

Computational Imaging

Lecture 23: Spatial Encoding: Coded Photography



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点昀技术（Point Spread Technology）



Today's Topic

- The Coded Photography Paradigm
- Dealing with Depth Blur: Coded Aperture
- Dealing with Depth Blur: Focal Sweep
- Dealing with Depth Blur: Generalized Optics

The Coded Photography Paradigm

Conventional Photography



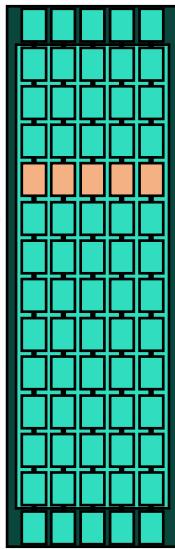
real world



optics



captured image



computation

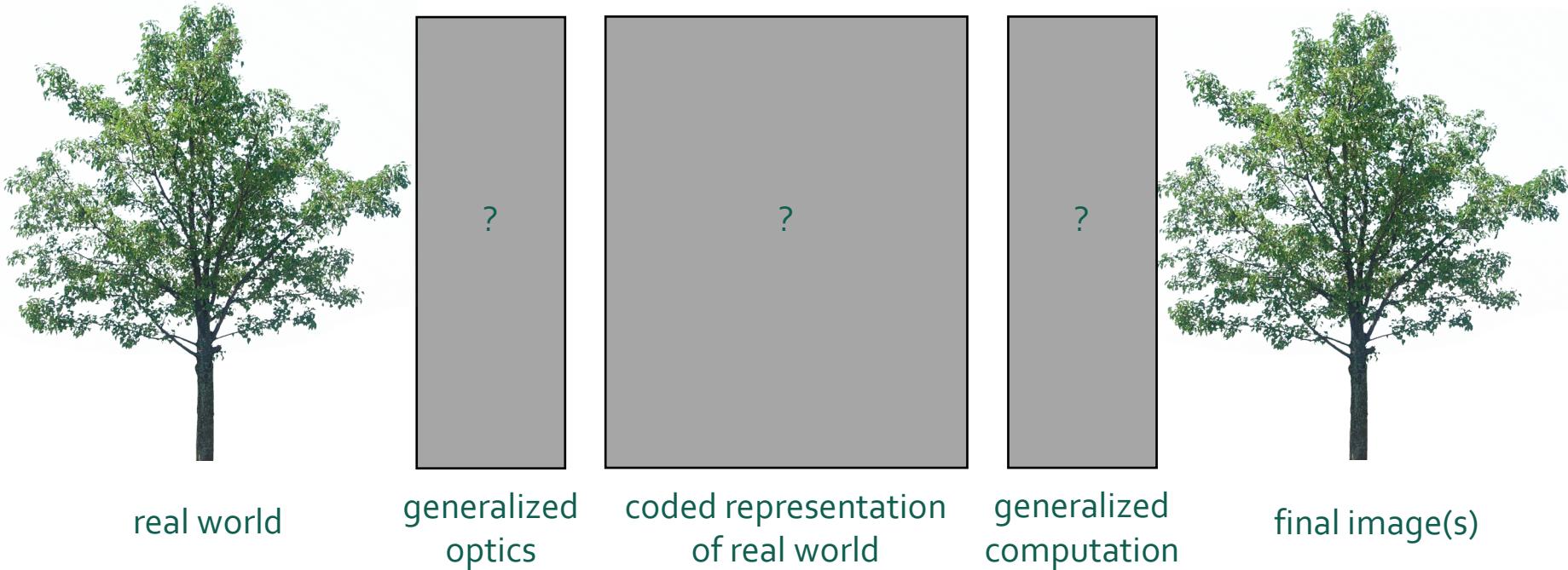


enhanced image

- Optics capture something that is (close to) the final image.
- Computation mostly “enhances” captured image (e.g., deblur).



Coded Photography



- Generalized optics encode world into intermediate representation.
- Generalized computation decodes representation into multiple images.

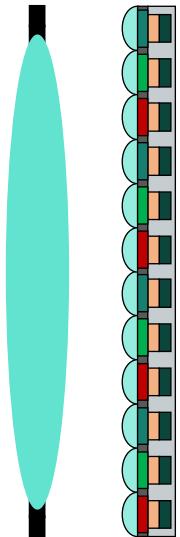
Can you think of
any examples?



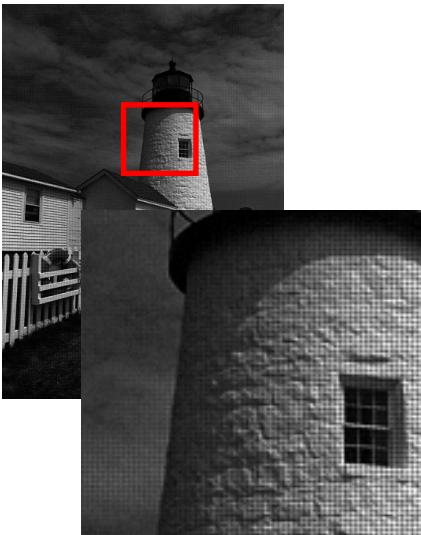
Early Example: Mosaicing



real world



generalized optics



coded representation of real world



generalized computation



final image(s)

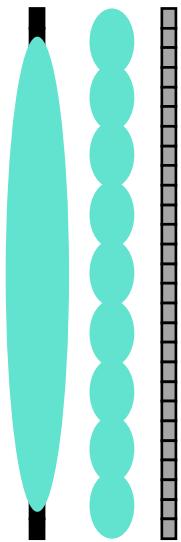
- Color filter array encodes color into a mosaic.
- Demosaicing decodes color into RGB image.



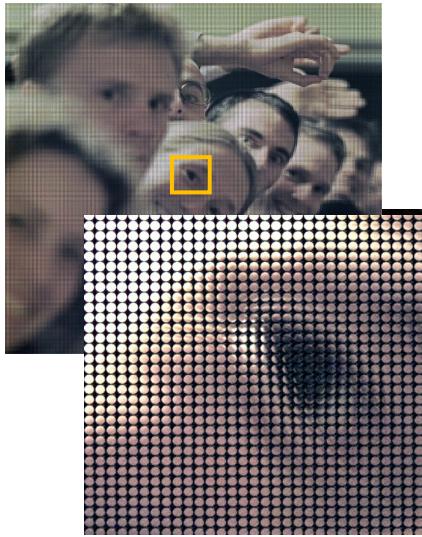
Recent Example: Plenoptic Camera



real world



generalized
optics



coded representation
of real world



generalized
computation



final image(s)

- Plenoptic camera encodes world into lightfield.
- Lightfield rendering decodes lightfield into refocused or multi-viewpoint images.

Why Are Our Images Blurry?

- Lens imperfections. ← previous lecture: deconvolution
- Camera shake. ← previous lecture: blind deconvolution
- Scene motion. ← flutter shutter, motion-invariant photo
- Depth defocus. ← coded aperture, focal sweep, lattice lens

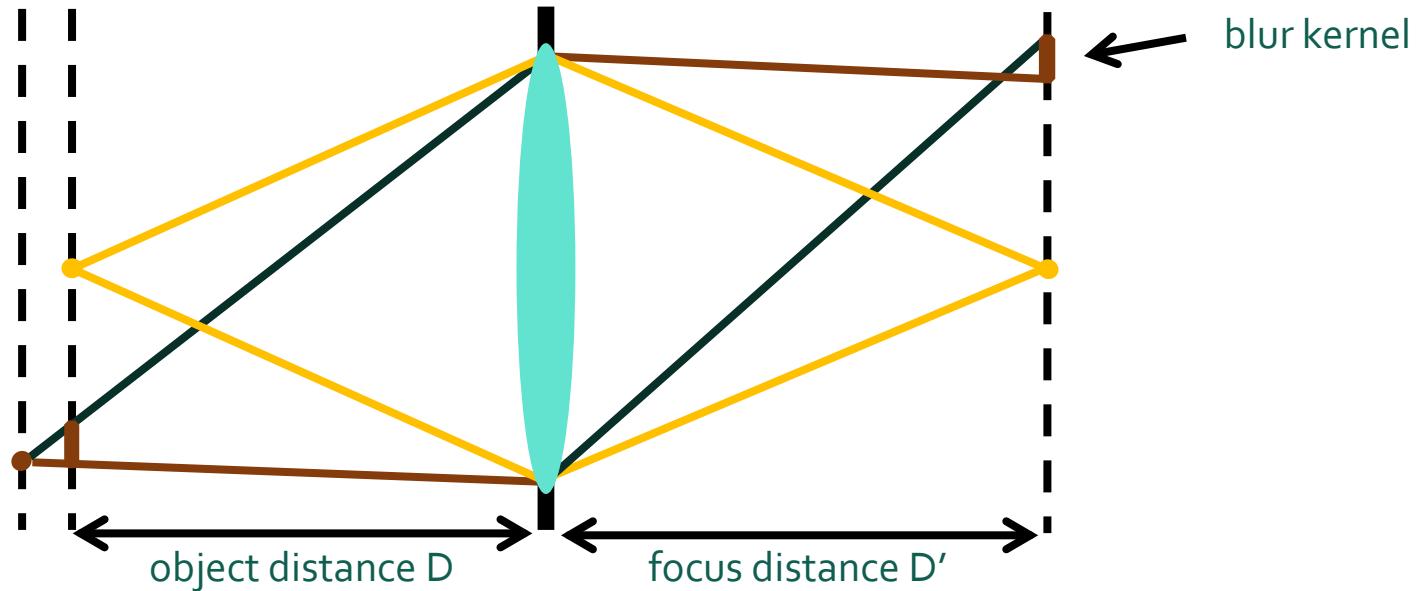
} conventional photography
} coded photography

Dealing with Depth Blur: Coded Aperture



Defocus Blur

Point spread function (PSF): The blur kernel of a (perfect) lens at some out-of-focus depth.

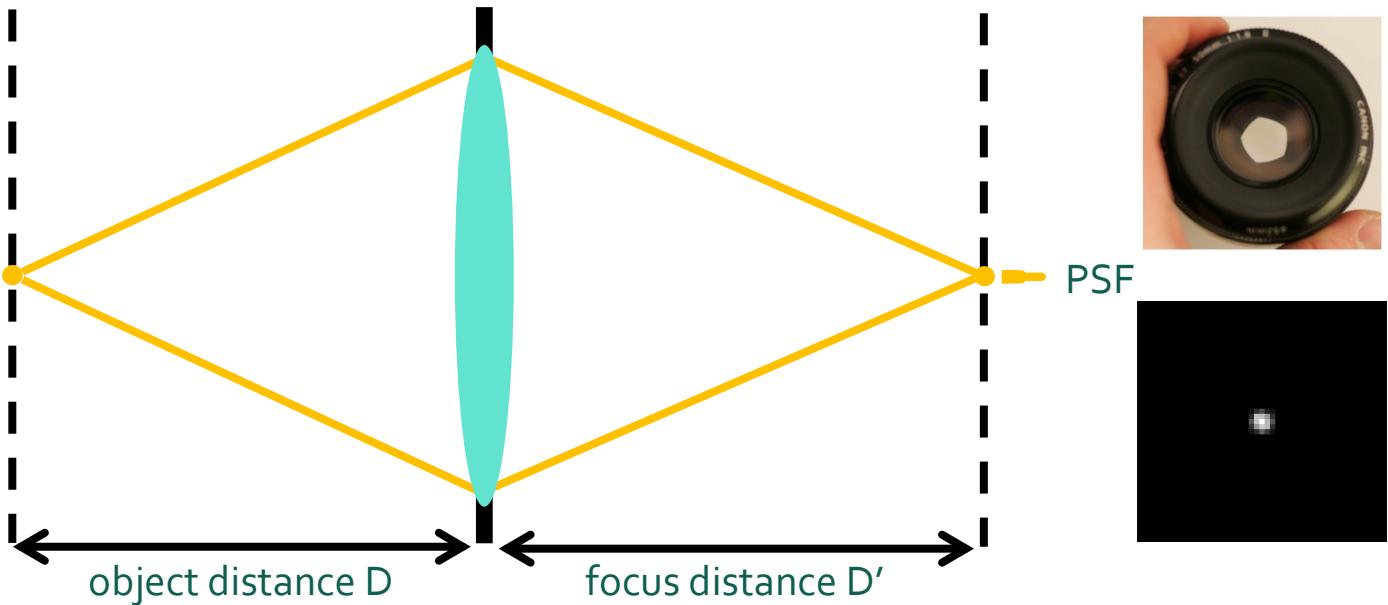


- Aperture determines *shape* of kernel.
- Depth determines *scale* of blur kernel.

What does the blur kernel depend on?

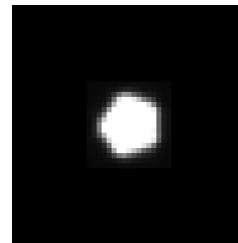
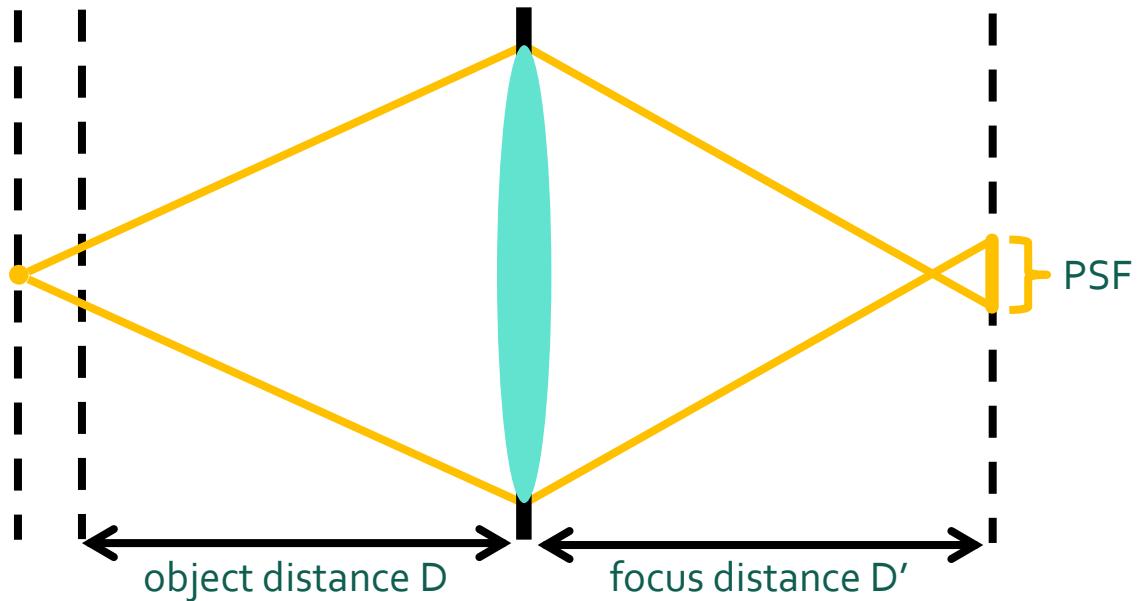


Depth Determines Scale of Blur Kernel



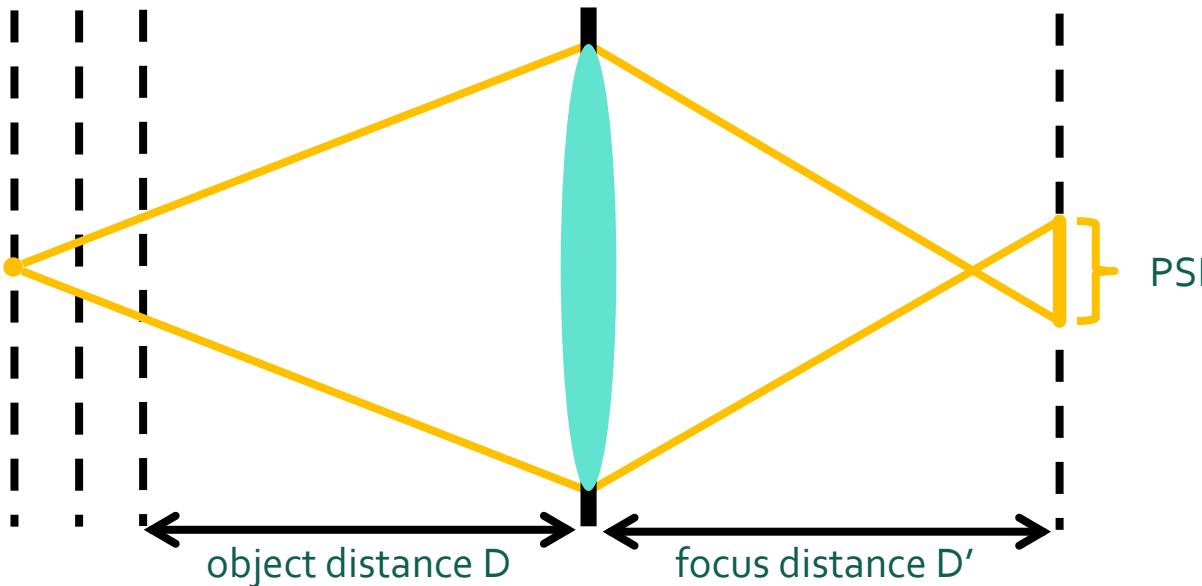


Depth Determines Scale of Blur Kernel

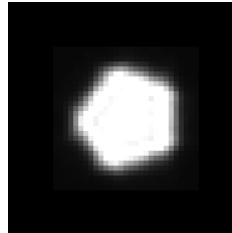




Depth Determines Scale of Blur Kernel

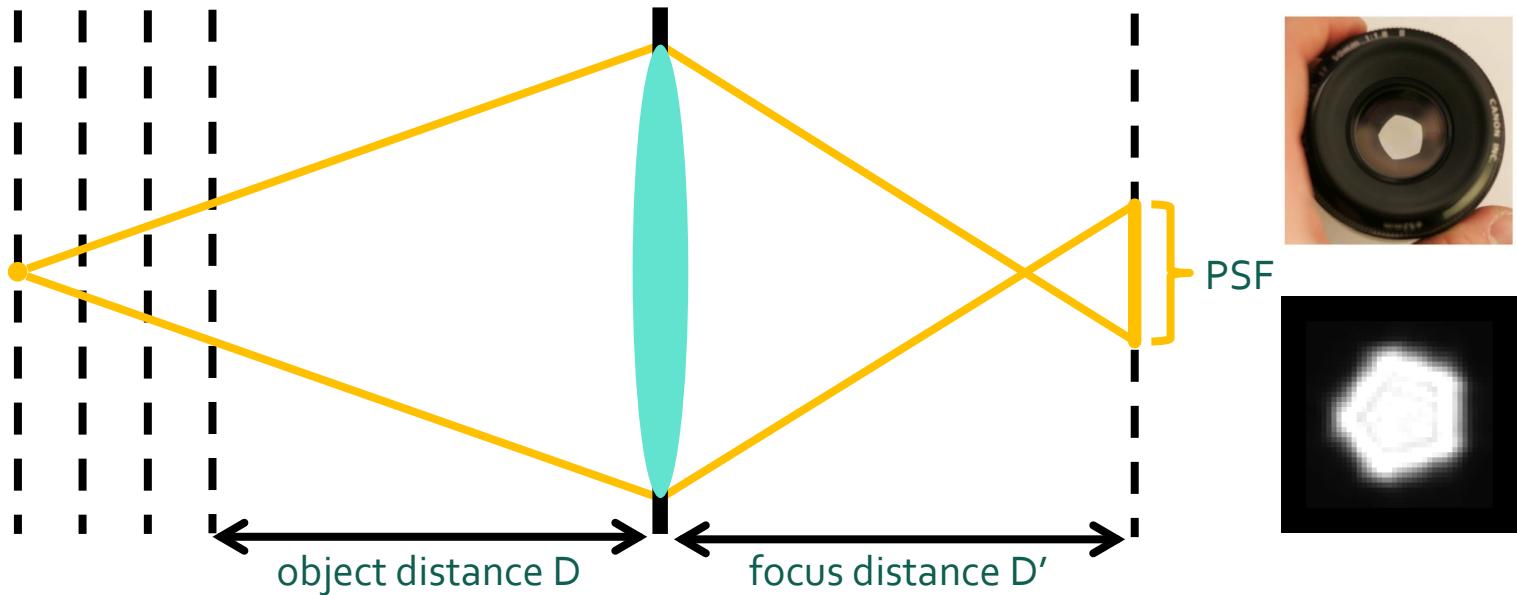


PSF



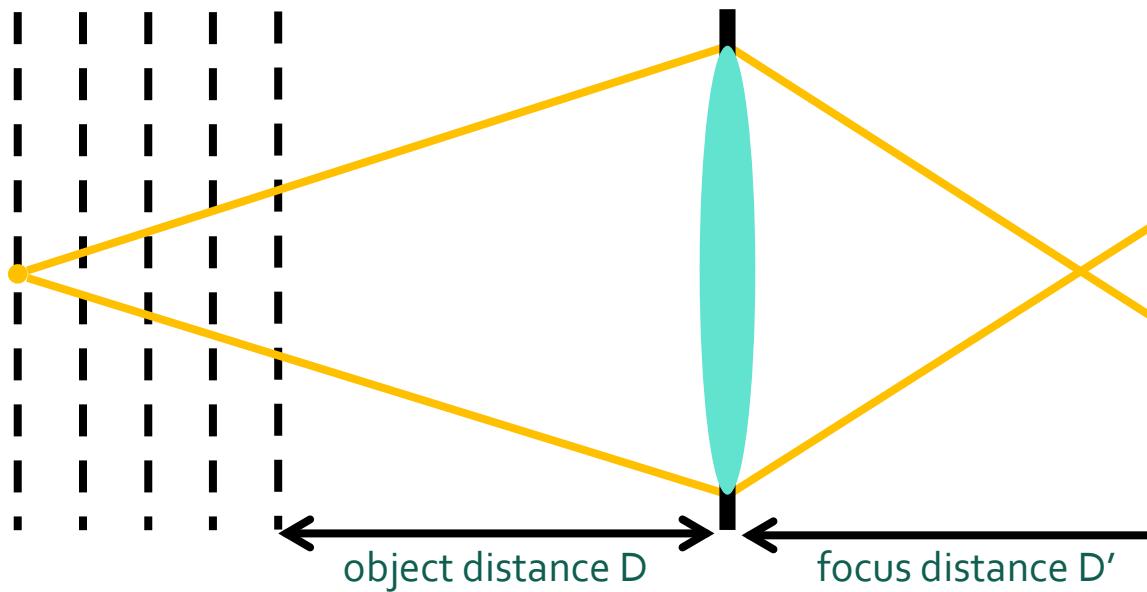


Depth Determines Scale of Blur Kernel





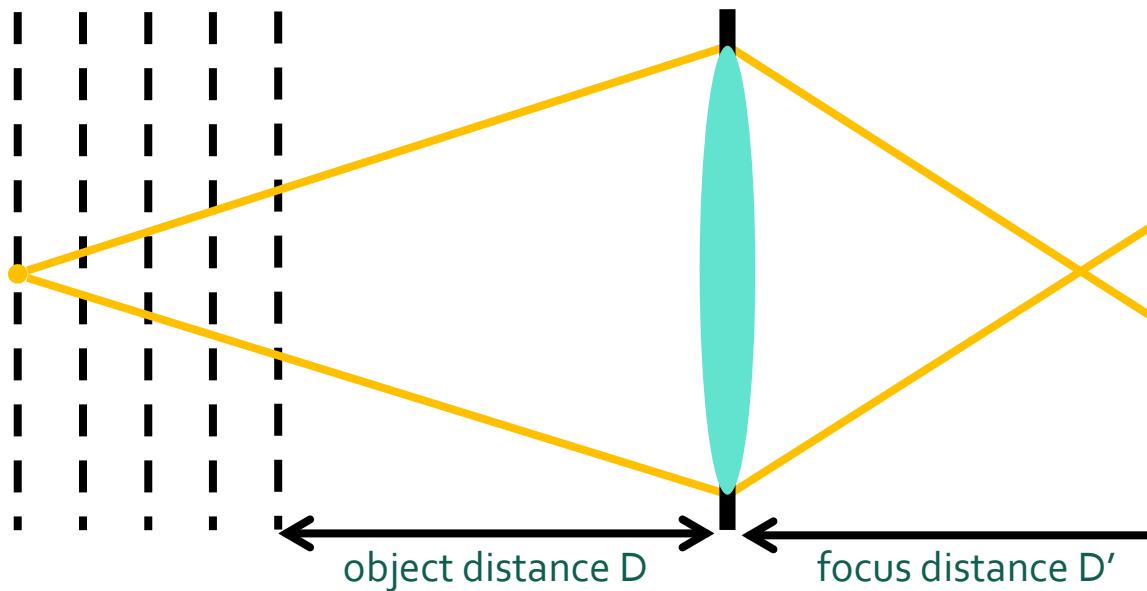
Depth Determines Scale of Blur Kernel



PSF



Aperture Determines Shape of Blur Kernel



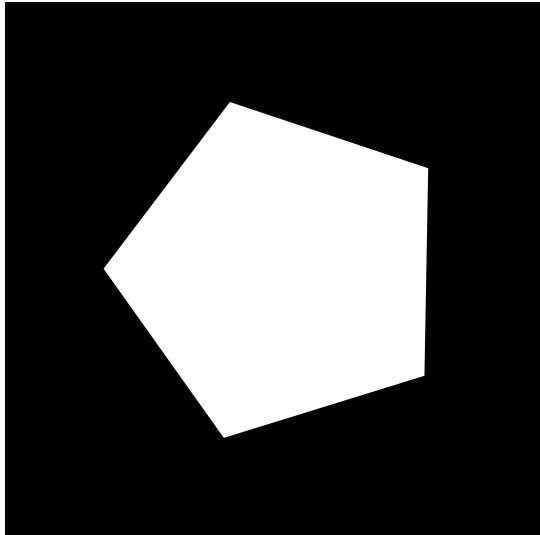
PSF



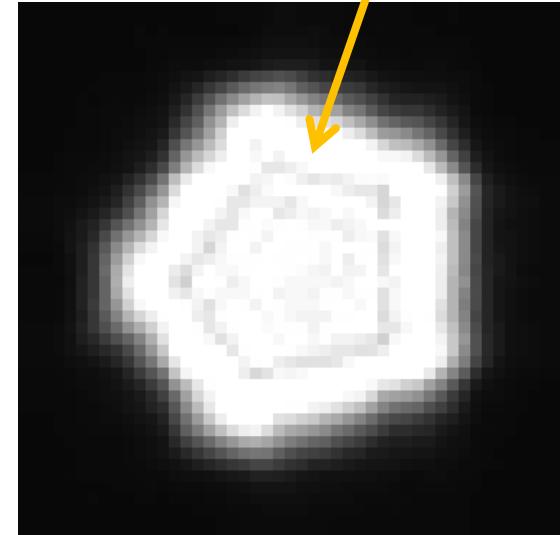
Aperture Determines Shape of Blur Kernel



photo of aperture



shape of aperture
(optical transfer function, OTF)



What causes these lines?

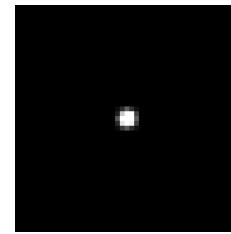
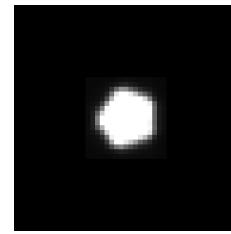
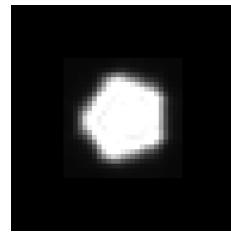
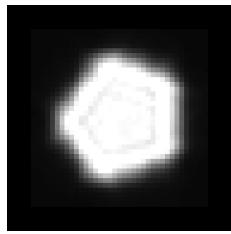
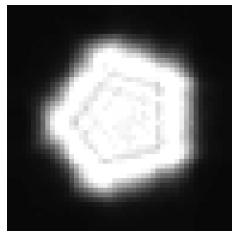


blur kernel
(point spread function, PSF)

How do the OTF and PSF relate to each other?



Removing Depth Defocus



measured PSFs at different depths



input defocused image

How would you create an all in-focus image given the above?

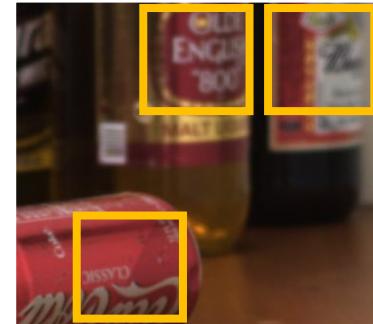


Removing Depth Defocus

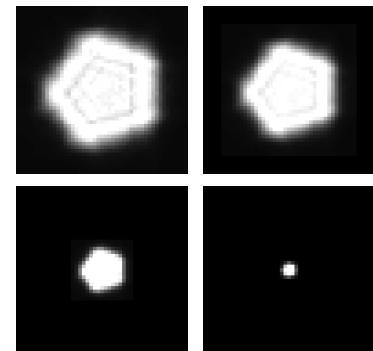
Defocus is *local* convolution with a depth-dependent kernel

$$\begin{array}{l} \text{depth 3} \\ \text{---} \\ \text{depth 2} \\ \text{---} \\ \text{depth 1} \end{array} = \begin{array}{c} \text{PSF at depth 3} \\ \text{---} \\ \text{PSF at depth 2} \\ \text{---} \\ \text{PSF at depth 1} \end{array} * \begin{array}{c} \text{in-focus image at depth 3} \\ \text{---} \\ \text{in-focus image at depth 2} \\ \text{---} \\ \text{in-focus image at depth 1} \end{array}$$

How would you create an all in-focus image given the above?



input defocused image

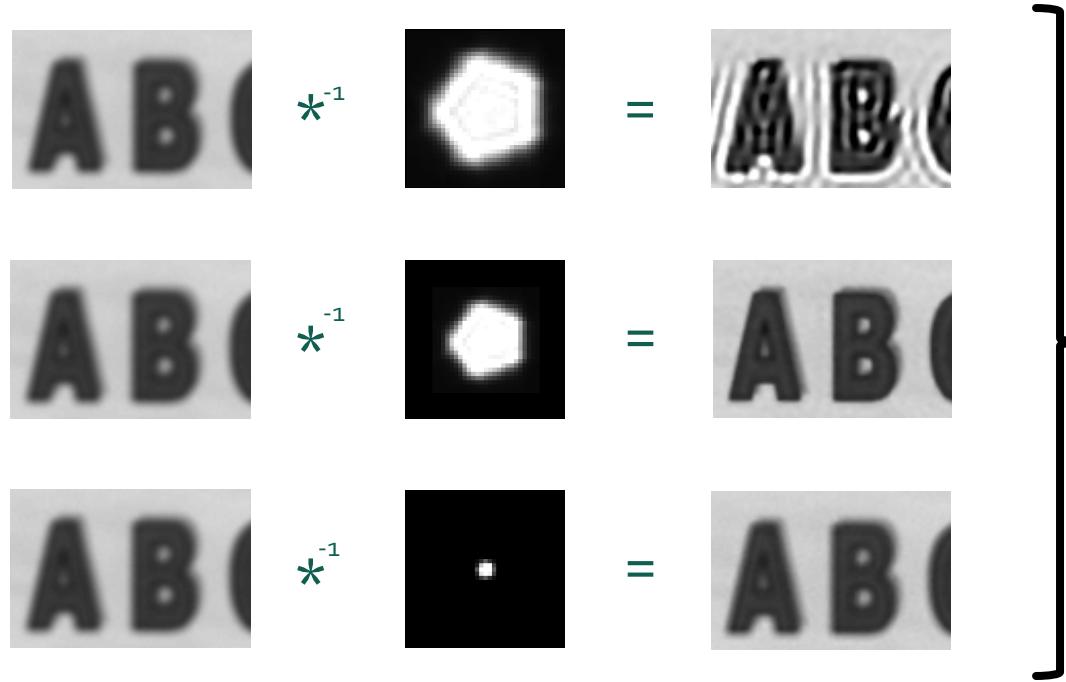


measured PSFs at different depths



Removing Depth Defocus

- Deconvolve each image patch with all kernels
- Select the right scale by evaluating the deconvolution results

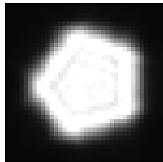


How do we
select the
correct scale?



Removing Depth Defocus

Problem: With standard aperture, results at different scales look very similar.

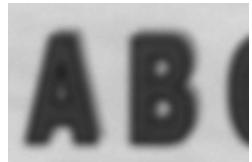
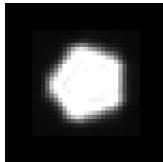
 \ast^{-1} 

=



wrong scale

✗

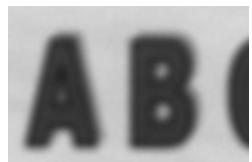
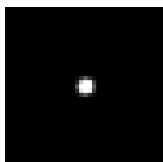
 \ast^{-1} 

=



correct scale

?

 \ast^{-1} 

=



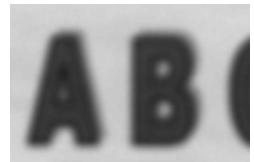
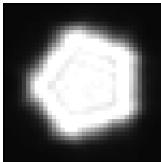
correct scale

?



Removing Depth Defocus

Problem: With standard aperture, results at different scales look very similar.

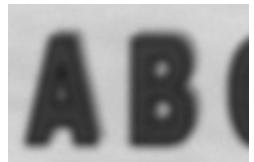
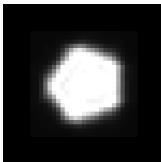
 \ast^{-1} 

=



wrong scale

✗

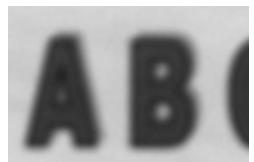
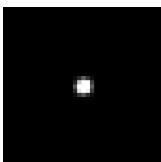
 \ast^{-1} 

=



correct scale

?

 \ast^{-1} 

=



correct scale

✗



Building a Coded Aperture



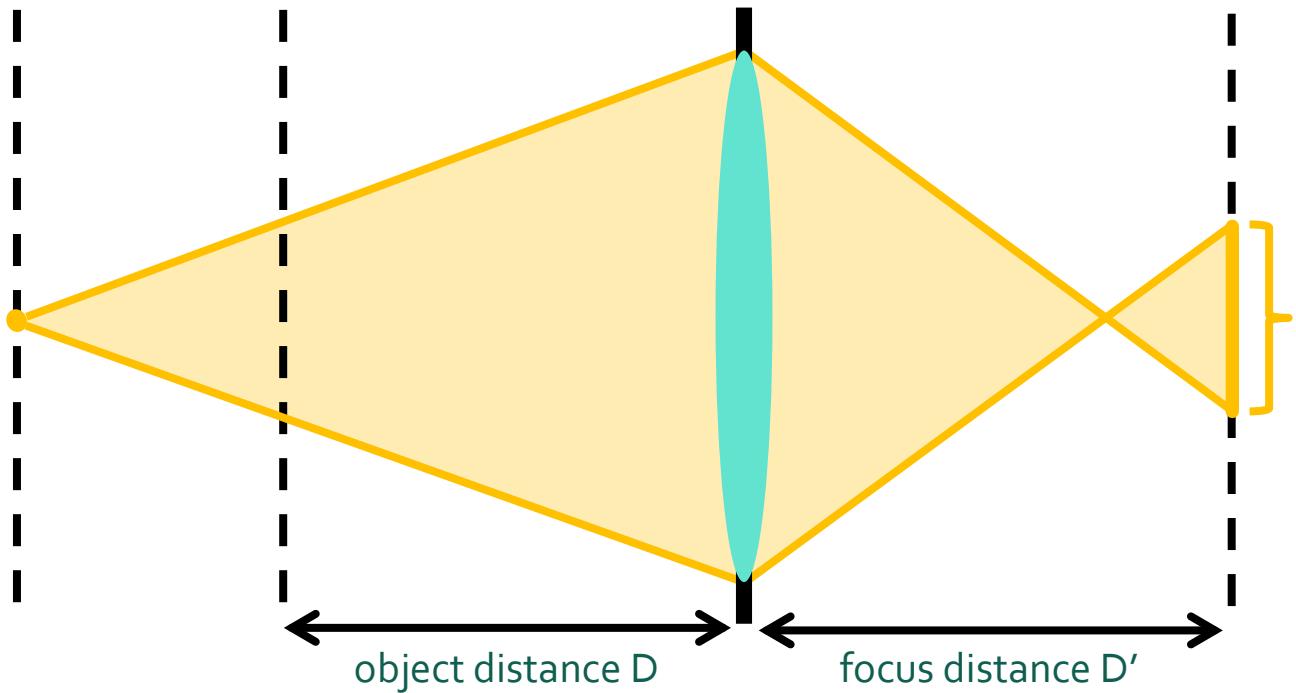
No Coded Aperture



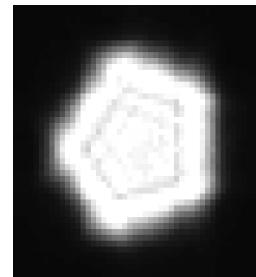
Coded Aperture



Coded Aperture Changes Shape of Kernel

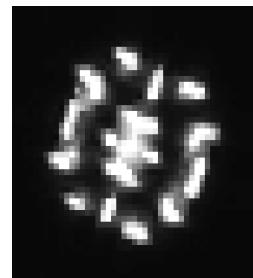
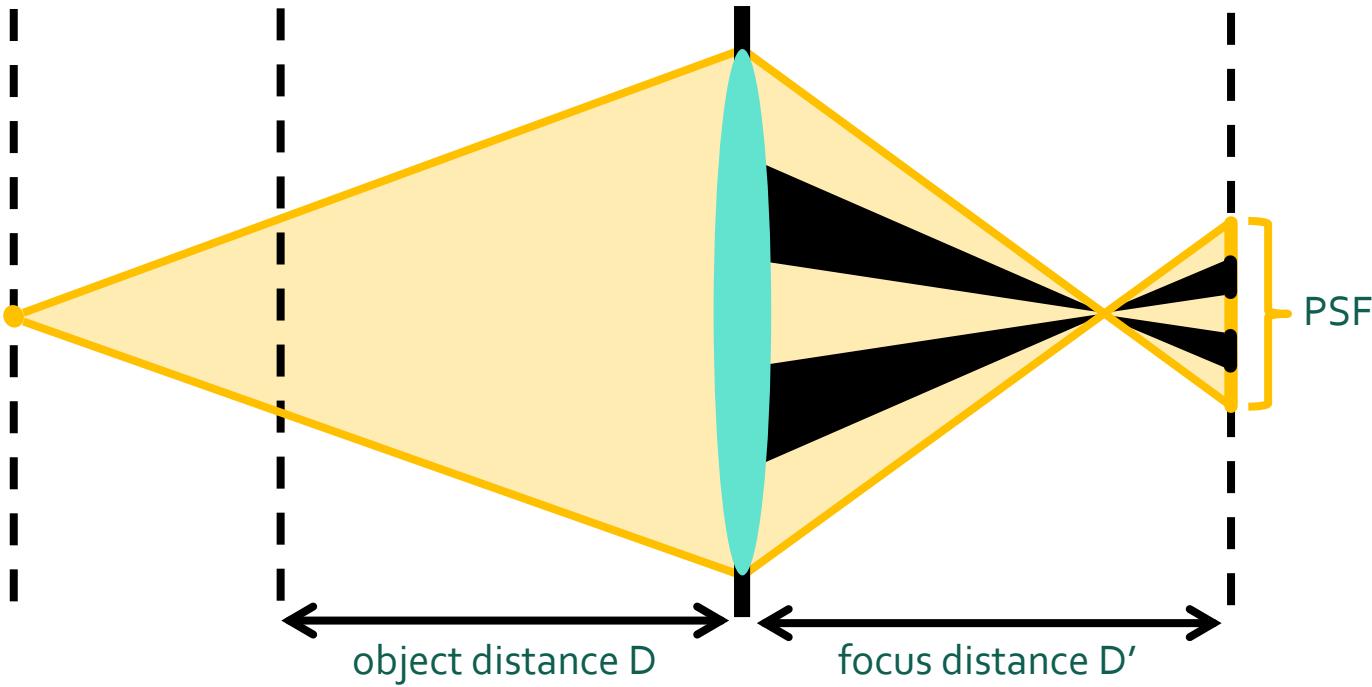


PSF



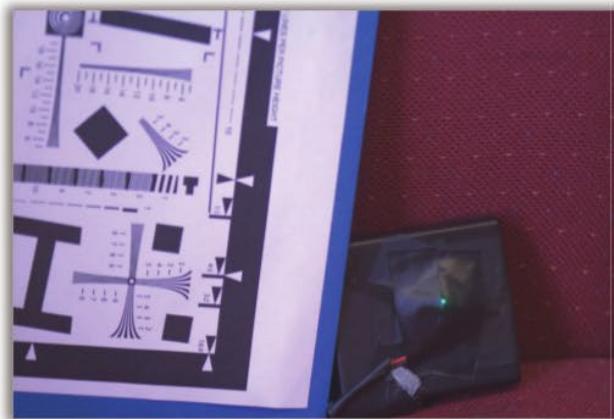


Coded Aperture Changes Shape of Kernel





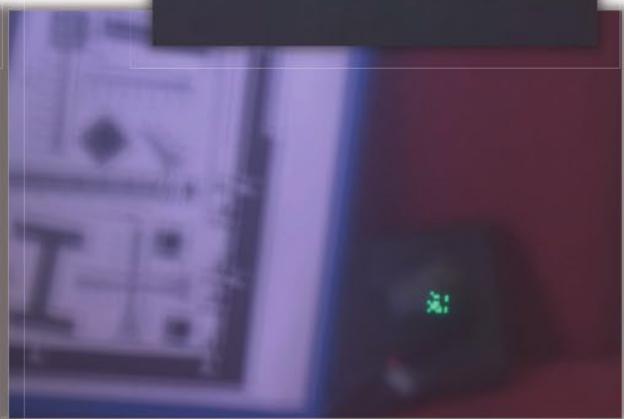
Coded Aperture Changes Shape of PSF



in-focus photo



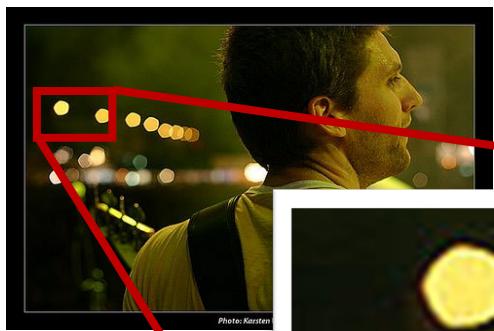
out-of-focus, circular aperture



out-of-focus, coded aperture



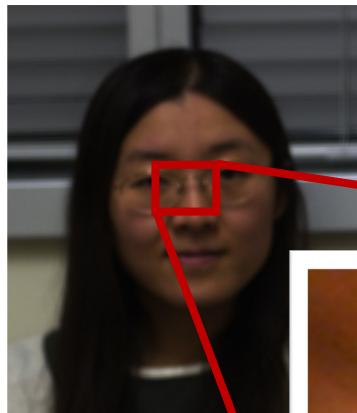
Image of A Point Light Source



Conventional
Aperture



Captured Image



Coded
Aperture



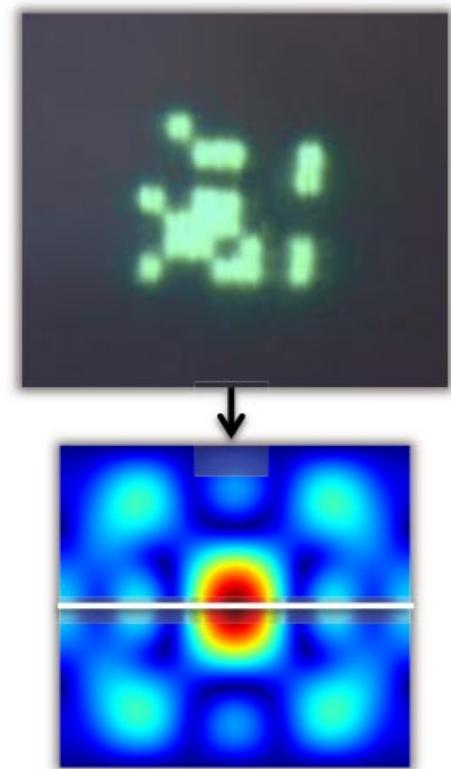
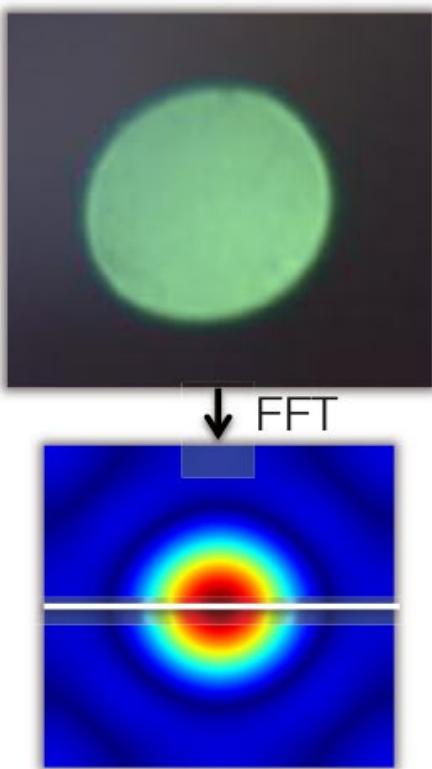
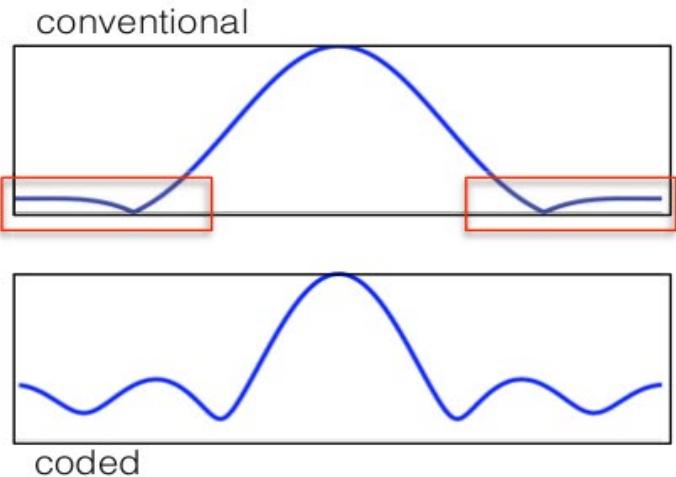
Captured Image



Coded Aperture Changes Shape of PSF

New PSF preserves high frequencies

- More content available to help us determine correct depth



Input

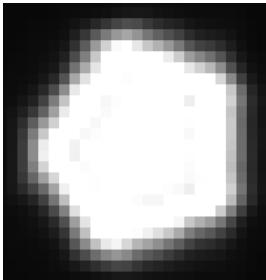


All-focused (deconvolved)





Standard and Coded Aperture



Ringing due to wrong scale estimation





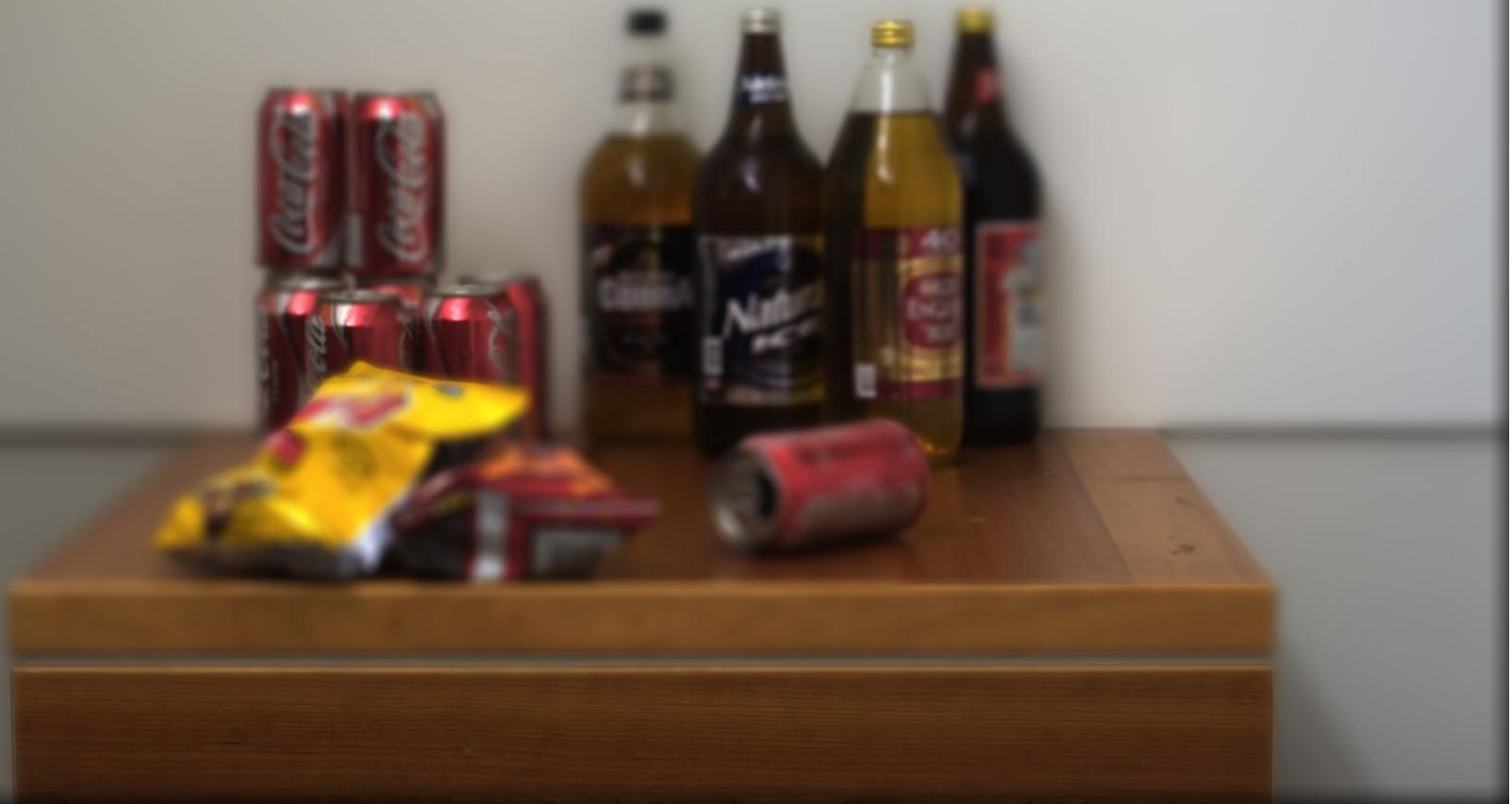
Standard and Coded Aperture



Refocusing



Refocusing



Refocusing



Depth Estimation



Input



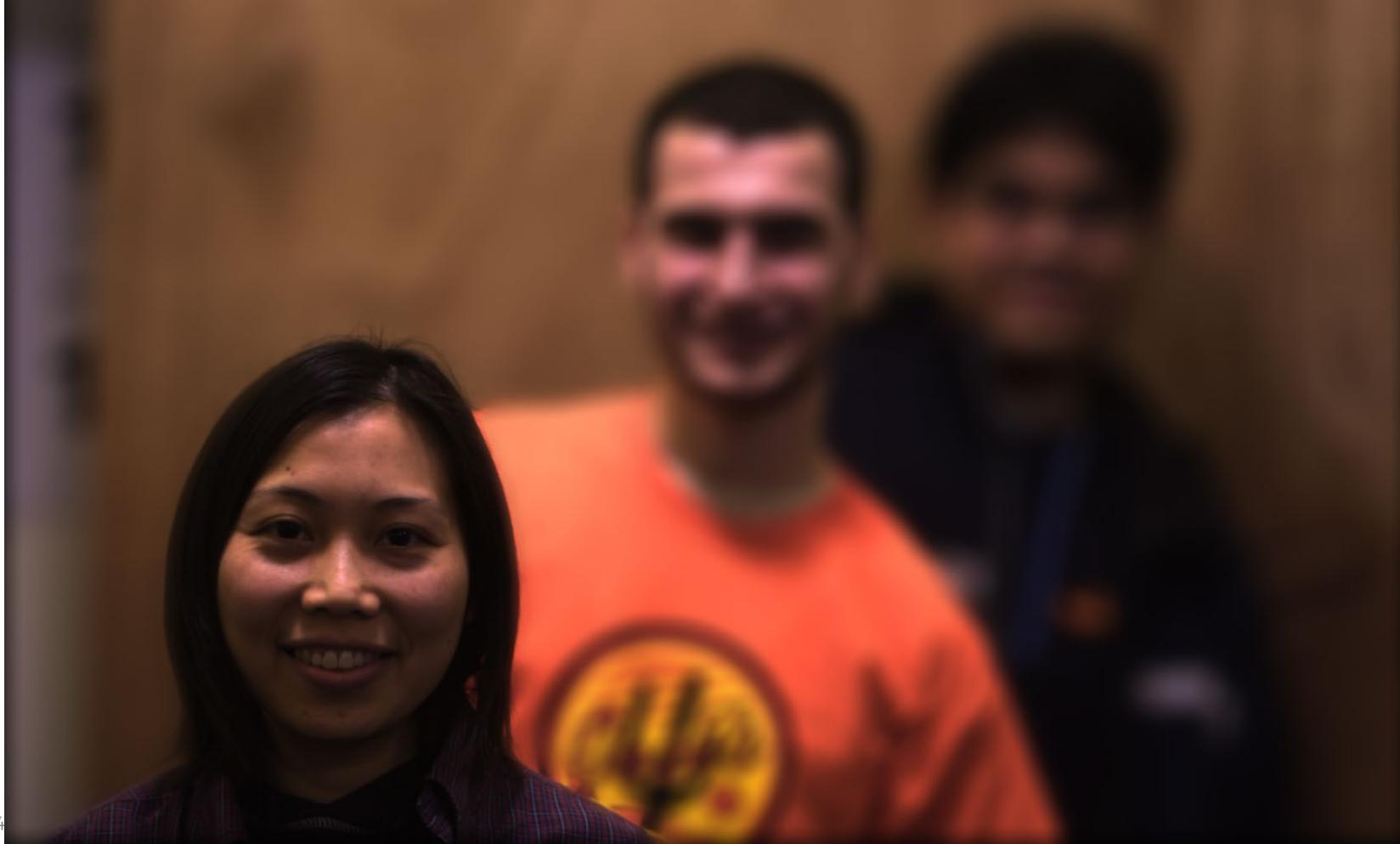
All-focused

(deconvolved)

点的 POINT SPREAD



Refocusing



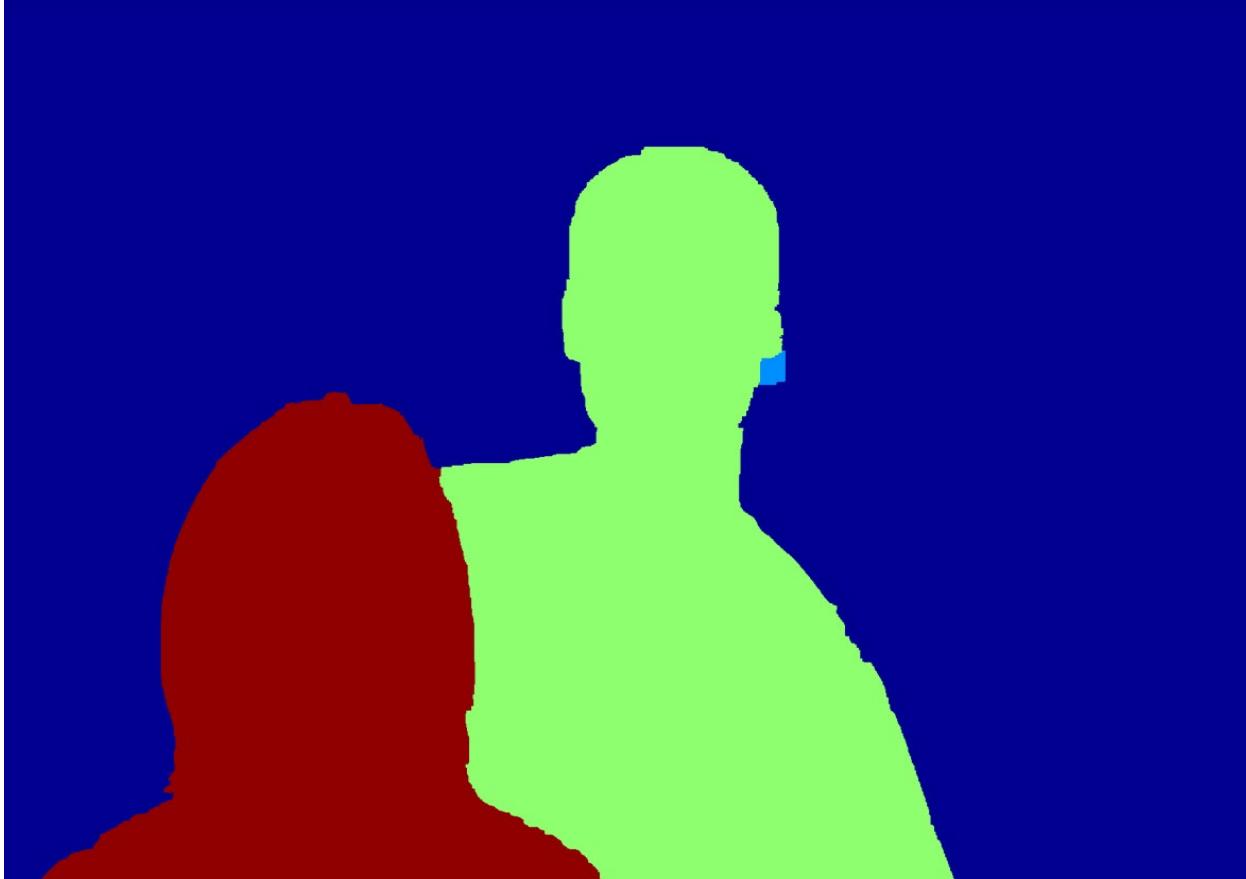
Refocusing



Refocusing



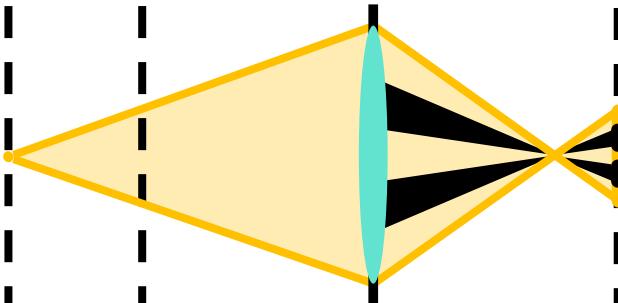
Depth Estimation



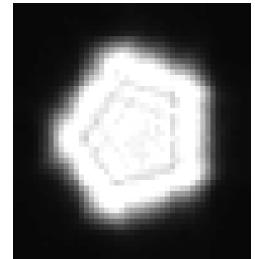
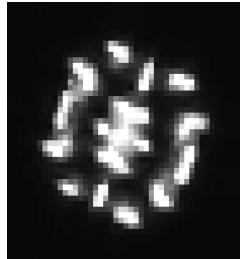
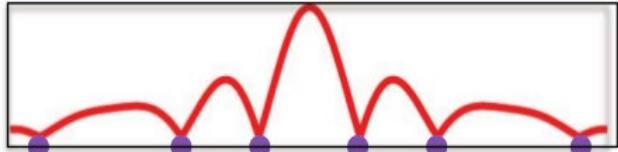


Problems with Using a Coded Aperture?

- We lose a lot of light due to blocking.



- The deconvolution becomes harder due to more diffraction/zeros in frequency domain.

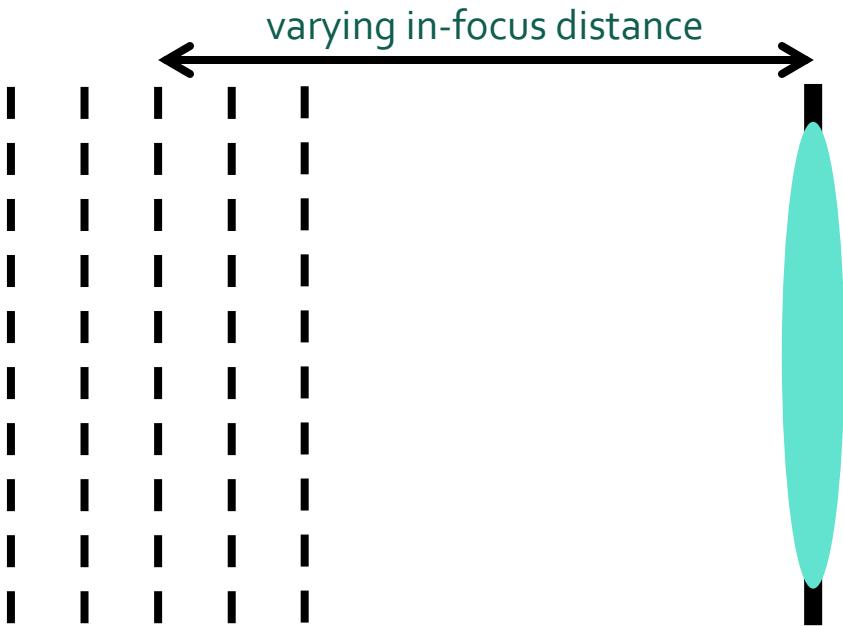


- We still need to select correct scale.

Dealing with Depth Blur: Focal Sweep

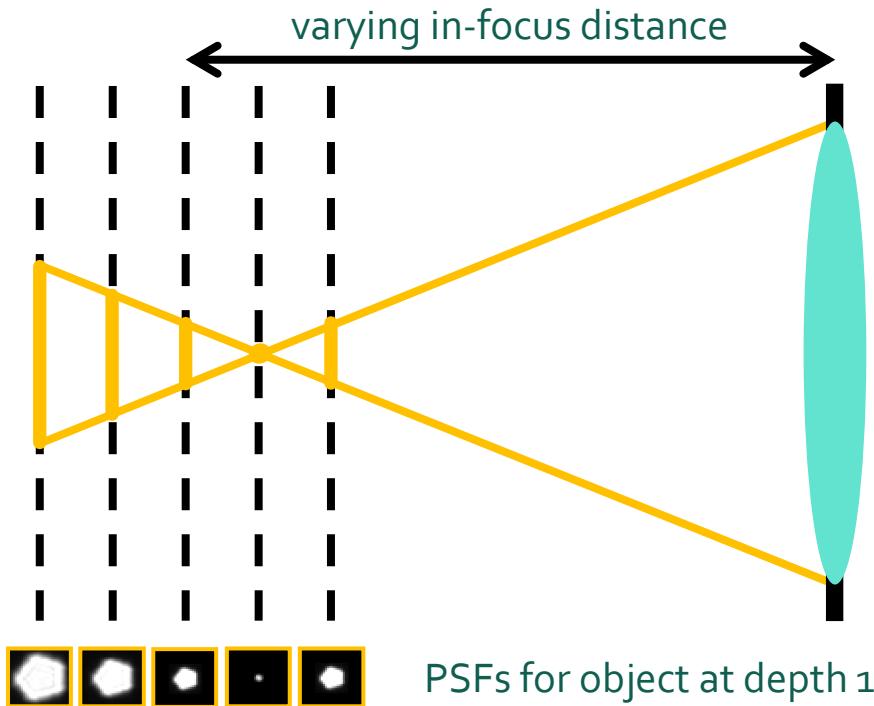


The Difficulty of Dealing with Depth Defocus



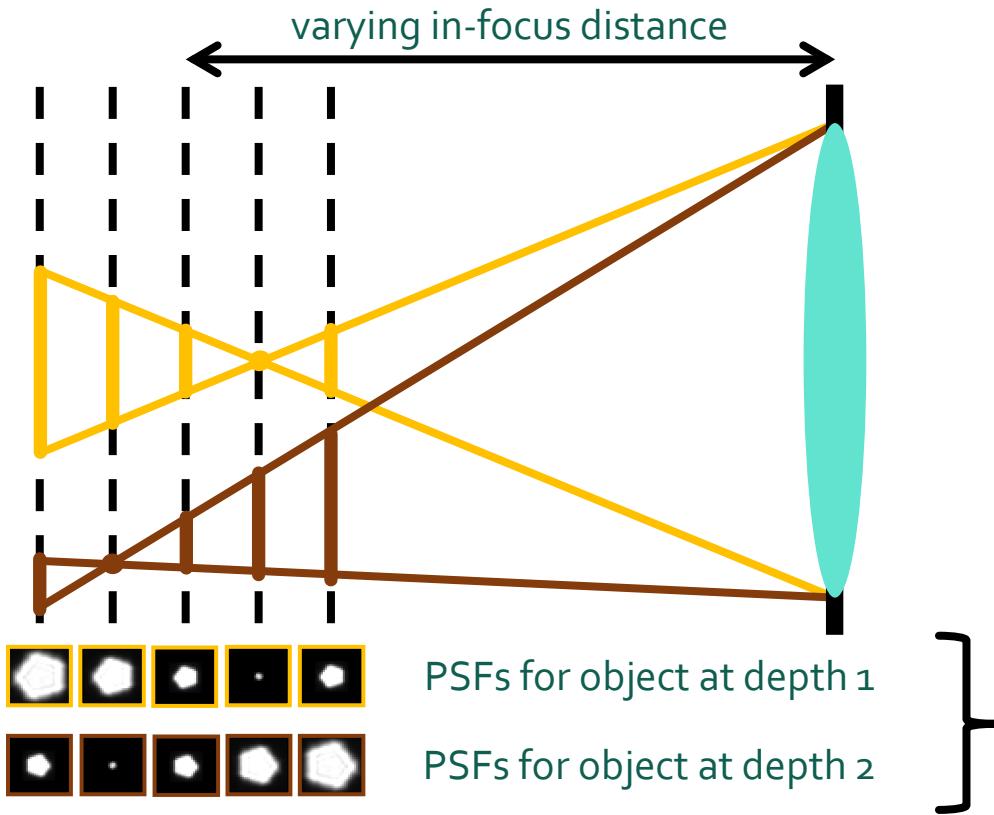
At every focus setting, objects at different depths are blurred by different PSF

The Difficulty of Dealing with Depth Defocus



At every focus setting, objects at different depths are blurred by different PSF

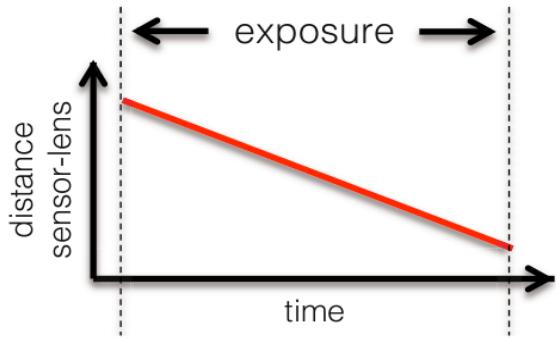
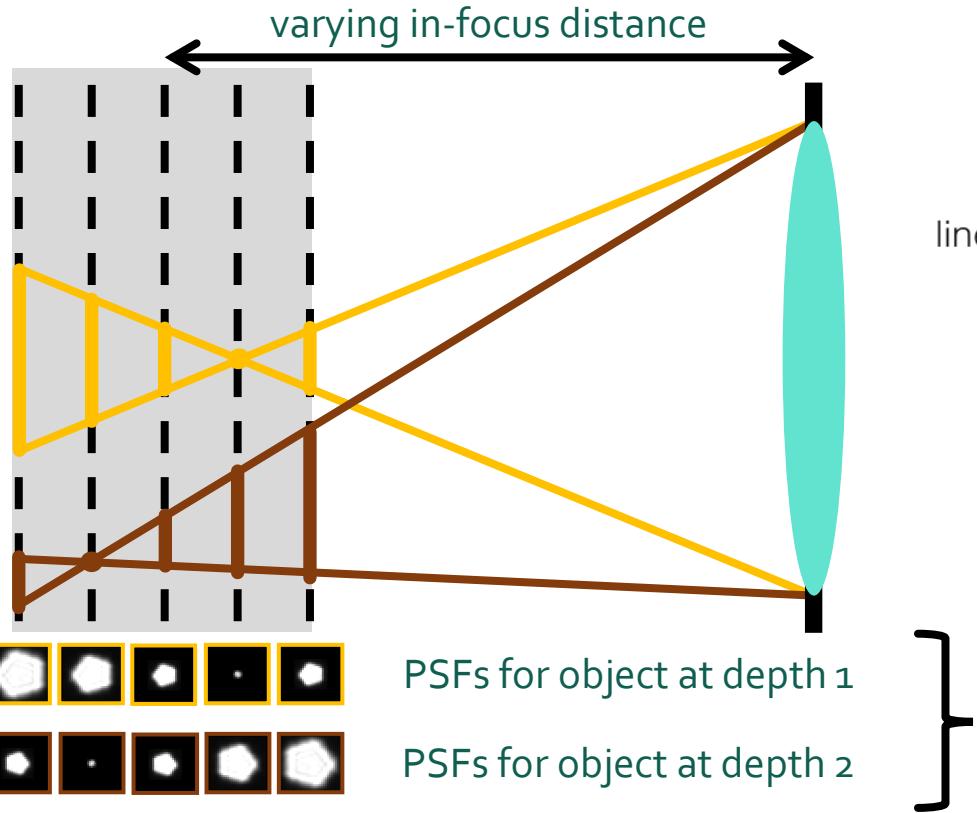
The Difficulty of Dealing with Depth Defocus



At every focus setting, objects at different depths are blurred by different PSF

As we sweep through focus settings, each point every object is blurred by all possible PSFs

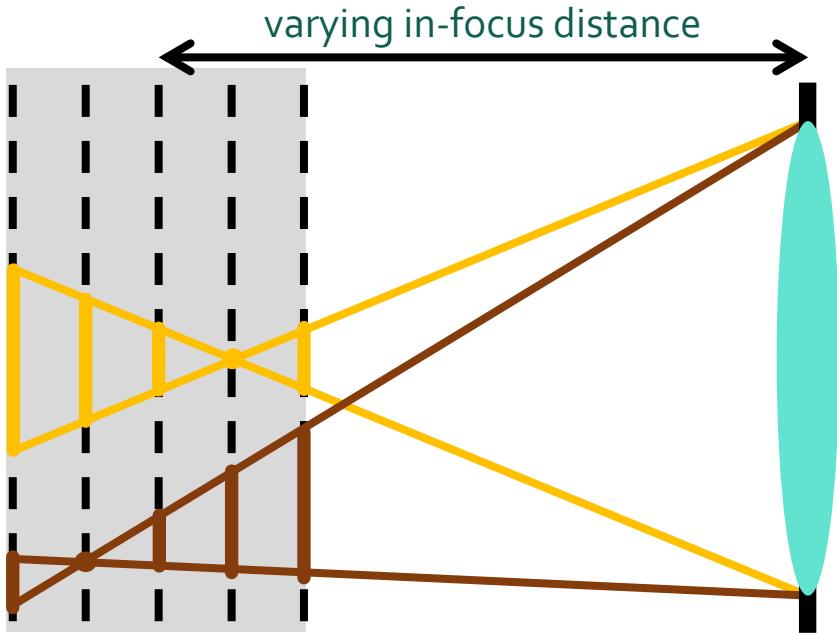
Focal Sweep



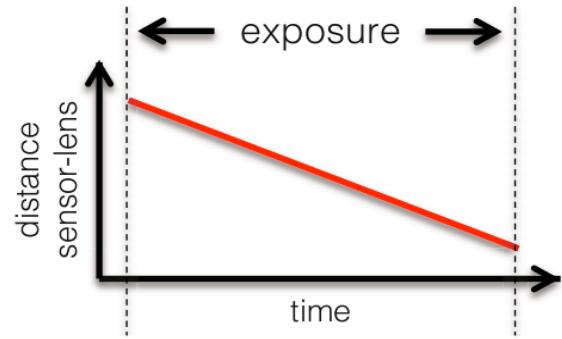
Go through all focus settings
during a single exposure

What is the effective
PSF in this case?

Focal Sweep



linear motion:



Go through all focus settings
during a single exposure

$$\int \left[\begin{array}{c} \text{hexagon PSF} \\ \text{square PSF} \\ \text{circle PSF} \\ \text{star PSF} \\ \text{dot PSF} \end{array} \right] dt = \left[\begin{array}{c} \text{hexagon PSF} \\ \text{square PSF} \end{array} \right]$$

effective PSF for object at depth 1

$$\int \left[\begin{array}{c} \text{dot PSF} \\ \text{star PSF} \\ \text{circle PSF} \\ \text{square PSF} \\ \text{hexagon PSF} \end{array} \right] dt = \left[\begin{array}{c} \text{dot PSF} \\ \text{star PSF} \end{array} \right]$$

effective PSF for object at depth 2

Anything special
about these
effective PSFs?



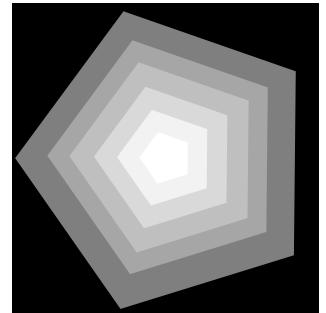
Focal Sweep

The effective PSF is:

1. Depth-invariant – all points are blurred the same way regardless of depth.
2. Never sharp – all points will be blurry regardless of depth.

What are the implications of this?

1. The image we capture will not be sharp anywhere; but
2. We can use simple (global) deconvolution to sharpen parts we want



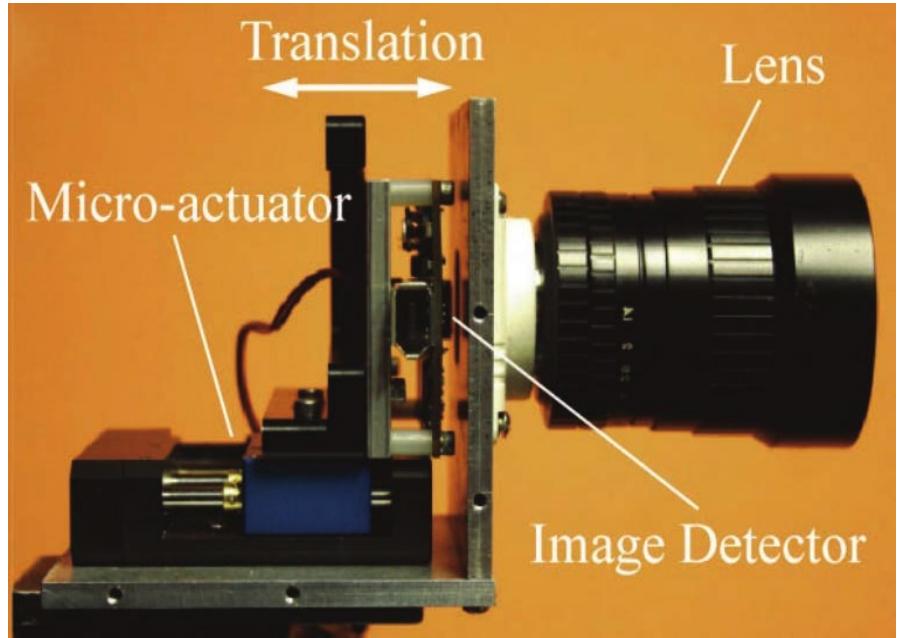
1. Can we estimate depth from this?
2. Can we do refocusing from this?

}

Depth-invariance of the PSF means that
we have lost all depth information



How Can You Implement Focal Sweep?

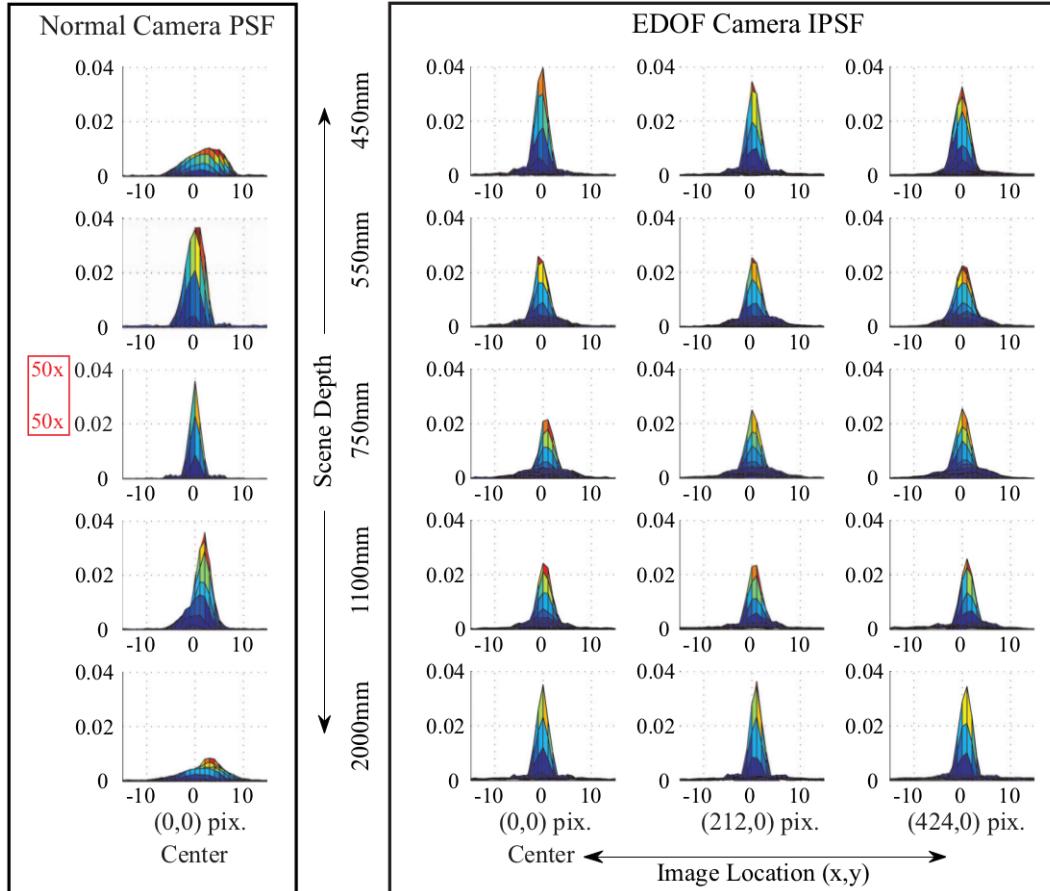


Use translation stage to move sensor relative to
fixed lens during exposure



Rotate focusing ring to move lens relative to
fixed sensor during exposure

Comparison of Different PSFs





Depth of Field Comparisons

conventional photo
(small DOF)



captured focal sweep
always blurry!



conventional photo
(large DOF, noisy)

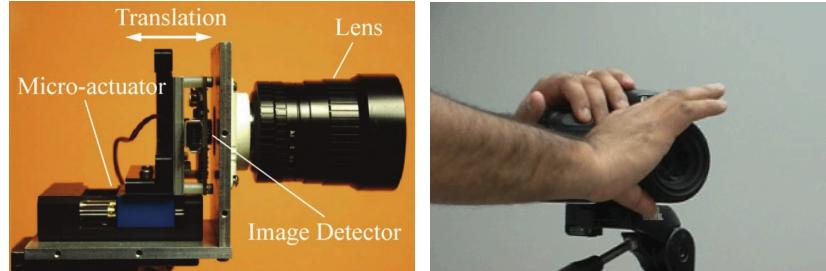


EDOF image

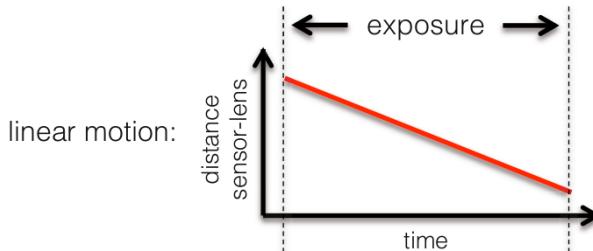


Any Problems with Using Focal Sweep?

- We have moving parts (vibrations, motion blur).



- Perfect depth invariance requires very constant speed.

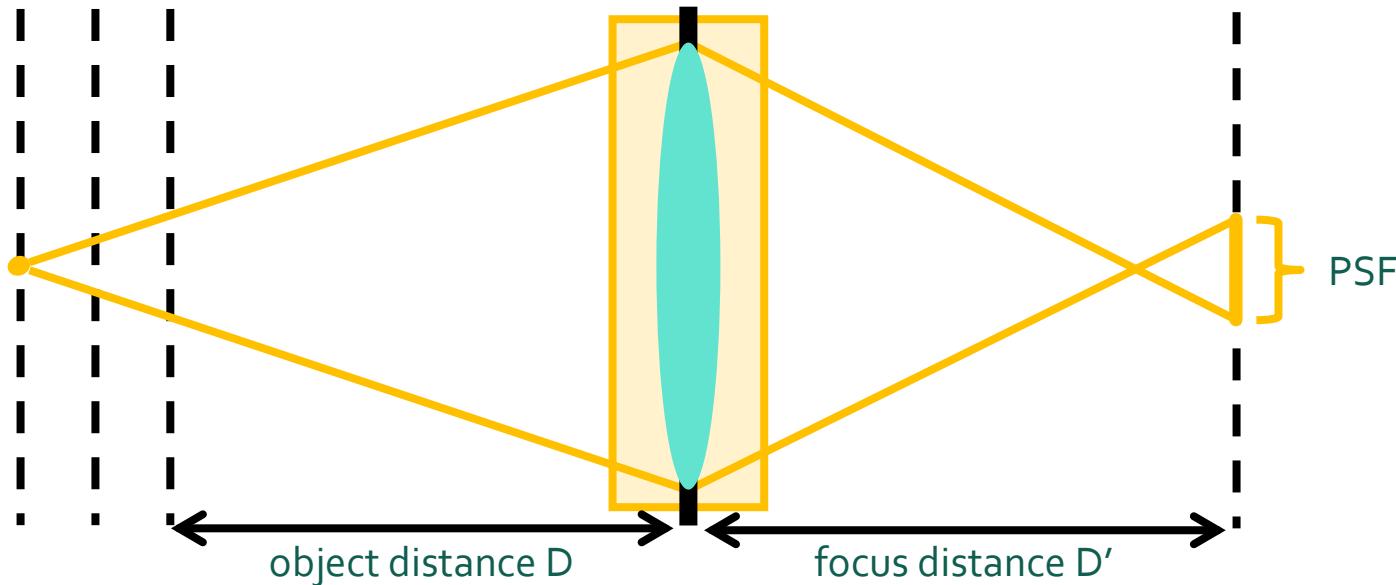


- We lose depth information.

Dealing with Depth Blur: Generalized Optics

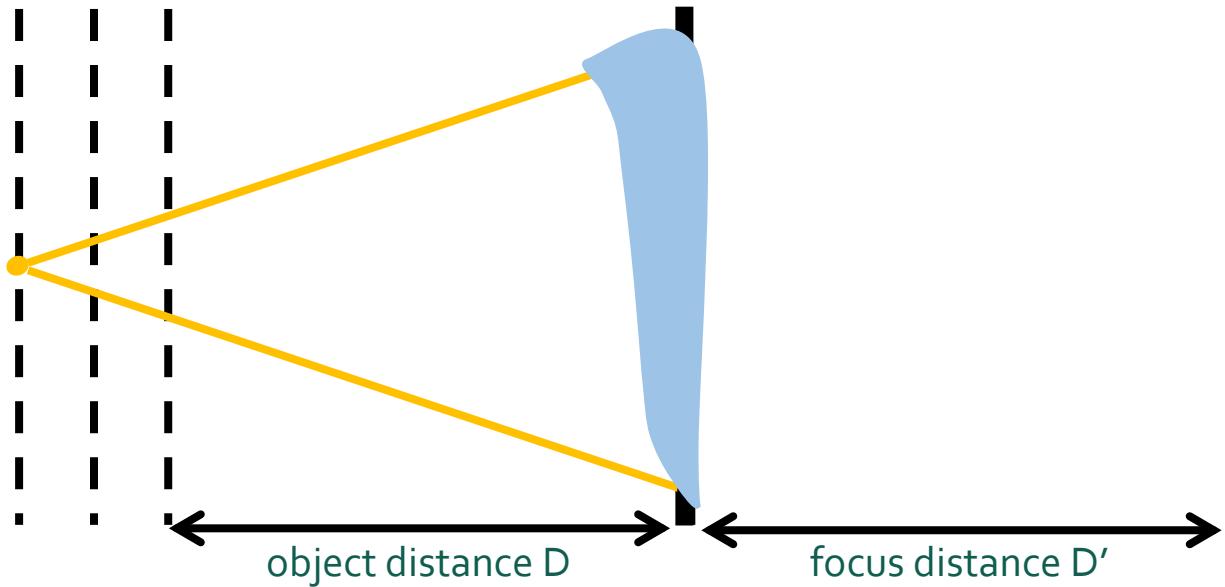


Change Optics, not Aperture





Wavefront Coding

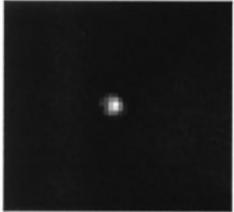


Replace lens with a cubic phase plate

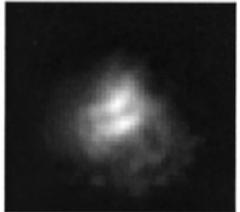


Wavefront Coding

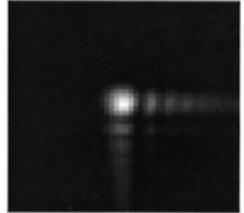
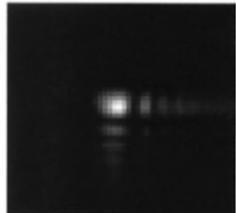
In focus



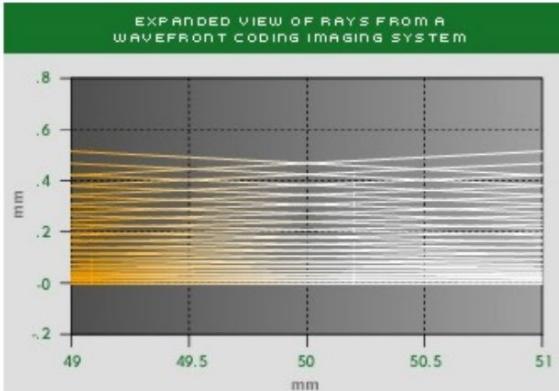
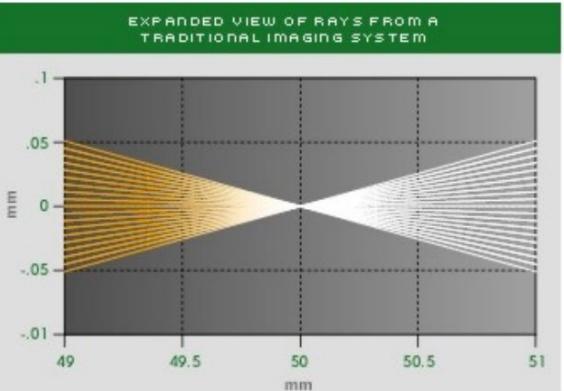
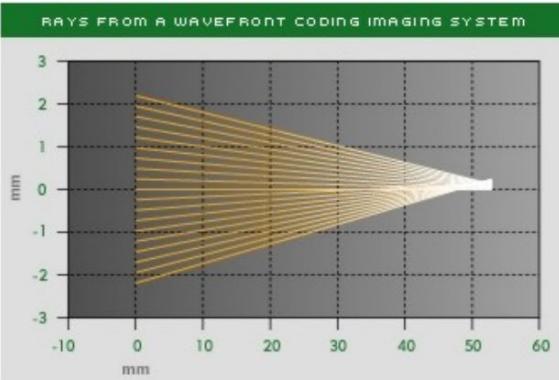
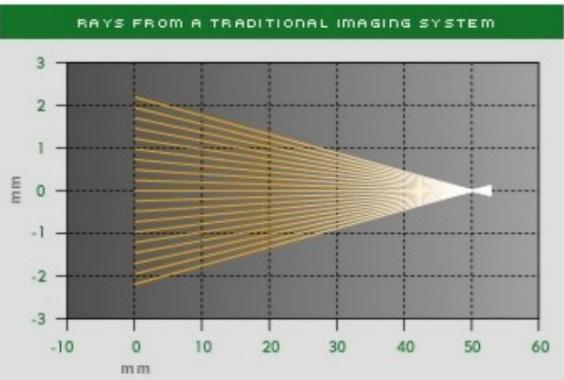
Out of focus



standard lens



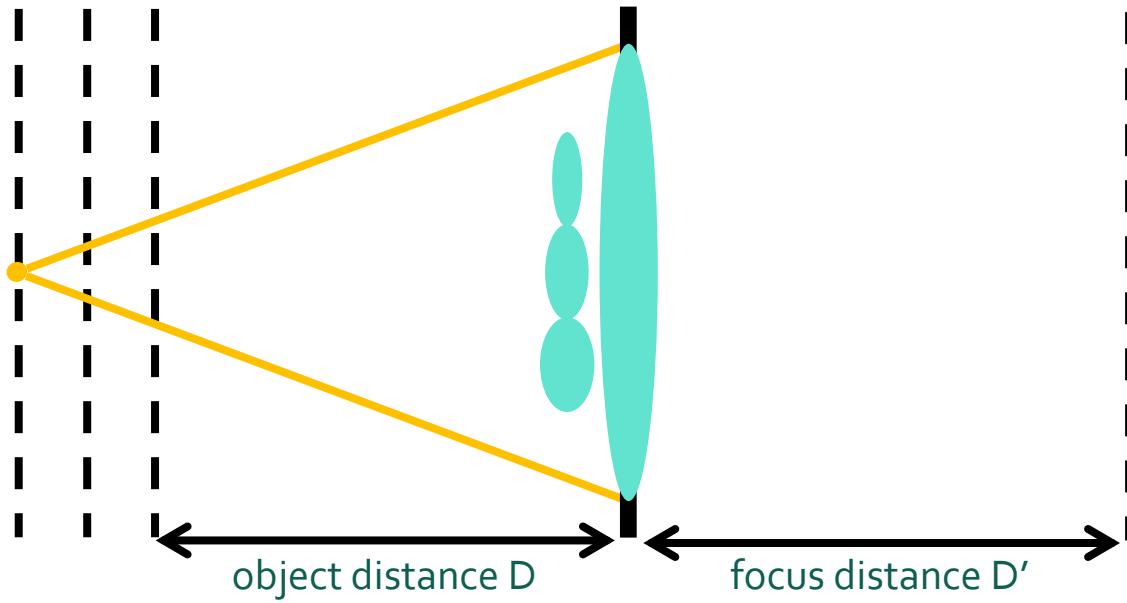
wavefront coding



- Rays no longer converge.
- Approximately depth-invariant PSF for certain range of depths.



Lattice Lens

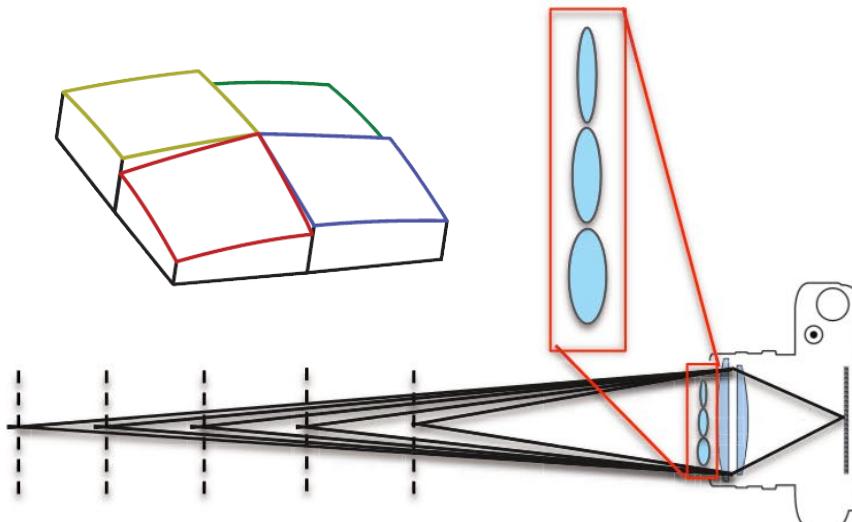


Add lenslet array with varying focal length in front of lens

Lattice Lens



Does this remind you of something?





Lattice Lens

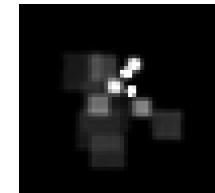
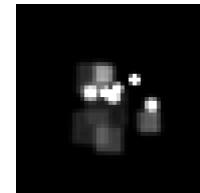
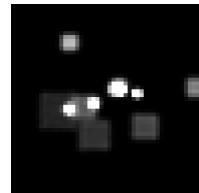
- Effectively captures only the “useful” subset of the 4D lightfield.

Light field spectrum: 4D
Image spectrum: 2D
Depth: 1D } 3D
→ Dimensionality gap (Ng 05)

Only the 3D manifold corresponding to physical focusing distance is useful

- PSF is not depth-invariant, so local deconvolution as in coded aperture.

PSFs at different depths





Results

Standard lens



Results

Lattice lens





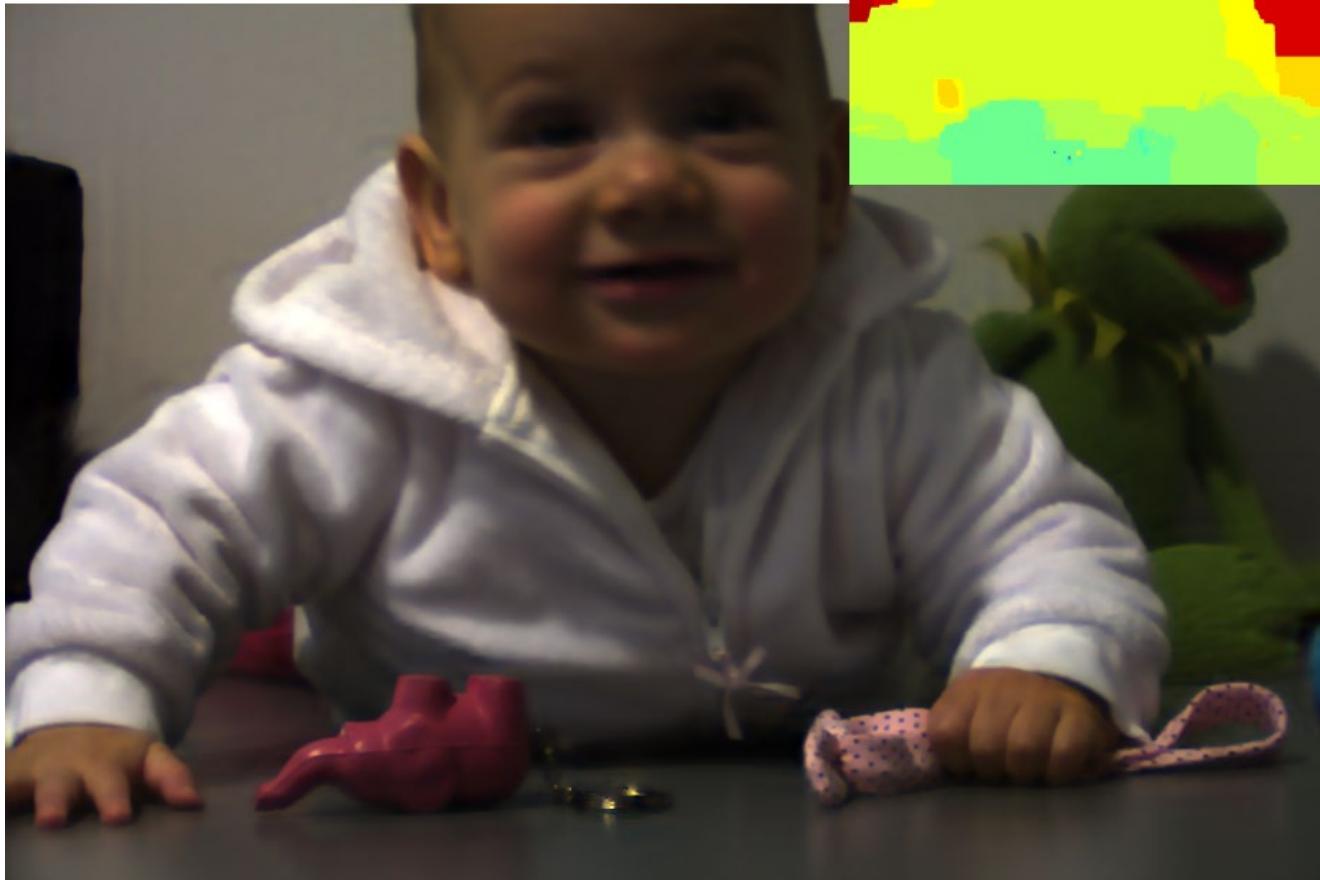
Results

Standard lens



Results

Lattice lens





Results

Standard lens



Results

Lattice lens

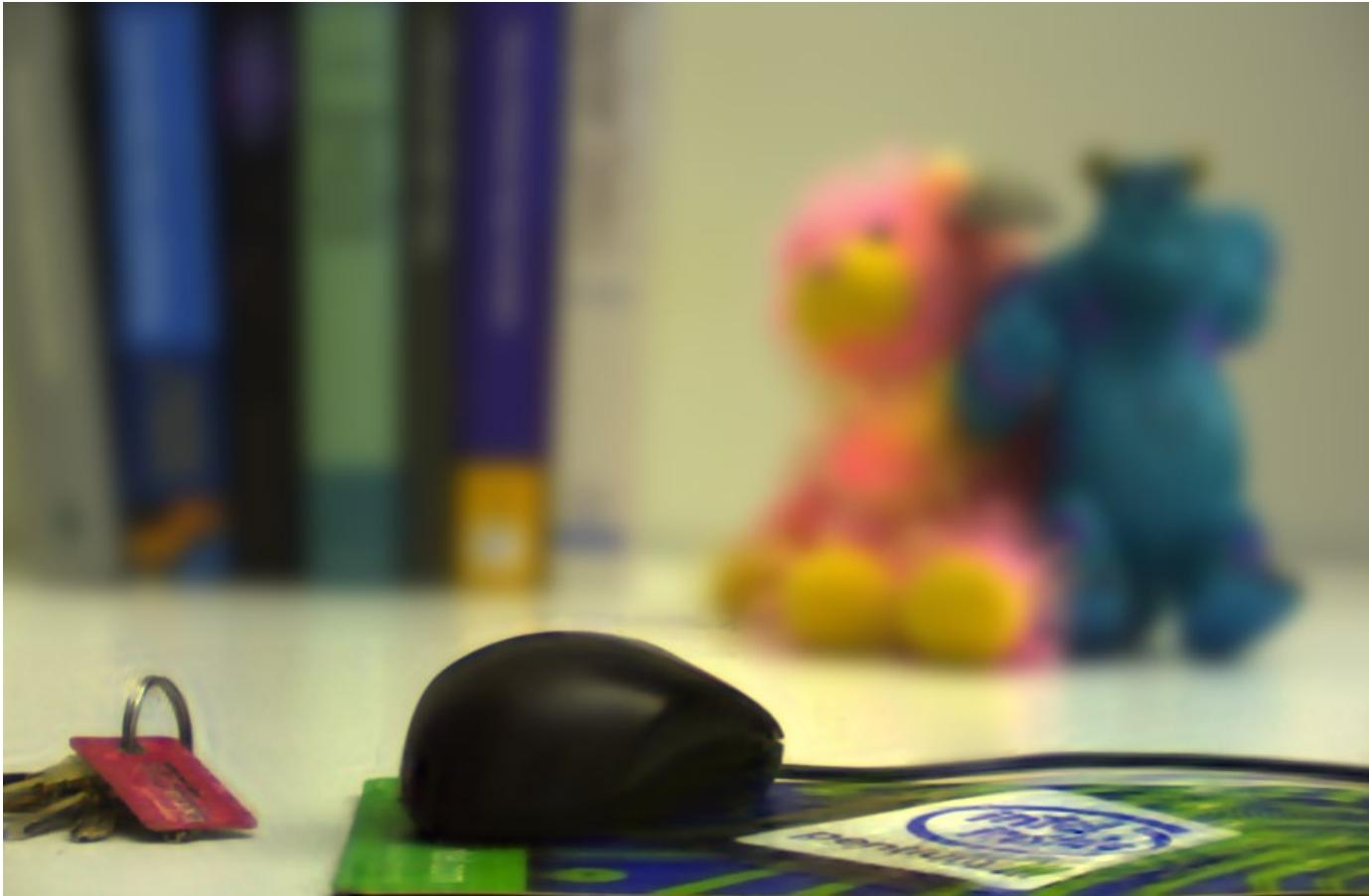




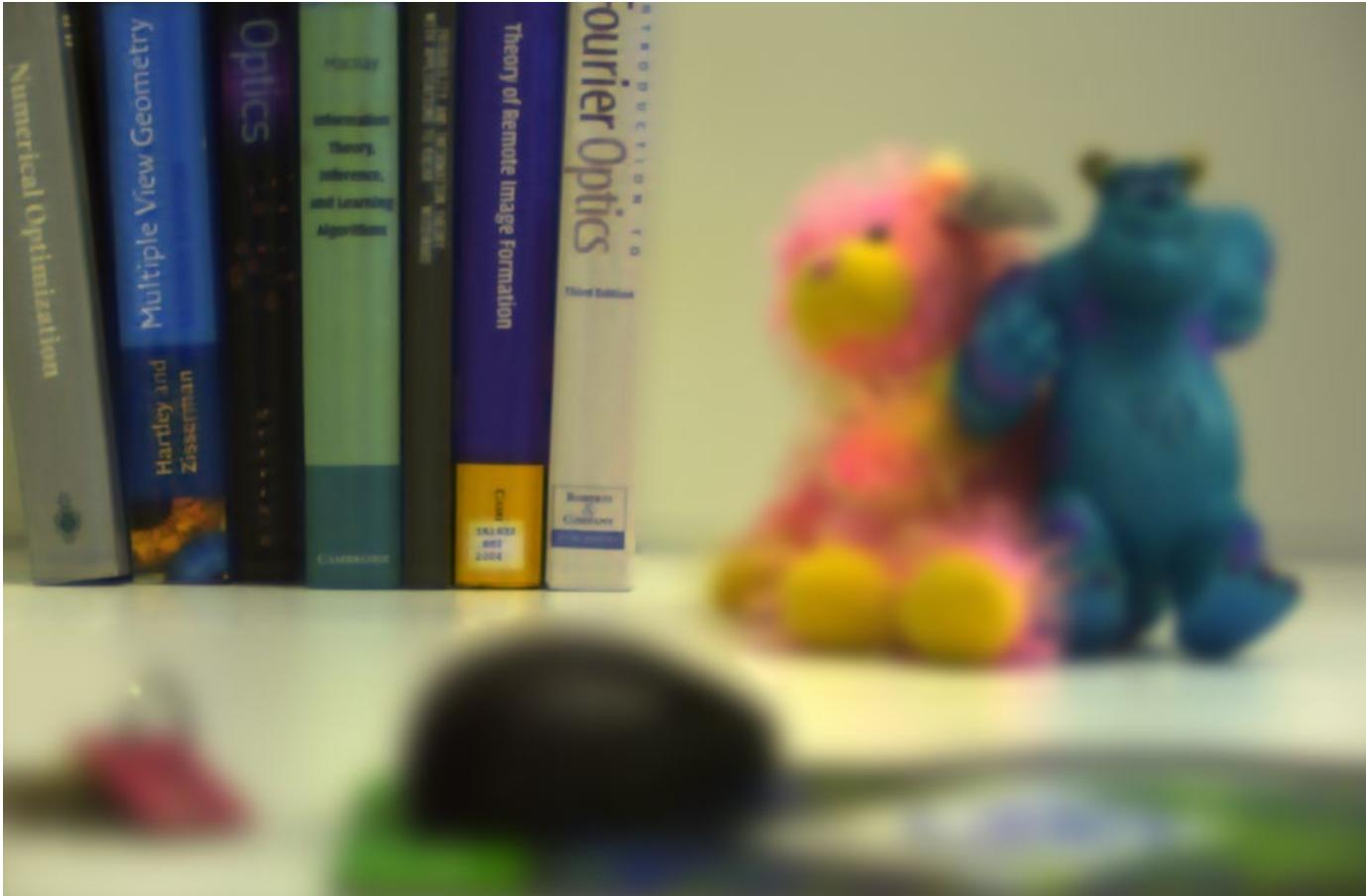
香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen



Refocusing Example



Refocusing Example



Refocusing Example





Comparison of Different Techniques

Depth of field
comparison:



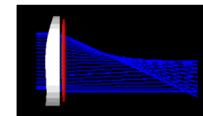
standard
lens



coded
aperture



focal
sweep



wavefront
coding



lattice
lens

Object at in-focus depth



Object at extreme depth





Diffusion Coded Photography

- can also do EDOF with diffuser as coded aperture, has better inversion characteristics than lattice focal lens



Conventional Camera



Diffusion Coded Camera

Can you think of any issues?



Today's Topic

- The Coded Photography Paradigm
- Dealing with Depth Blur: Coded Aperture
- Dealing with Depth Blur: Focal Sweep
- Dealing with Depth Blur: Generalized Optics



Thank You!



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点昀技术（Point Spread Technology）