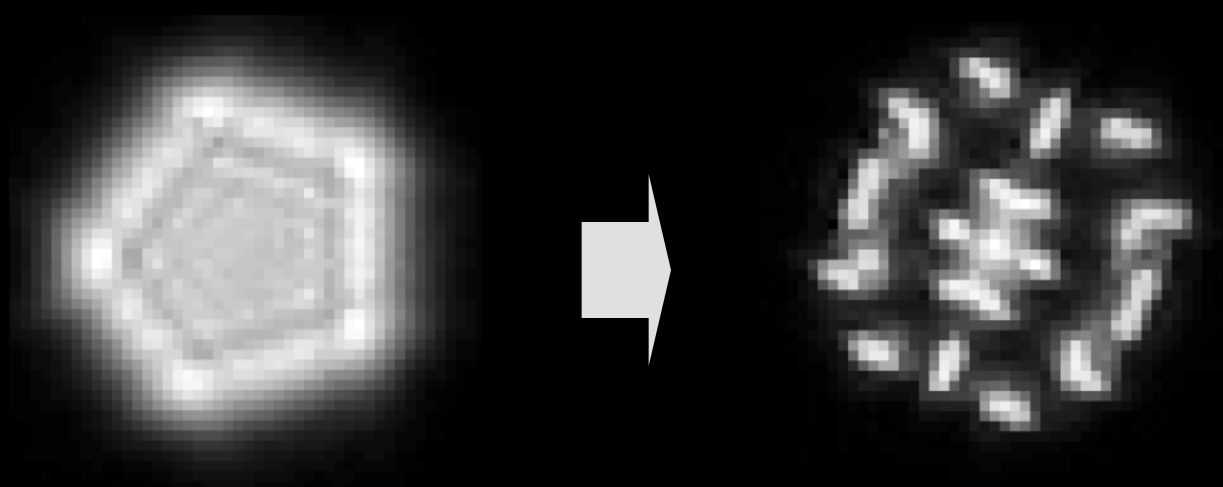

Conventional aperture

Coded aperture

Idea 2: Coded Aperture

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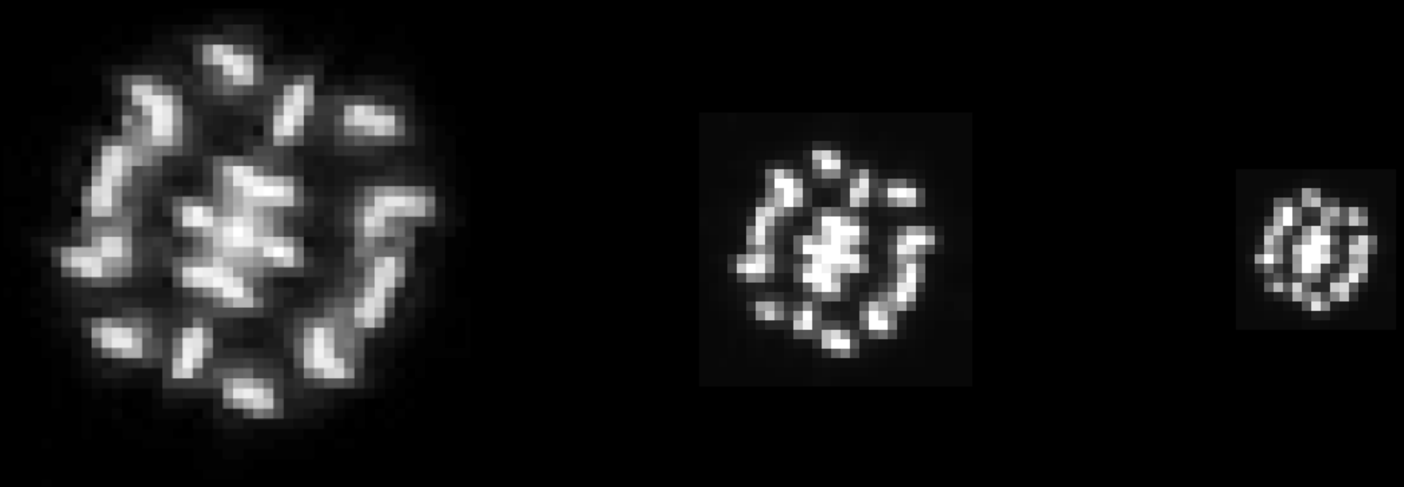
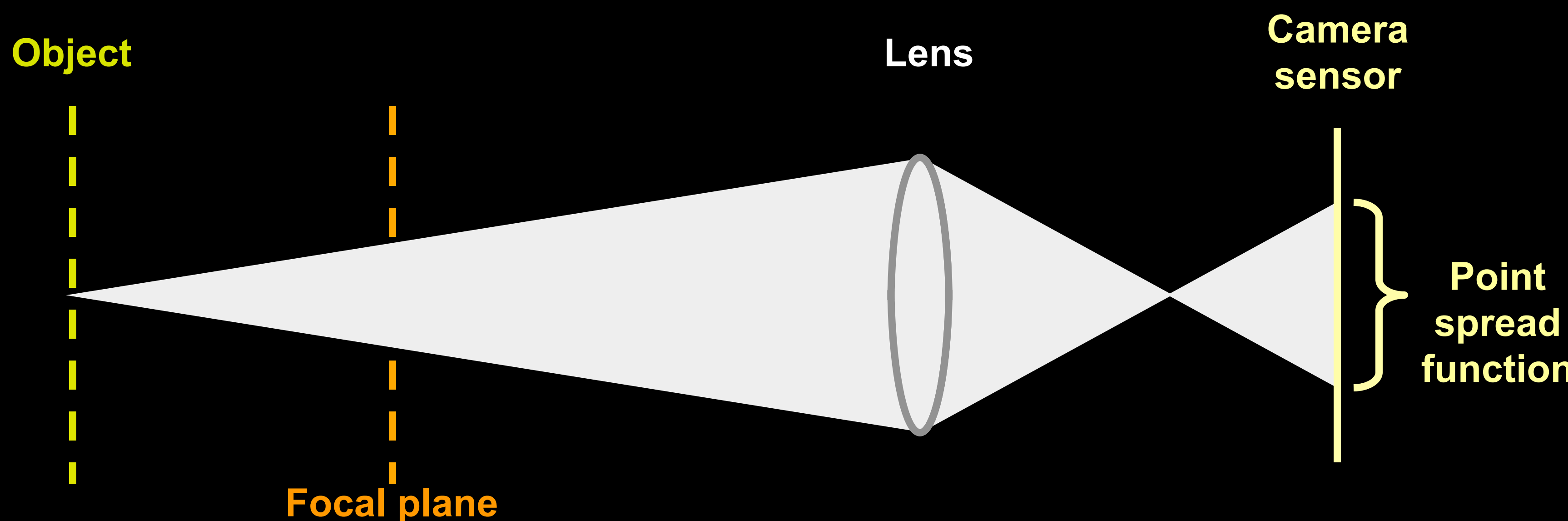


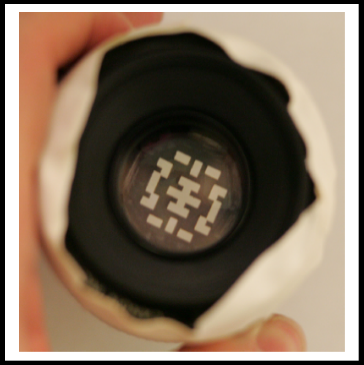
Coded aperture

Solution: lens with occluder



Solution: lens with occluder

Aperture pattern



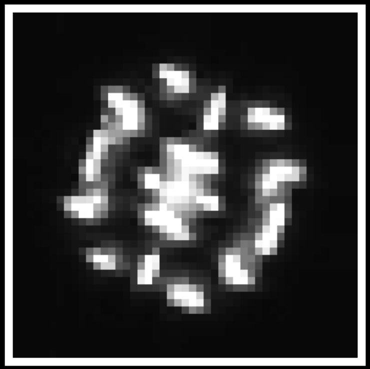
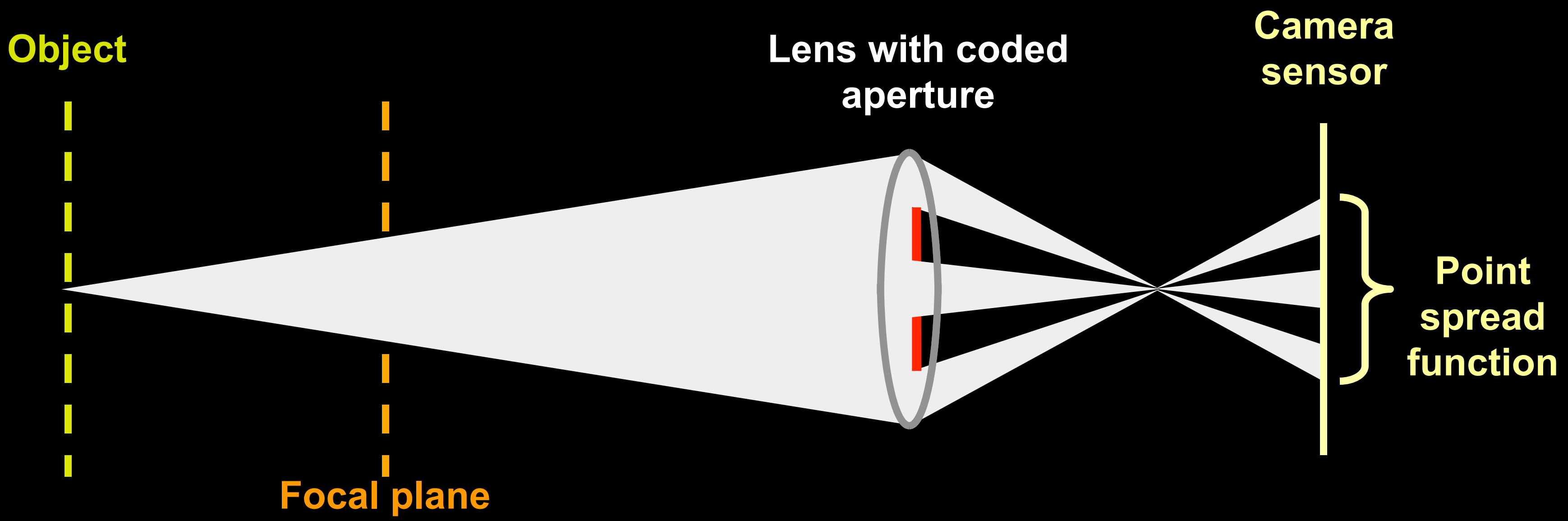


Image of a defocused point light source



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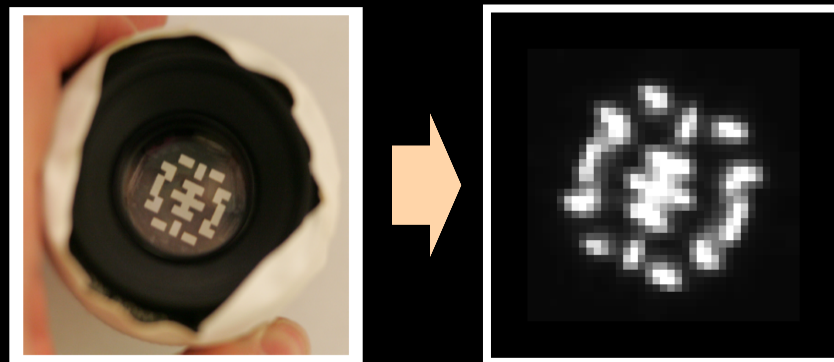
Aperture pattern



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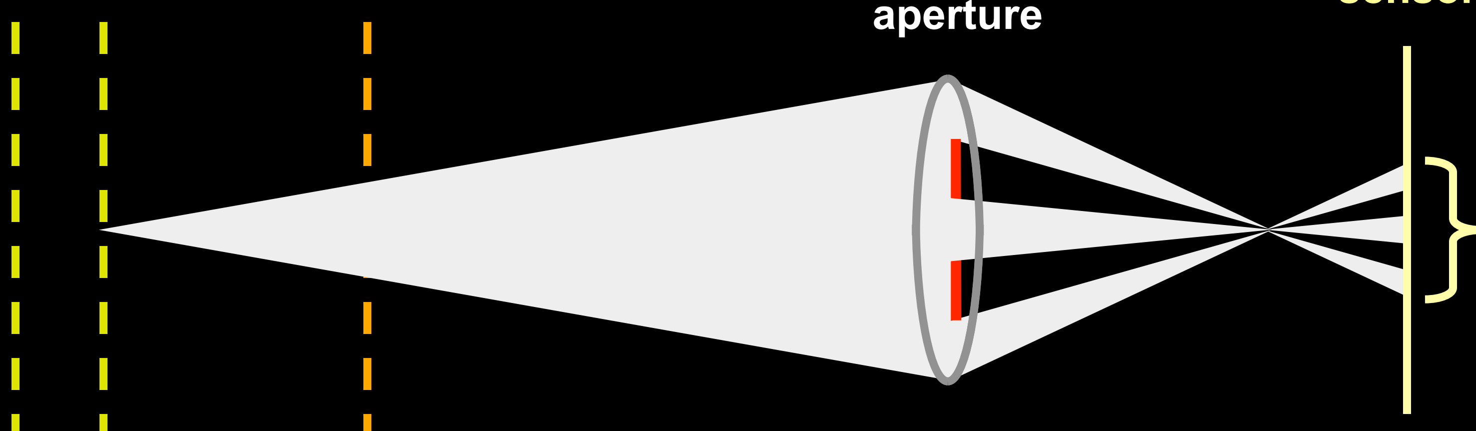
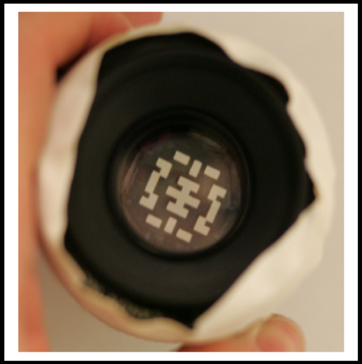


Solution: lens with occluder

Aperture pattern



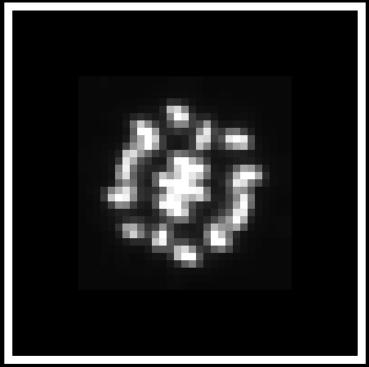
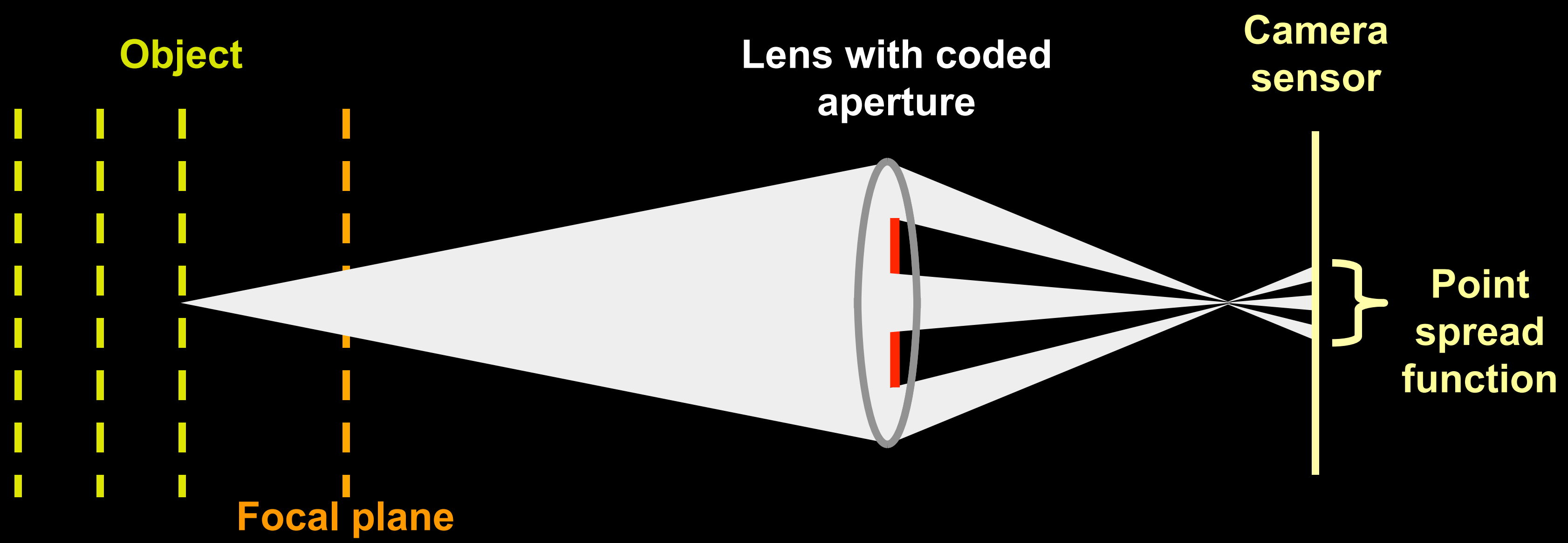


Image of a defocused point light source



Solution: lens with occluder

Aperture pattern

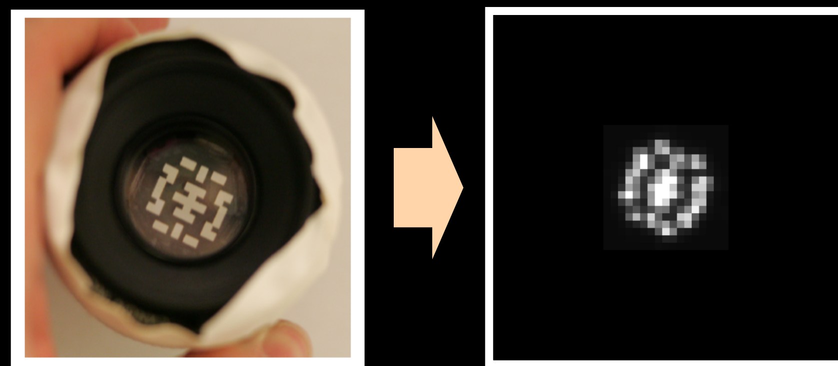
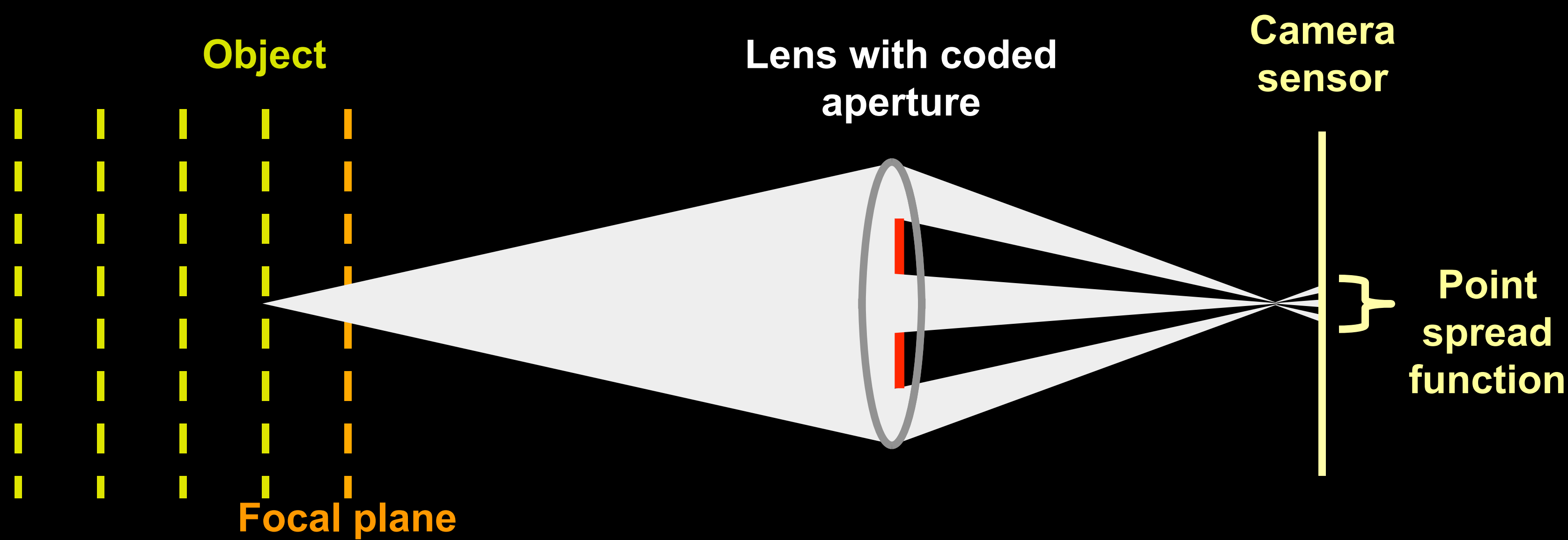


Image of a defocused point light source



Solution: lens with occluder

Aperture pattern

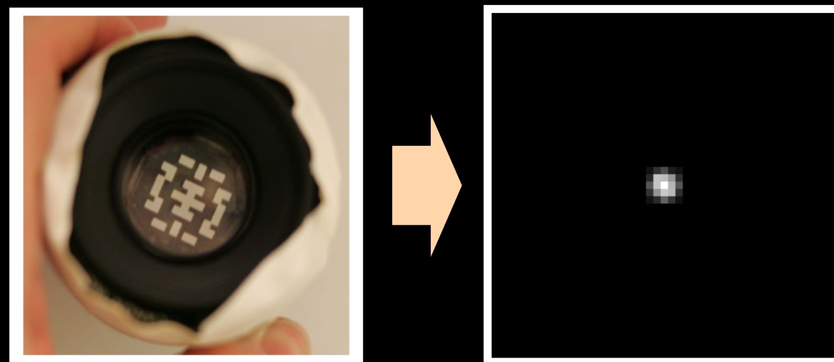
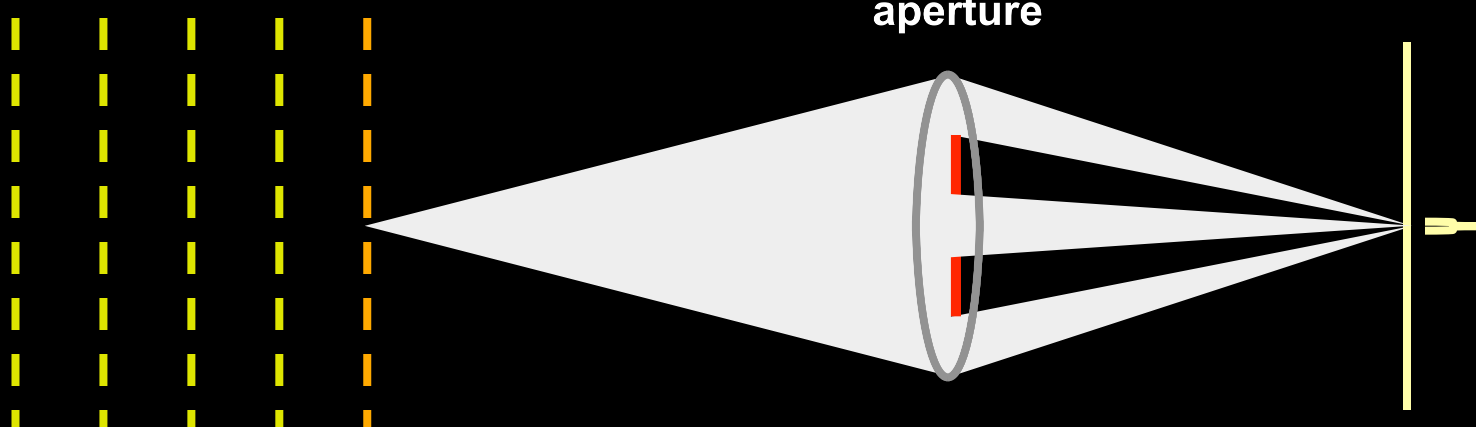
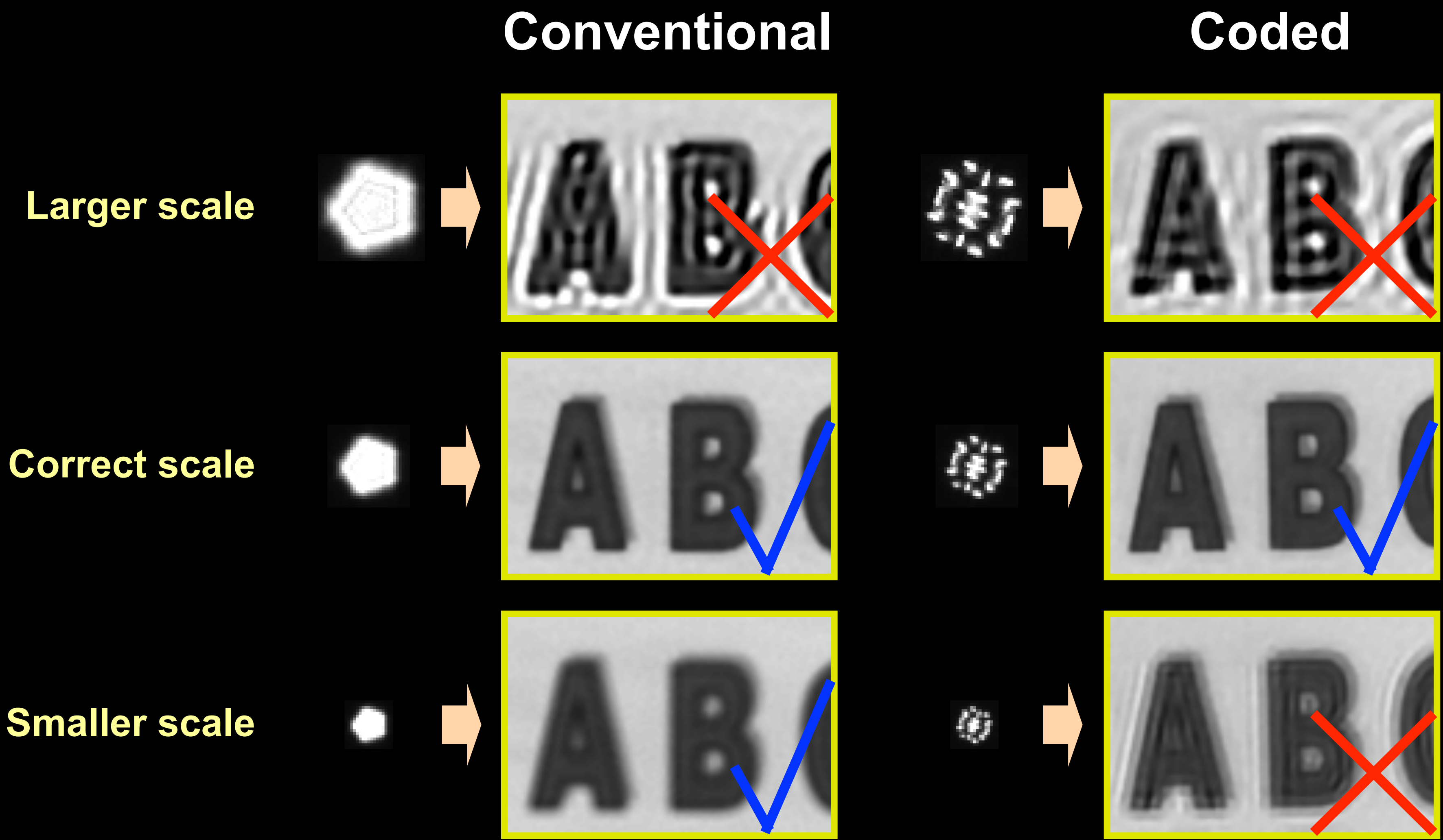


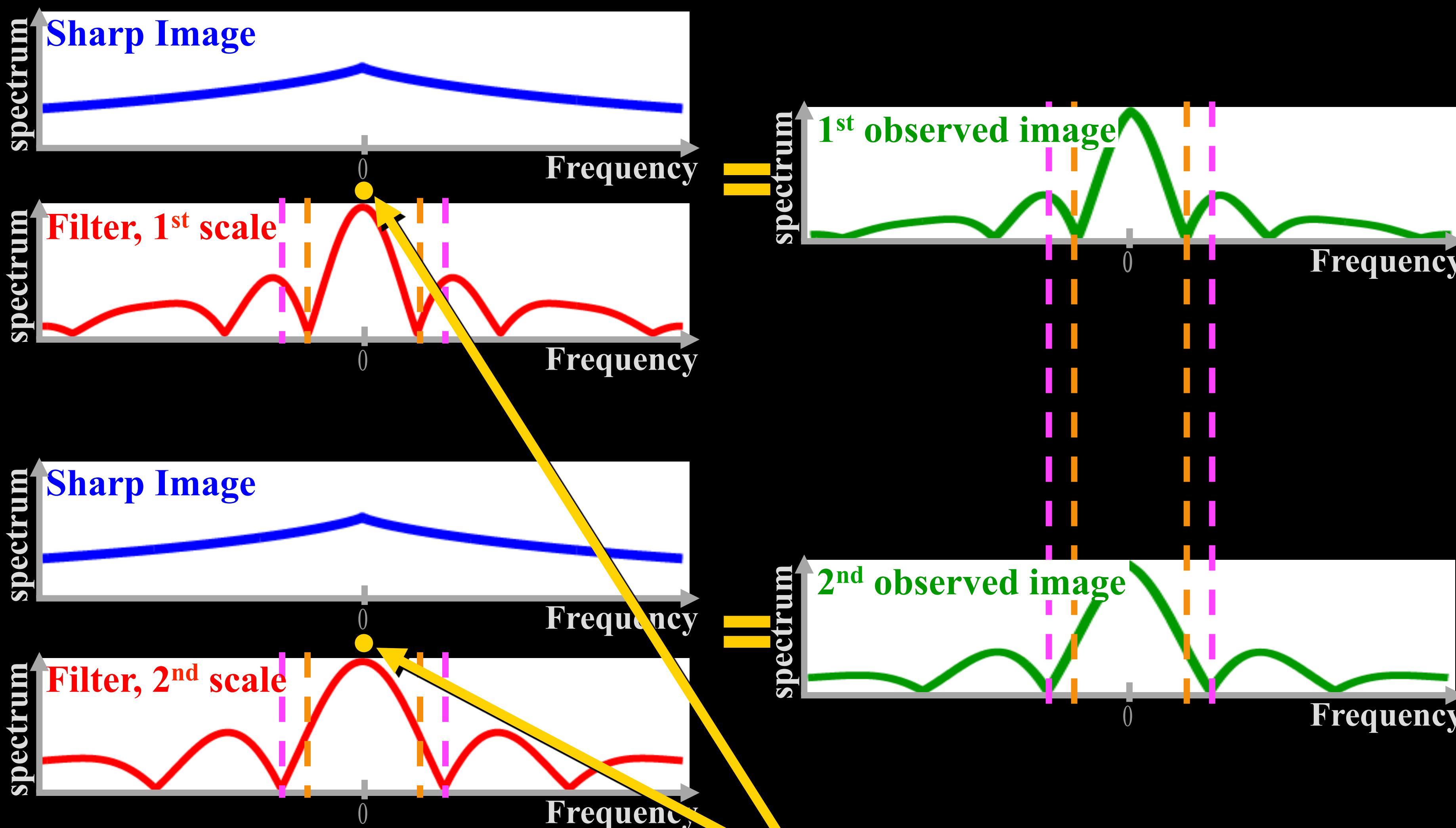
Image of a defocused point light source



Coded aperture reduces uncertainty in scale identification



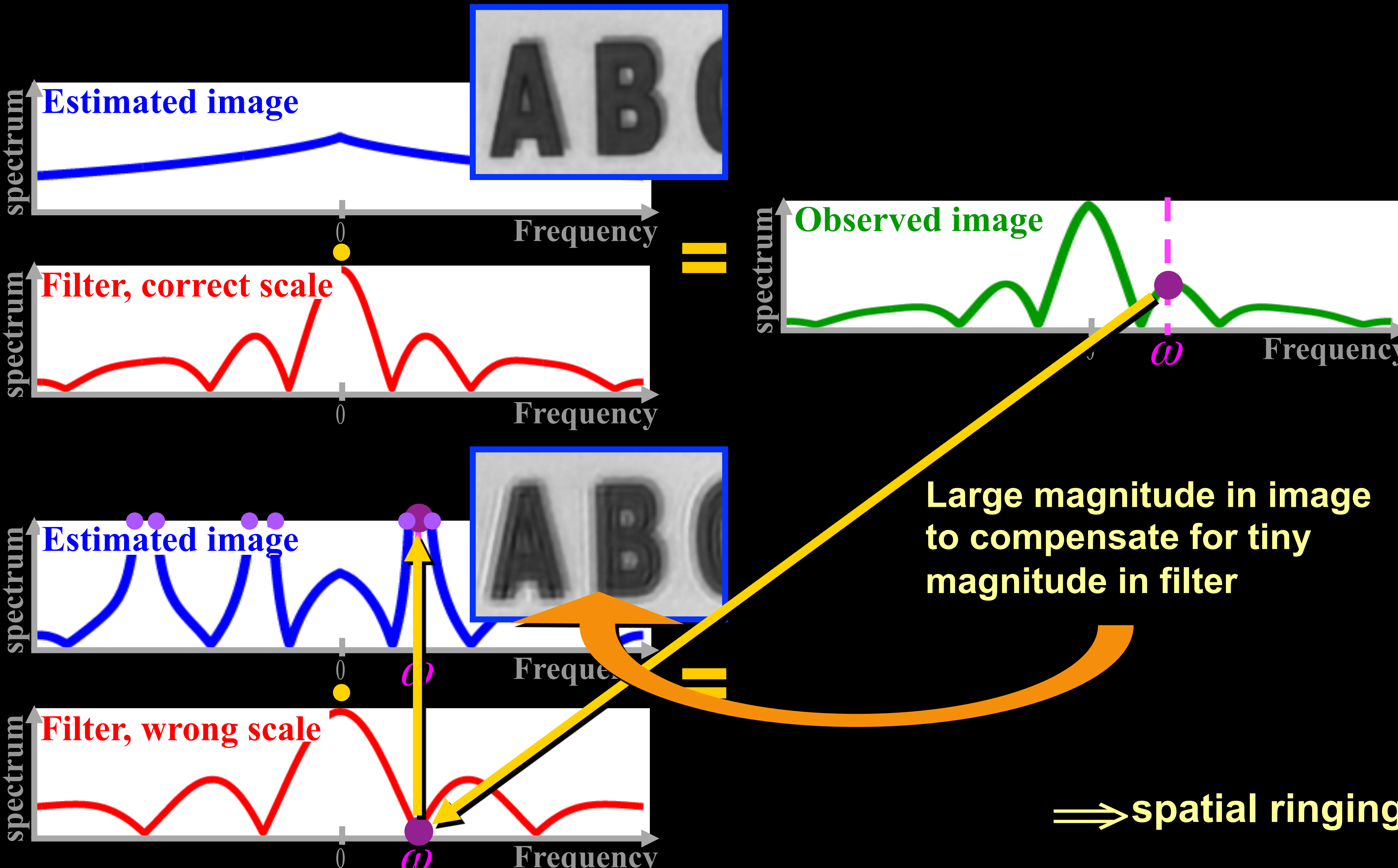
Convolution- frequency domain representation



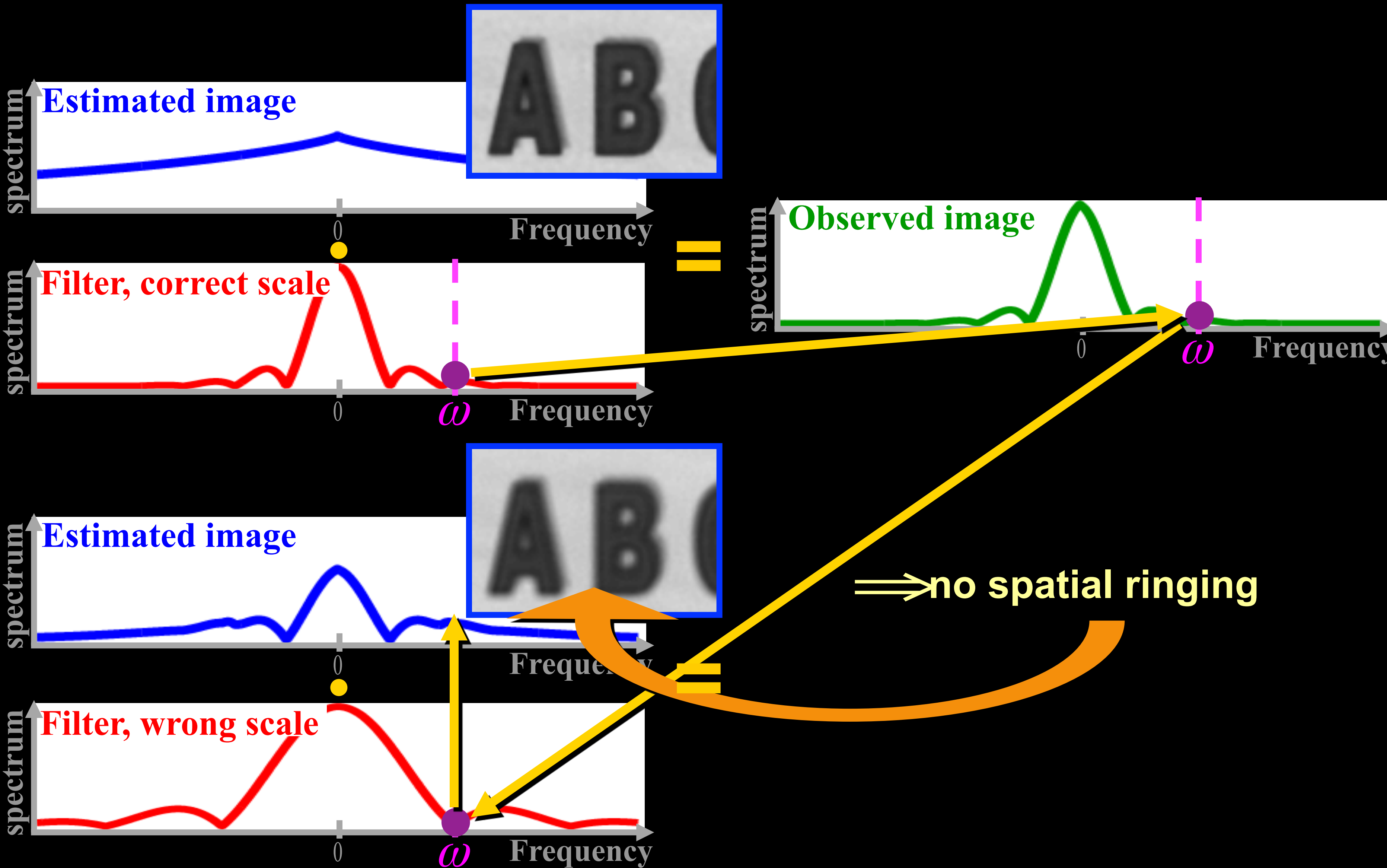
Output spectrum has zeros where filter spectrum has zeros

Spatial convolution ⇔ frequency multiplication

Coded aperture: Scale estimation and division by zero



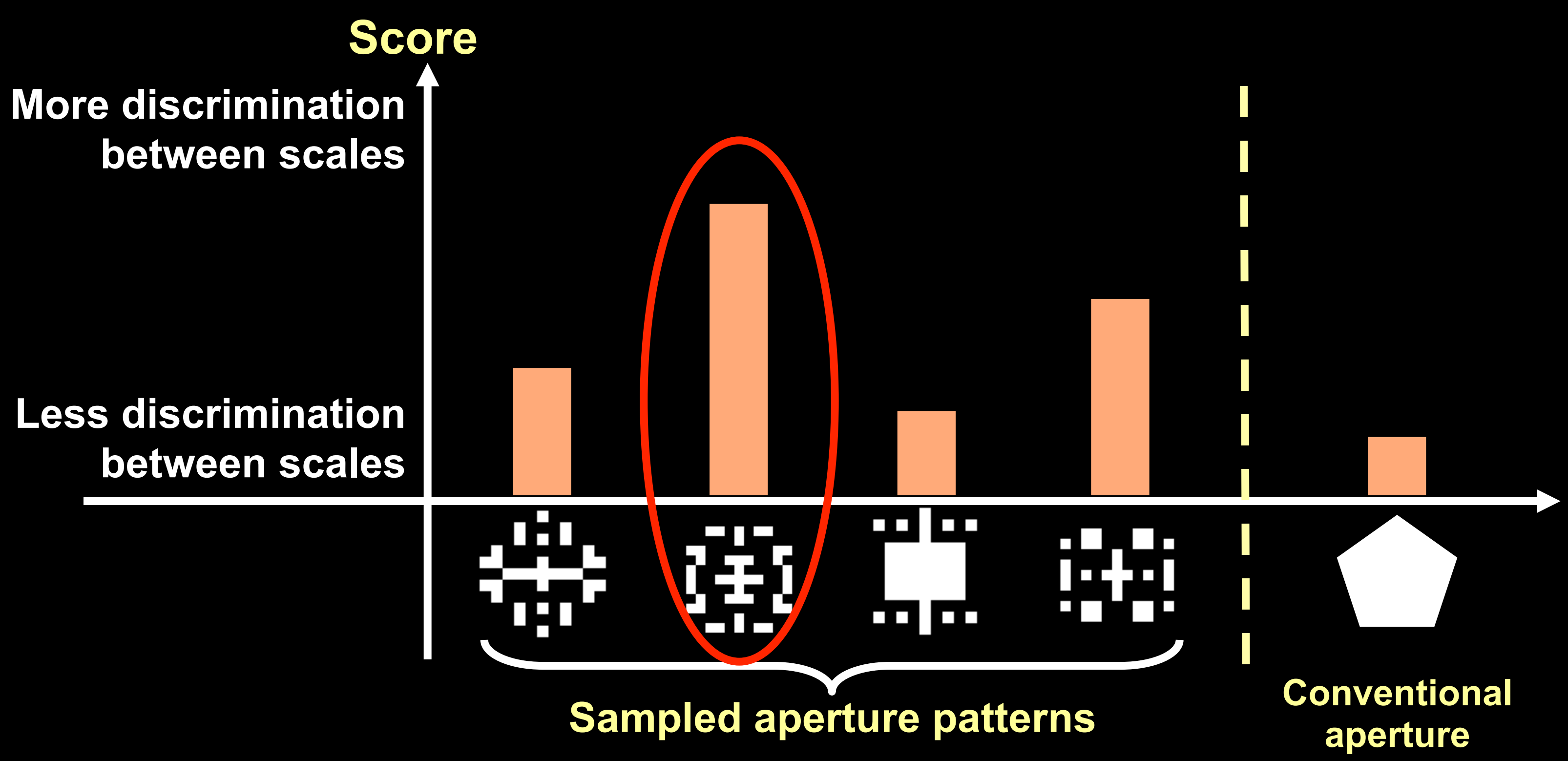
Division by zero with a conventional aperture?



Filter Design

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

Account for image prior and physical constraints

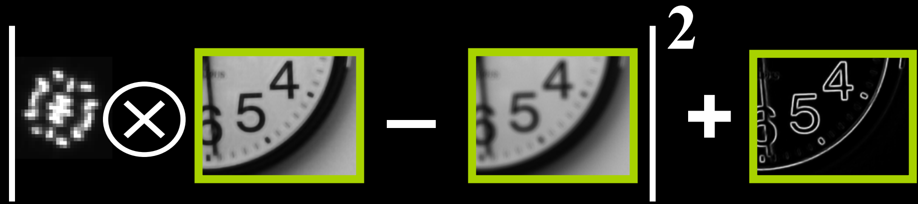


Depth results

Regularizing depth estimation

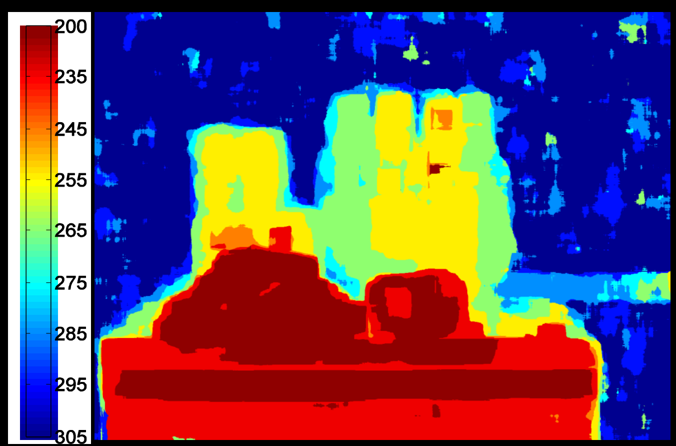
Try deblurring with 10 different aperture scales

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



Keep minimal error scale in each local window + regularization

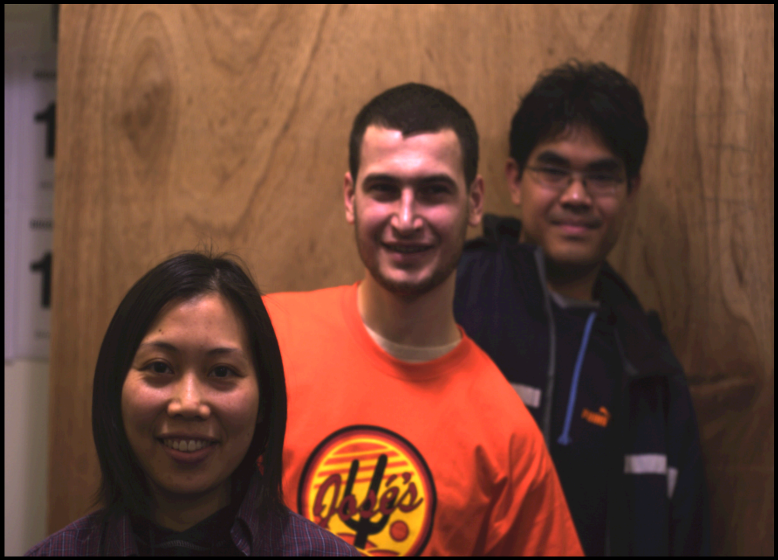
Input



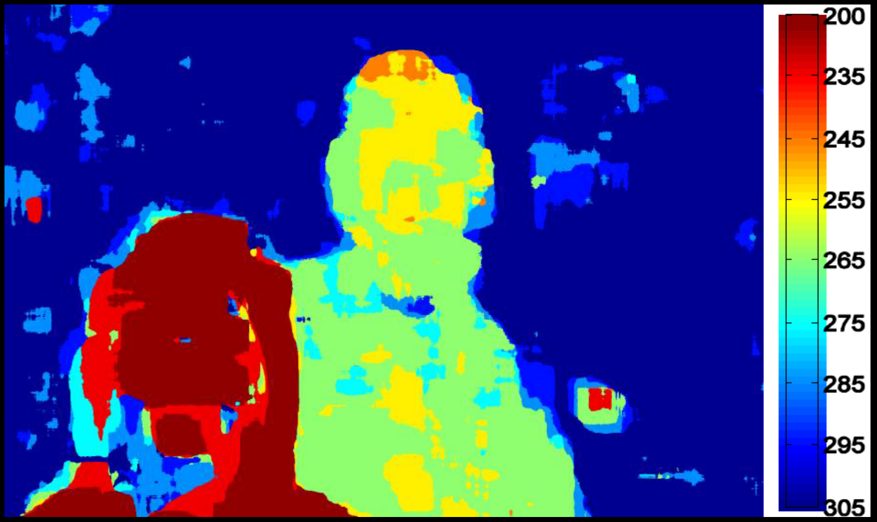
Local depth estimation

Regularized depth

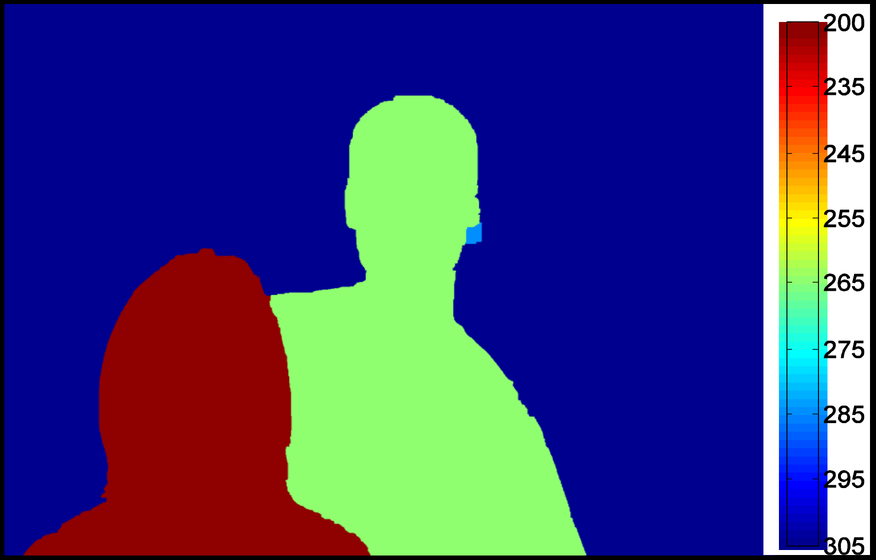
Regularizing depth estimation



Input



Local depth estimation



Regularized depth

All focused results

Input


Coca-Cola
COBRA
Natural
40
OLDE ENGLISH
"800"
CLASSIC
Coca-Cola

All-focused (deconvolved)

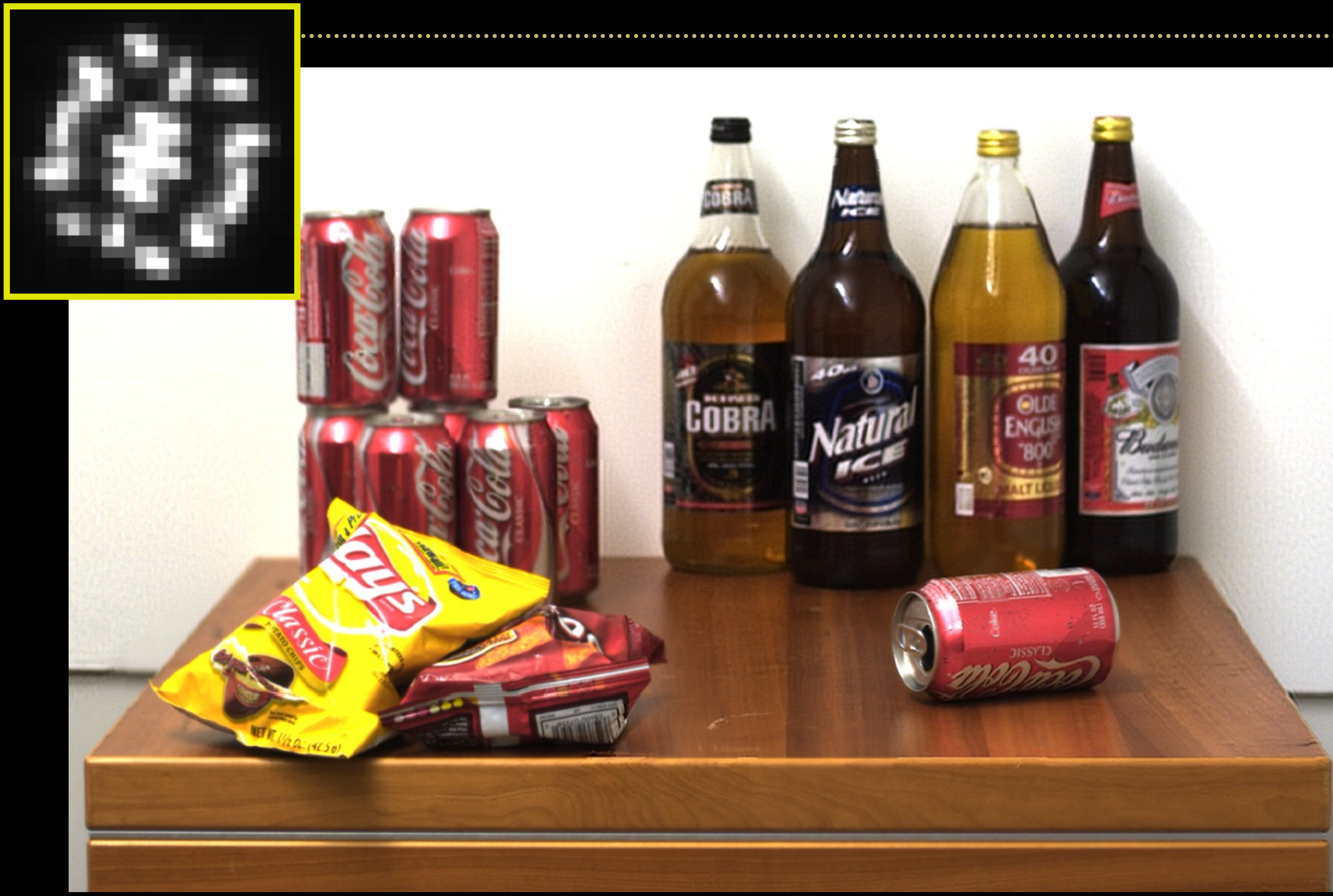
Close-up

Original image

All-focus image

Comparison- conventional aperture result

Comparison- coded aperture result



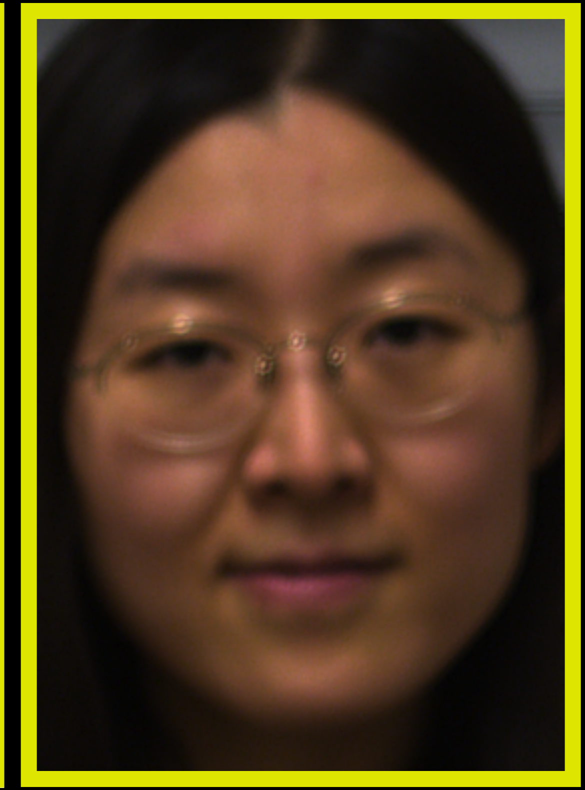

Input


All-focused
(deconvolved)

Close-up

Original image

All-focus image



Naïve sharpening

Application: Digital refocusing from a single image

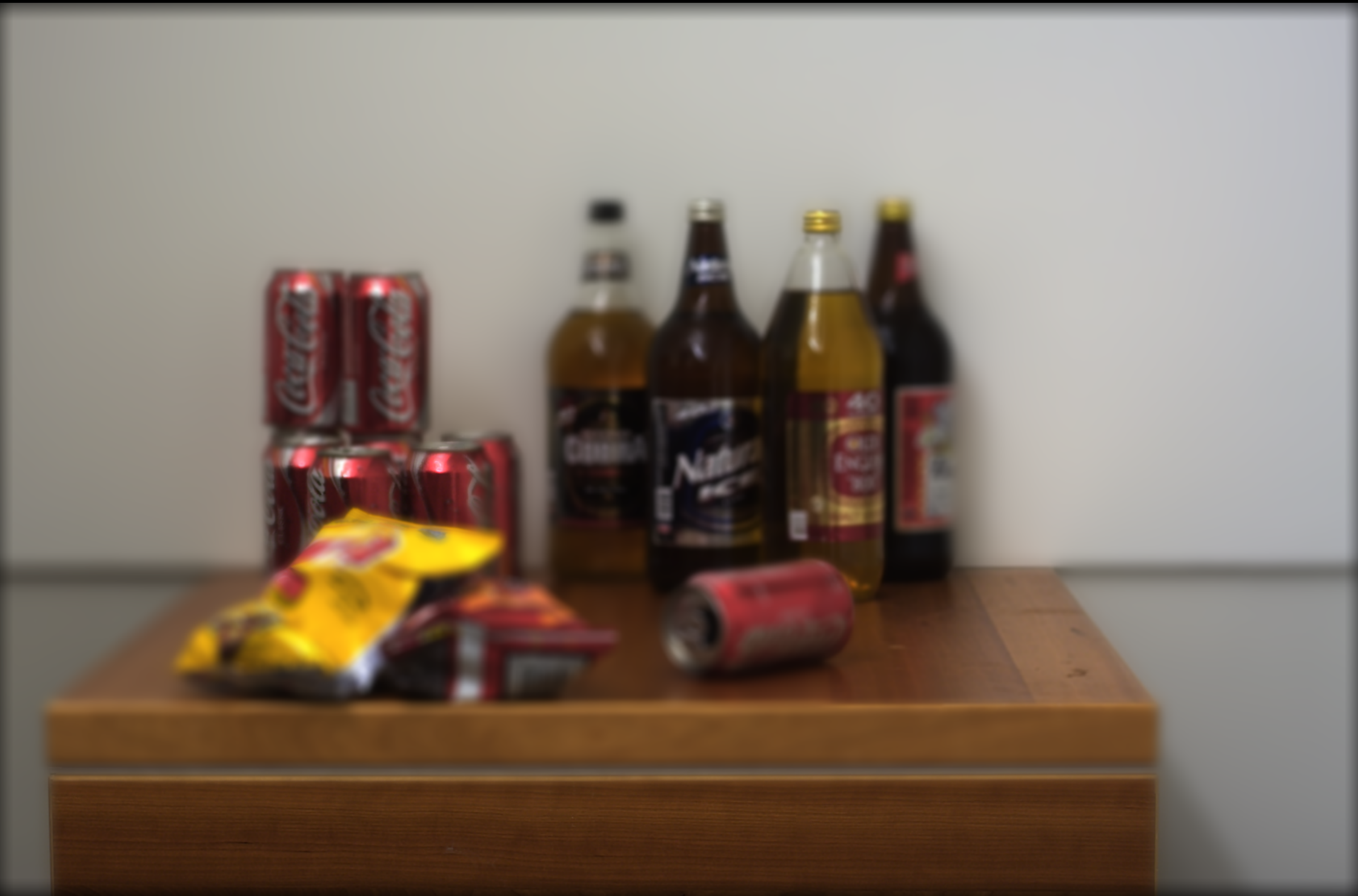
Application: Digital refocusing from a single image

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

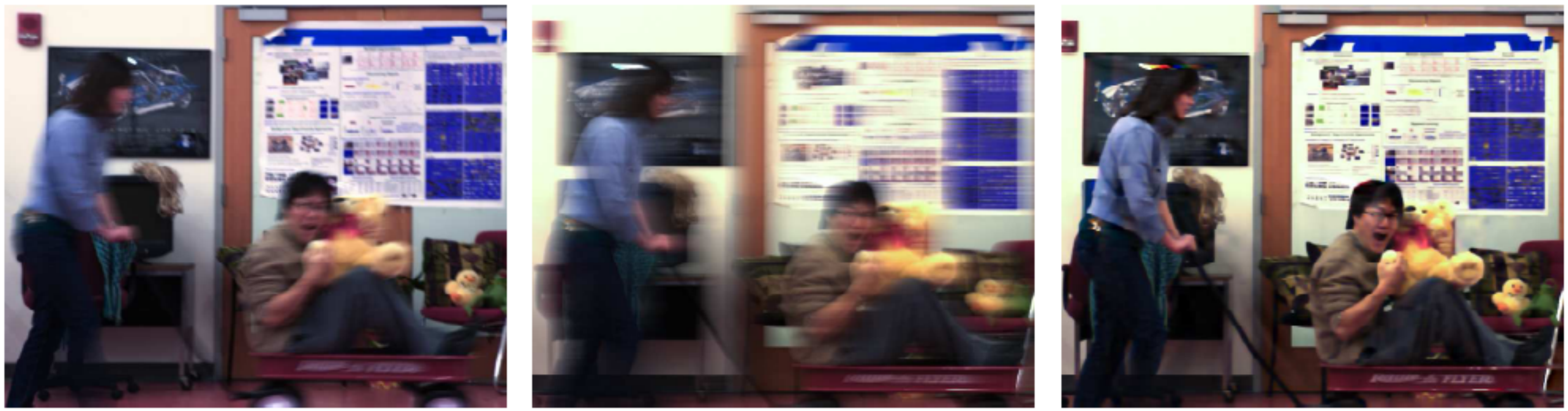
CodedAperture

Some more quick examples

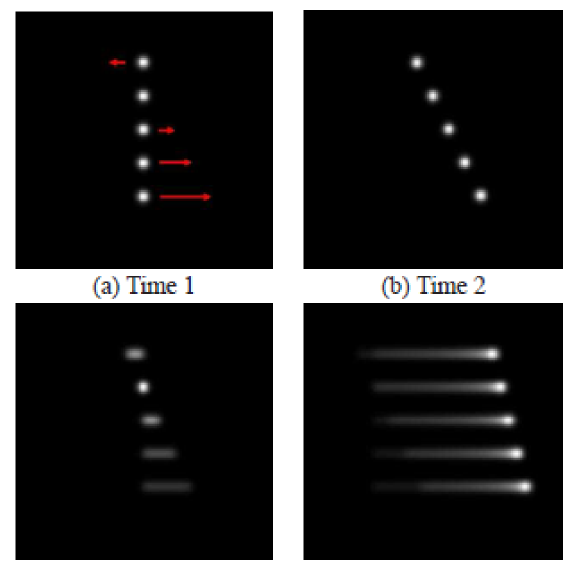
Motion-Invariant Photography

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

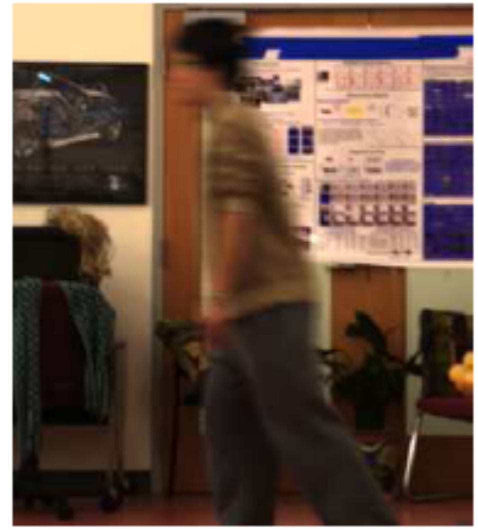


(a) Time 1 (b) Time 2

(c) Static camera (d) Parabolic camera

Results

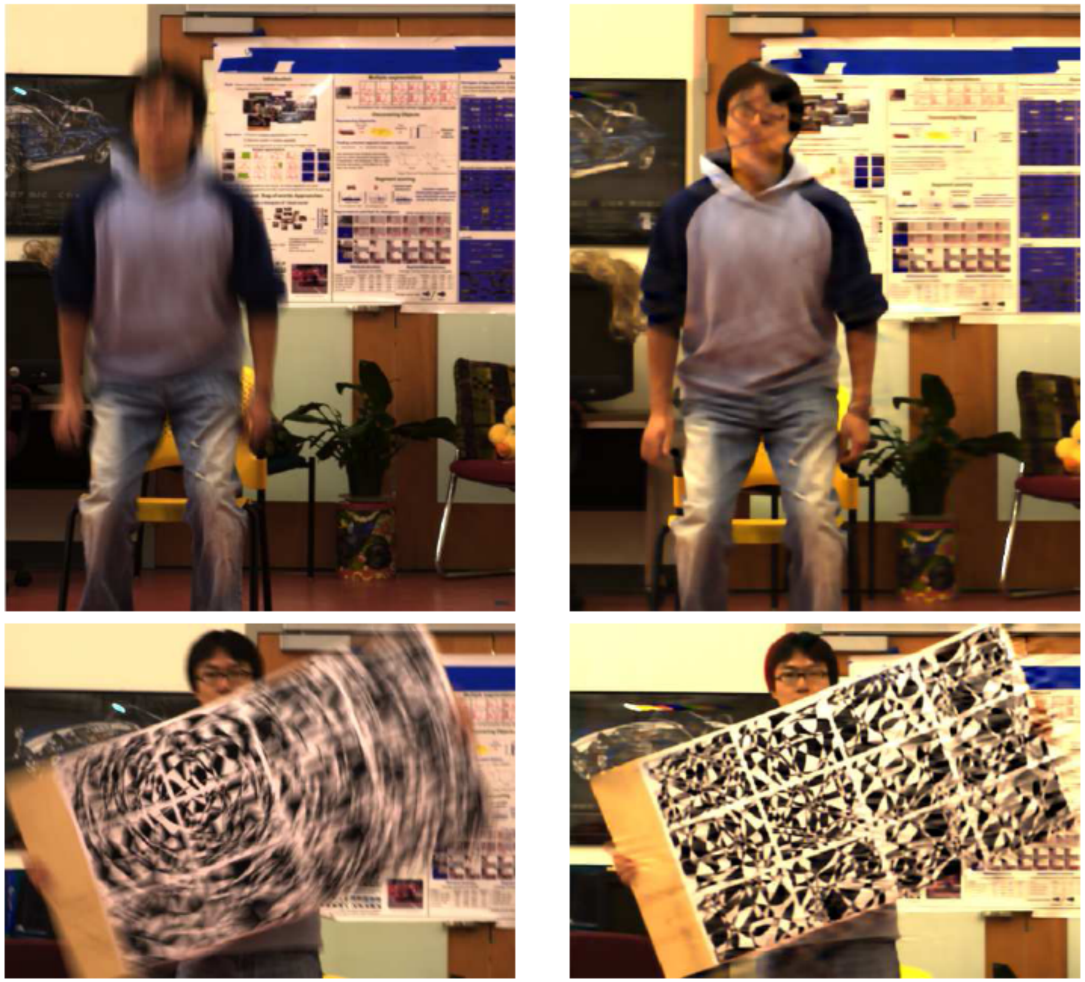
Static Camera



Parabolic Camera

Results

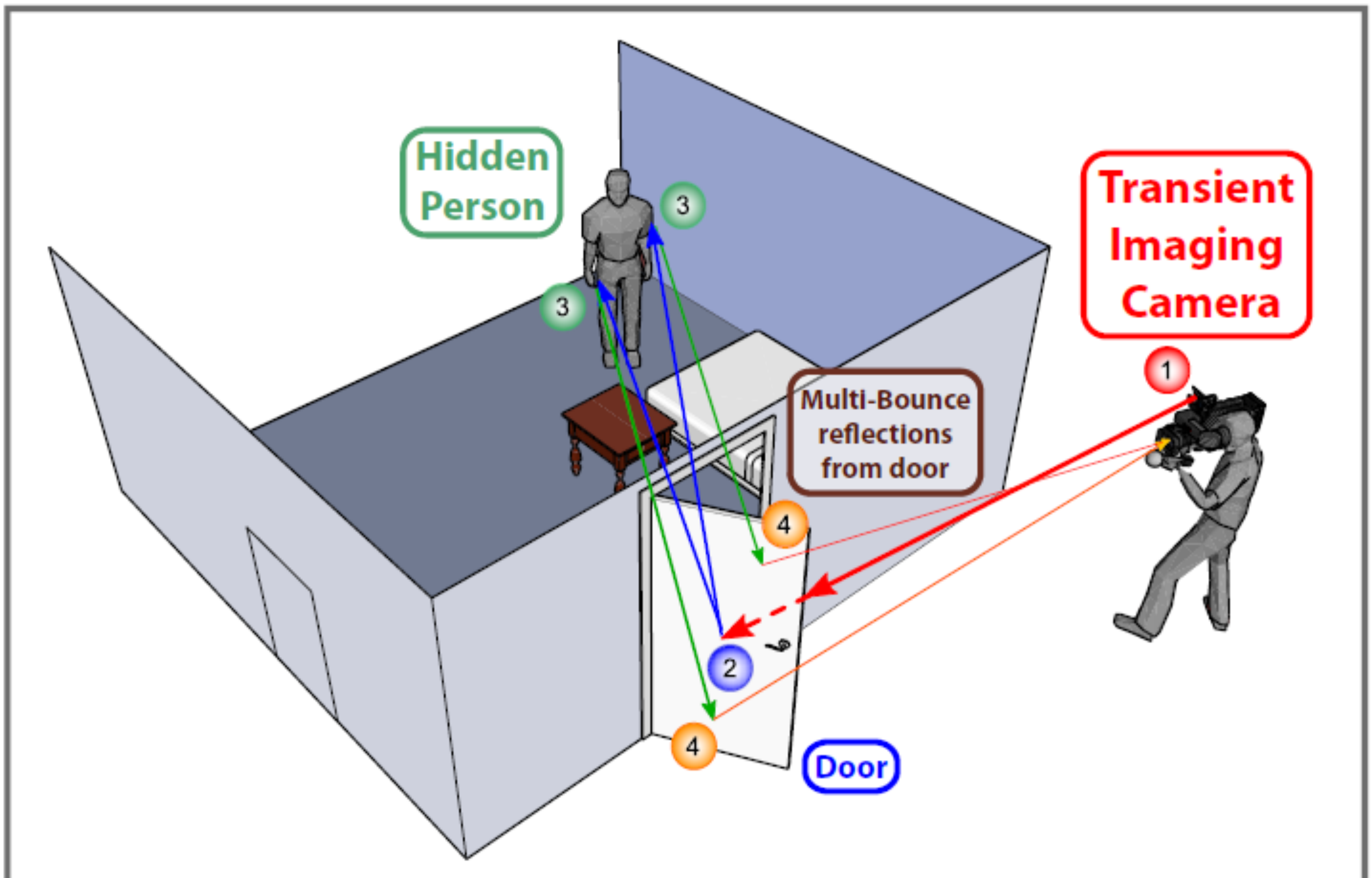
Static Camera | Parabolic Camera



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



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

- Exam review