

# Computational Photography

- \* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.

# Coded Photography

- \* Cameras that capture additional information about a scene, by using controlled patterns built into the imaging process

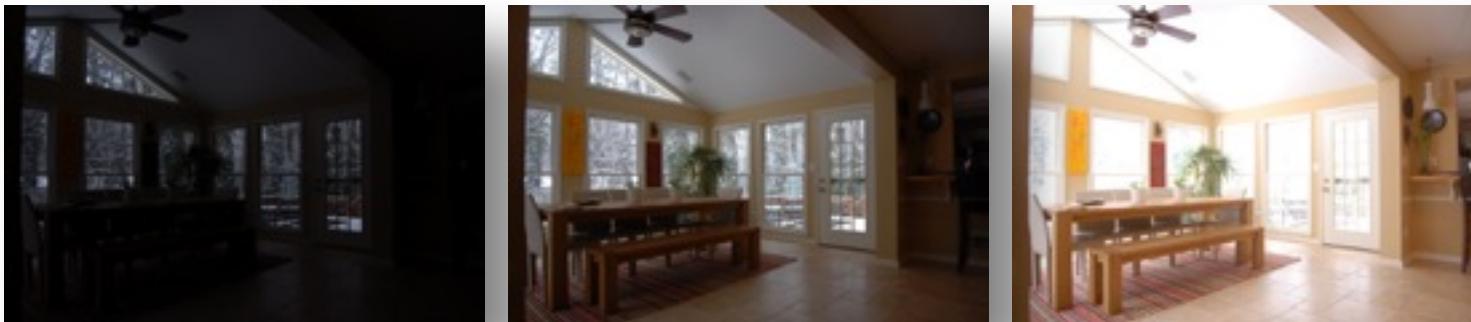


## Lesson Objectives

1. From Epsilon Photography  
to Coded Photography
2. Concept/Ideals of Coded  
Photography
3. Coded Aperture
4. Flutter Shutter Camera

# Recall: Epsilon Photography

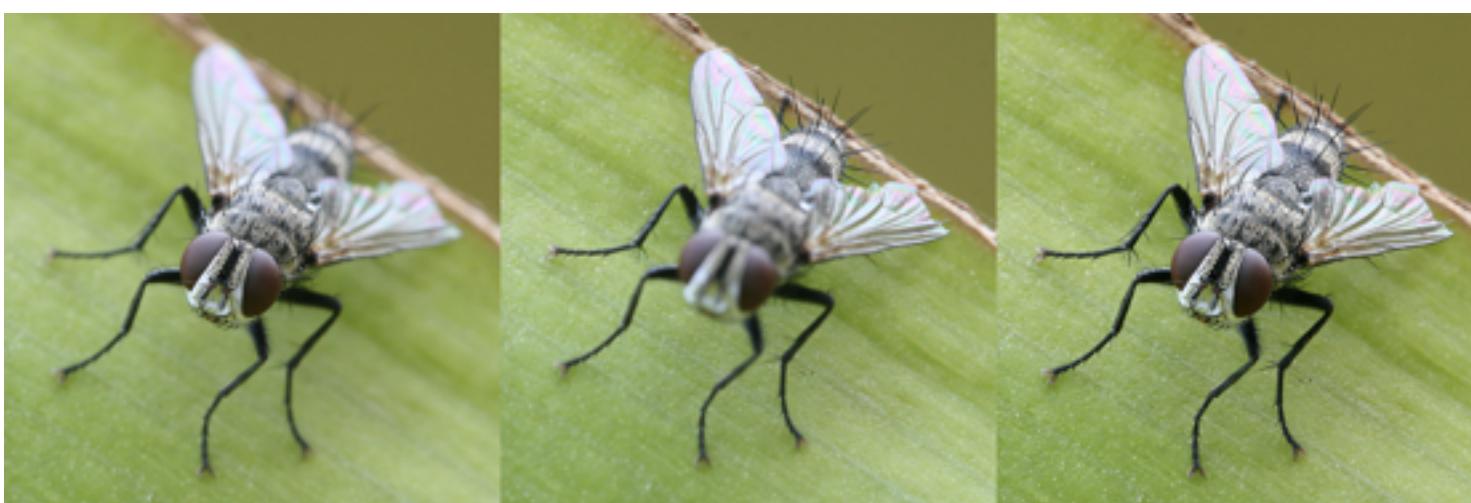
exposure



viewpoint

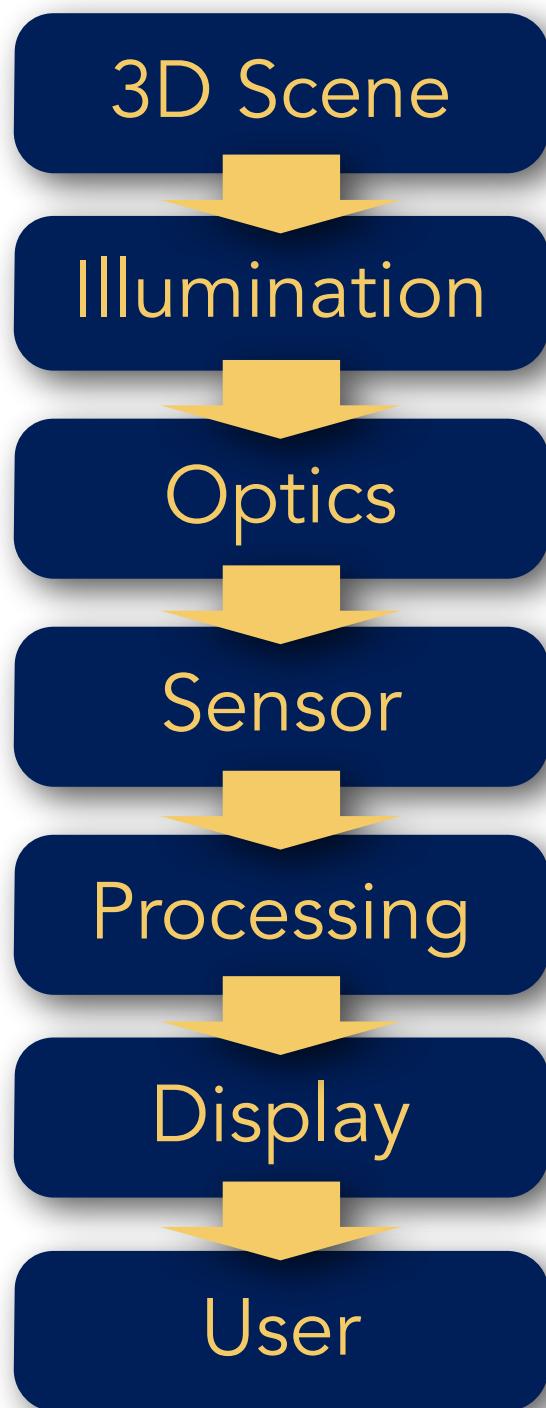


focus

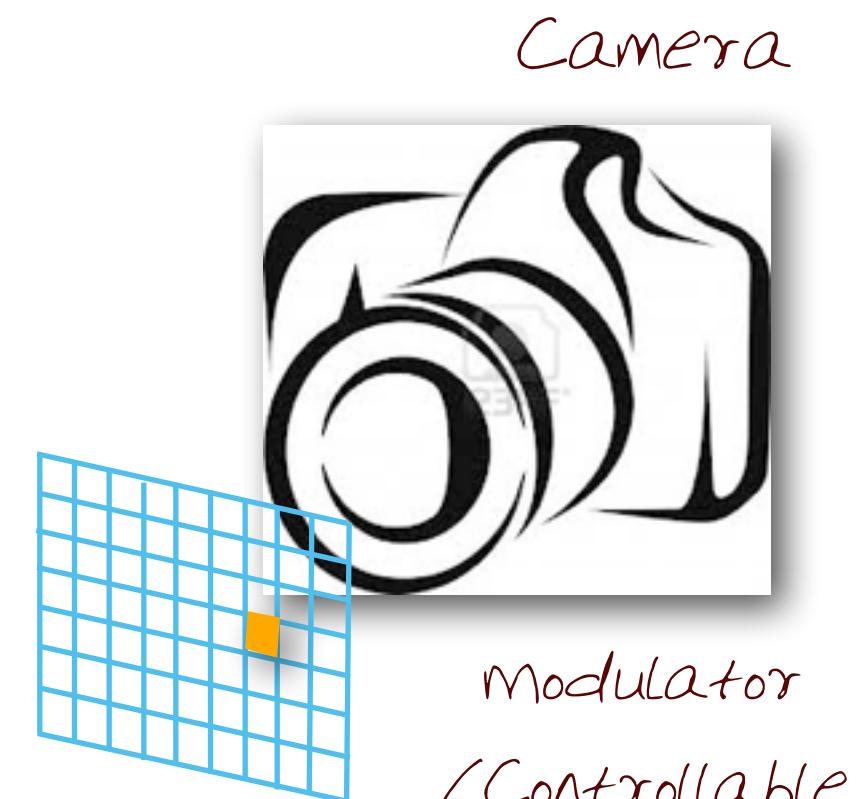


- \* Multiple sequential photos
- \* Changing some parameters
- \* Fusing the photos to create a richer representation
- \* Synthesizing novel pictures by multiple captures of single images

# Recall: Computational Photography



Modulator  
(Controllable Aperture)



# Coded Photography

- \* Coded Exposure

- Control light in time

- \* Coded aperture

- Control light near the sensor

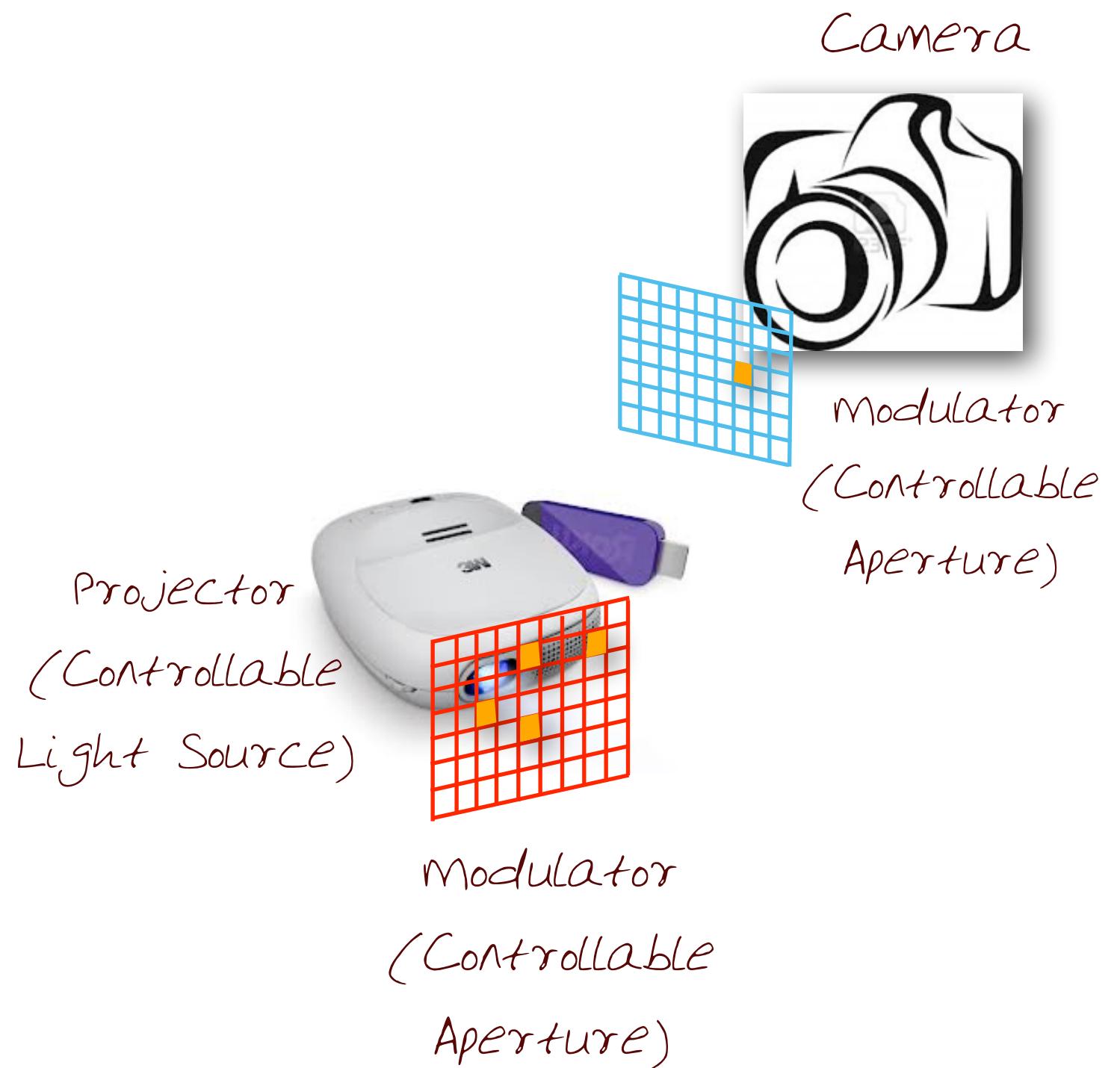
- \* Coded illumination

- Control light in the scene

- \* Coded sensing

- Control intensities

Raskar 2009

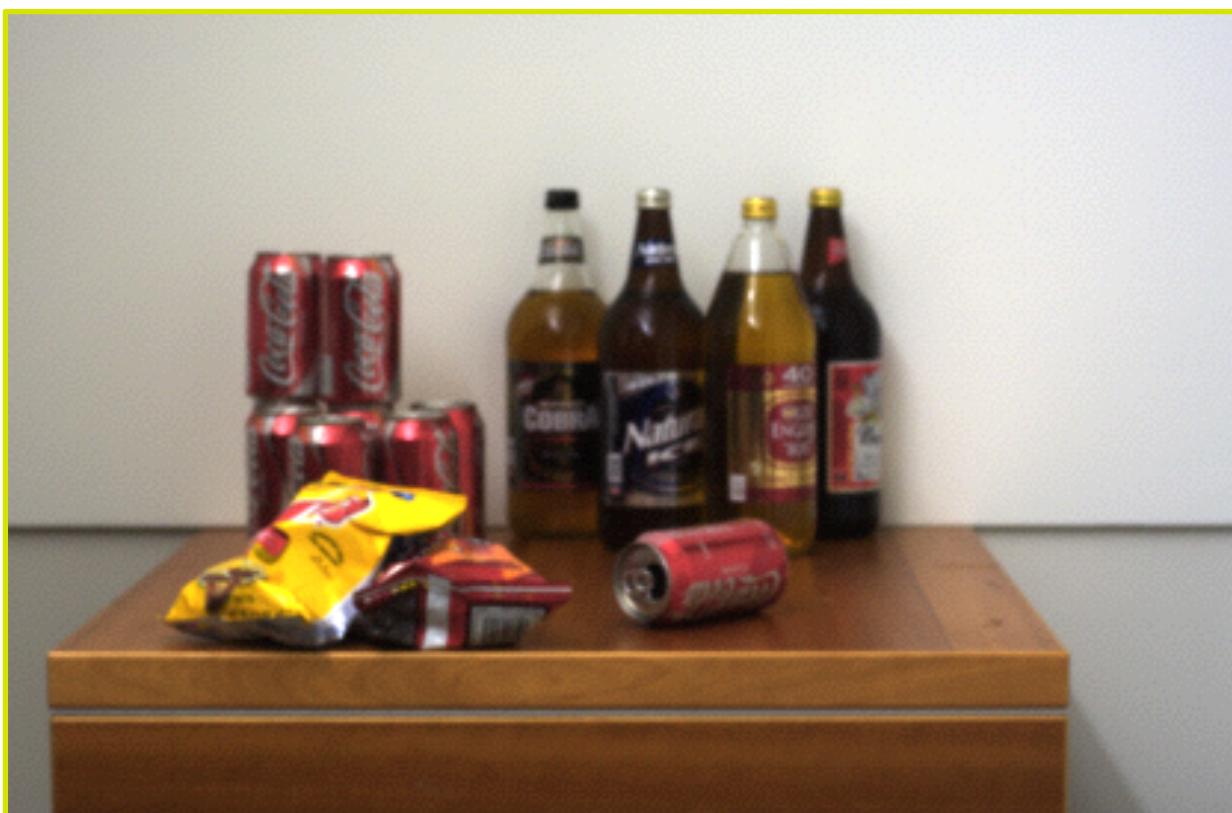


# Epsilon $\leftrightarrow$ Coded Photography

- \* Coded photography encodes the photographic signal and post-capture decoding for improved scene analysis
- \* Epsilon Photography: successive frames may have different variations
- \* Coded Photography: neighborhood pixels may have different variations
  - \* Controlling light over time or space
  - \* Preserve details about the scene in the recorded photograph
- \* Coded photography  $\leftrightarrow$  Epsilon photography

Raskar 2009

# Coded Photography

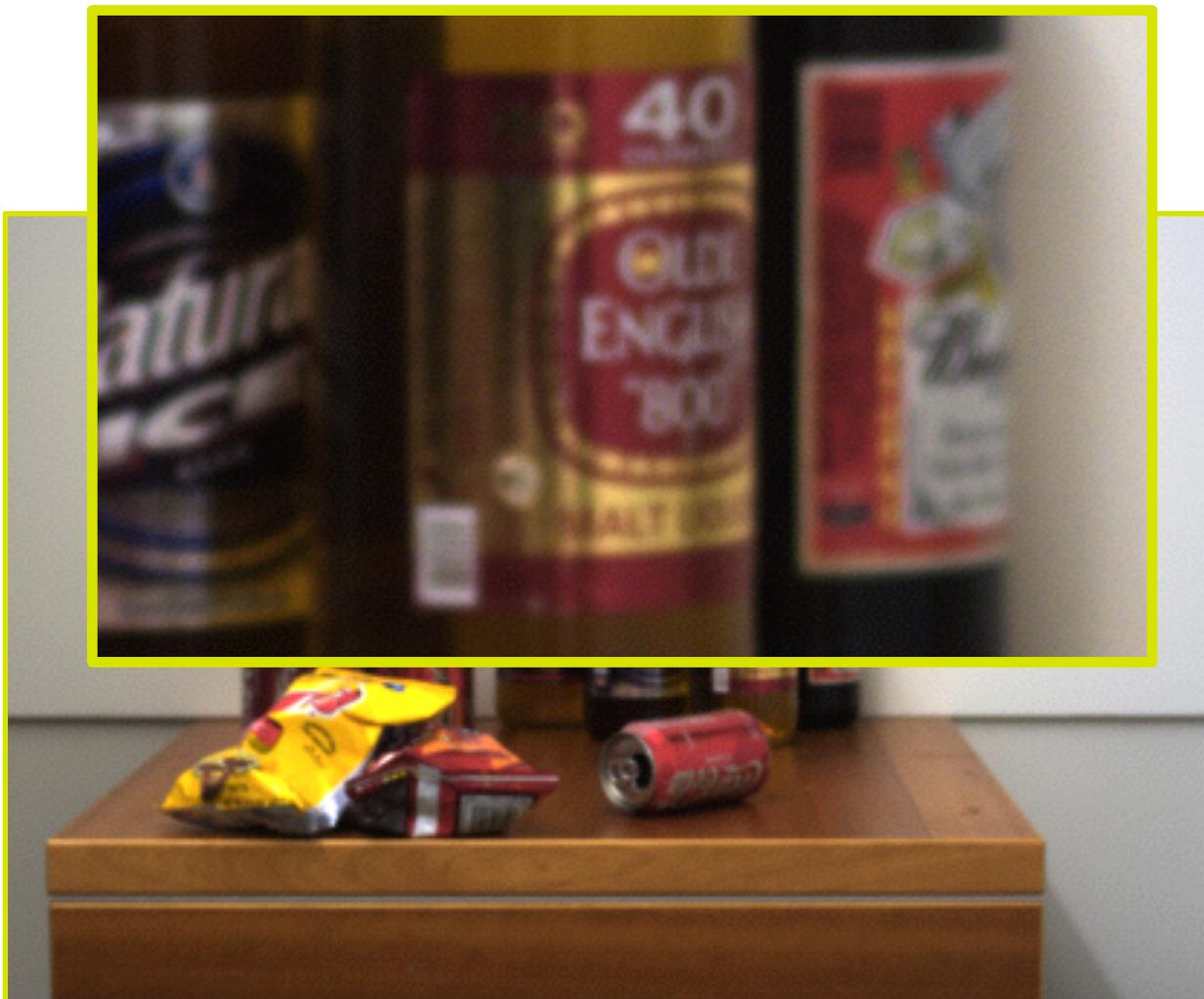


Single input image

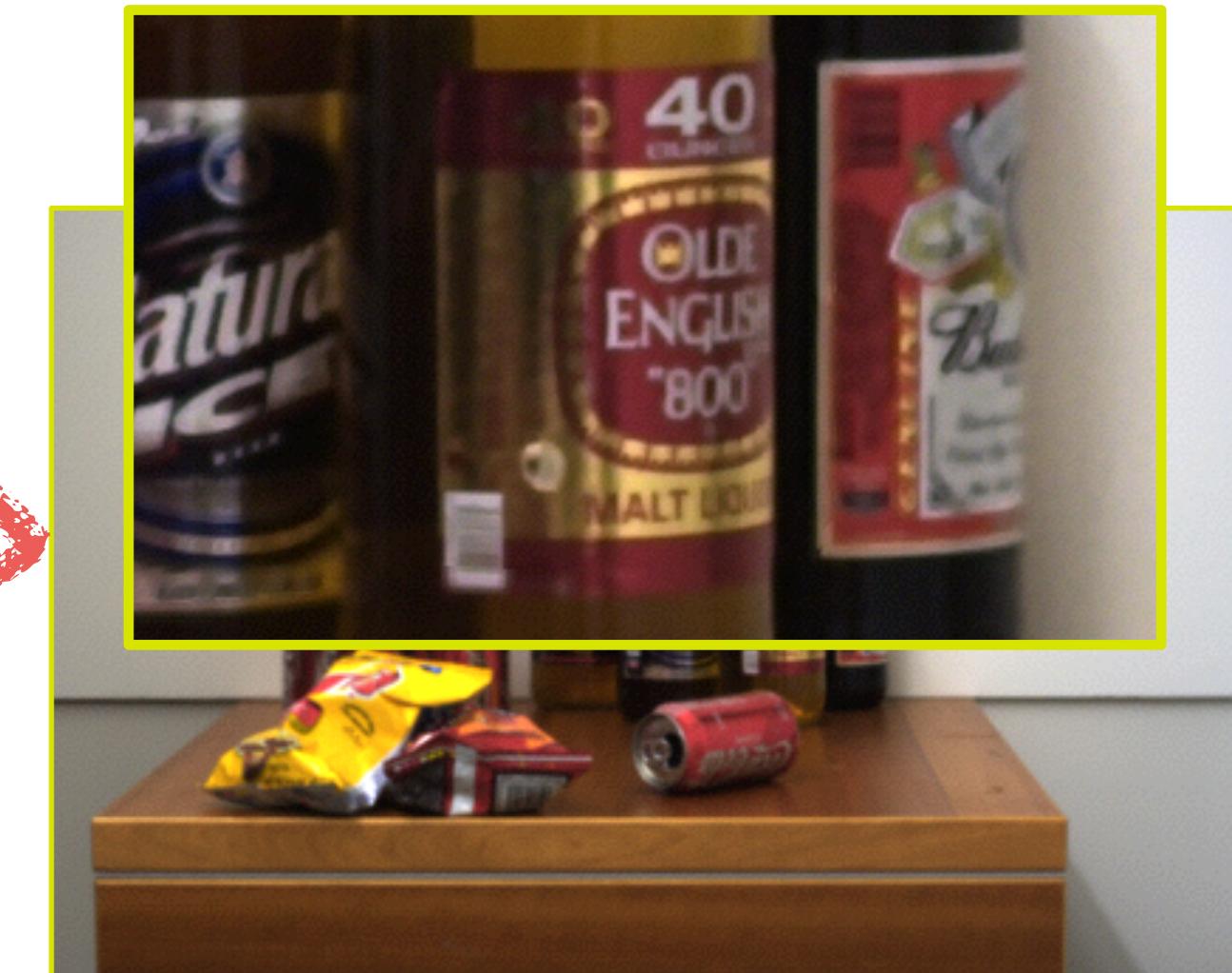


Output #1: Depth map

# Coded Photography



Single input image



Output #2: ALL-focused image

# Lens and defocus

Lens' aperture

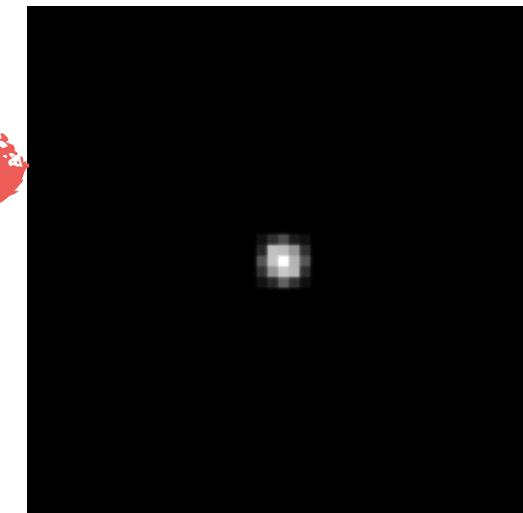
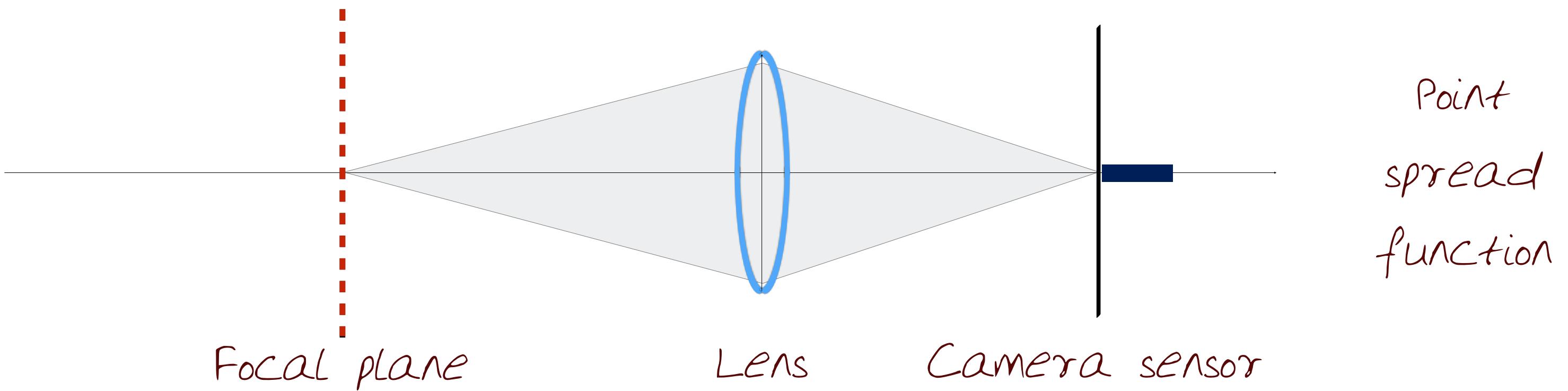


Image of a point light source

Object



# Lens and defocus

Lens' aperture

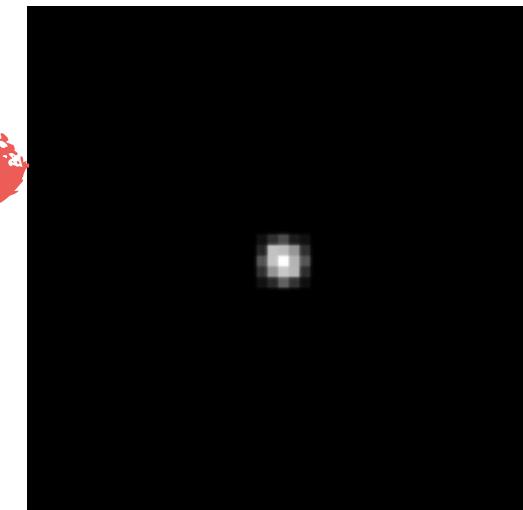
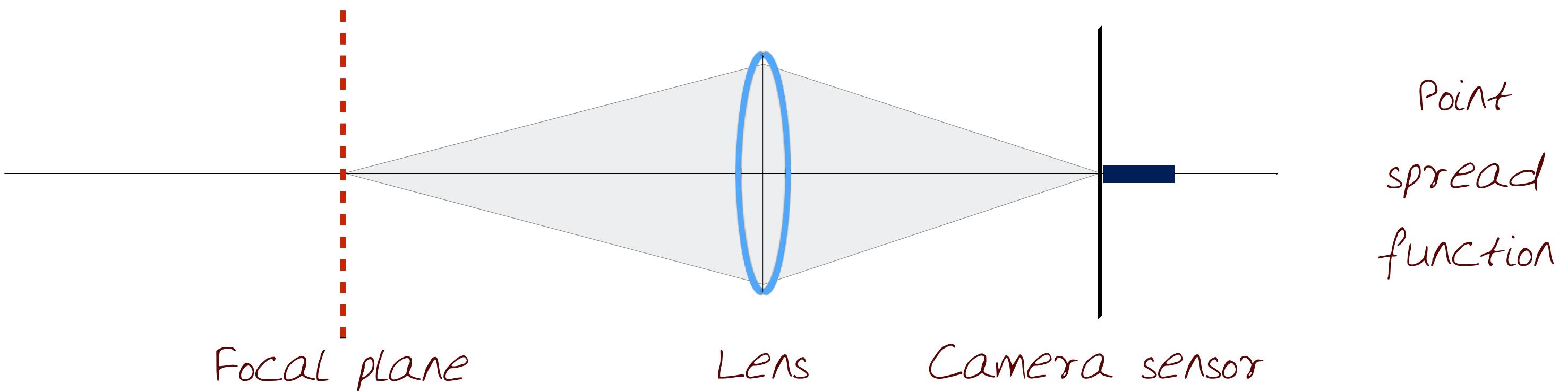


Image of a point light source

Object



# Lens and defocus

Lens' aperture

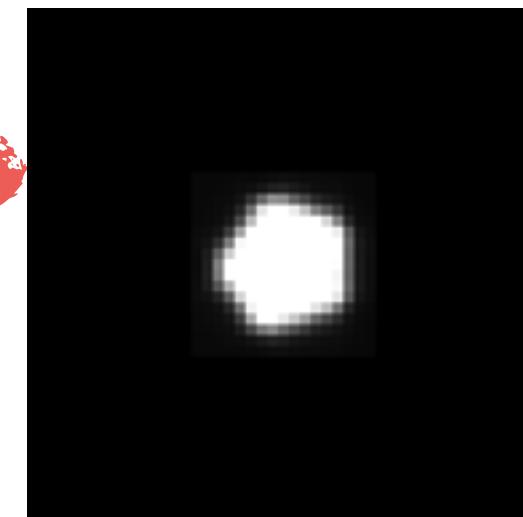
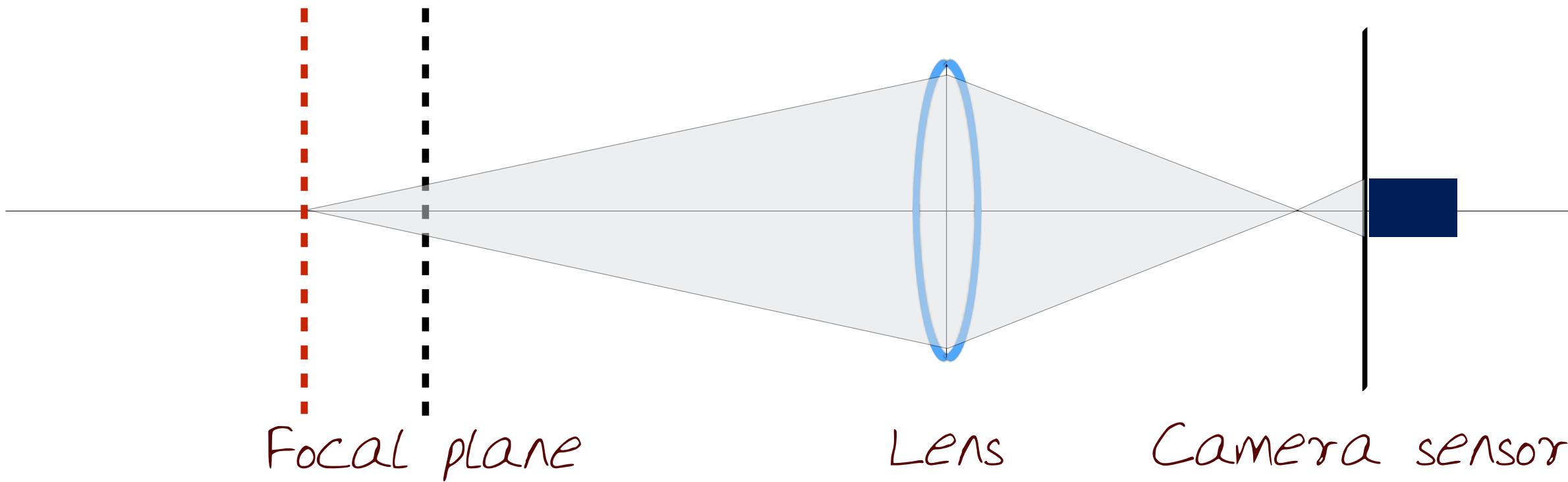


Image of a  
defocused point  
light source

Object



Point  
spread  
function

# Lens and defocus

Lens' aperture

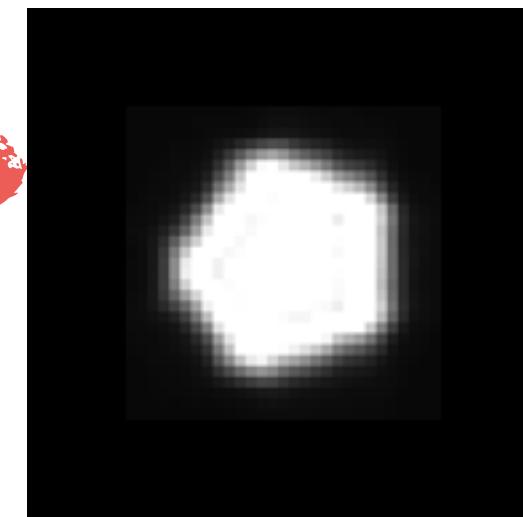
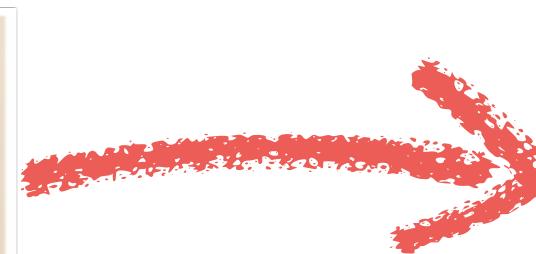
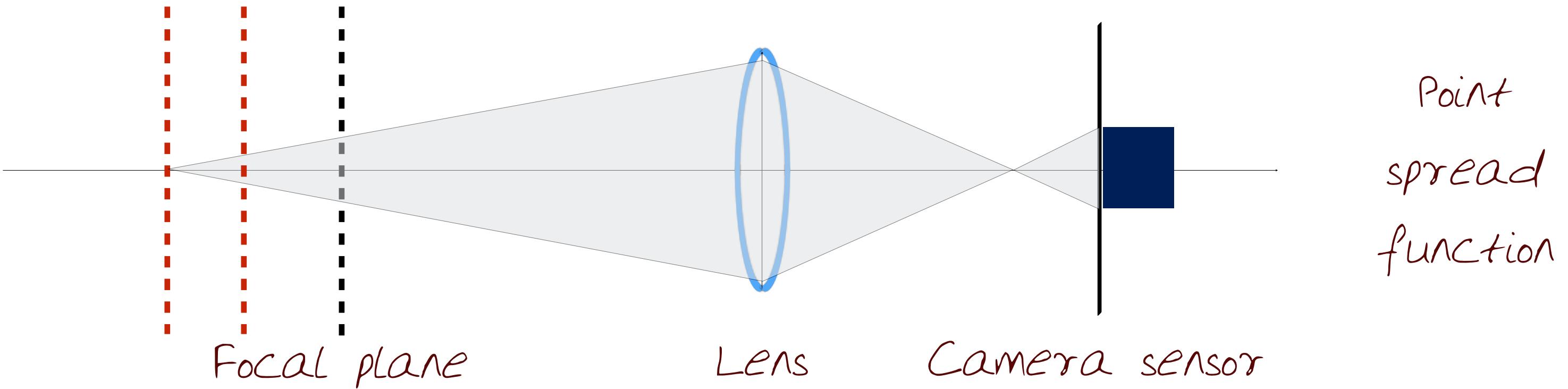


Image of a  
defocused point  
light source

Object



# Lens and defocus

Lens' aperture

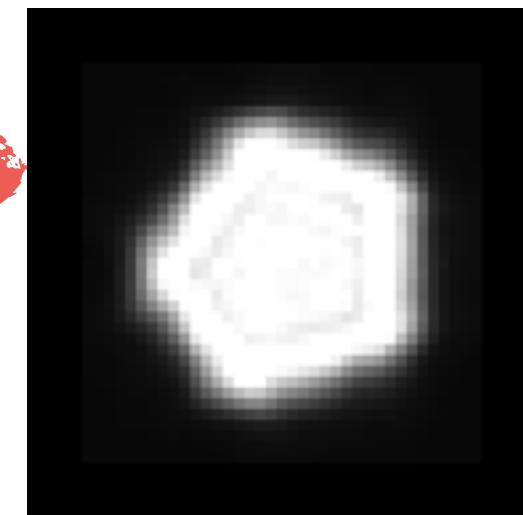
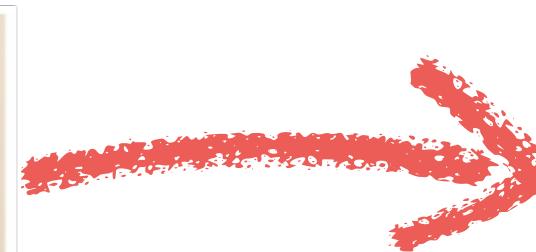
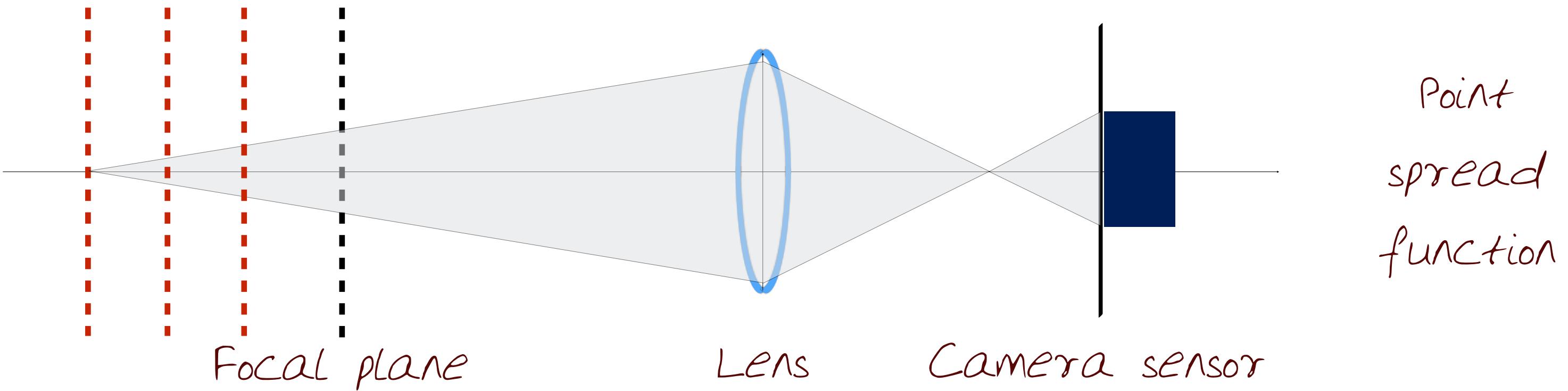


Image of a  
defocused point  
light source

Object



Focal plane

Lens

Camera sensor

# Lens and defocus

Lens' aperture

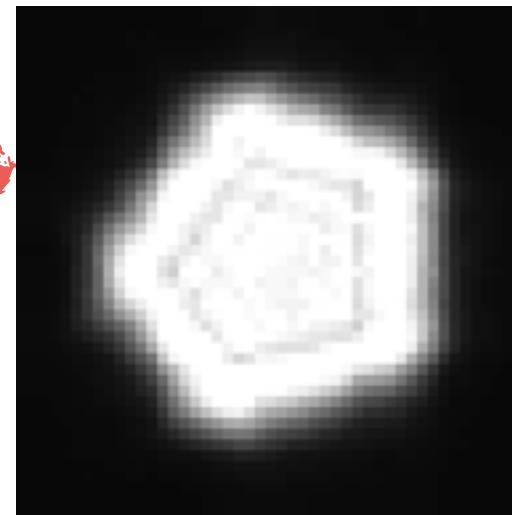
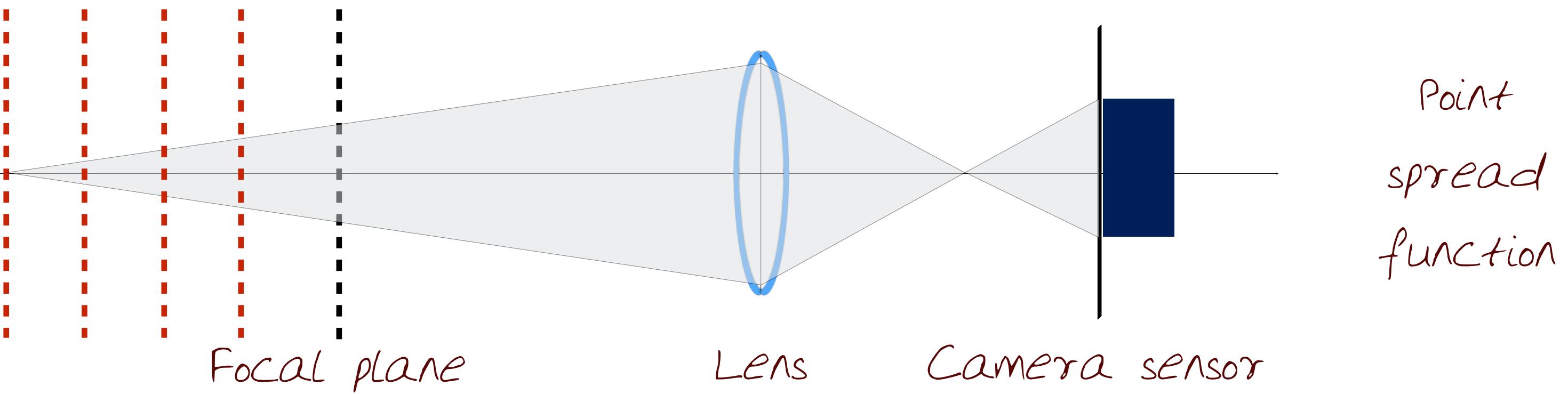
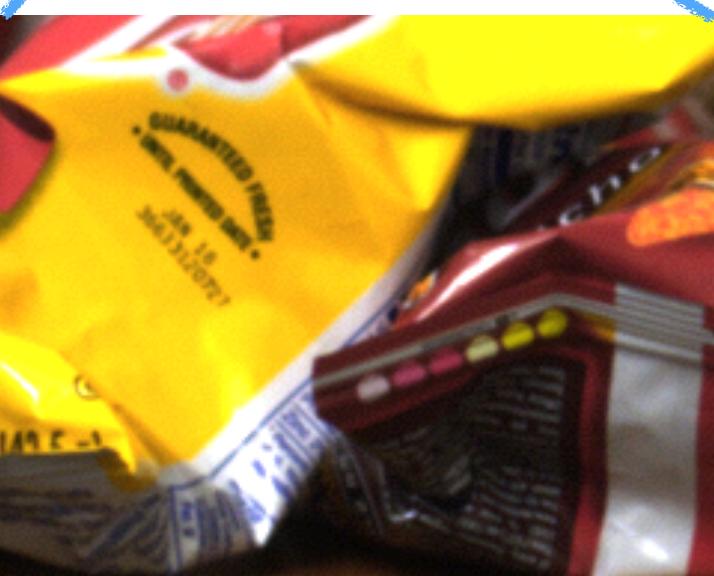
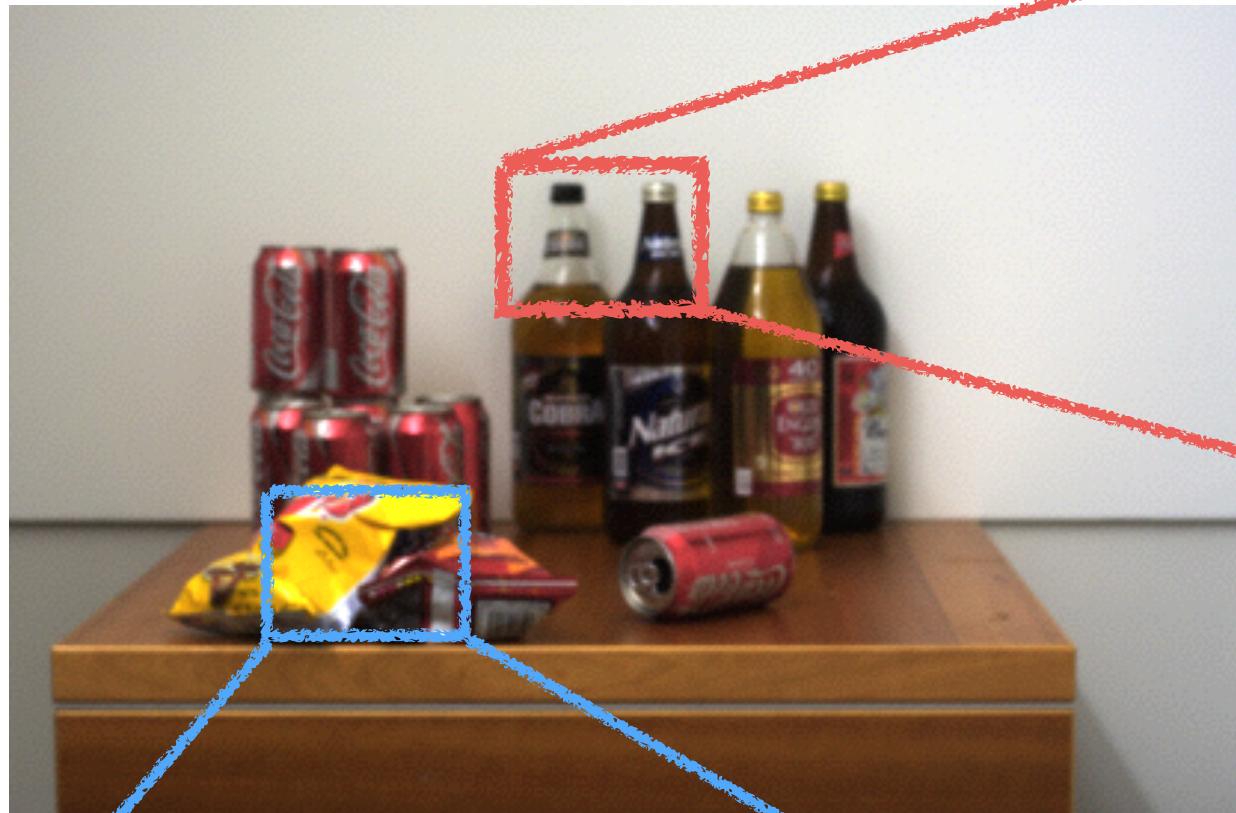


Image of a  
defocused point  
light source

Object



# Depth and defocus



In focus



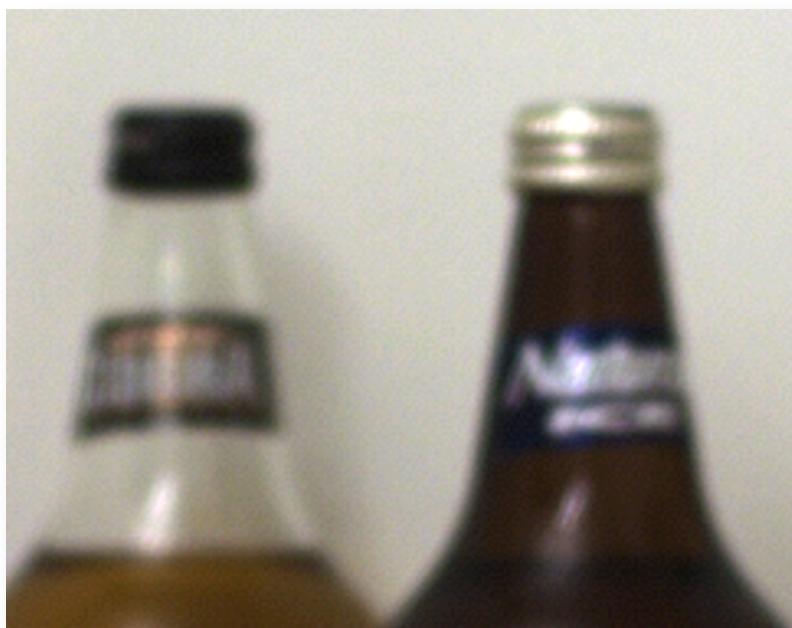
Out of focus

*ill-posed*

Depth from defocus:  
Infer depth by  
analyzing local scale  
of defocus blur

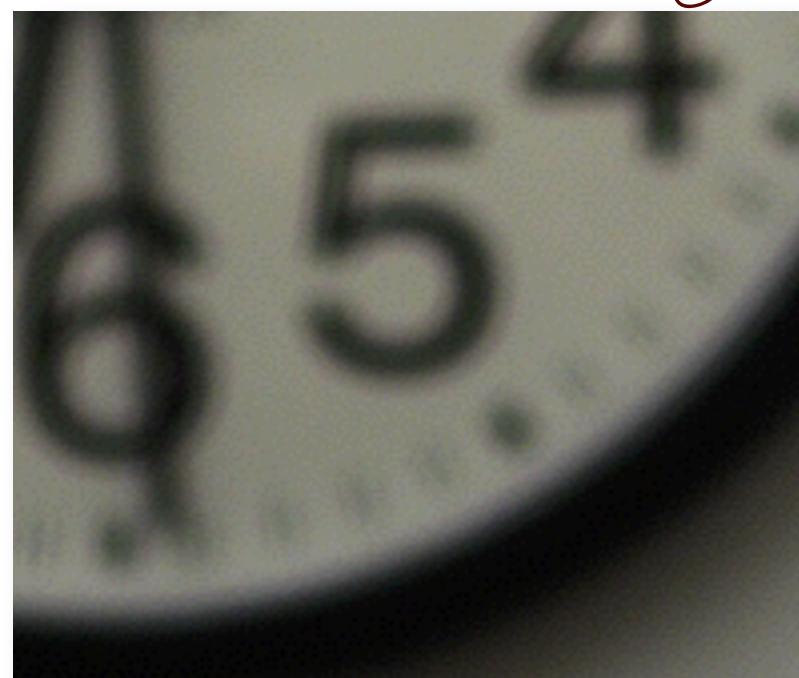
# Depth and defocus: Challenges

- \* Hard to discriminate a smooth scene from defocus blur
- \* Hard to undo defocus blur



Out of focus?

Given this image



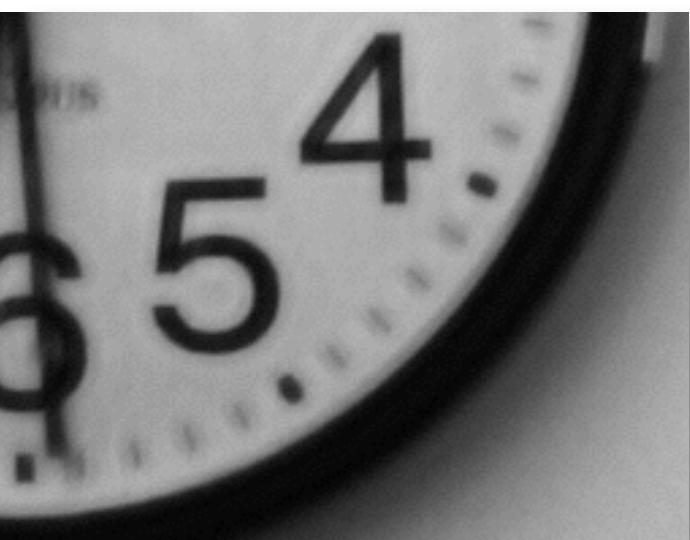
Conventional de-blurring algorithm



Lucy-Richardson Deconvolution 1972-74

# Possible Approaches

- \* Levin et al 2007
- \* Exploit prior on natural images
  - \* Improve deconvolution
  - \* Improve depth discrimination
- \* Make defocus patterns different from natural images and easier to discriminate
- \* Coded aperture (mask inside lens)



Natural



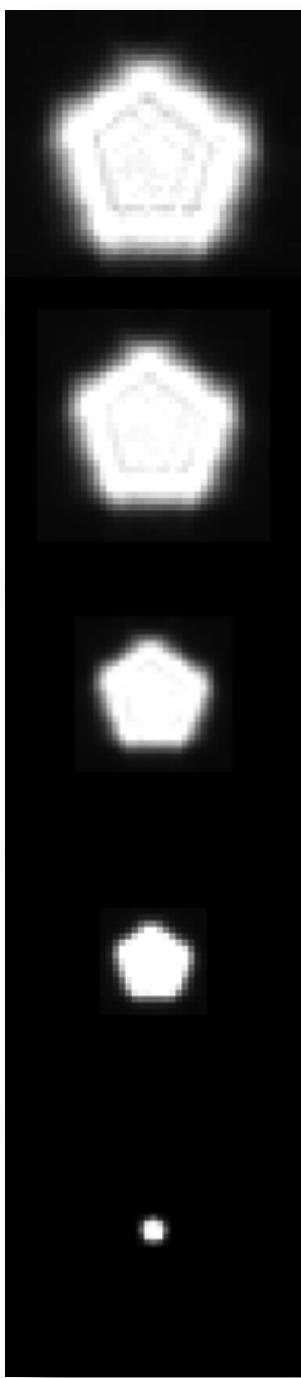
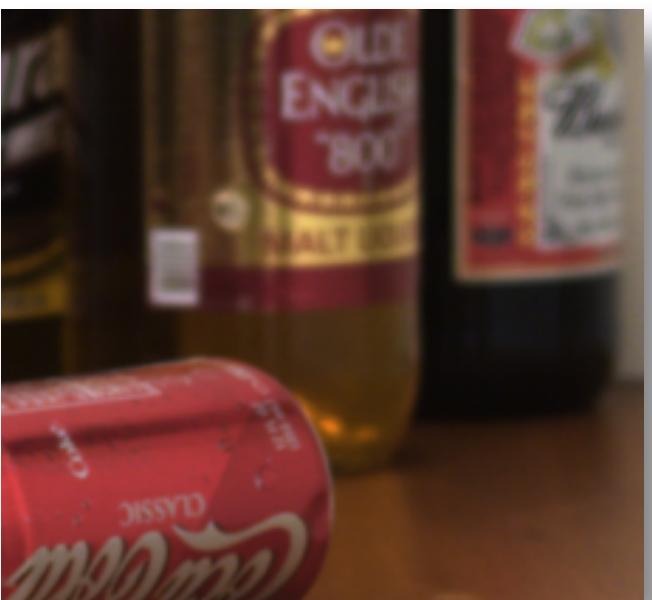
Unnatural



Levin et al 2007, Lucy-Richardson Deconvolution 1972-74

# Defocus as Local Convolution

Input  
defocused  
image

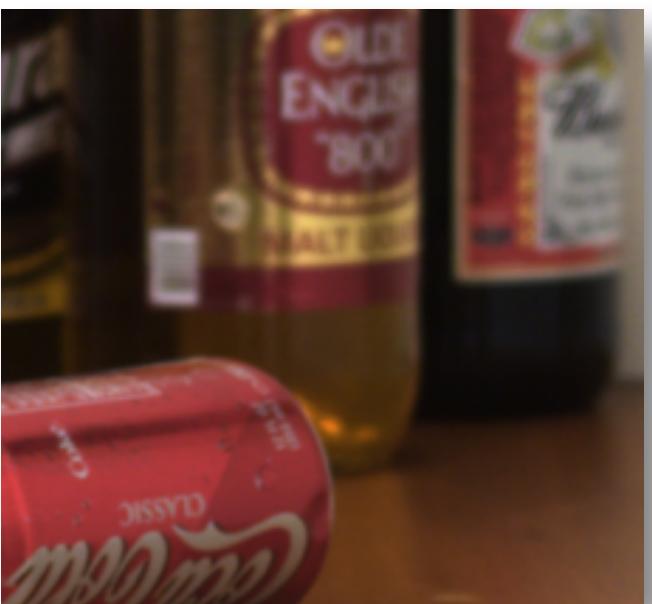


Calibrated blur  
kernels at  
different depths

Levin et al 2007

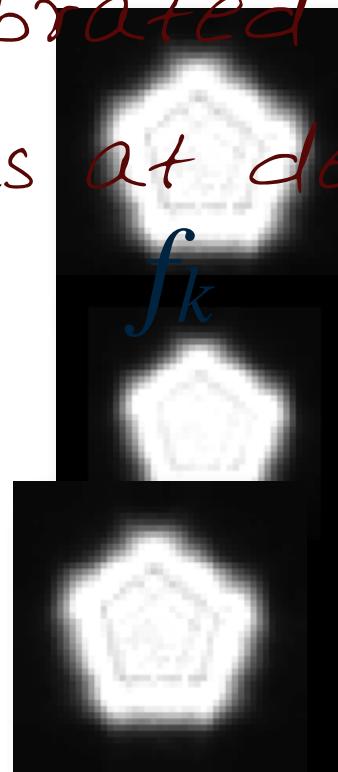
# Defocus as Local Convolution

INPUT  
defocused  
image

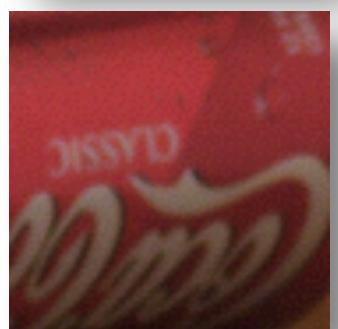
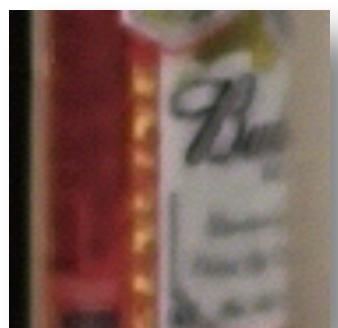


Local sub-  
window  
 $y_k$

Calibrated blur  
kernels at depth  $k$



Sharp  
sub-window  
 $x$



$$y_k = f_k \star x$$

Depth  $k=1$



Depth  $k=2$



Depth  $k=3$



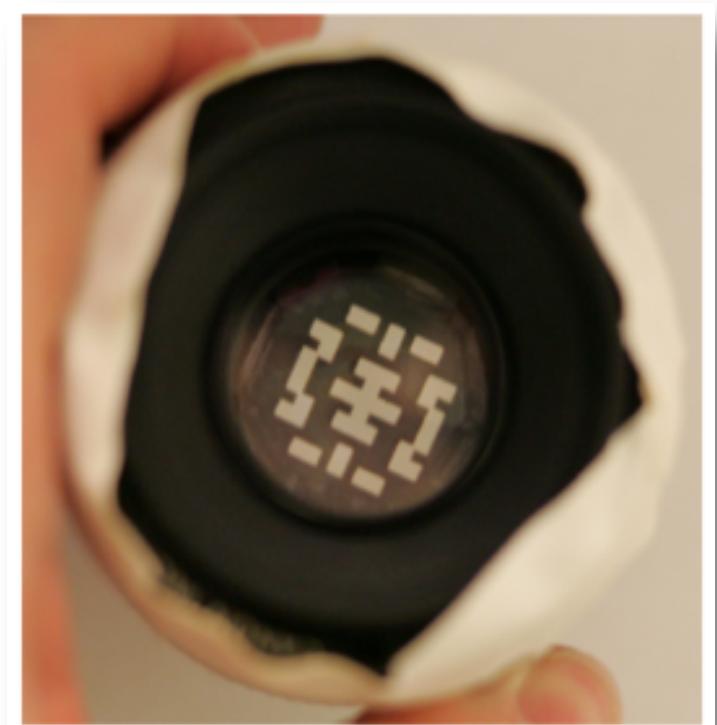
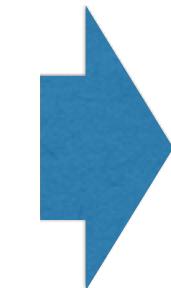
Levin et al 2007

# Coded Aperture

- \* mask (code) in aperture plane
- \* make defocus patterns different and easier to discriminate



Conventional  
aperture



Our coded  
aperture

# Lens and defocus

Lens' aperture

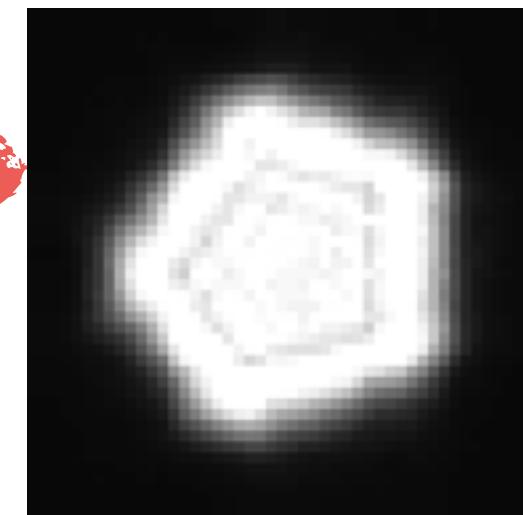
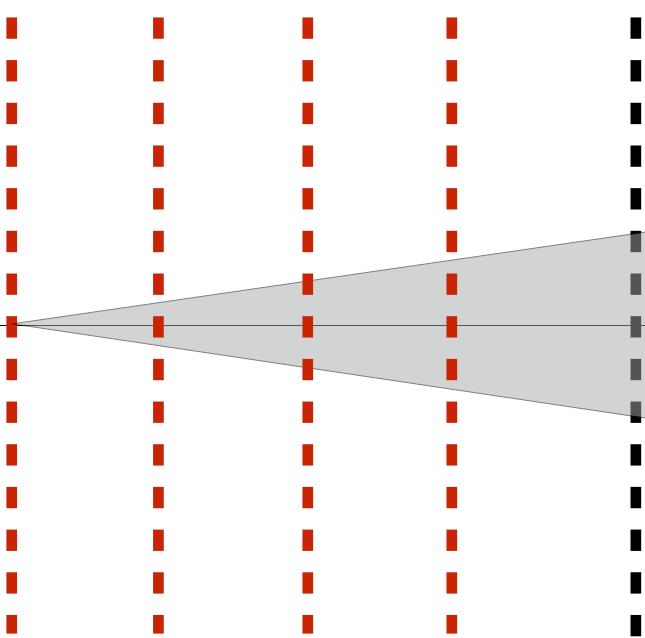
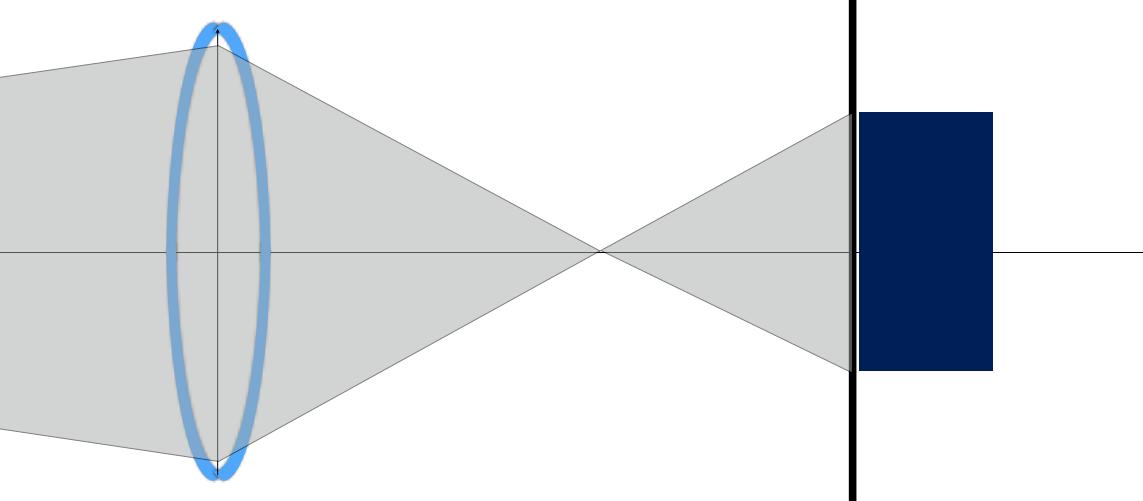


Image of a  
defocused point  
light source

Object



Lens



Focal plane

Camera sensor

Point  
spread  
function

# Coded Lens and Defocus

Lens with  
coded  
aperture

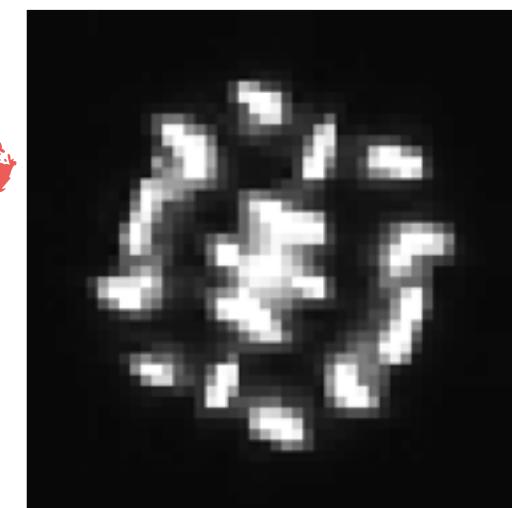
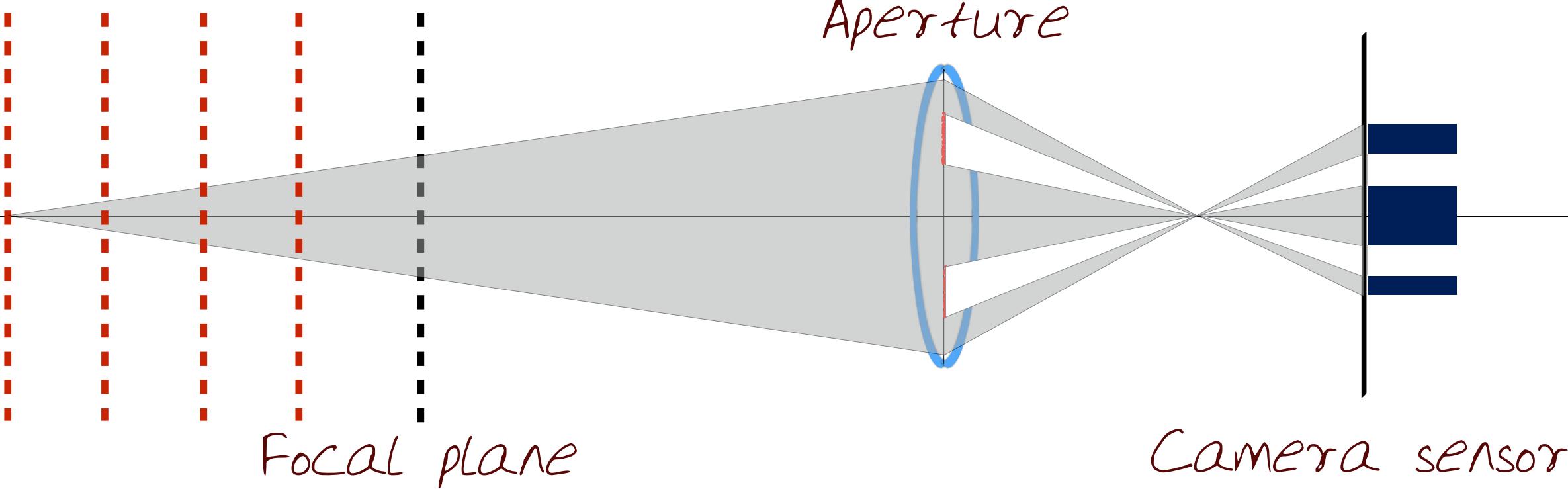


Image of a  
defocused point  
light source

Lens with  
coded  
Aperture

Object



Point  
spread  
function

# Coded Lens and Defocus

Lens with  
coded  
aperture

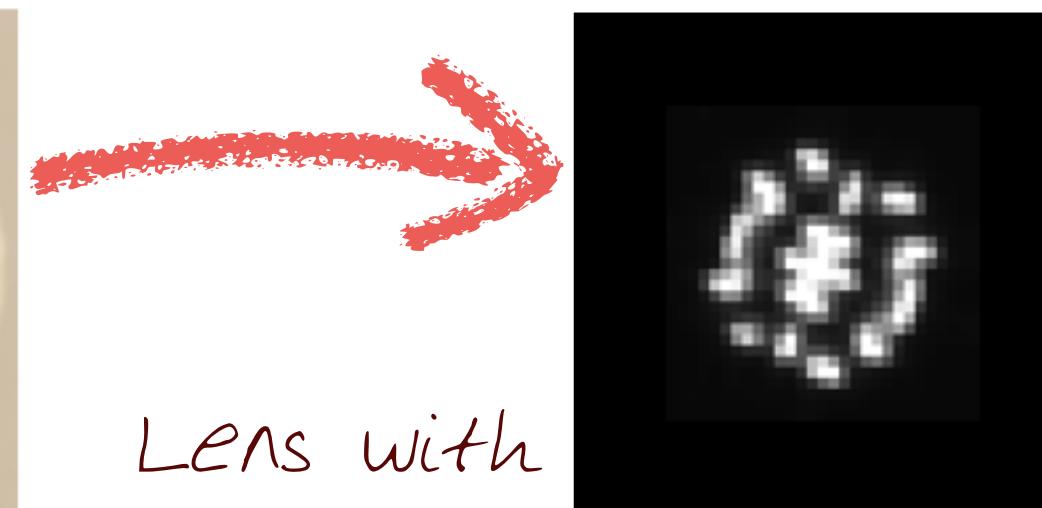
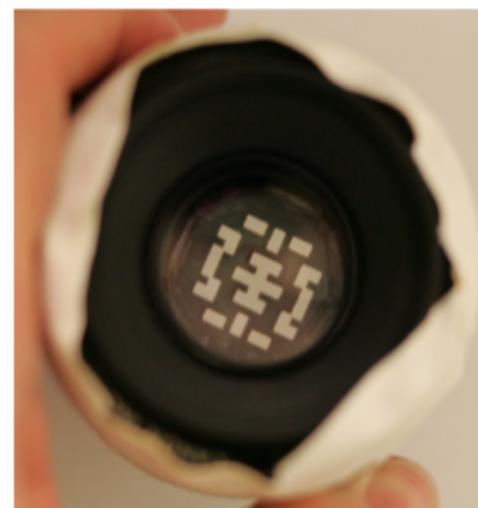
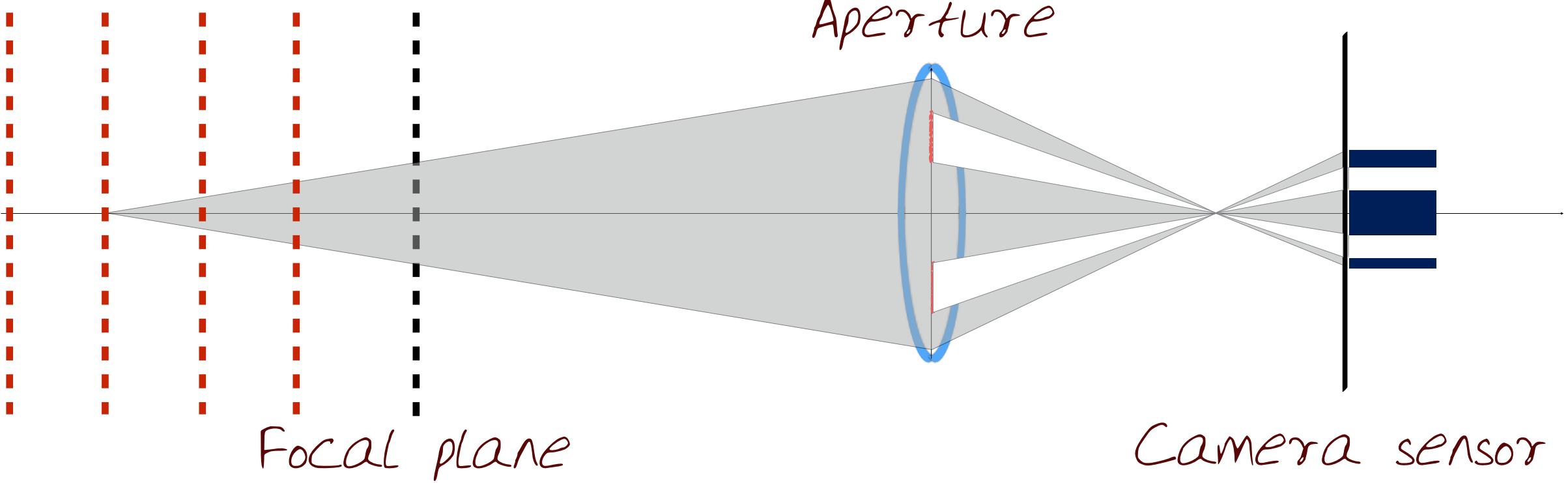


Image of a  
defocused point  
light source

Object



# Coded Lens and Defocus

Lens with  
coded  
aperture

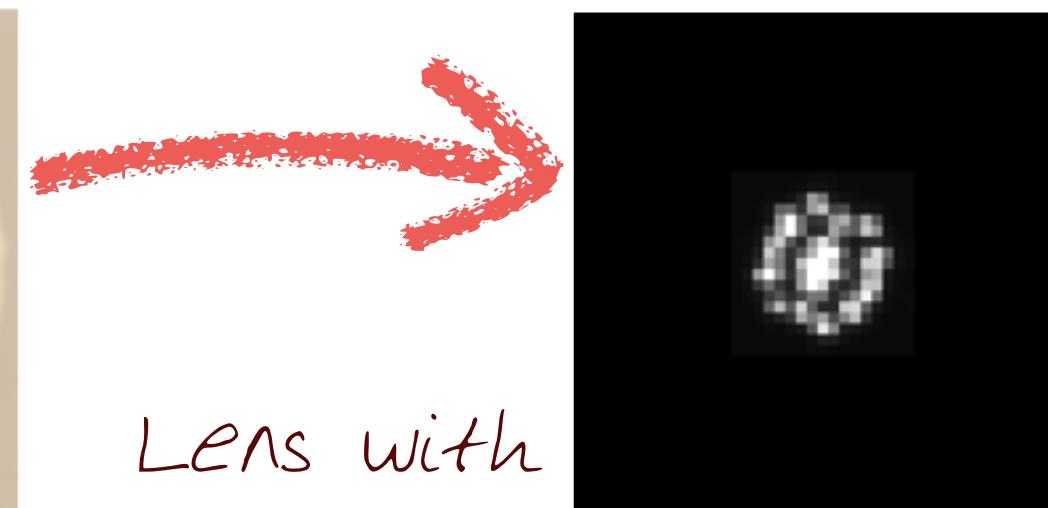
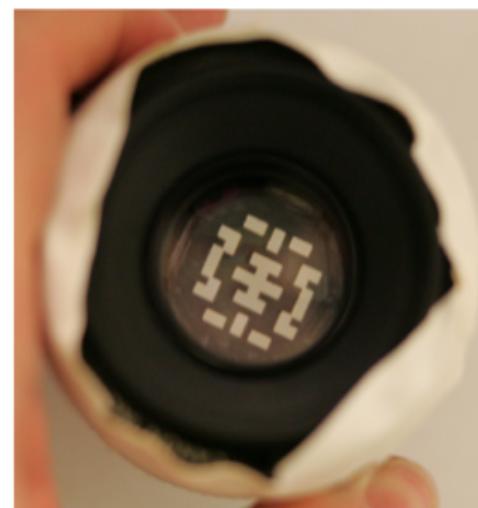
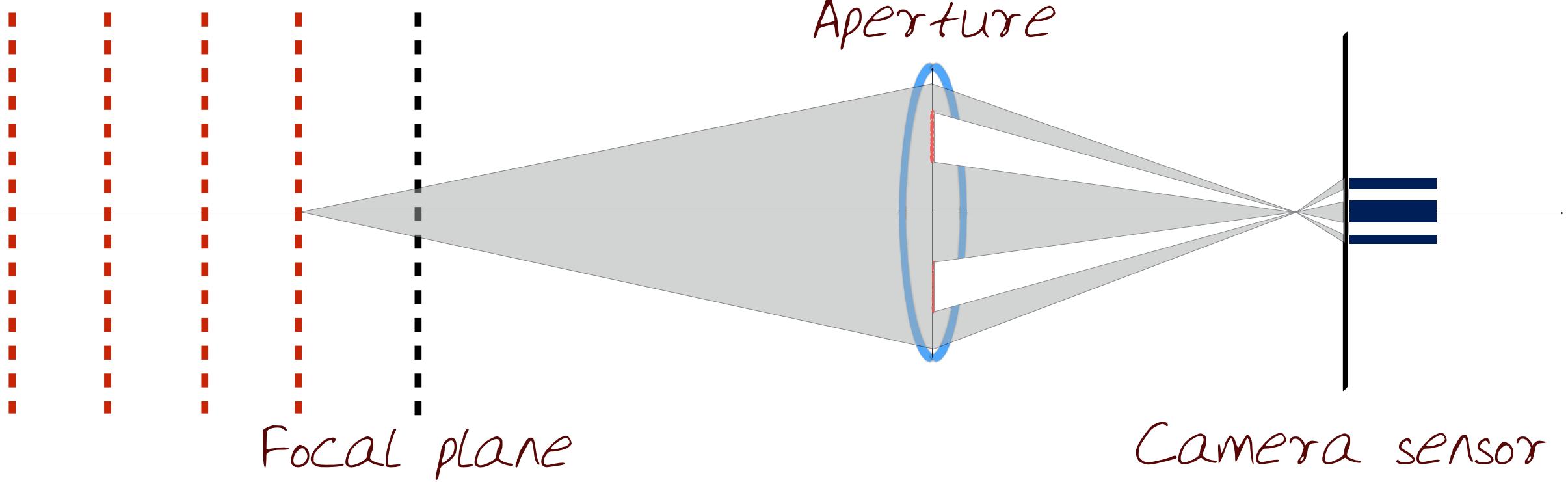


Image of a  
defocused point  
light source

Object



# Coded Lens and Defocus

Lens with  
coded  
aperture

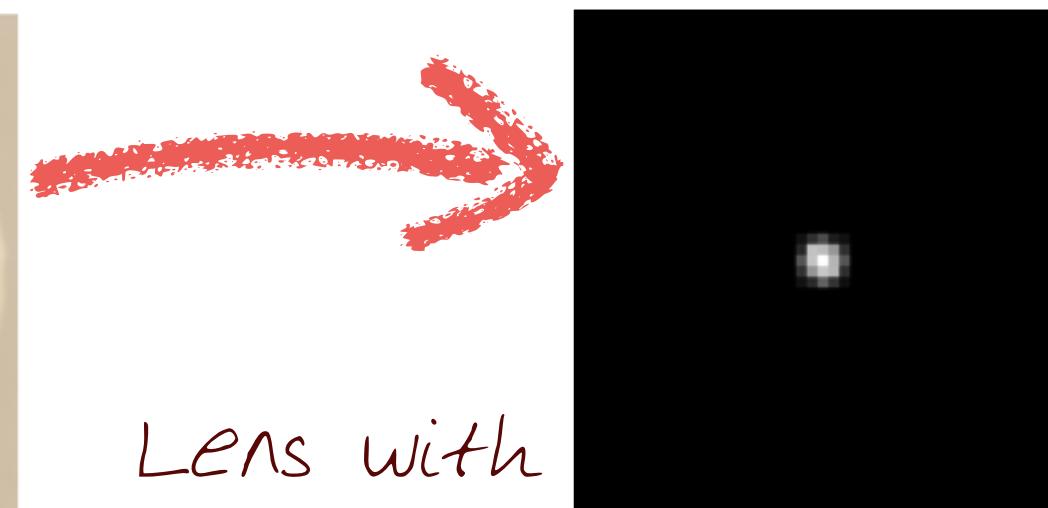
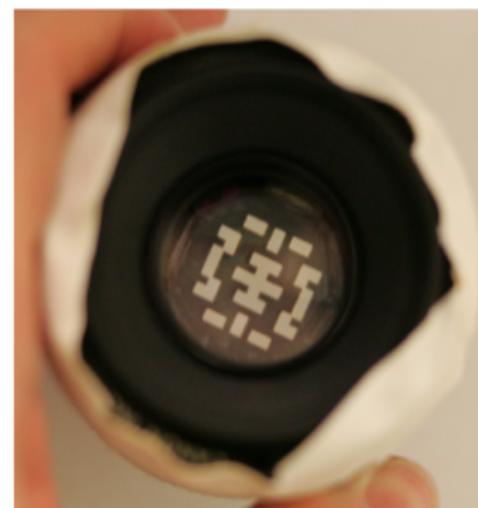
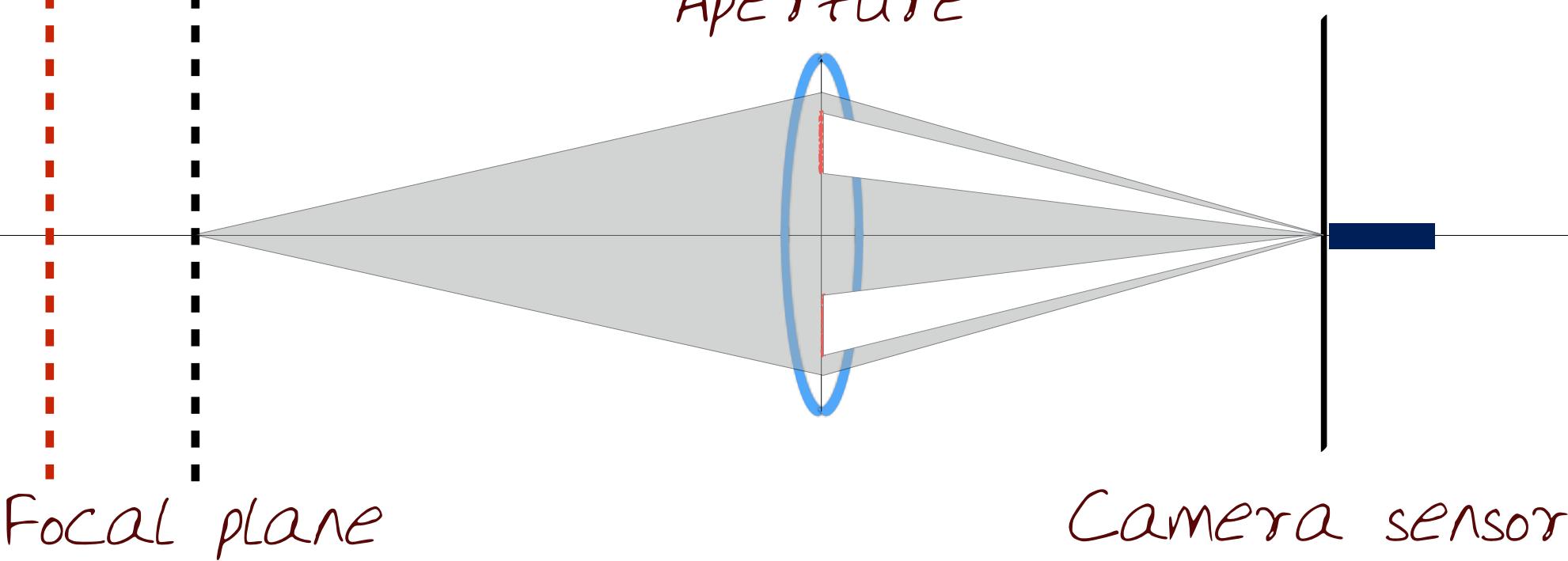


Image of a  
defocused point  
light source

Object



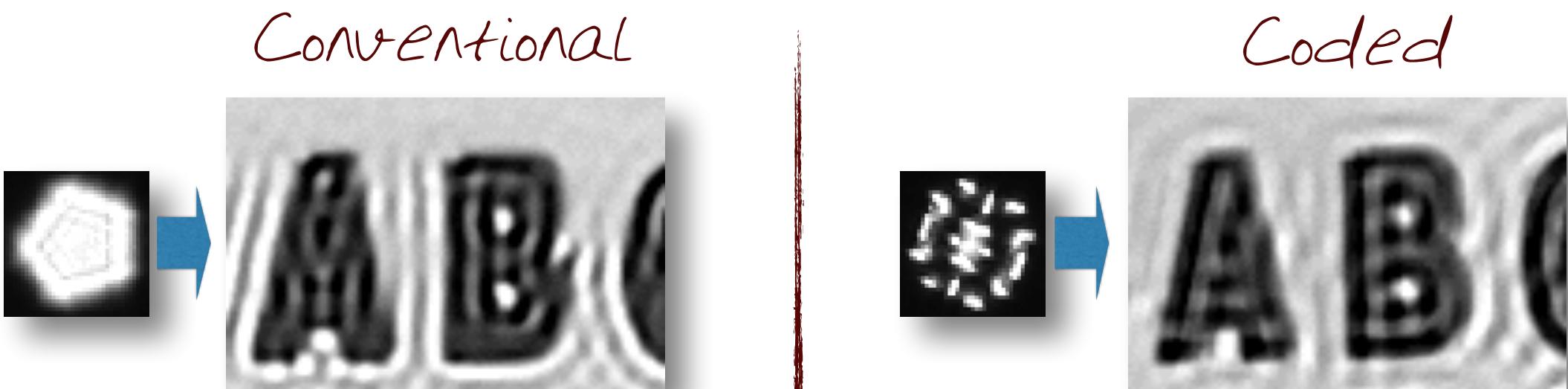
coded  
Aperture



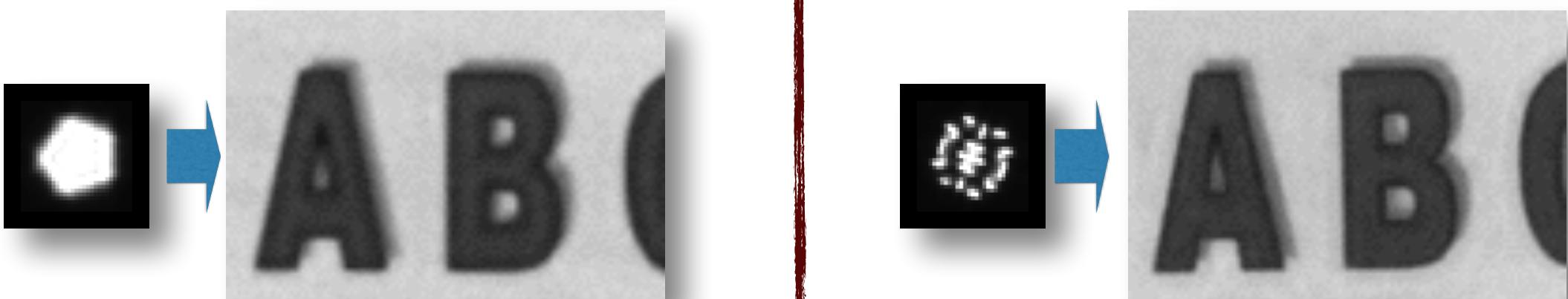
Point  
spread  
function

# Benefits of Coded Aperture

Larger scale



Correct scale



Smaller scale



Lucy-Richardson Deconvolution

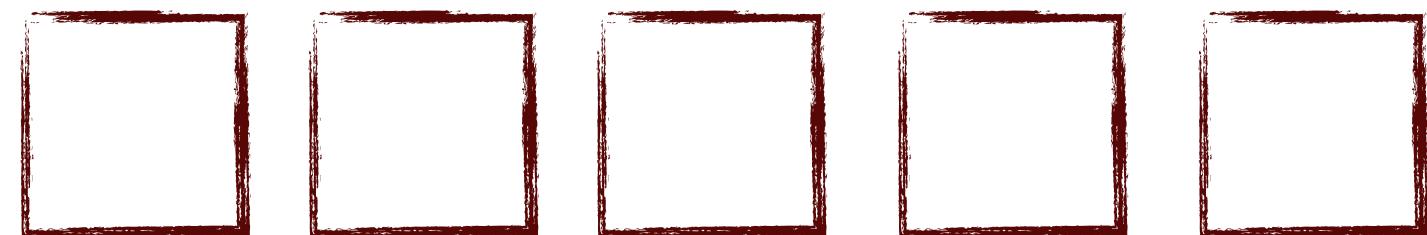


# Aperture Occluder!

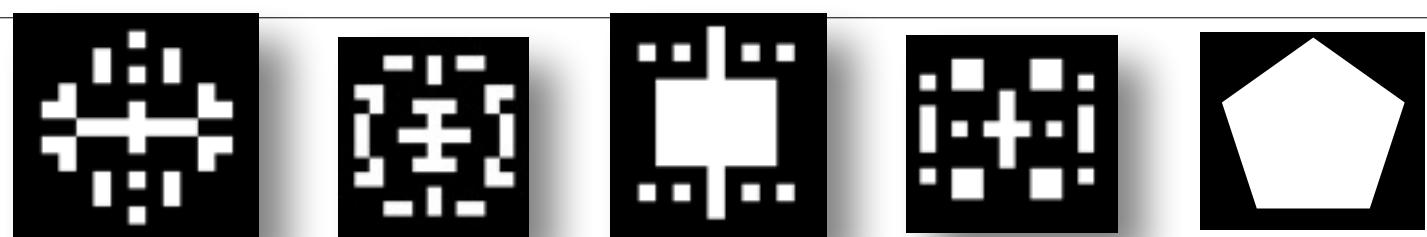
Analytically  
search for a  
pattern maximizing  
discrimination  
between images  
at different  
defocus scales

More discrimination

SCORE Enter relative discrimination:  
1 = least,  
5 = most



Less discrimination



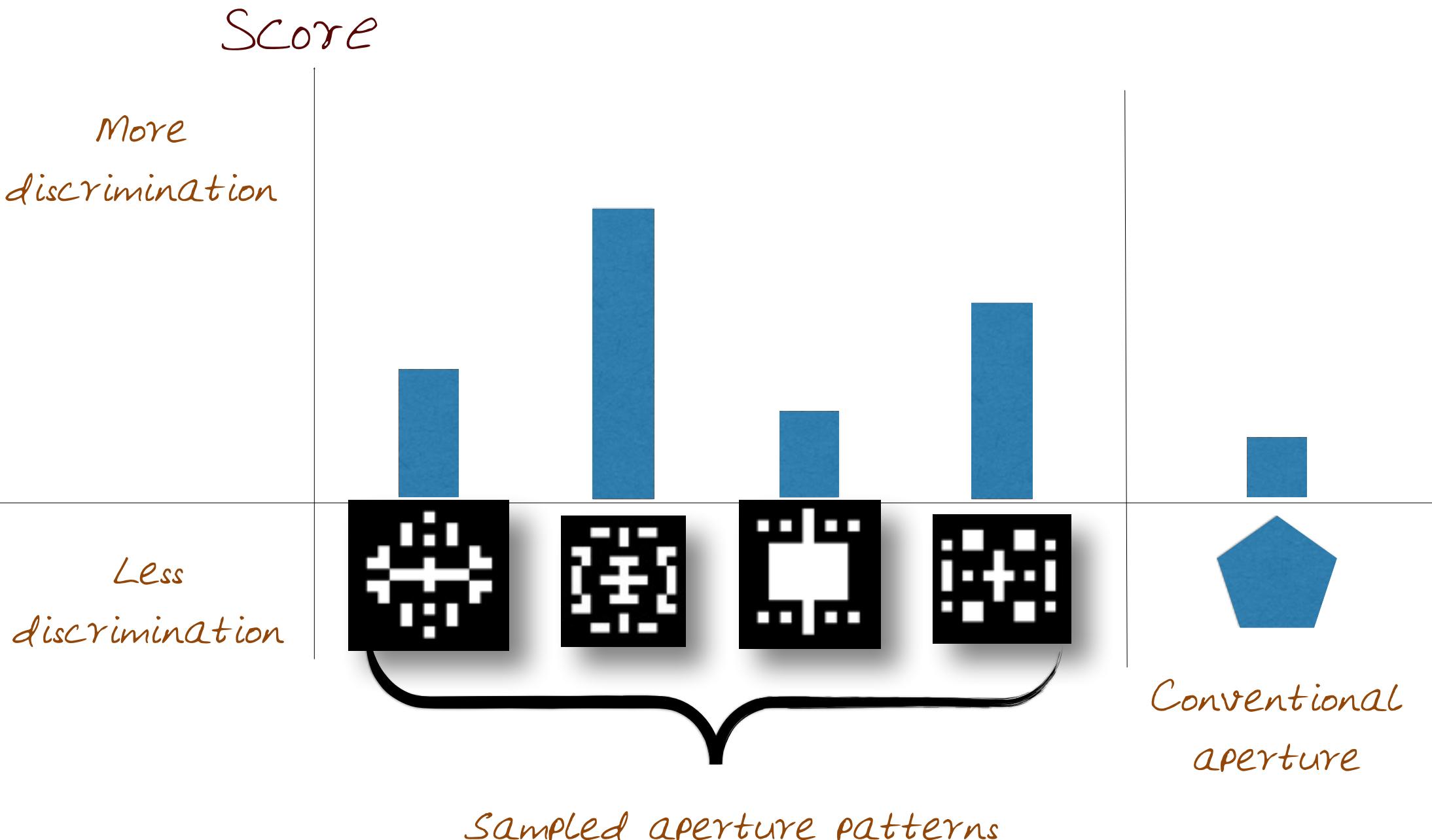
Sampled aperture patterns

Conventional  
aperture

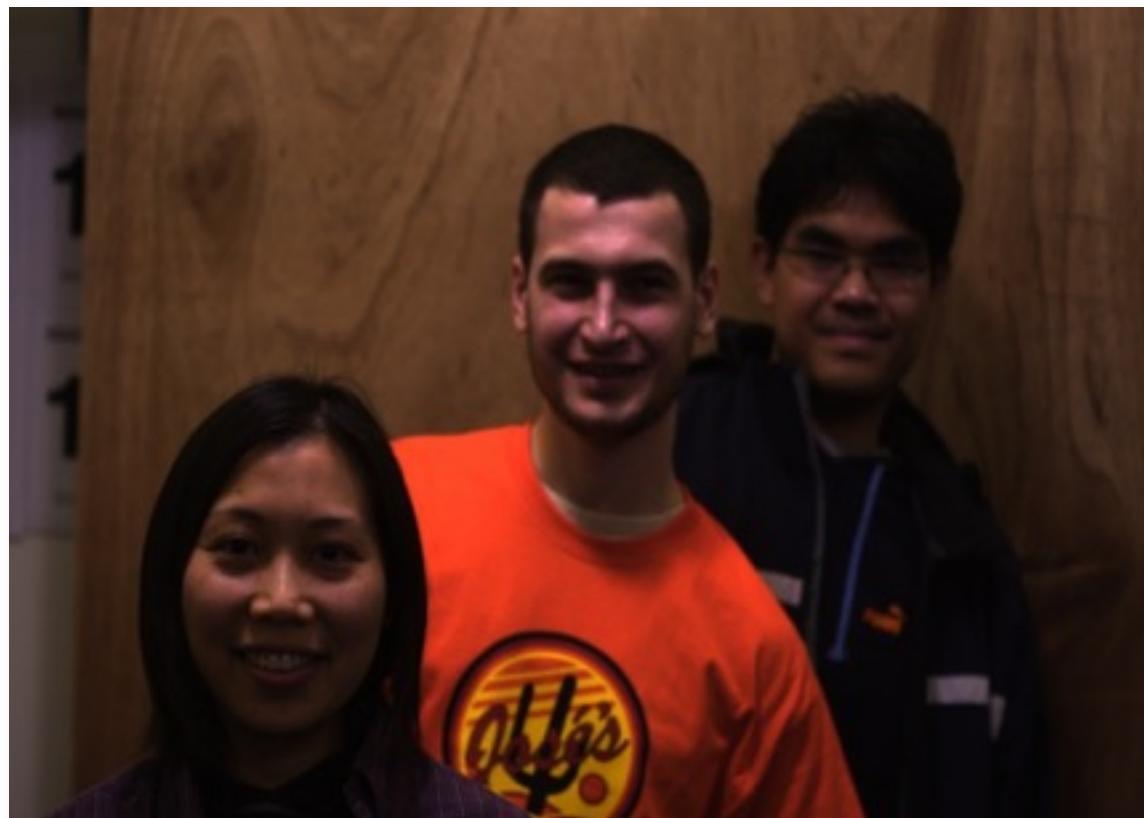


# Aperture Occluder!

Analytically  
search for a  
pattern maximizing  
discrimination  
between images  
at different  
defocus scales

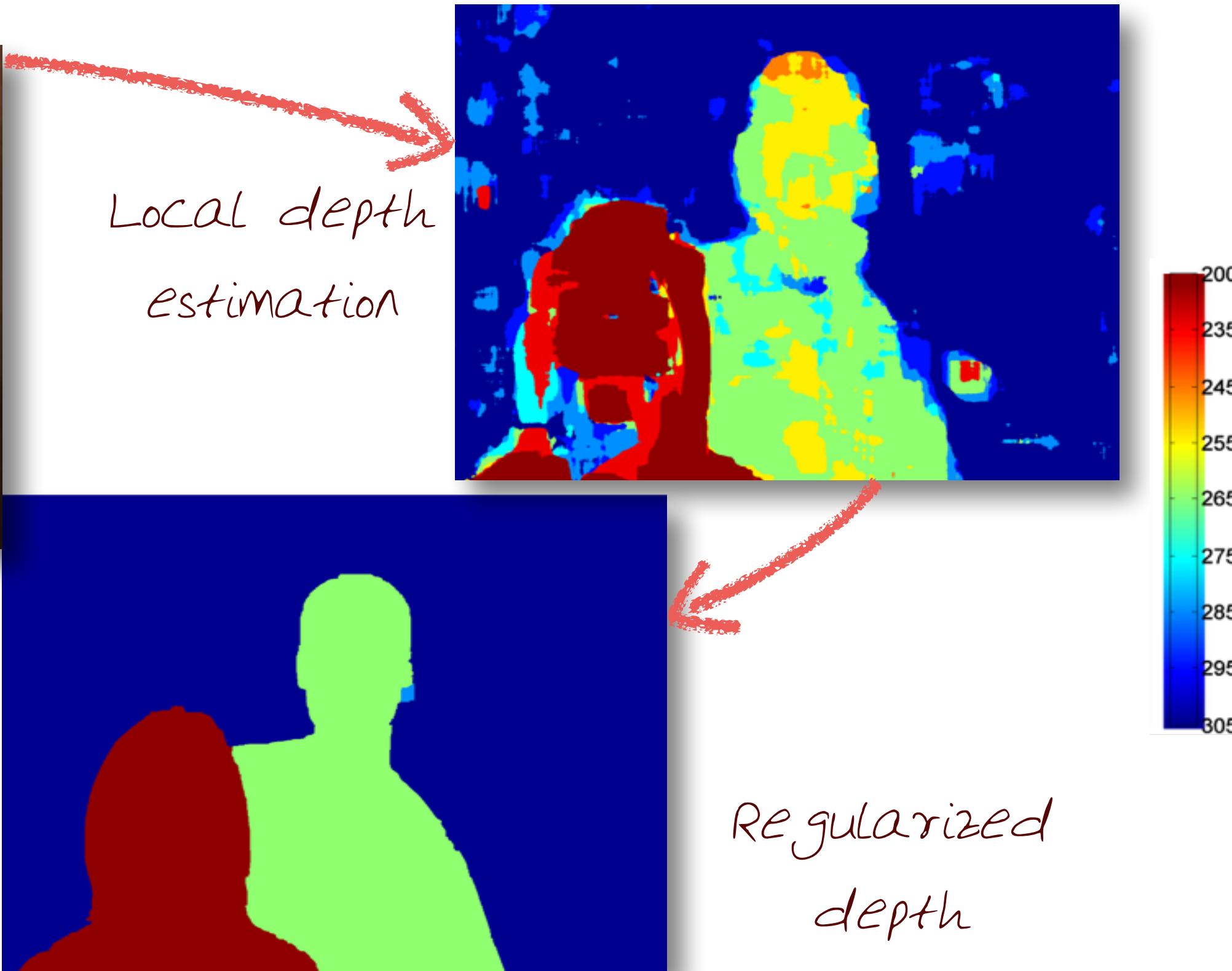


# Depth Estimation



INPUT

Levin et al 2007

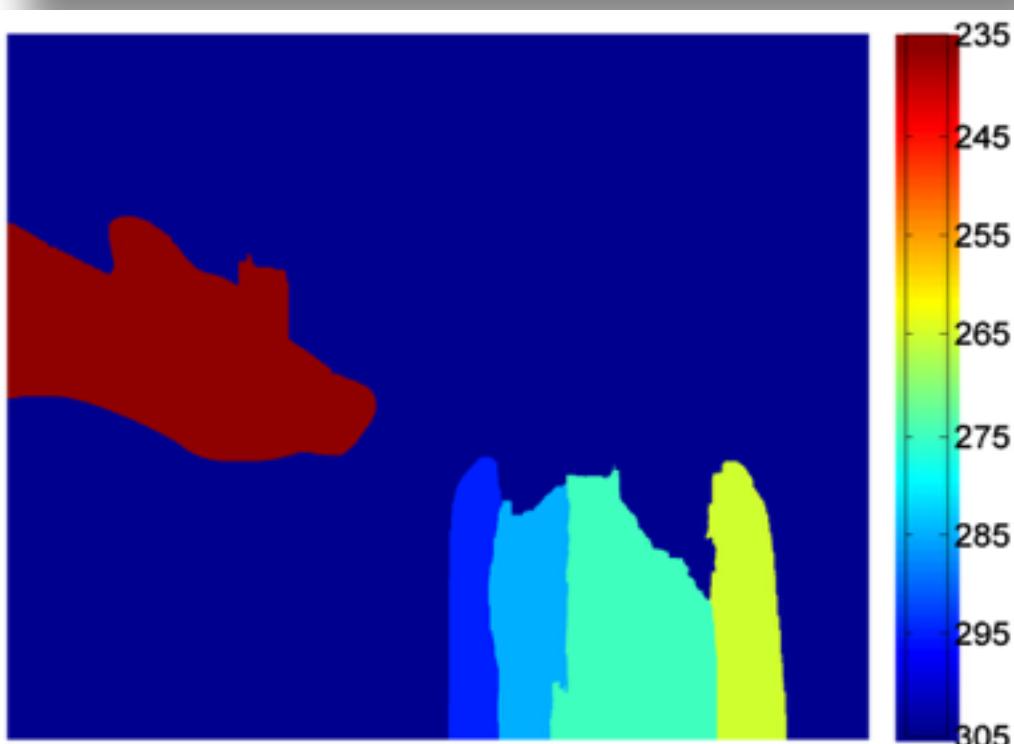


# Depth

INPUT

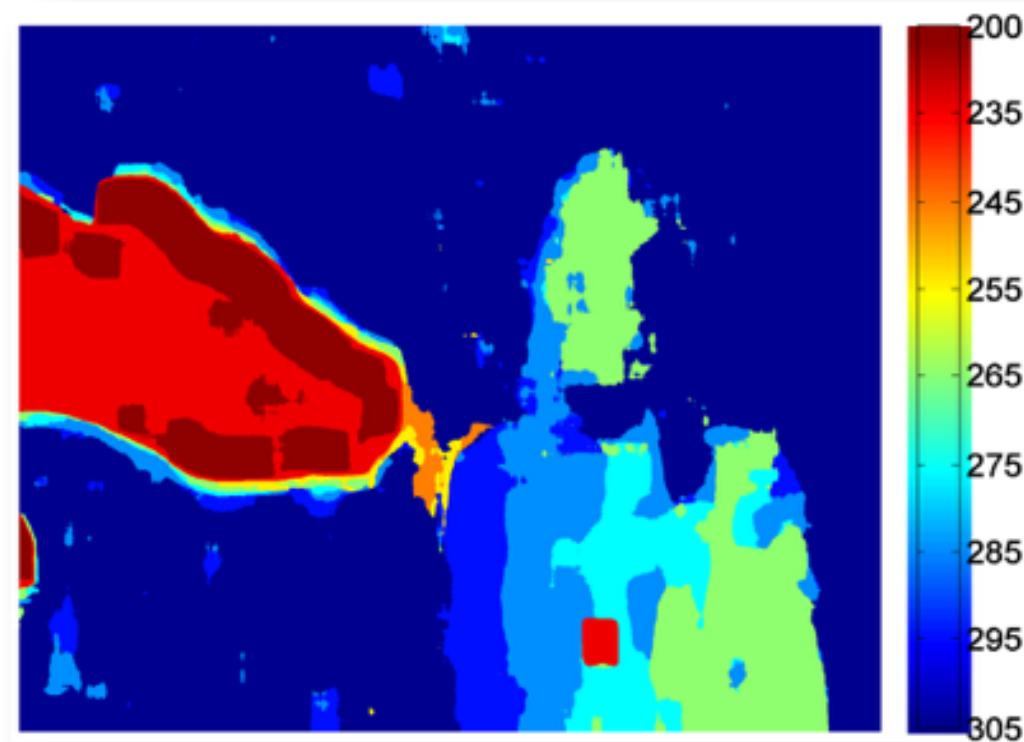


Regularized  
depth

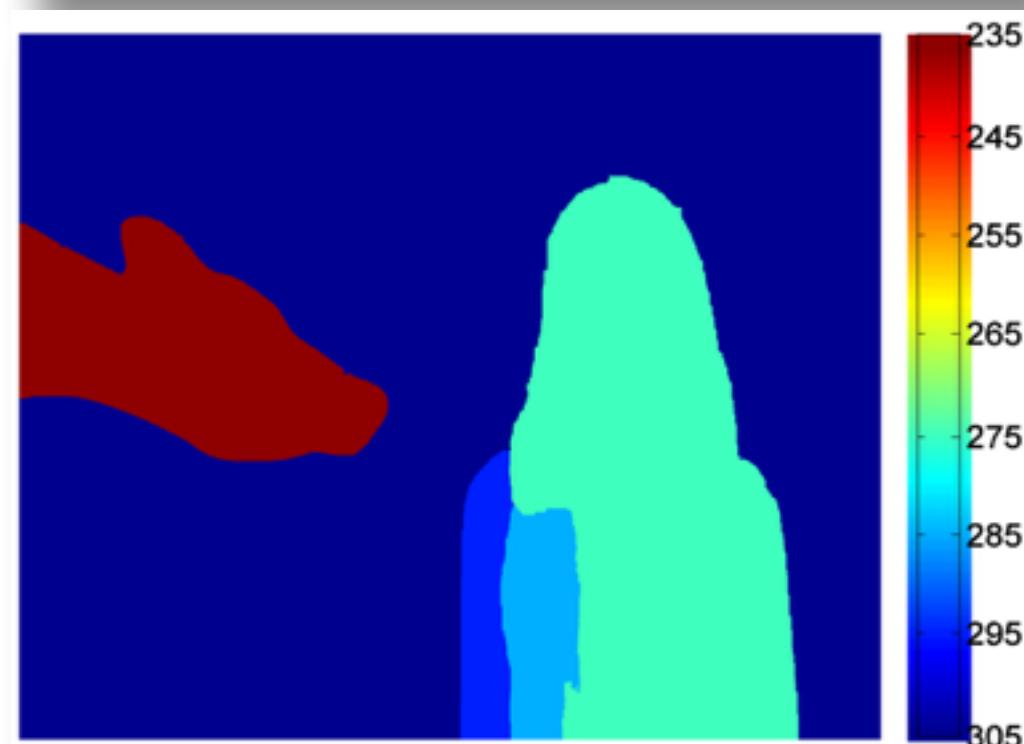


Levin et al 2007

Local  
depth  
estimation



After user  
corrections



Focus Corrections: Input

ALL-focused (deconvolved)

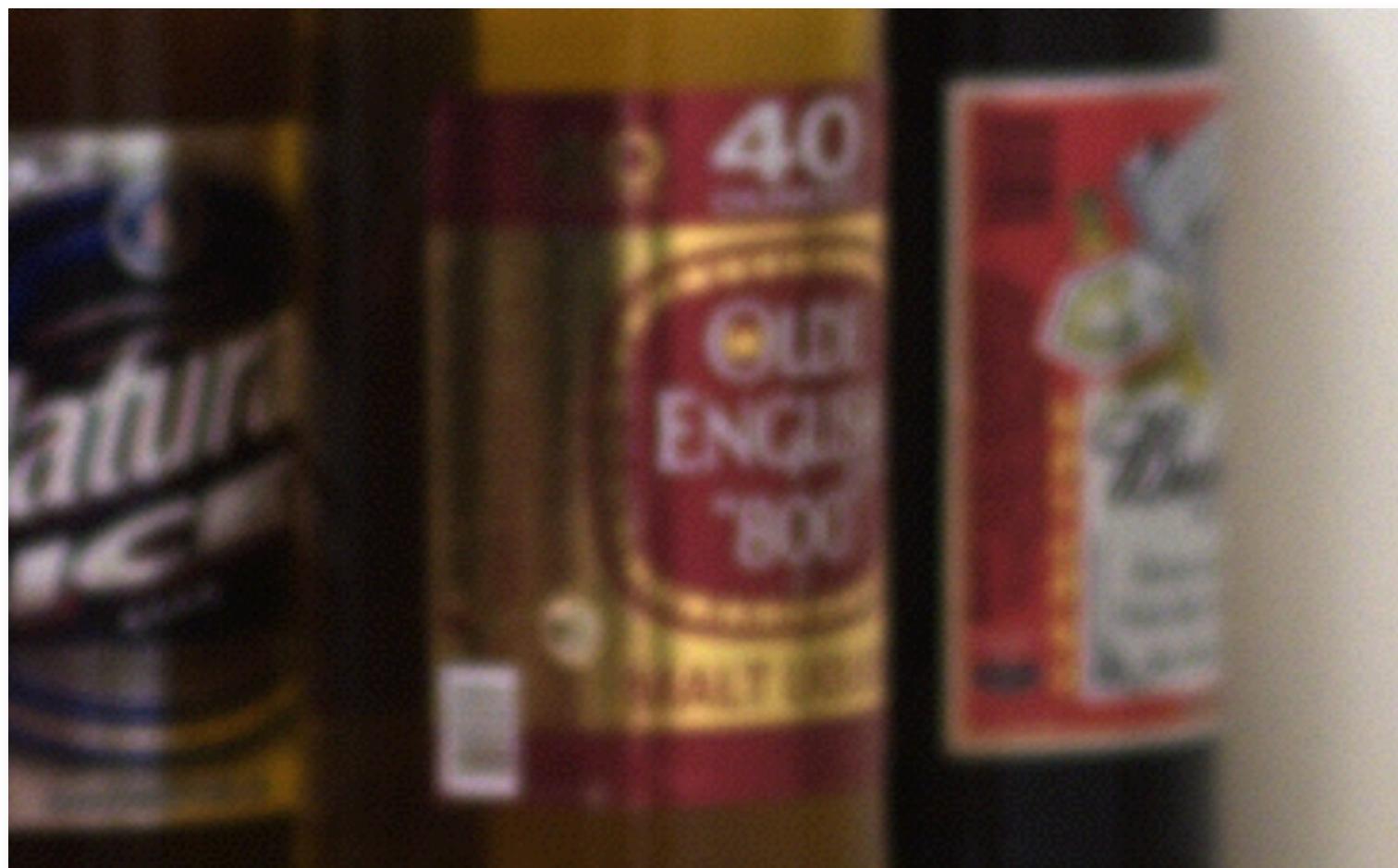


Focus Corrections: Input



All-focused (deconvolved)

# Focussed Images



Original image

ALL-focus image



Levin et al 2007

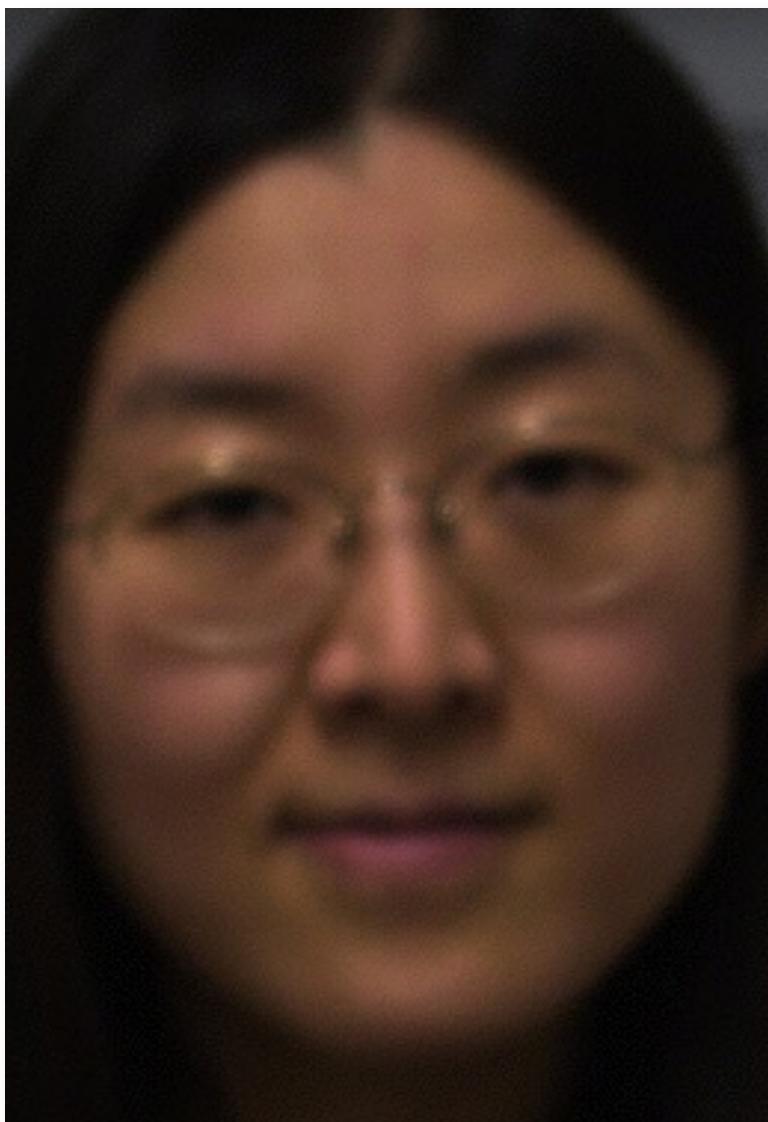
Input



All-focused (deconvolved)



# Close-up

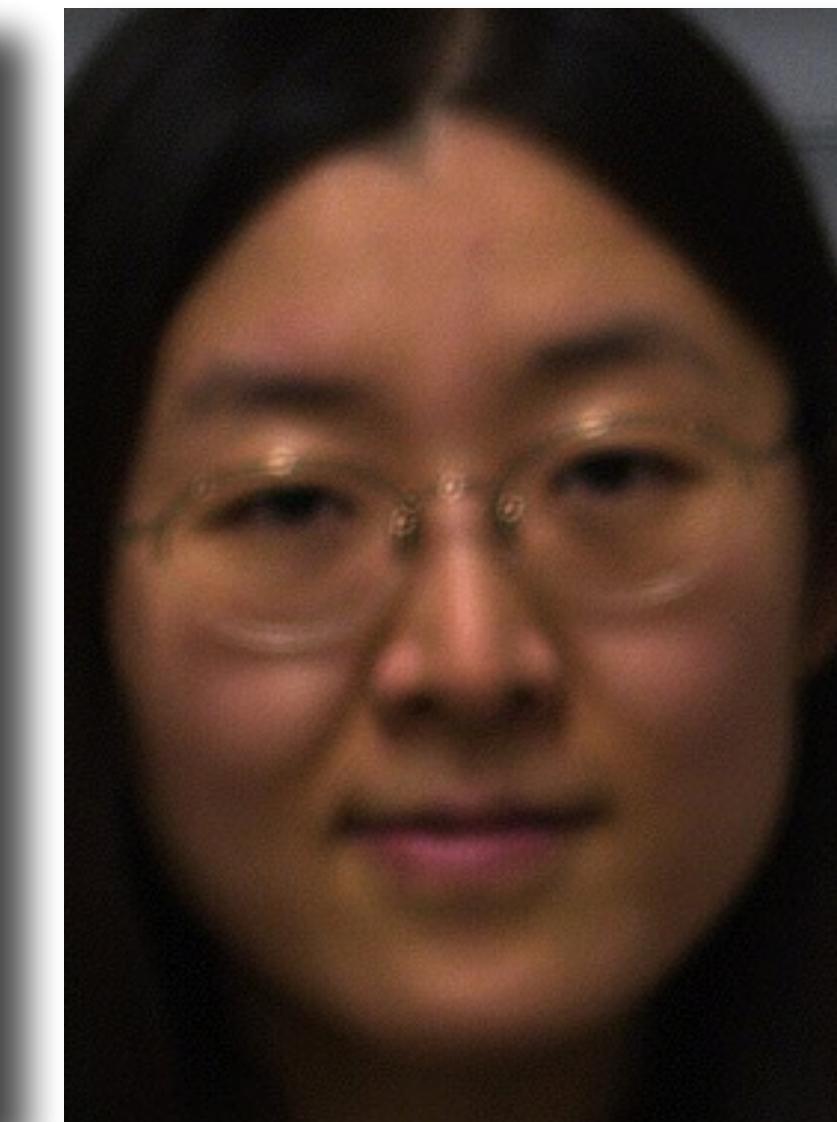


Original image

Levin et al 2007



ALL-focus image



Naive sharpening

# Comparison-conventional Aperture Result



Ringing due  
to wrong  
scale  
estimation

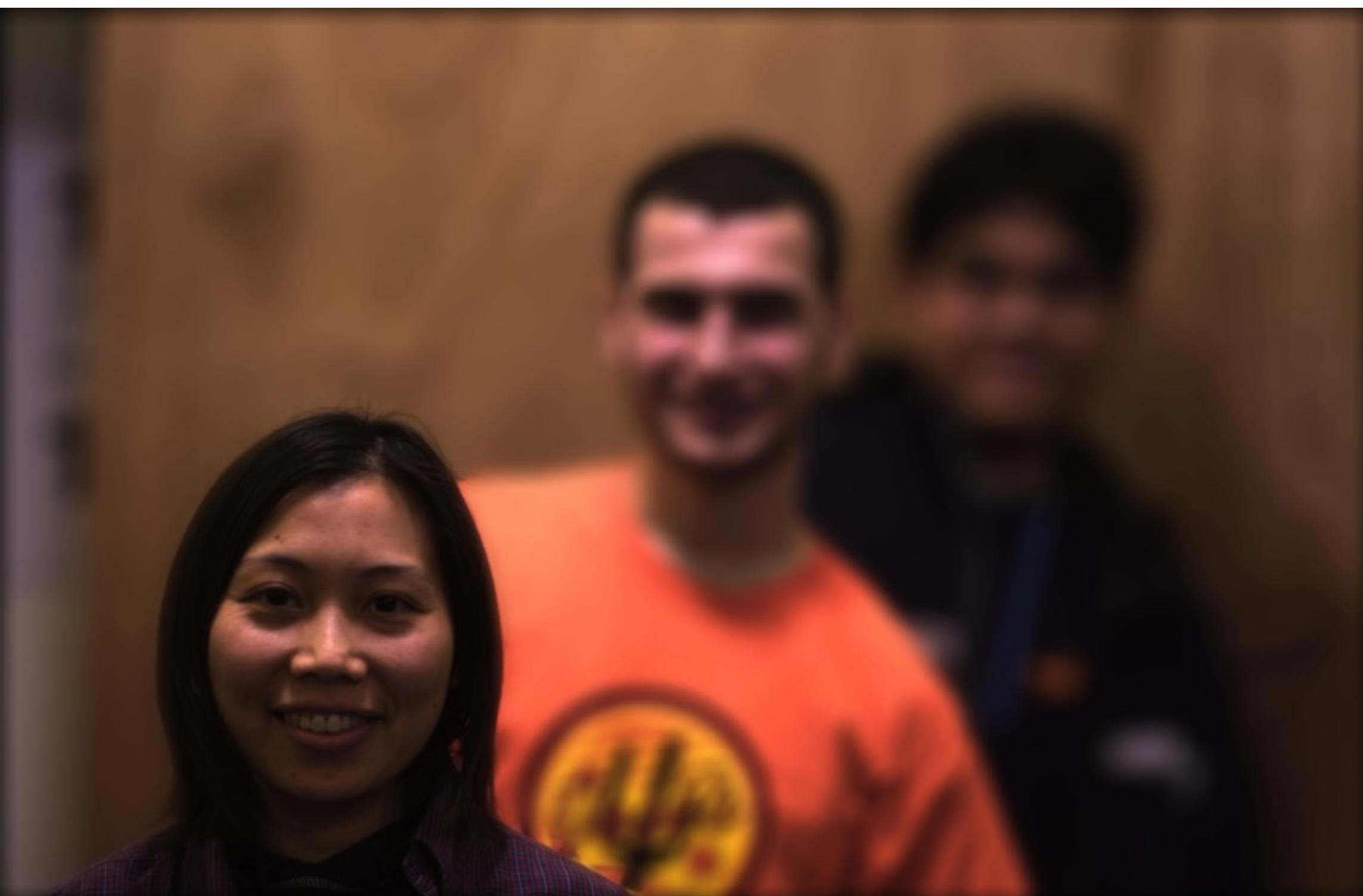
# Comparison-coded Aperture Result



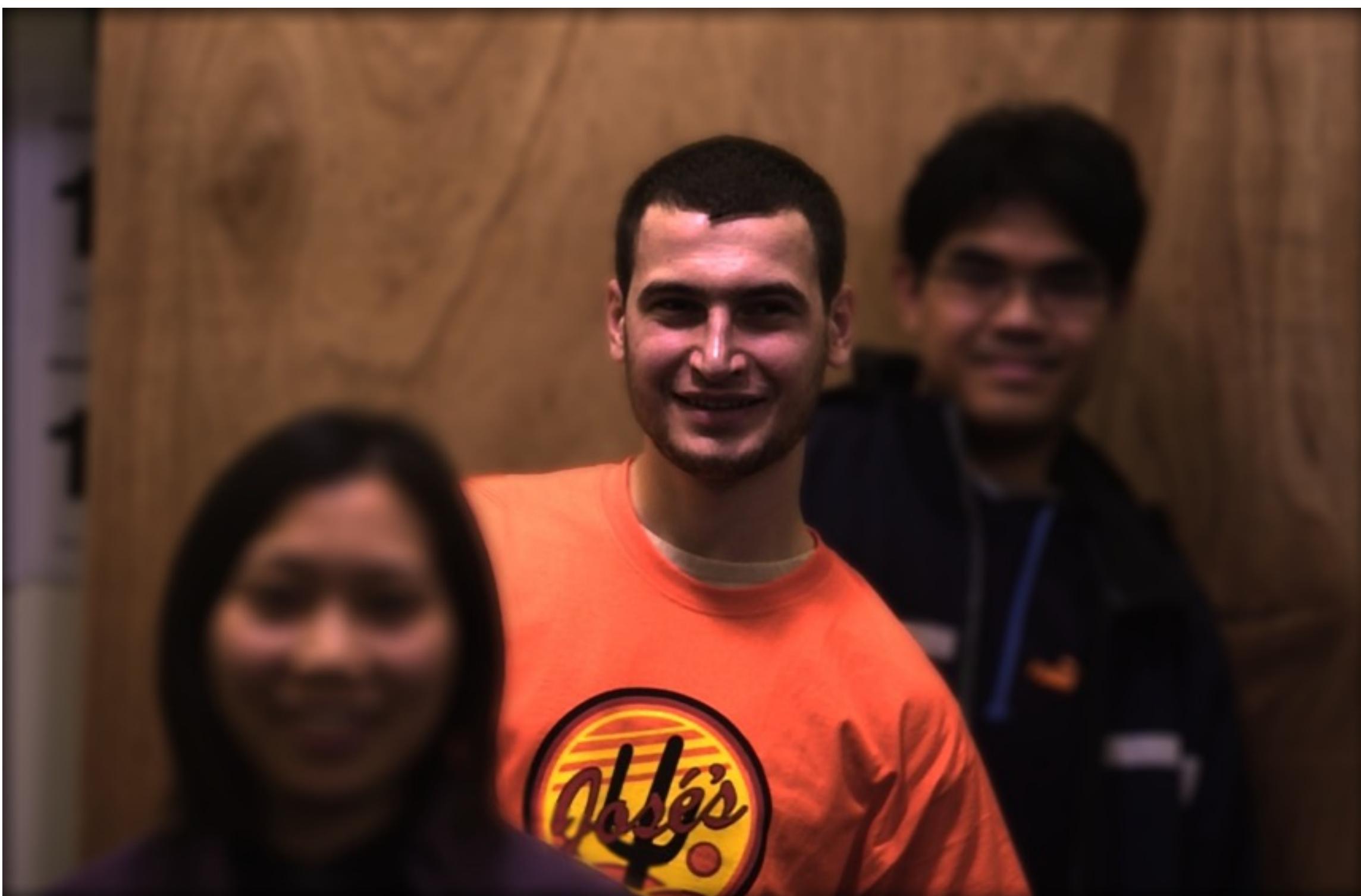
# Refocusing from a single image



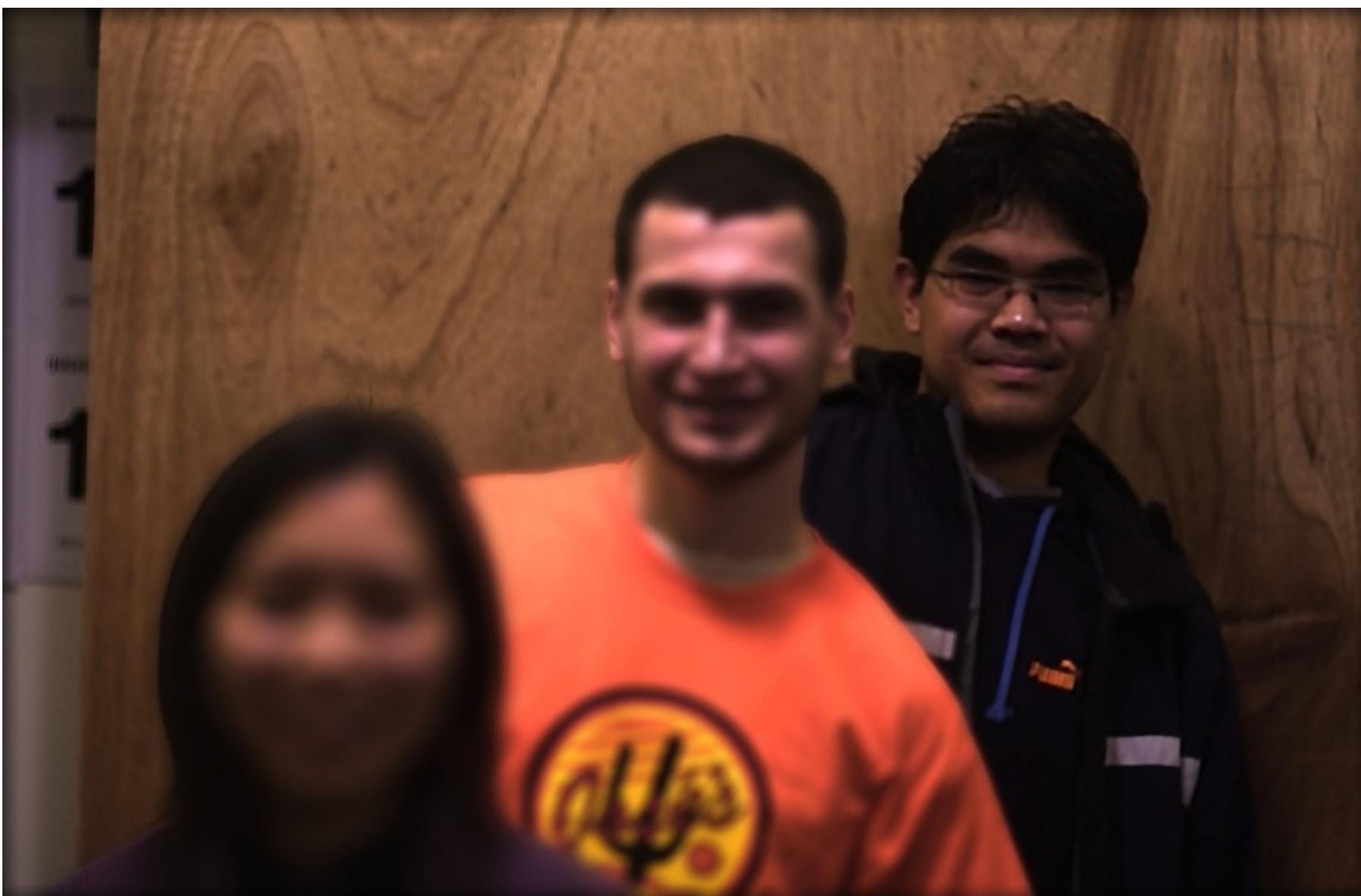
# Refocusing from a single image



# Refocusing from a single image



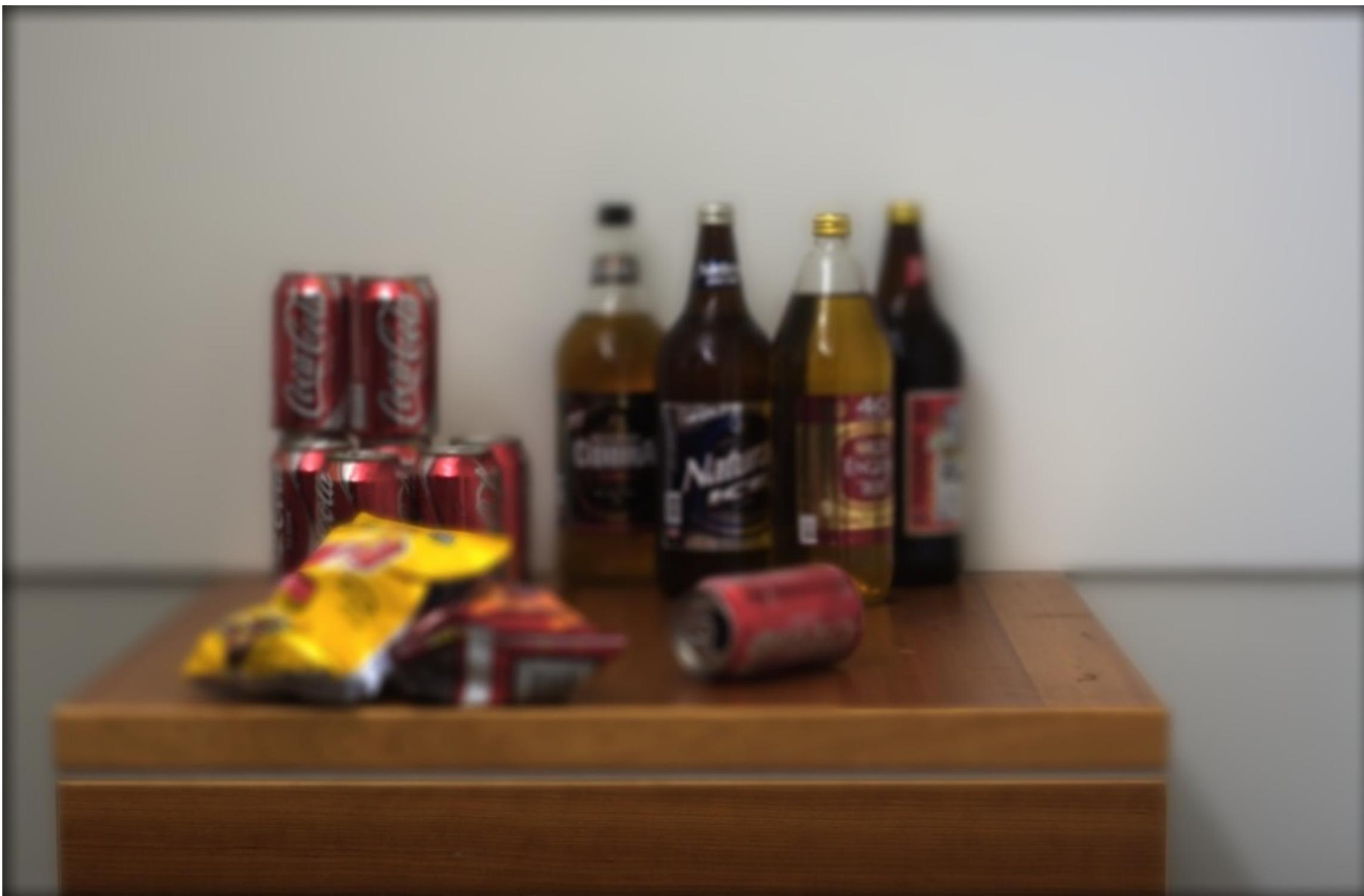
# Refocusing from a single image



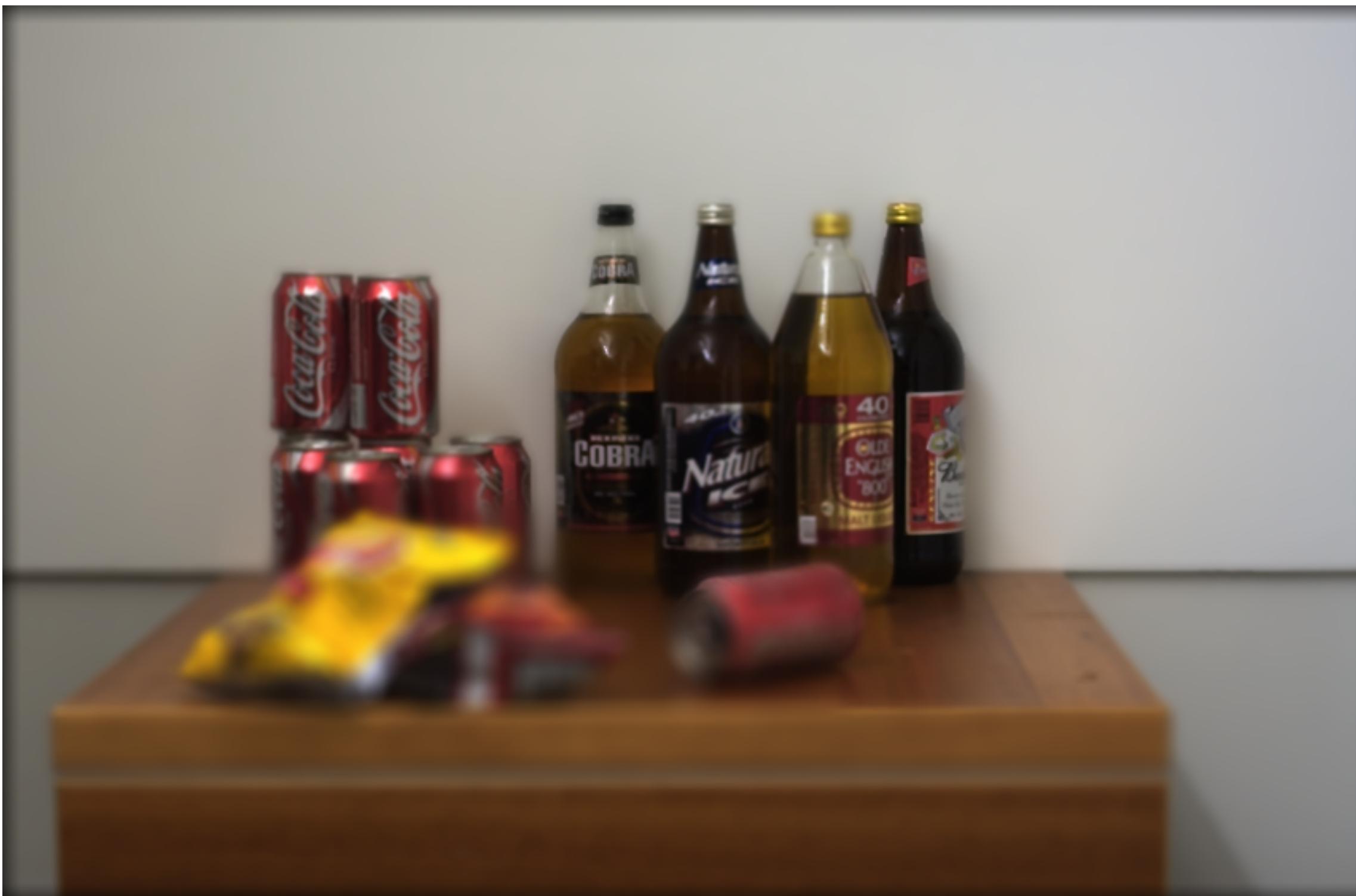
# Refocusing from a single image



# Refocusing from a single image



# Refocusing from a single image



# Build your own coded aperture

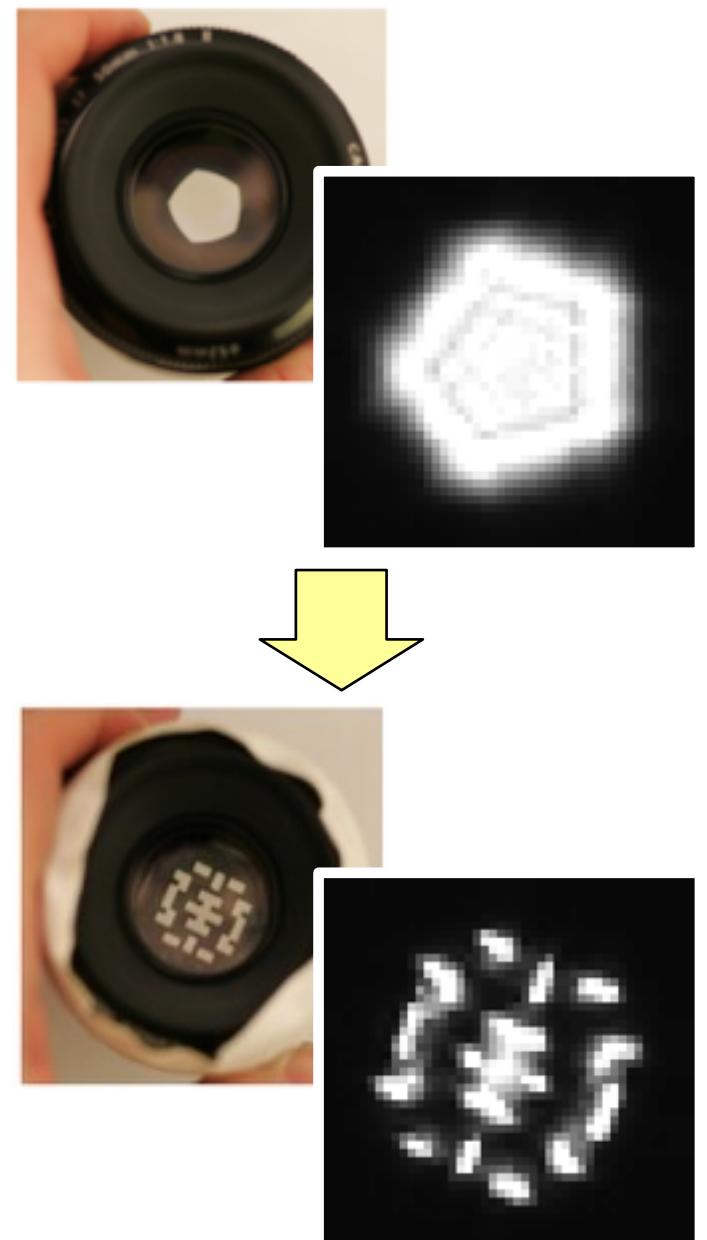


# Voila!



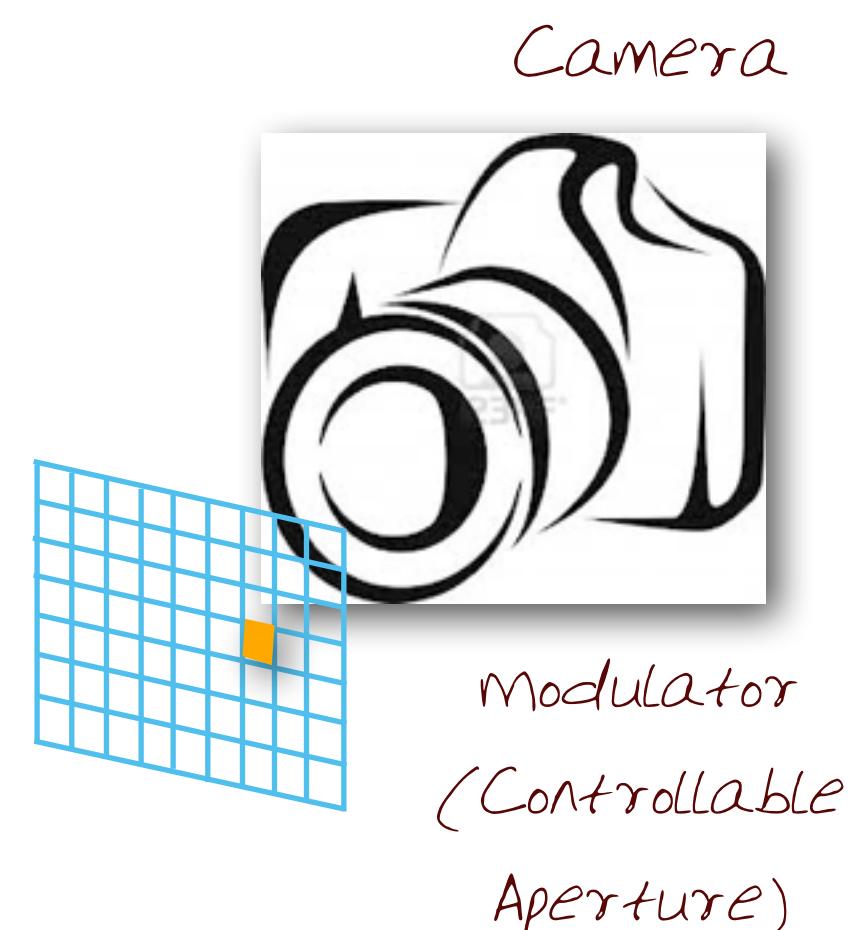
# Coded Aperture

- \* Image AND depth at a single shot +
- \* No loss of image resolution +
- \* Simple modification to lens +
- \* Depth is coarse -
- \* But depth is a pure bonus +
- \* Lose some light -
- \* But deconvolution increases depth of field +

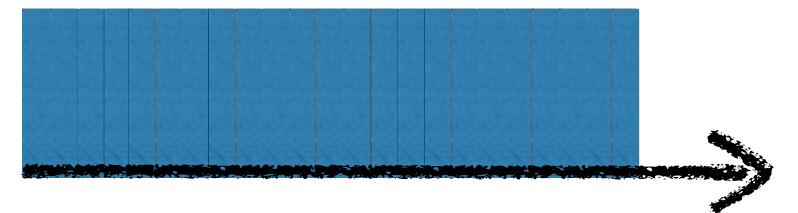
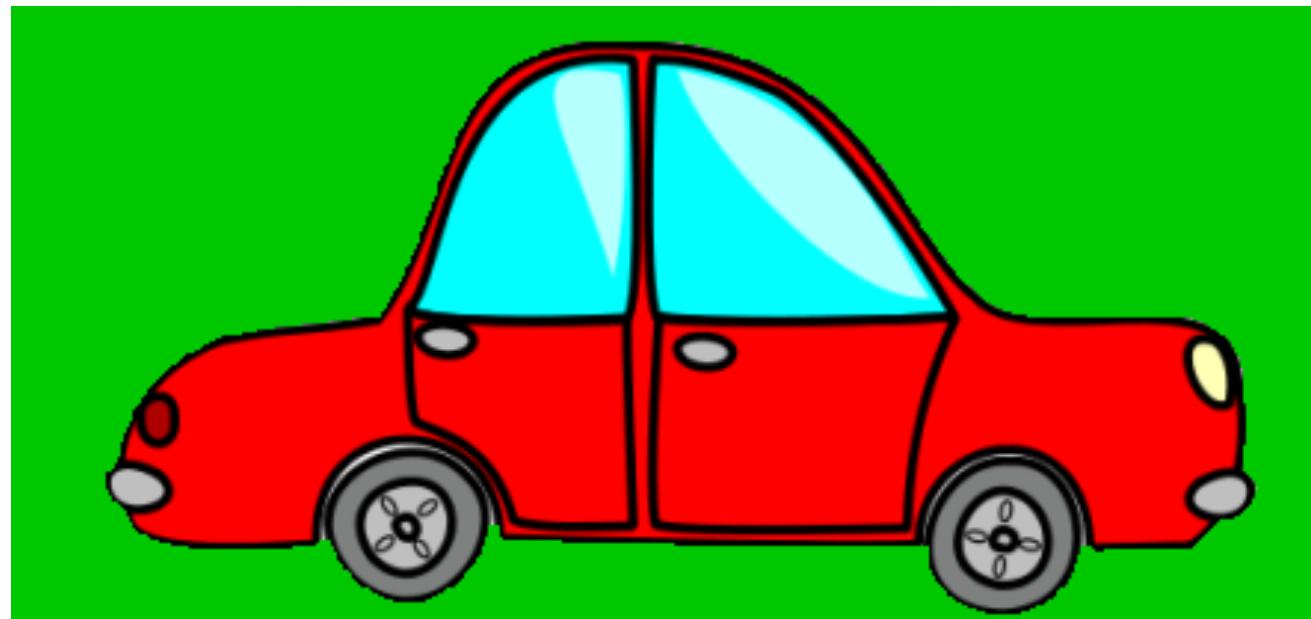


# Flutter Shutter Camera

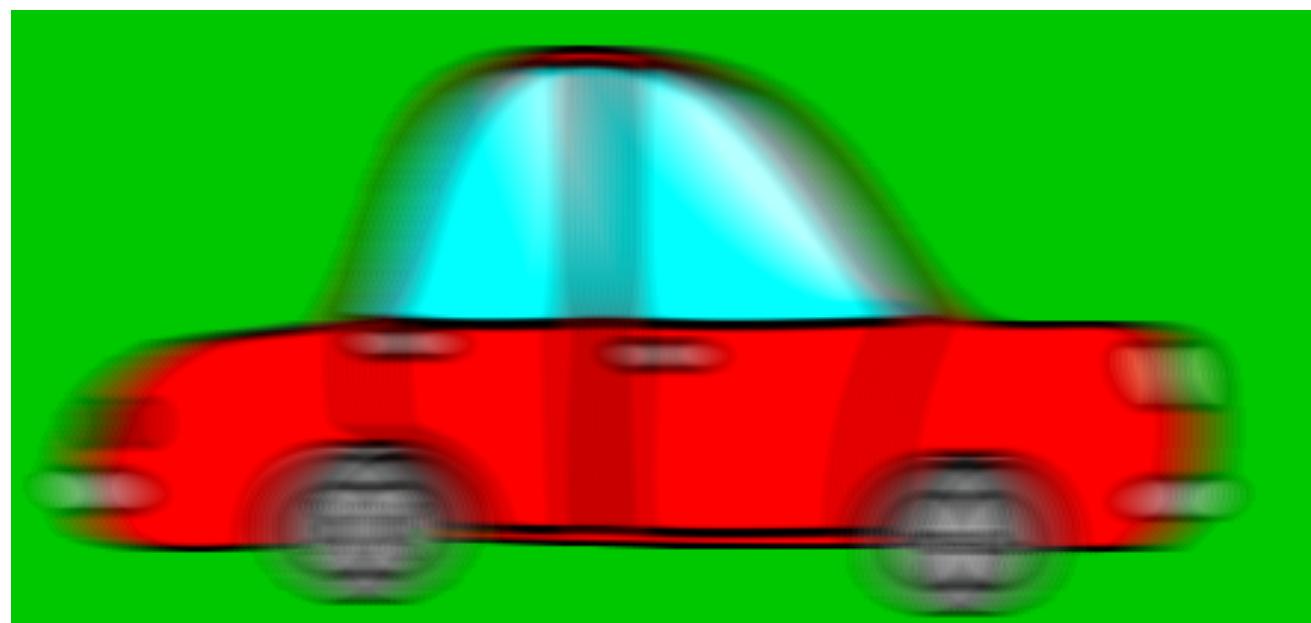
- \* Coded Aperture: Add "obstructions" to aperture
- \* Flutter Shutter: Control when the shutter opens/closes



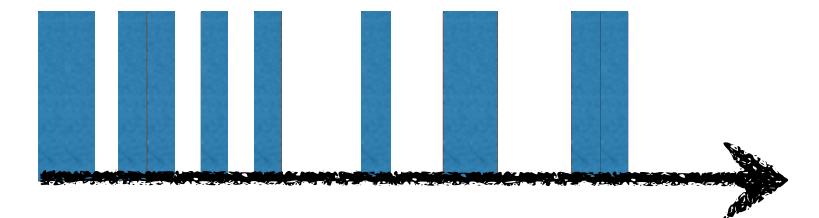
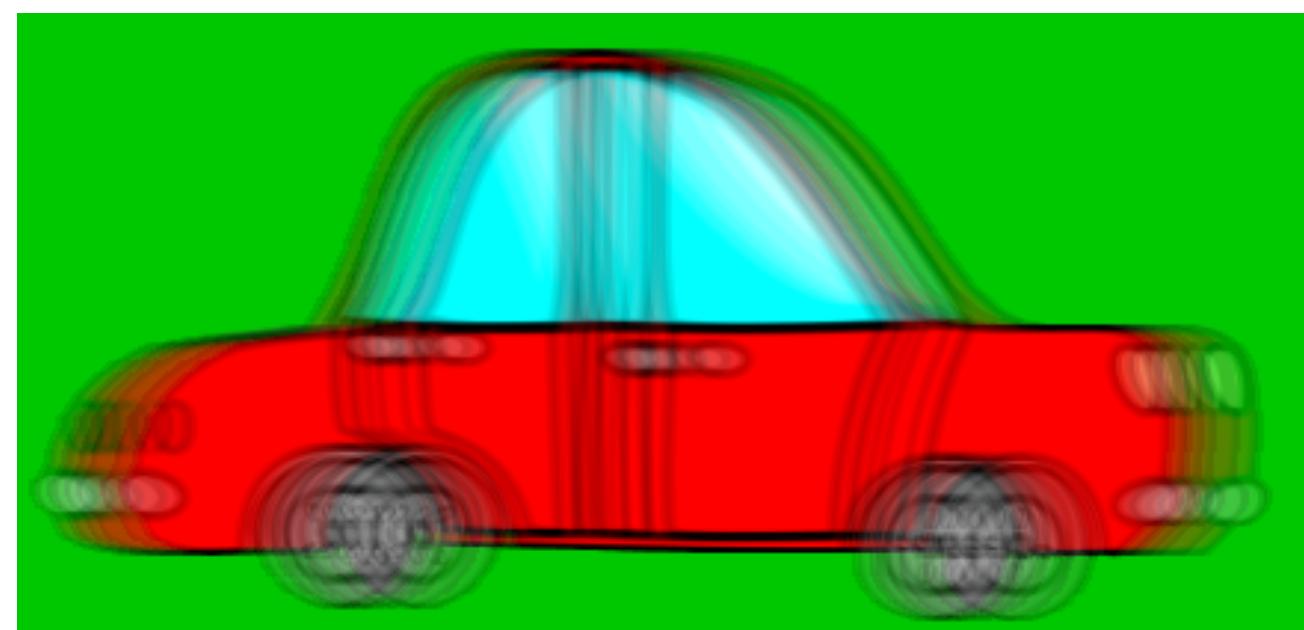
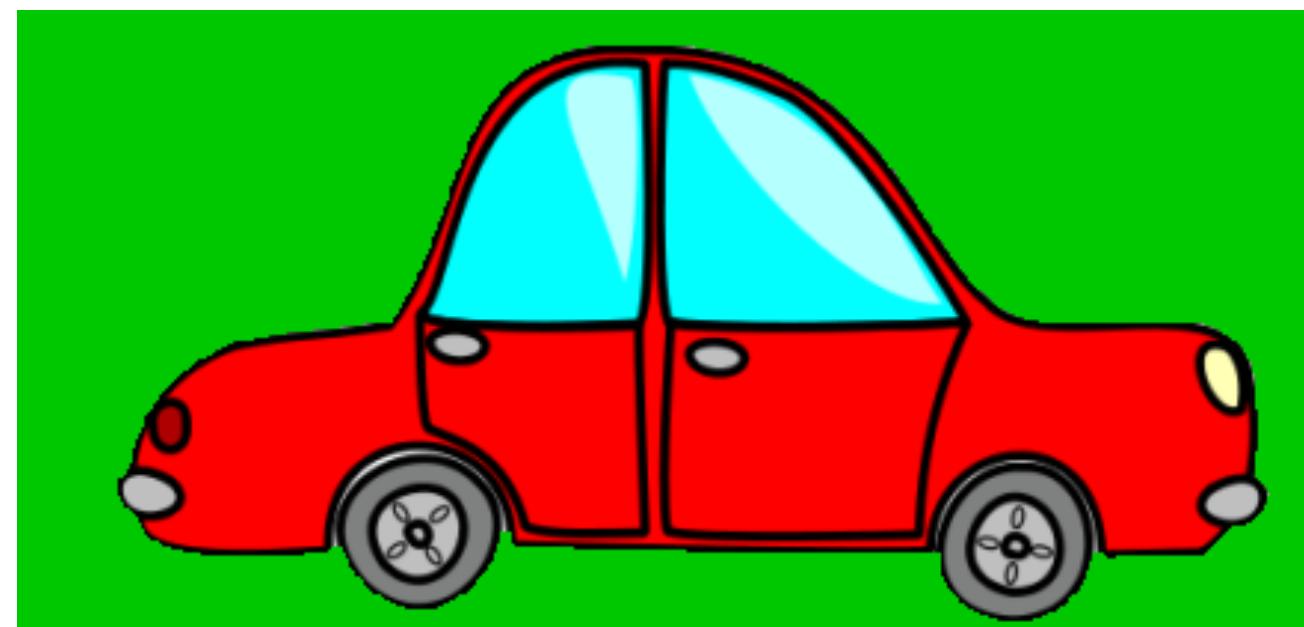
# Traditional Camera



Shutter is OPEN

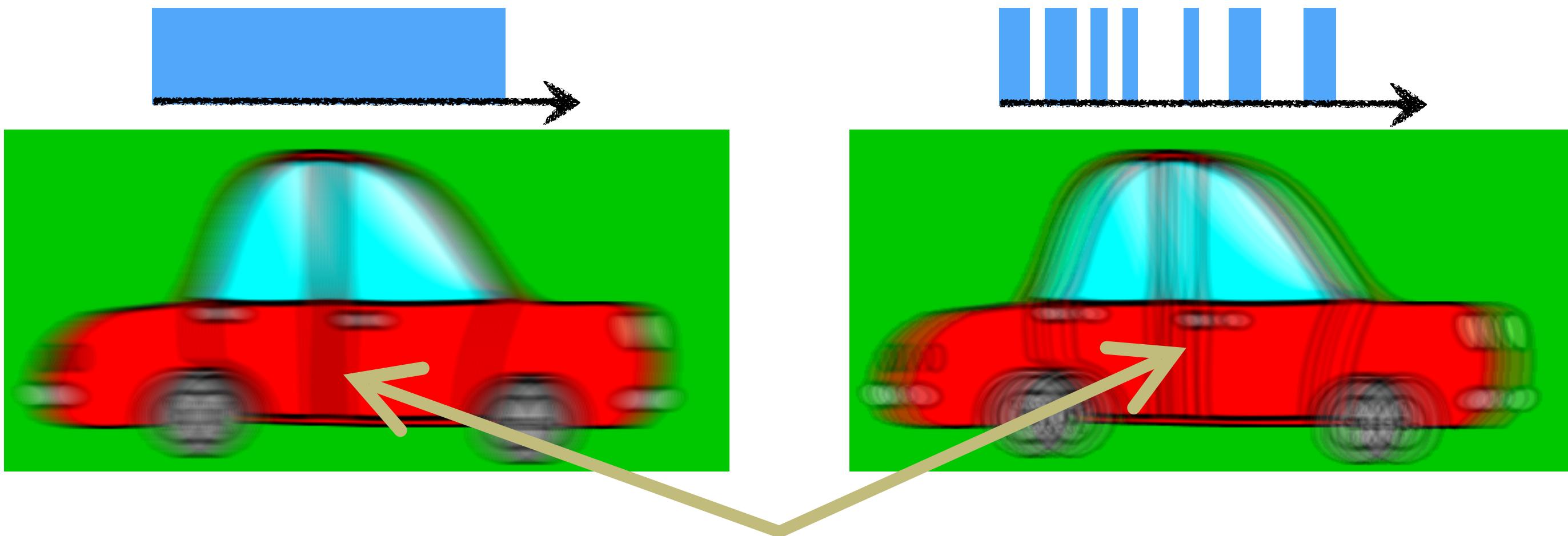


# Flutter Shutter Camera

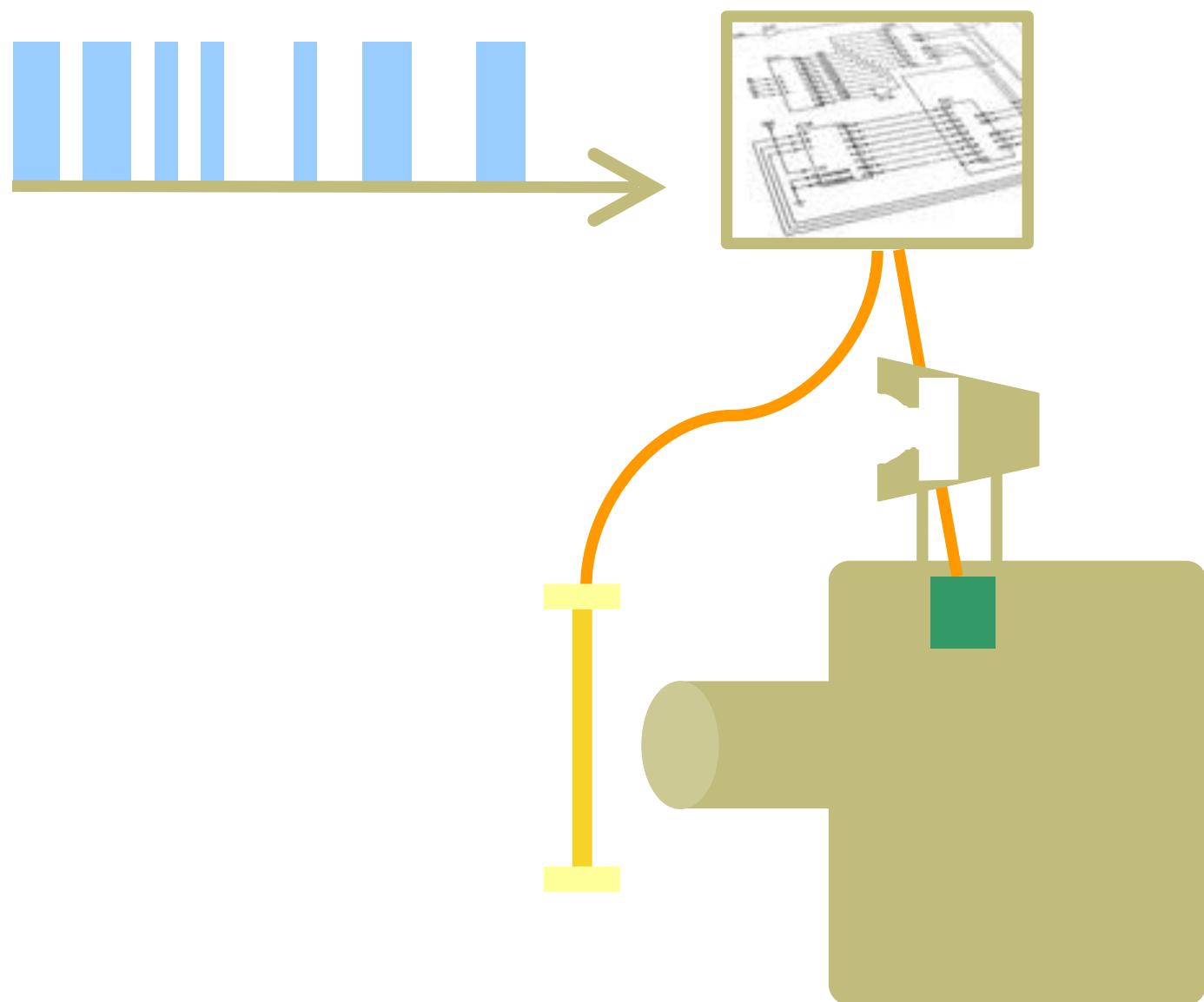


The Shutter opens  
and closes

# Traditional vs. F-S Camera

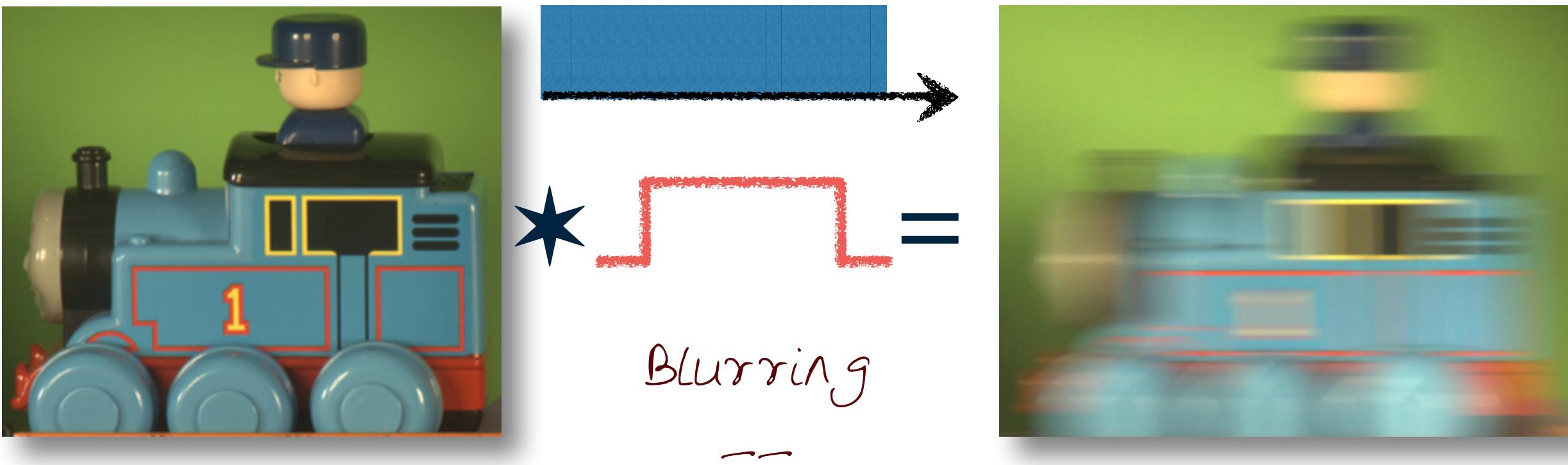


# F-S Camera



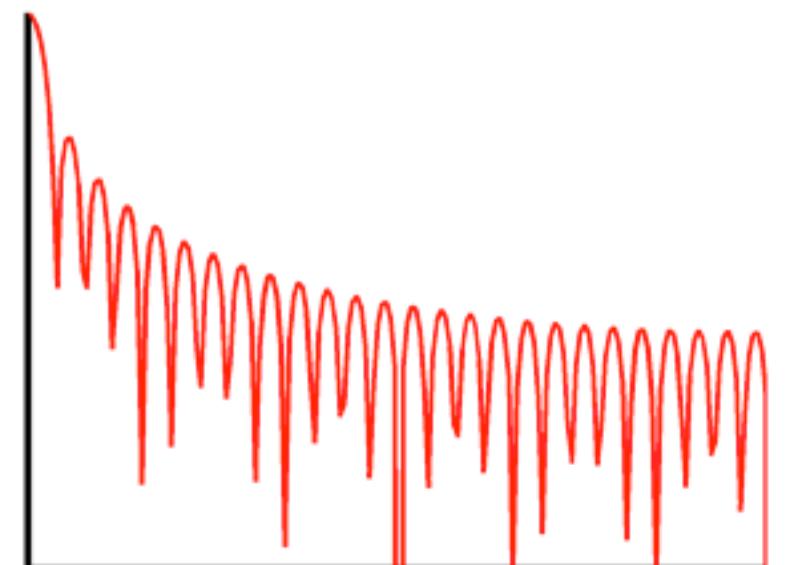
Raskar et al 2006

# Traditional Camera: Box Filter



The sinc function is of the convolution  
general form  $\sin(x)/x$  and is  
a sine wave that decays in  
amplitude as  $1/x$ .

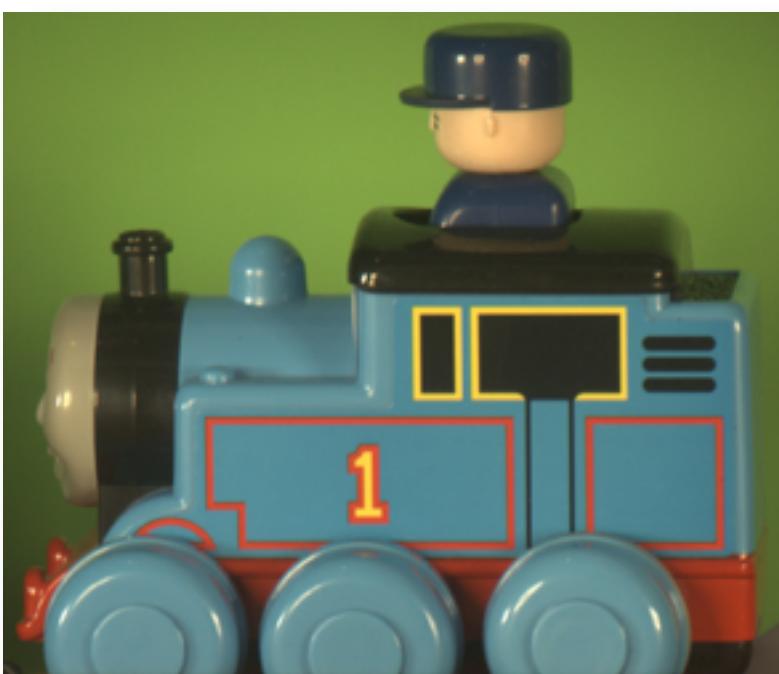
Sinc Function



Raskar et al 2006

Sinc Function: <http://www.dspguide.com/ch11/2.htm>

# Flutter Shutter: Coded Filter

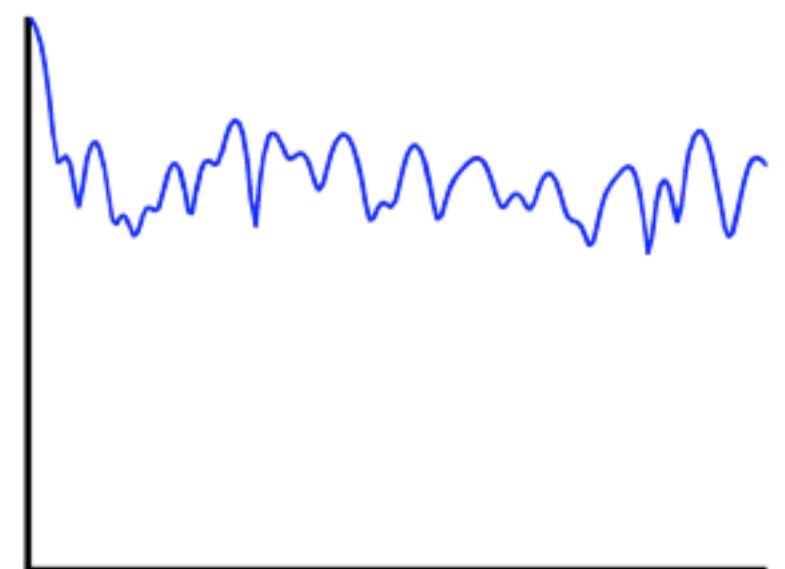


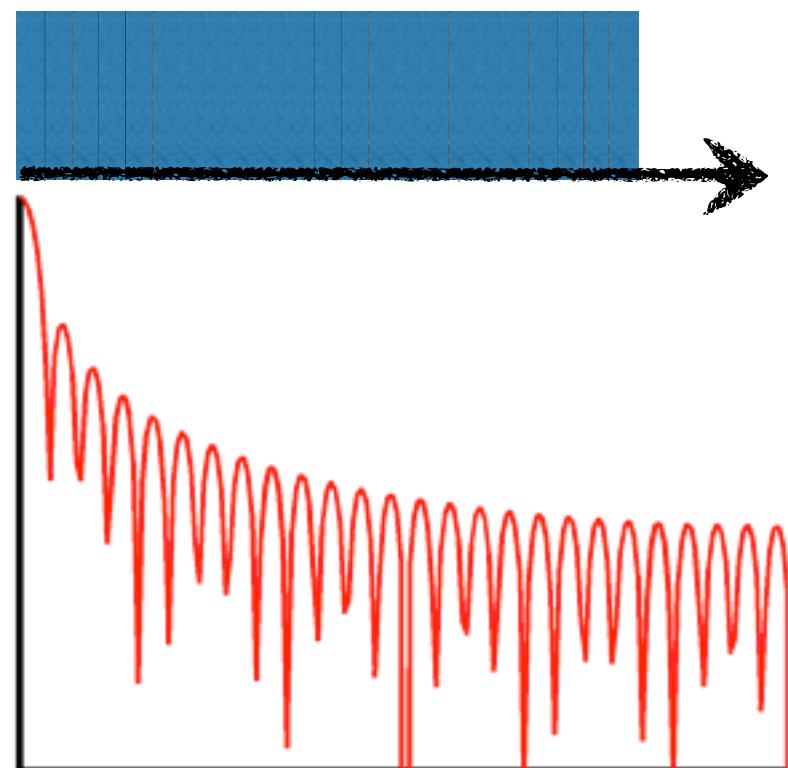
$$\begin{array}{c} \text{---|---|---|---|---|---|} \\ \star \text{---|---|---|---|---|} = \end{array}$$



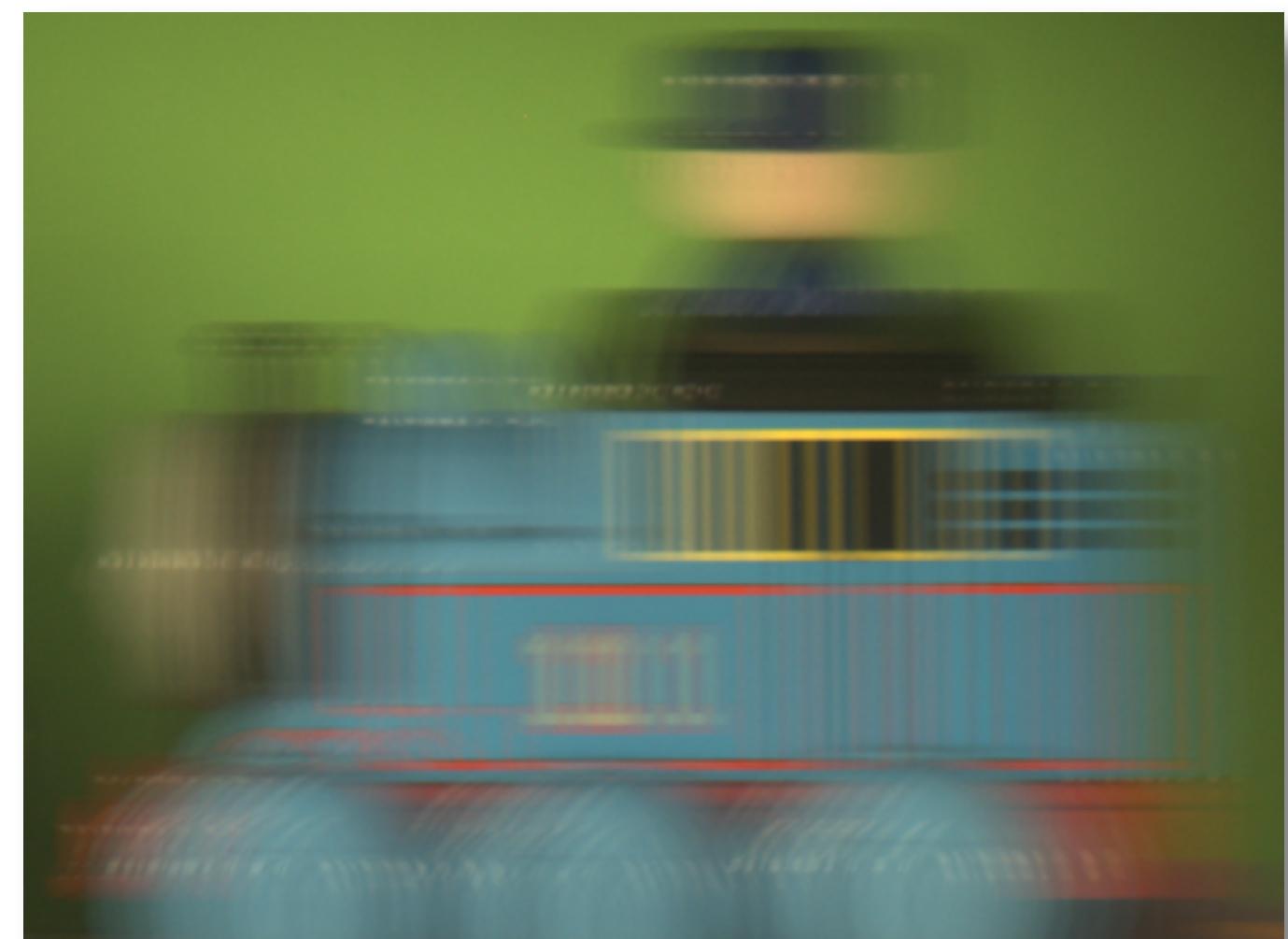
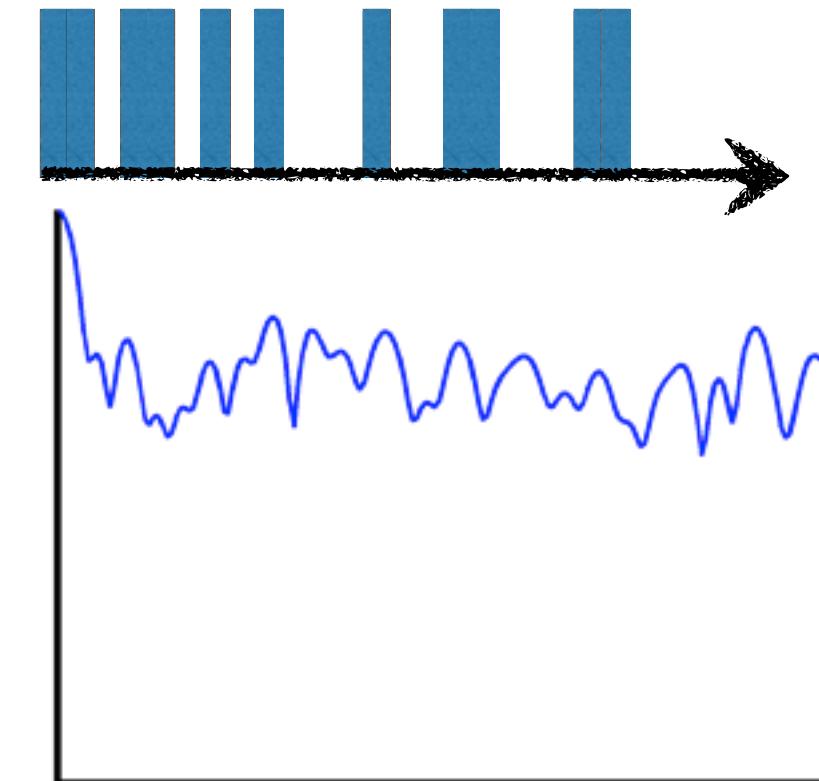
Sinc Function

Preserves High  
Frequencies!!!

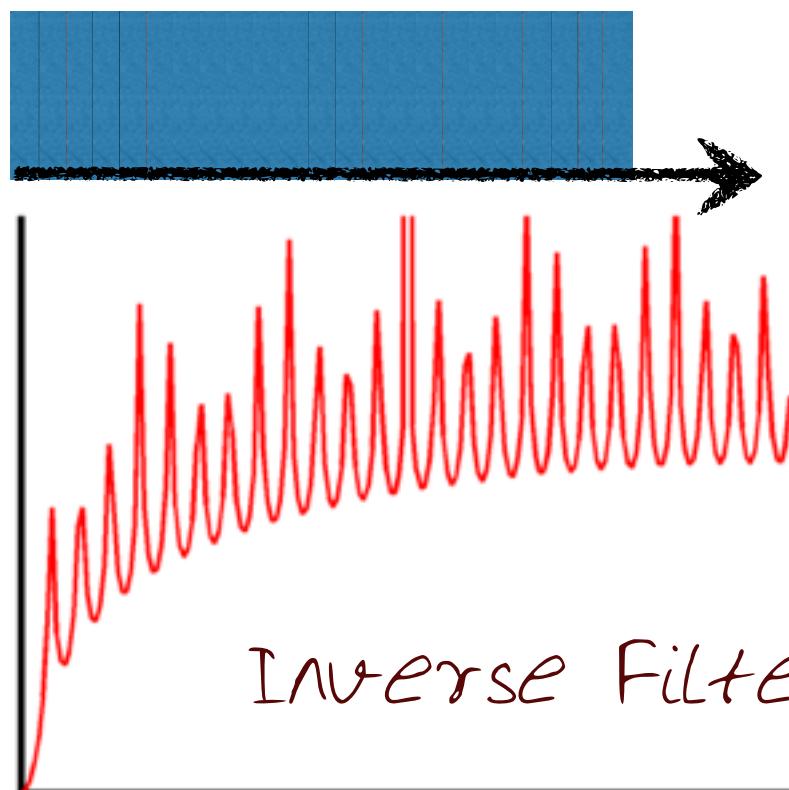




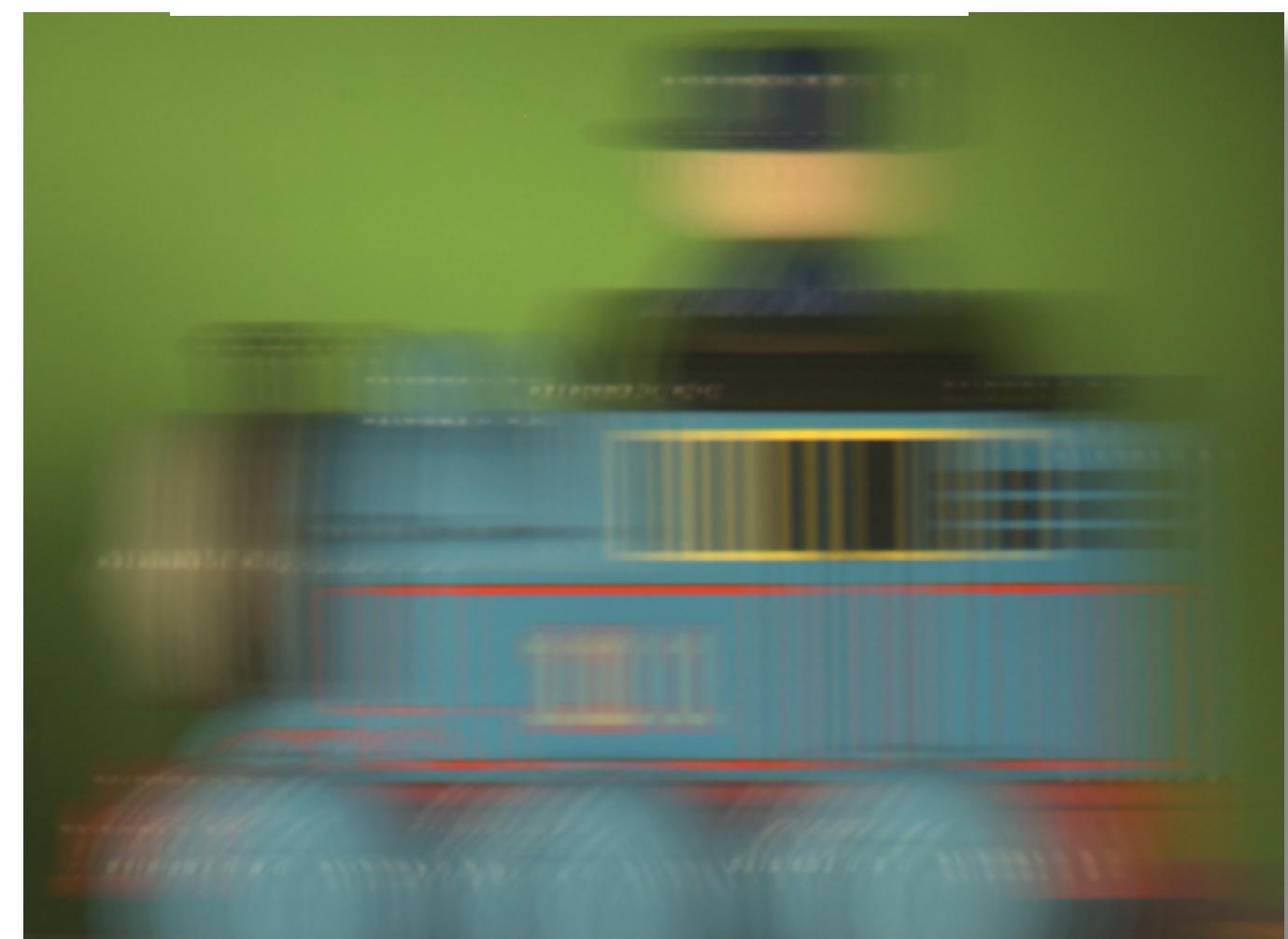
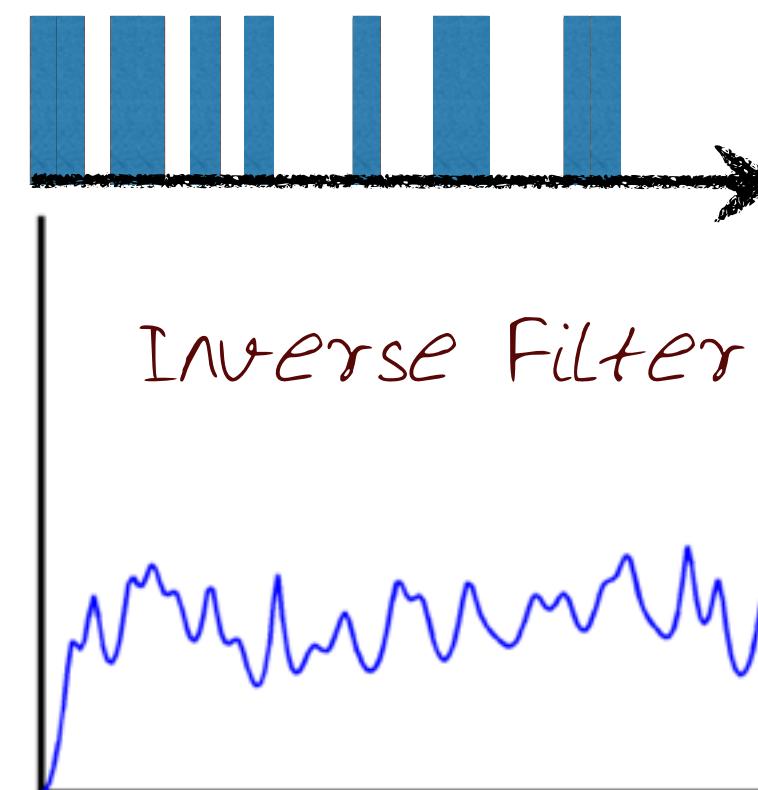
Comparison of  
Coded vs.  
Box Filter



Inverse  
sinc  
function  
for  
IDFT

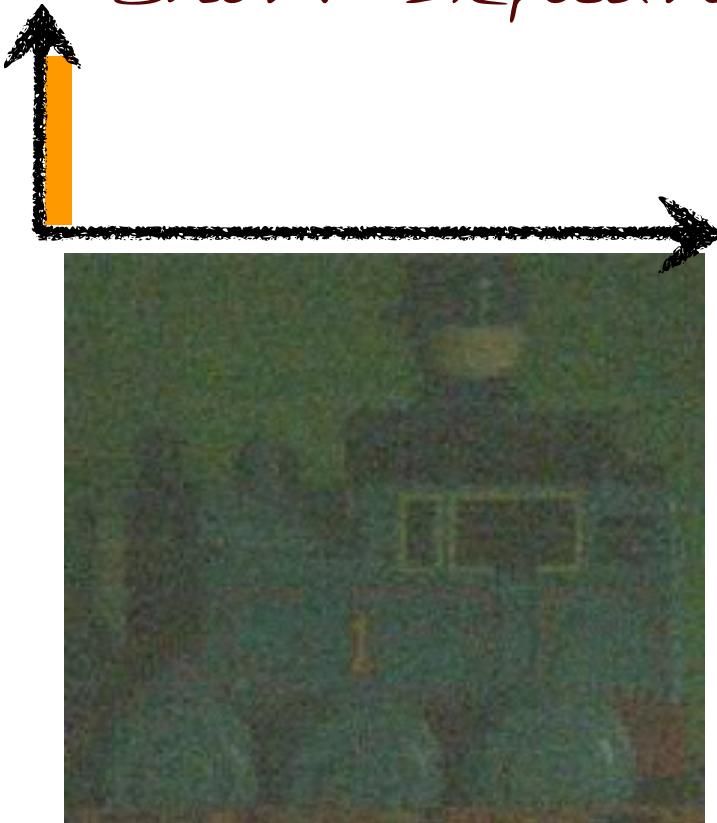


Inversion

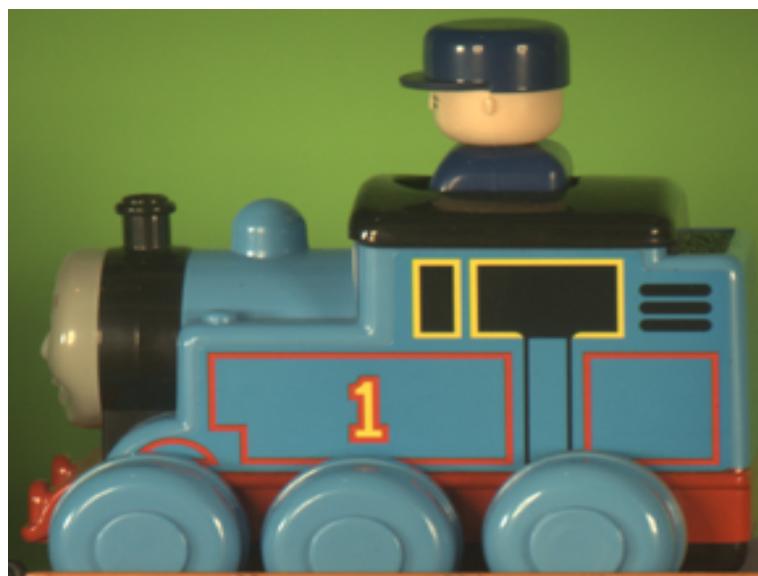


# Long vs. Coded Exposure

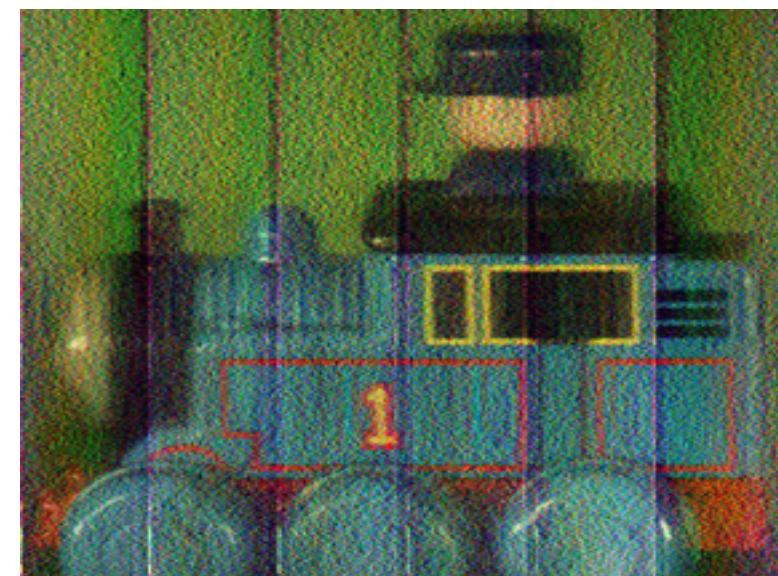
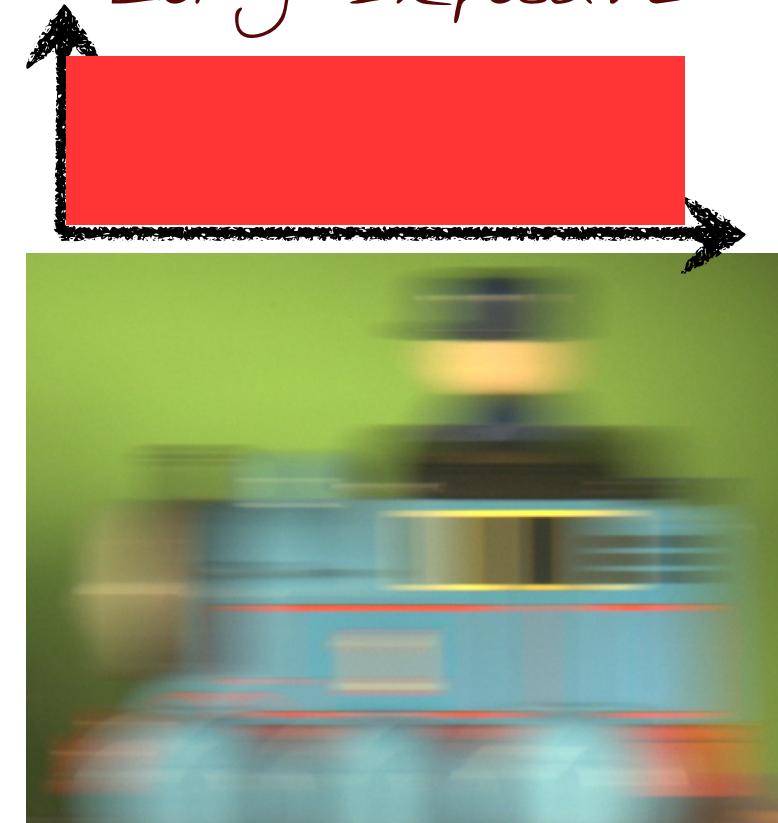
Short Exposure



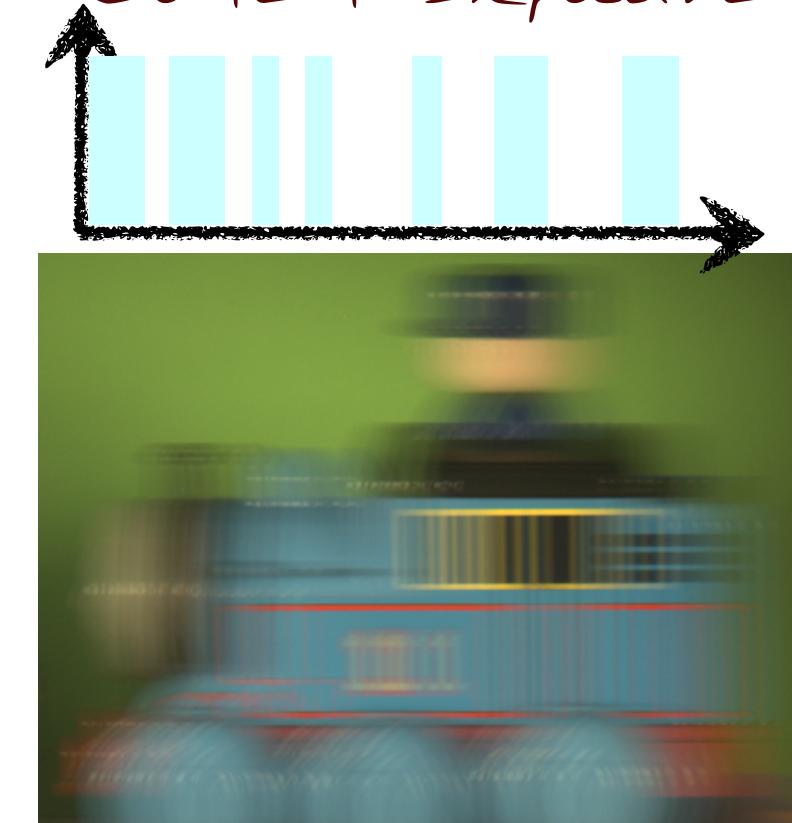
Ground  
Truth



Long Exposure



Coded Exposure



De  
blurred



License Plate Retrieval



License Plate Retrieval







Input Image



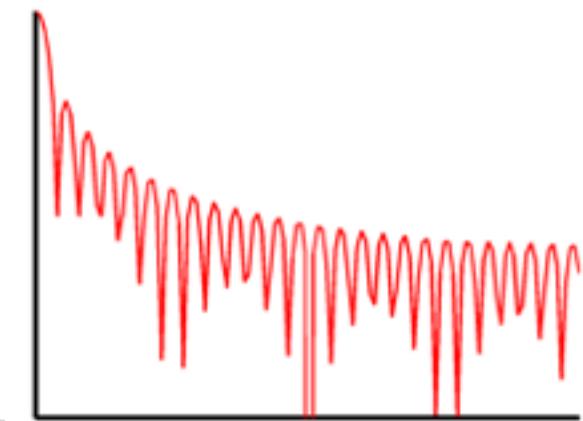
Rectified Crop



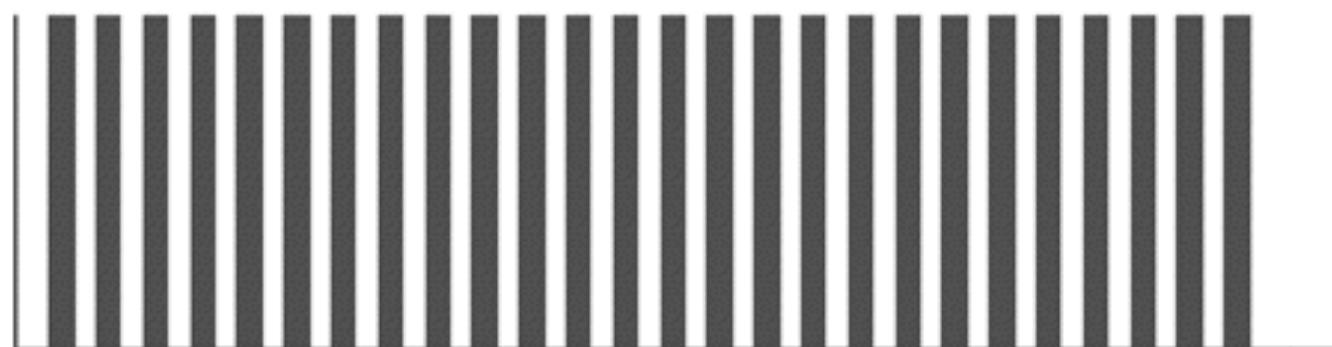
Deblurred Result

# Different Codes

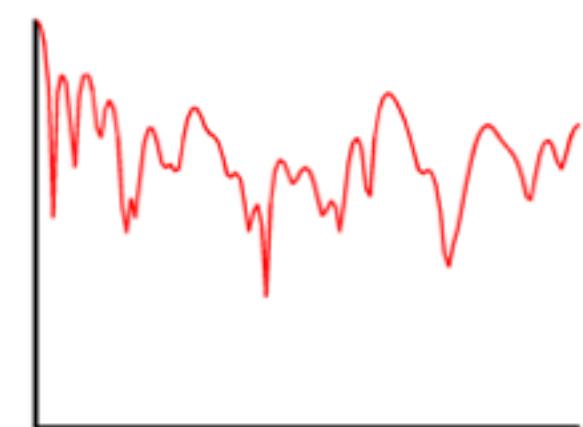
ALL ones



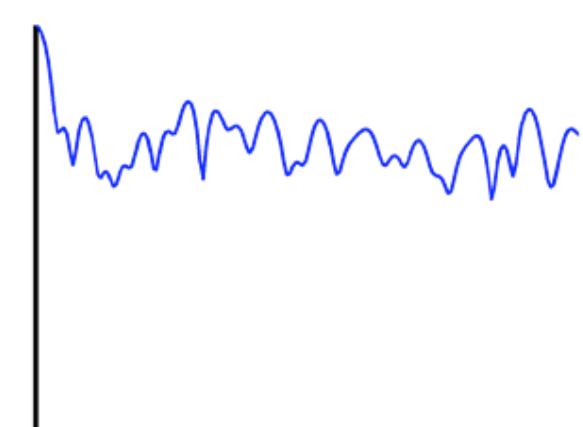
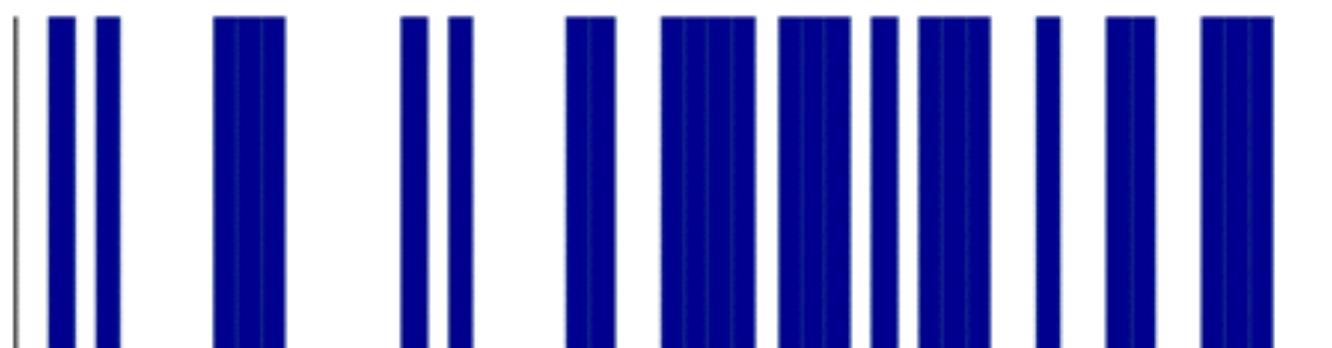
Alternate



Random



F/S  
Camera



# Summary



- \* Epsilon Photography
- \* Coded Photography
- \* Coded Aperture
- \* Flutter-Shutter Camera

# Further Reading



- \* Raskar (2009) "Computational Photography: Epsilon to Coded Photography", Emerging Trends in Visual Computing, Springer 2009 [[PDF](#)]
- \* Levin, Fergus, Durand, Freeman (2007), "Image and Depth from a Conventional Camera with a Coded Aperture" ACM SIGGRAPH 2007 [[PDF](#)]
- \* Raskar, Agrawal, Tumblin (2006) "Coded Exposure Photography: Motion Deburring using Fluttered Shutter" ACM SIGGRAPH 2006 [[PDF](#)]
- \* Lucy-Richardson Deconvolution (see wikipedia)
- \* Smith (1998), The Scientist and Engineer's Guide to Digital Signal Processing (<http://www.dspguide.com/>)

# Credits

- \* For more information, see
- \* Richard Szeliski (2010) Computer Vision: Algorithms and Applications, Springer
- \* [http://groups.csail.mit.edu/graphics/  
CodedAperture/](http://groups.csail.mit.edu/graphics/CodedAperture/)
- \* <http://web.media.mit.edu/~raskar/deblur/>
- \* [http://en.wikipedia.org/wiki/Richardson  
%E2%80%93Lucy\\_deconvolution](http://en.wikipedia.org/wiki/Richardson%E2%80%93Lucy_deconvolution)
- \* Sinc Function: [http://www.dspguide.com/  
ch11/2.htm](http://www.dspguide.com/ch11/2.htm)



# Computational Photography

- \* Study the basics of computation and its impact on the entire workflow of photography, from capturing, manipulating and collaborating on, and sharing photographs.



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