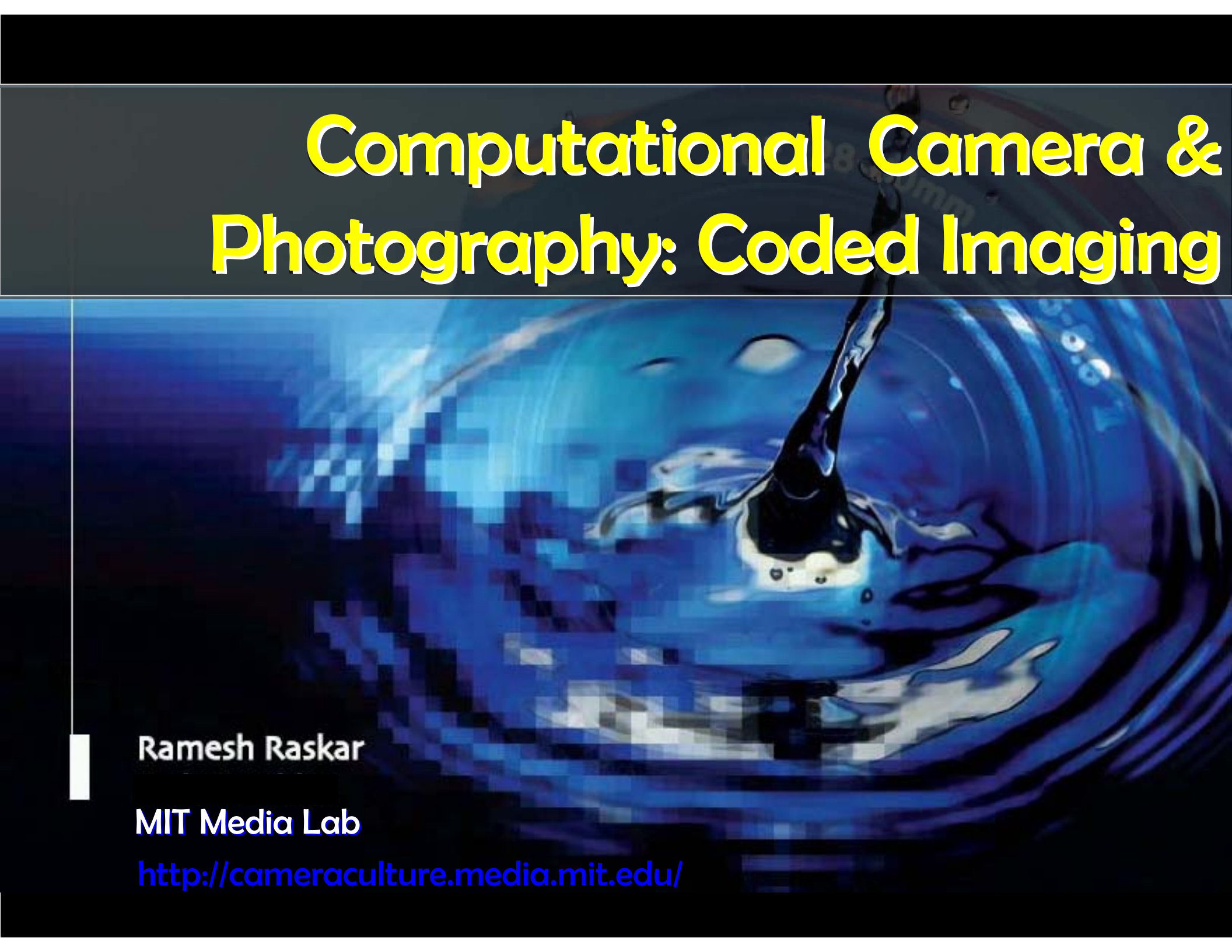


# Computational Camera & Photography: Coded Imaging



Ramesh Raskar

MIT Media Lab

<http://cameraculture.media.mit.edu/>

Shadow

Refractive

Reflective

Image removed due to copyright restrictions.

See Fig. 1, “Eight major types of optics in animal eyes.”

In Fernald, R. D. “Casting a Genetic Light on the Evolution of Eyes.”

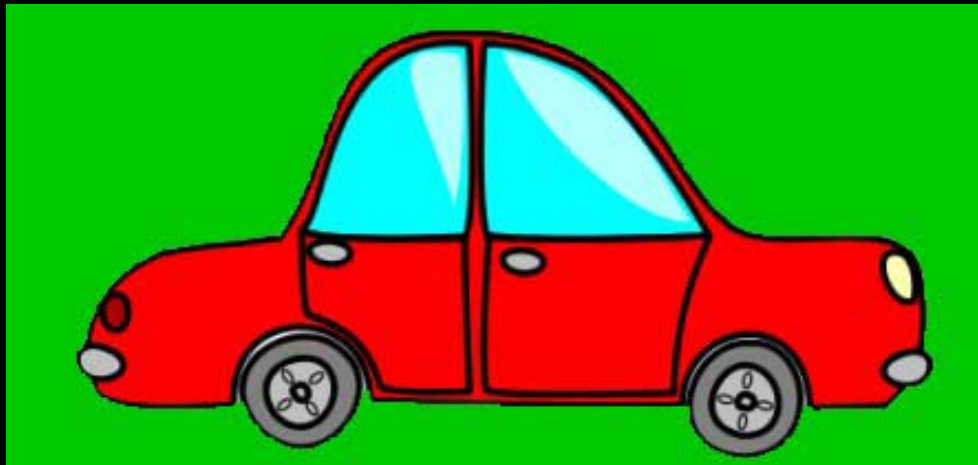
*Science* 313, no. 5795 (September 29, 2006): 1914-1918.

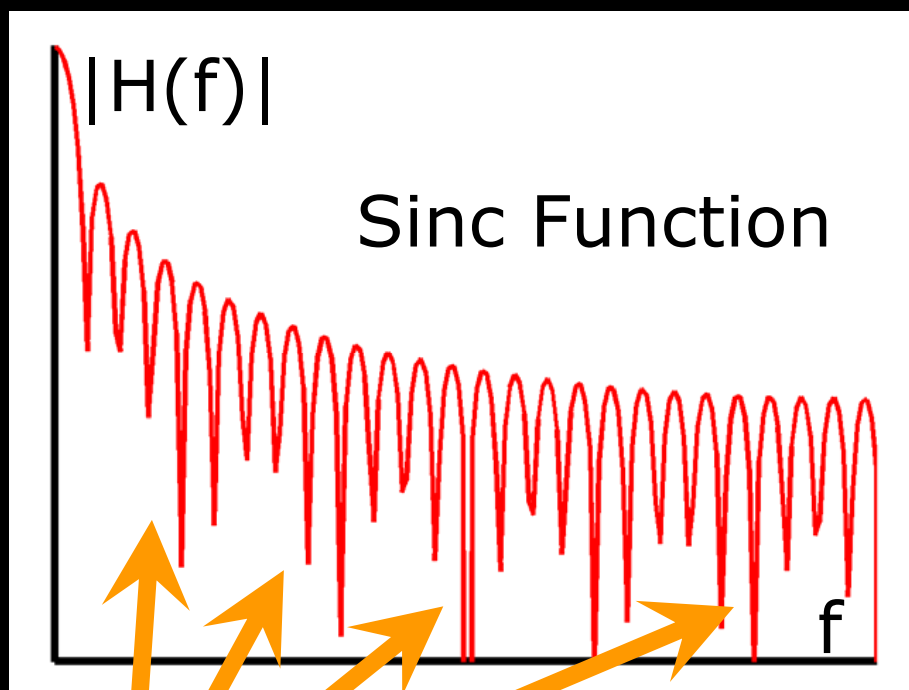
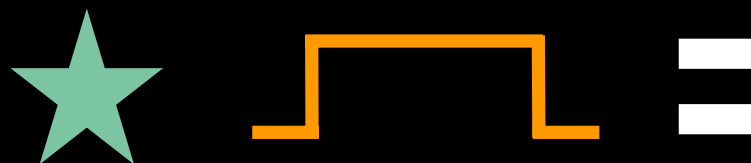
<http://dx.doi.org/10.1126/science.1127889>



Traditional Camera

Shutter is OPEN



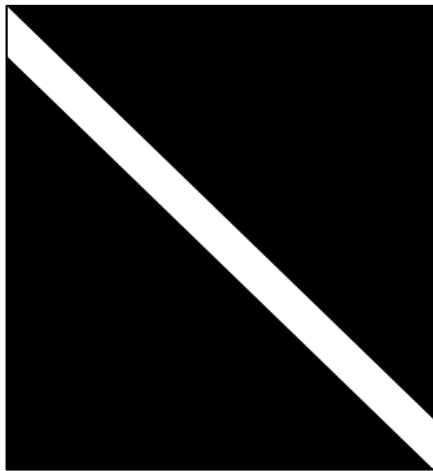


Blurring  
==  
Convolution



Traditional Camera: Box Filter

# Blurring Process for Linear Motion



A

Smear  
Matrix

\*



X

Unknown  
Image

$T$

=

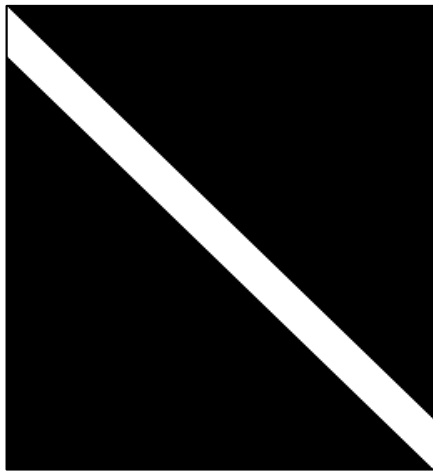


$T$

b

Blurred  
Image

# Deblurring Process



$A$

Smear  
Matrix

$\backslash$

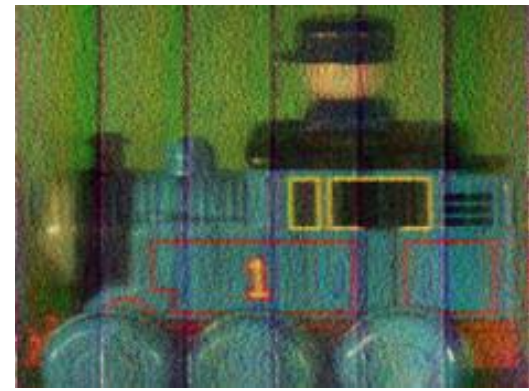


$b$

Blurred  
Image

$T$

?



- Condition number for the smearing matrix is large
- Thus invertibility is bad

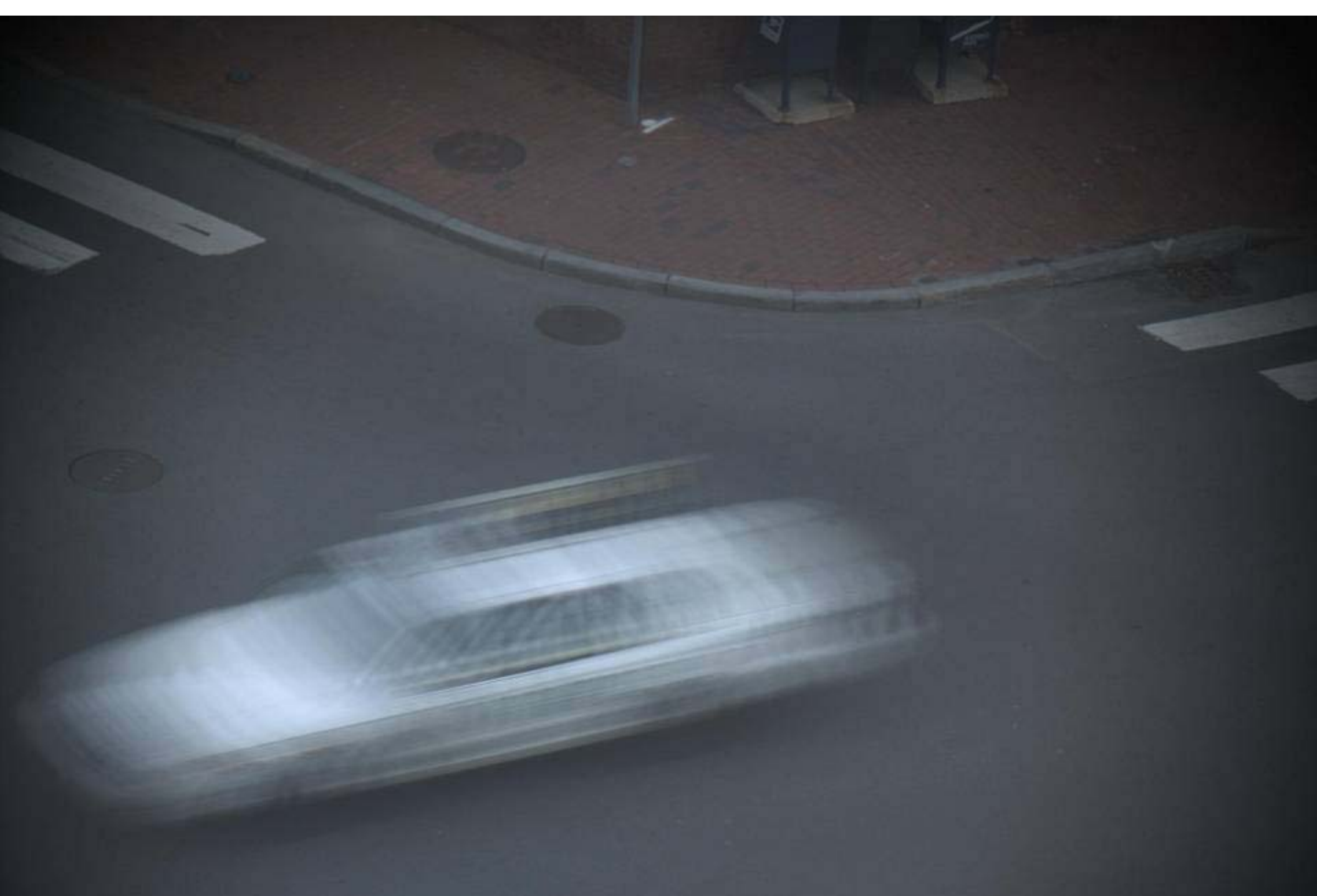


Source: Raskar, Agrawal and Tumblin. "Coded Exposure  
Photography: Motion Deblurring via Fluttered Shutter."  
*Proceedings of SIGGRAPH 2006.*



Source: Raskar, Agrawal and Tumblin. "Coded Exposure  
Photography: Motion Deblurring via Fluttered Shutter."  
*Proceedings of SIGGRAPH 2006.*





Input Image

Source: Raskar, Agrawal and Tumblin. "Coded Exposure  
Photography: Motion Deblurring via Fluttered Shutter."  
*Proceedings of SIGGRAPH 2006.*

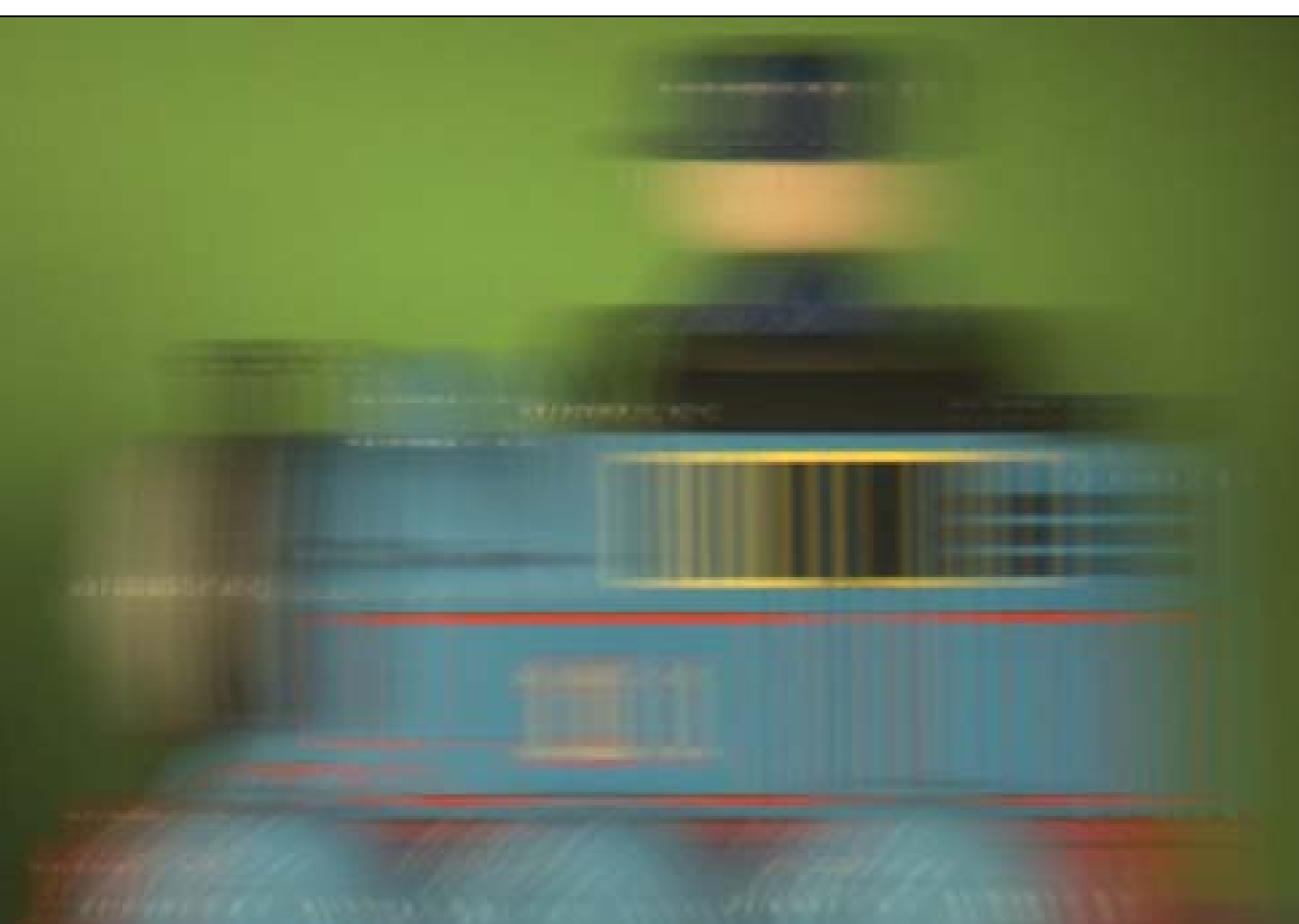
Source: Raskar, Agrawal and Tumblin. "Coded Exposure  
Photography: Motion Deblurring via Fluttered Shutter."  
*Proceedings of SIGGRAPH 2006.*



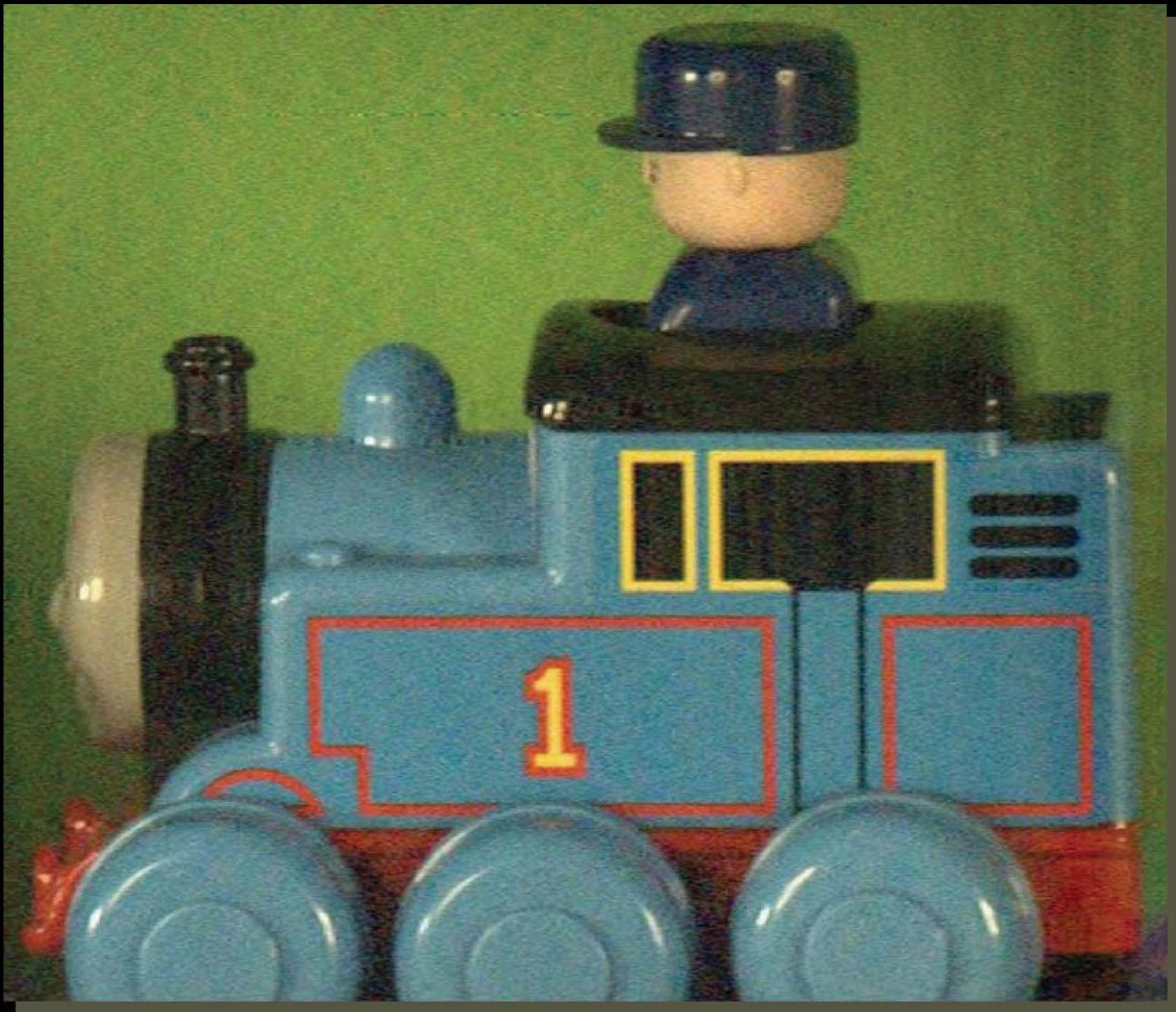
Rectified Crop



Deblurred Result



Source: Raskar, Agrawal and Tumblin. "Coded Exposure Photography: Motion Deblurring via Fluttered Shutter." *Proceedings of SIGGRAPH 2006*.



Source: Raskar, Agrawal and Tumblin. "Coded Exposure  
Photography: Motion Deblurring via Fluttered Shutter."  
*Proceedings of SIGGRAPH 2006.*



Input Photo



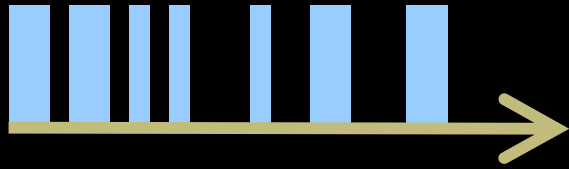
Deblurred Result



Traditional Camera

Shutter is OPEN

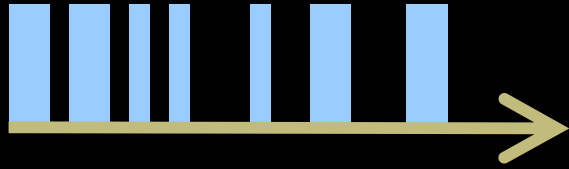




Our Camera

Flutter Shutter

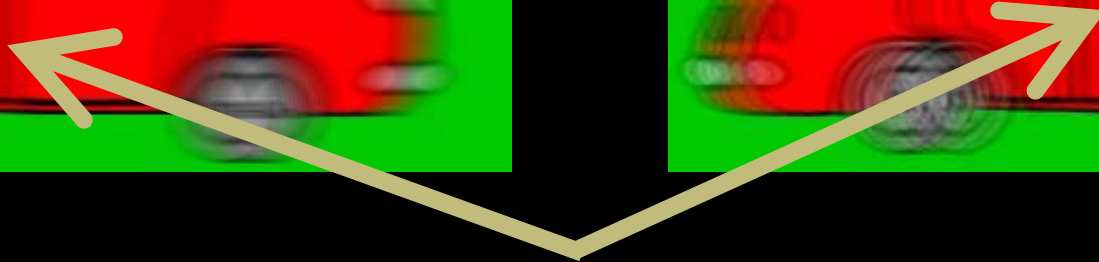
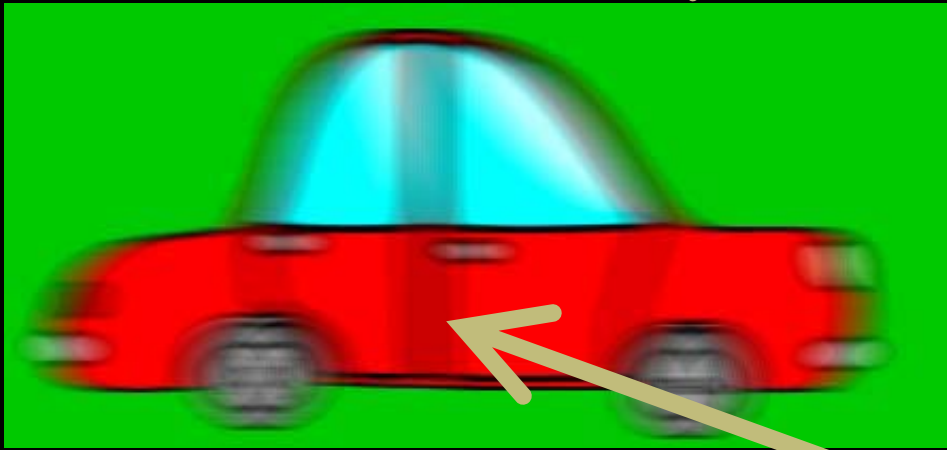
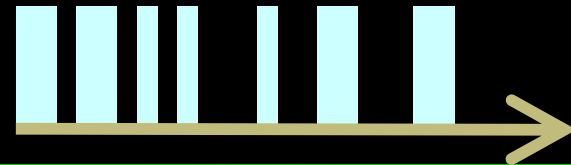




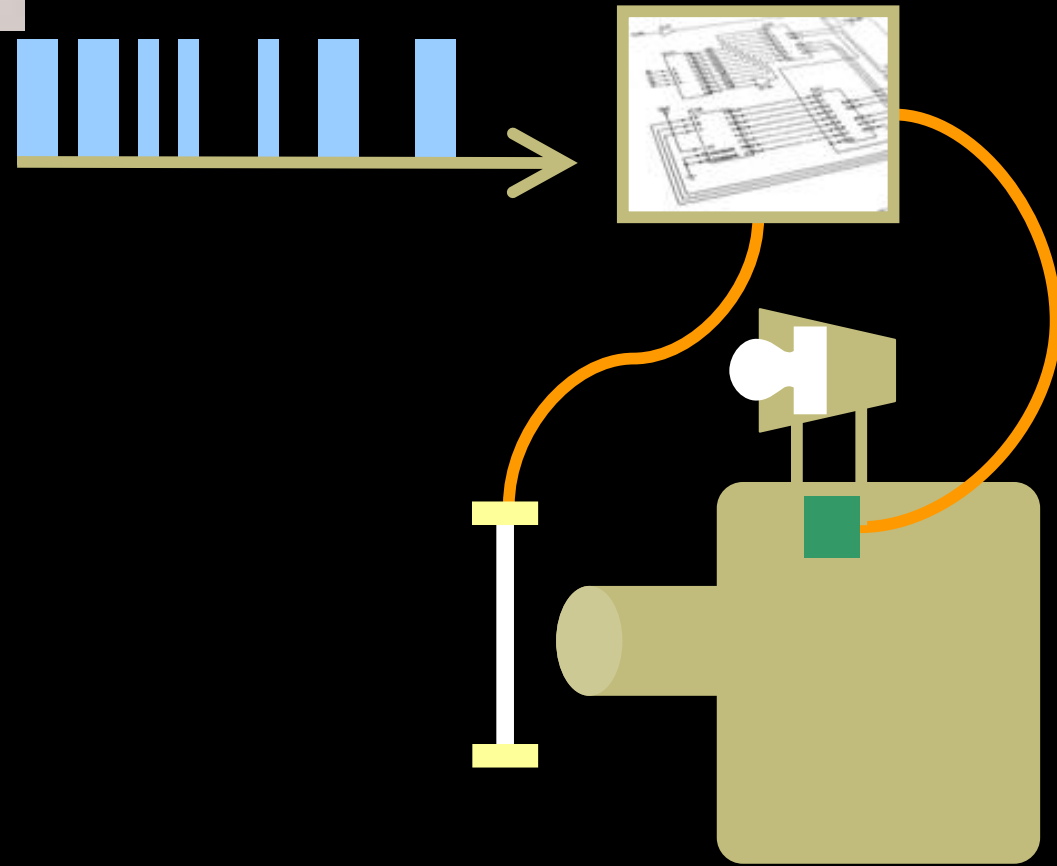
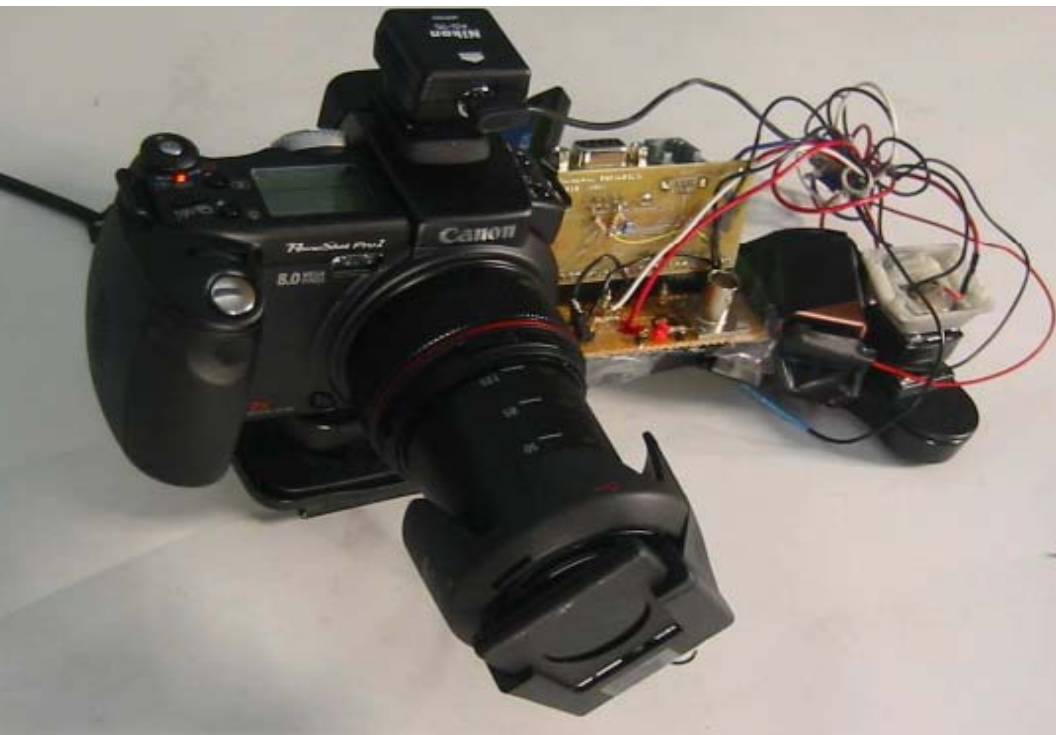
Shutter is OPEN  
and CLOSED







Comparison of Blurred Images



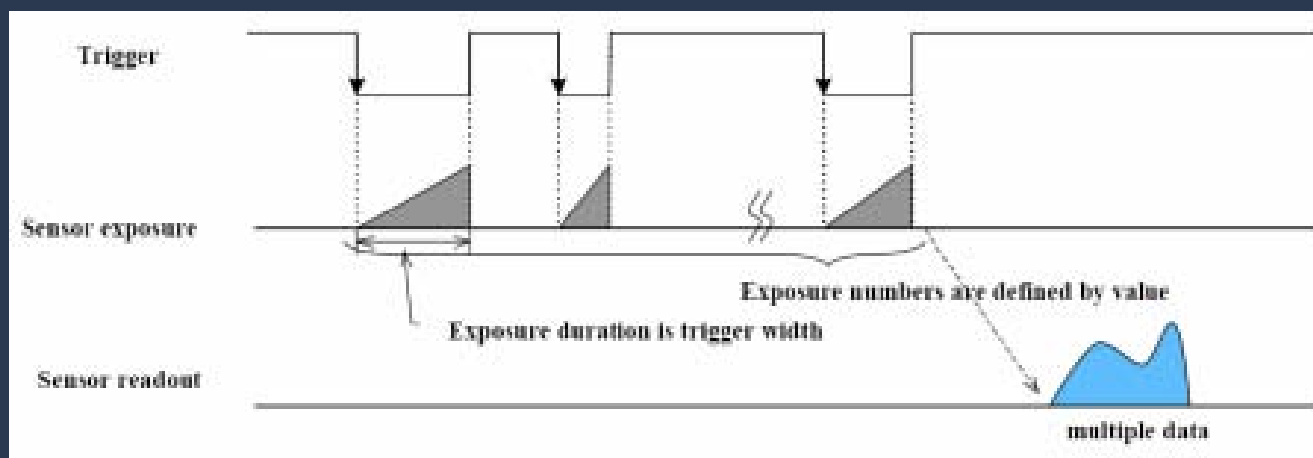
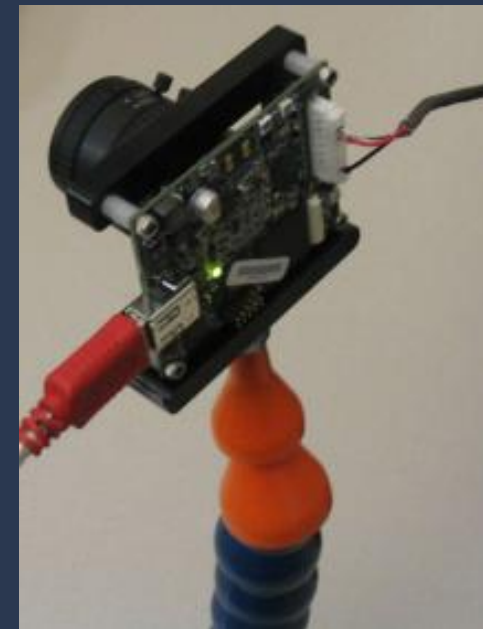
Implementation

Completely Portable

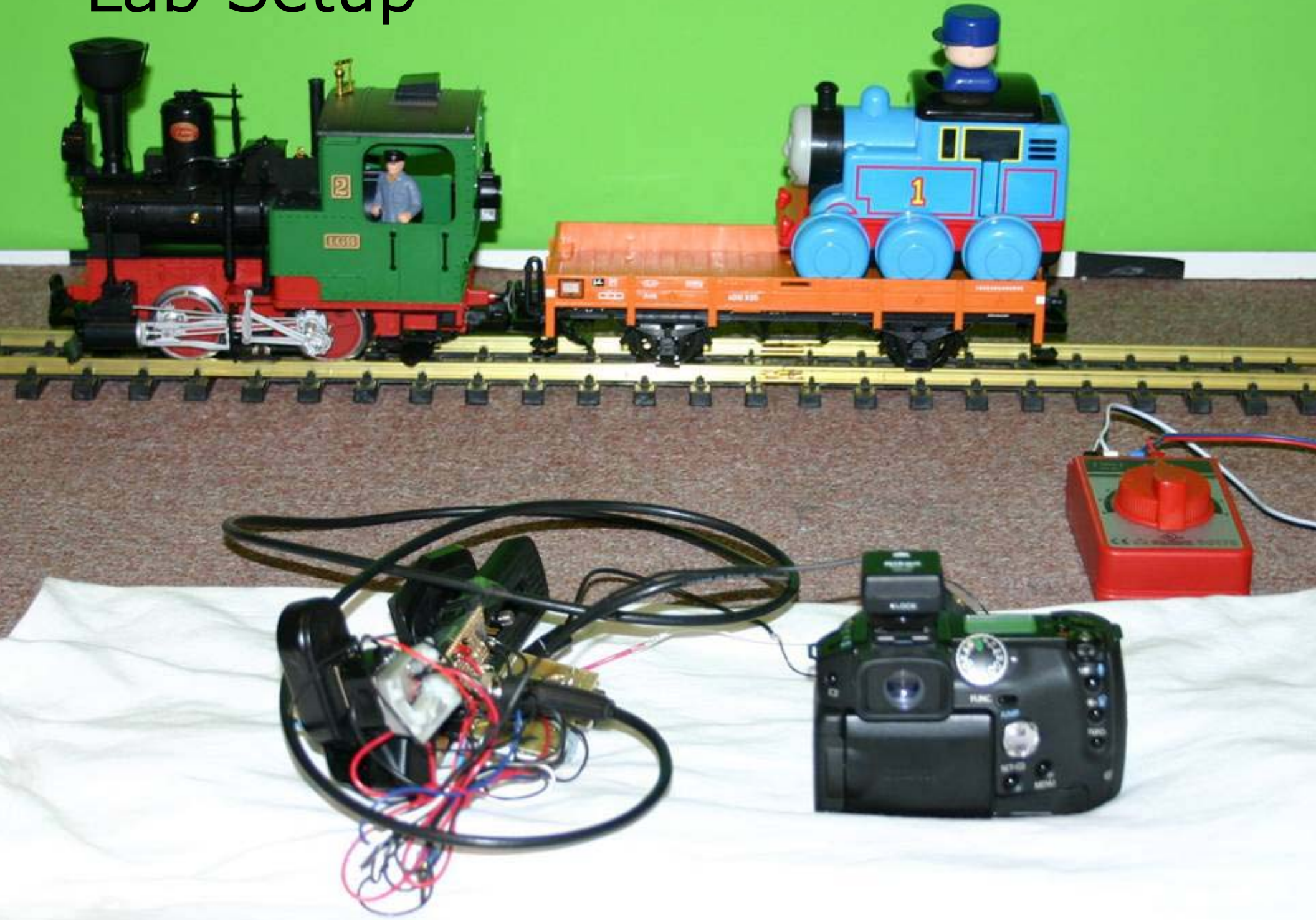


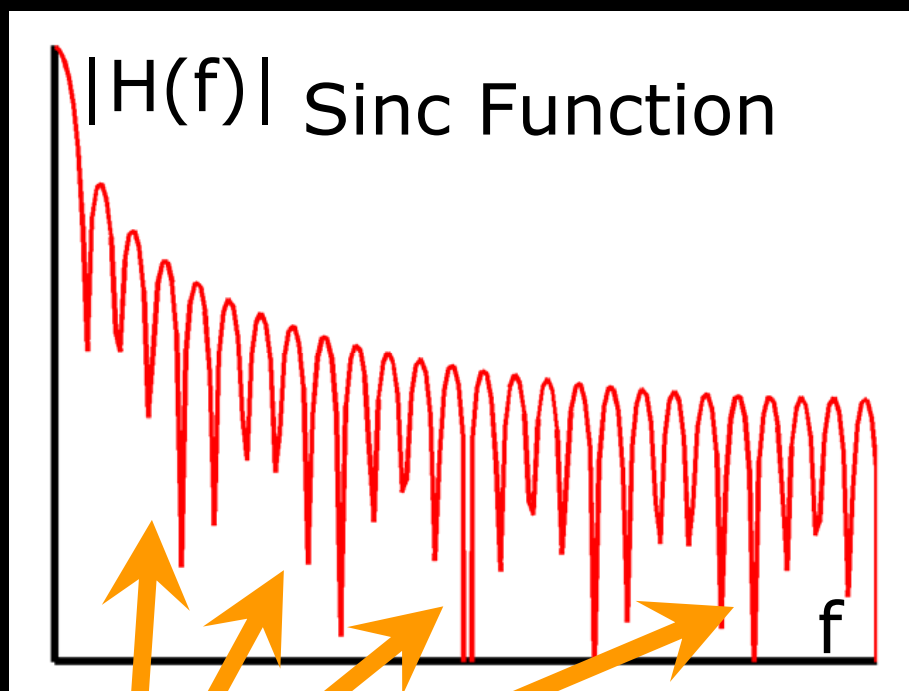
# Flutter Shutter On PointGrey Camera

- Dragonfly2 camera
- External Trigger
  - Mode 5
  - Multiple Exposure Pulse Width Mode
- On Chip Fluttered Integration, no extra cost



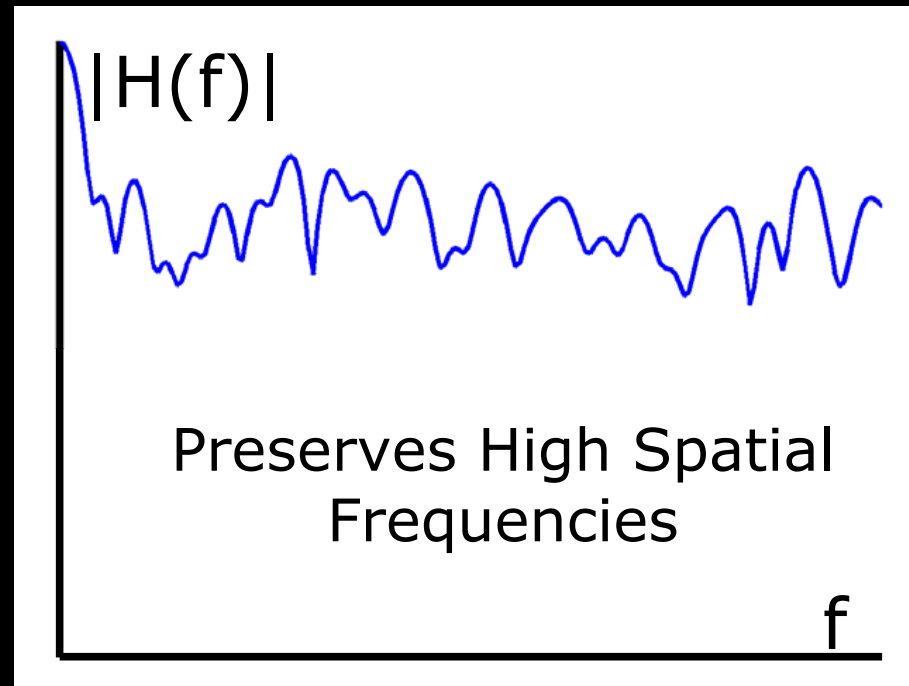
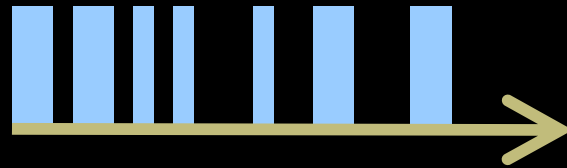
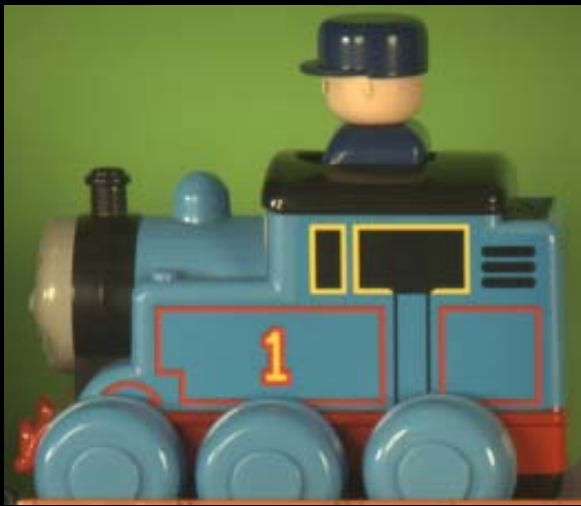
# Lab Setup





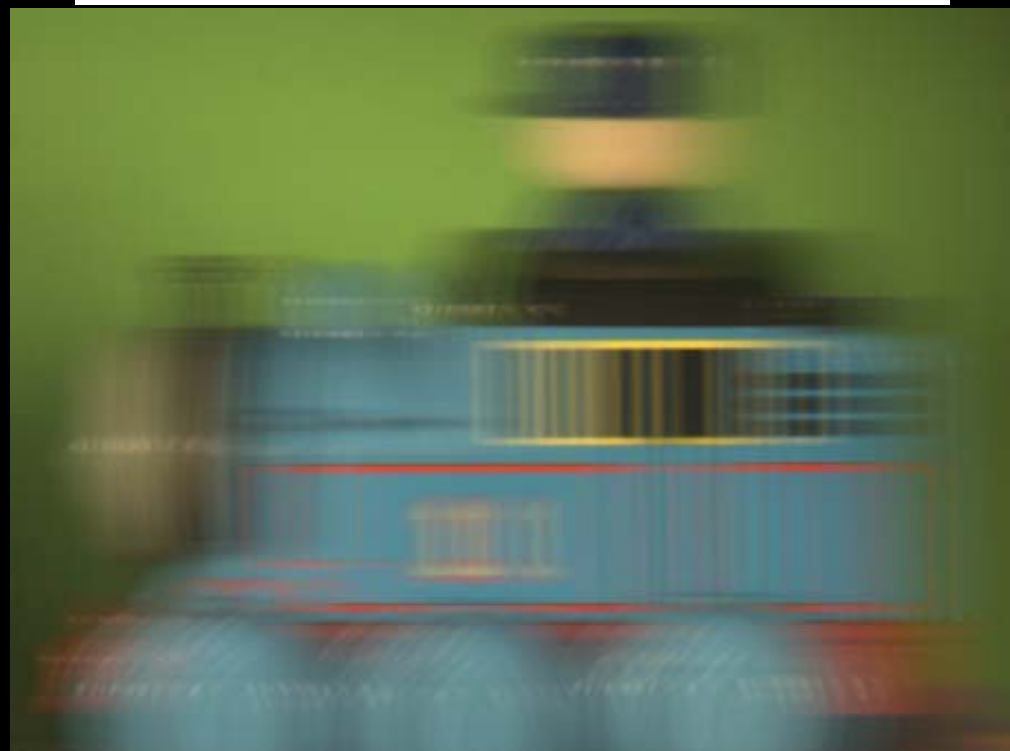
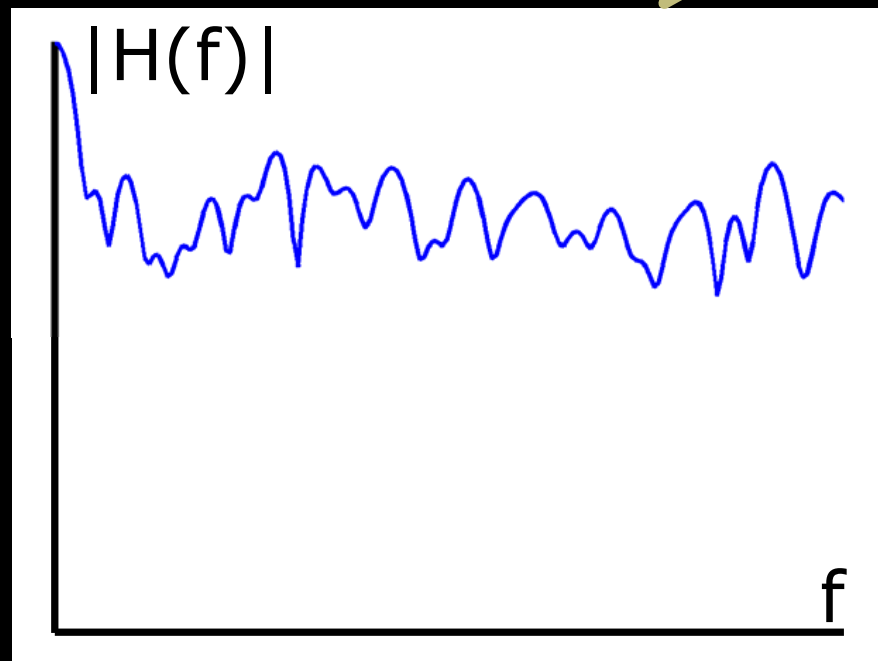
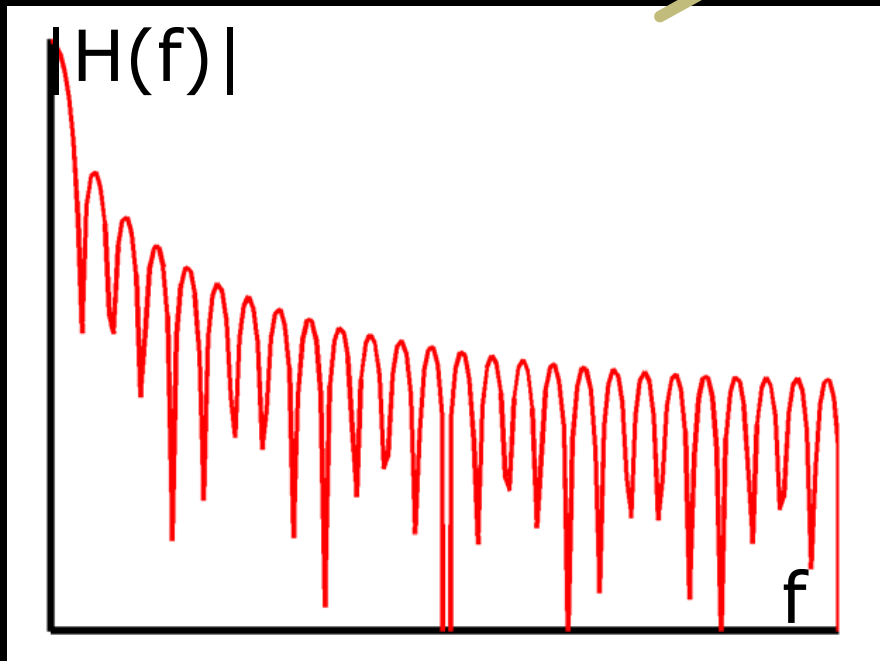
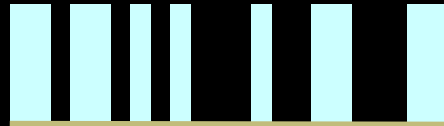
Blurring  
==  
Convolution

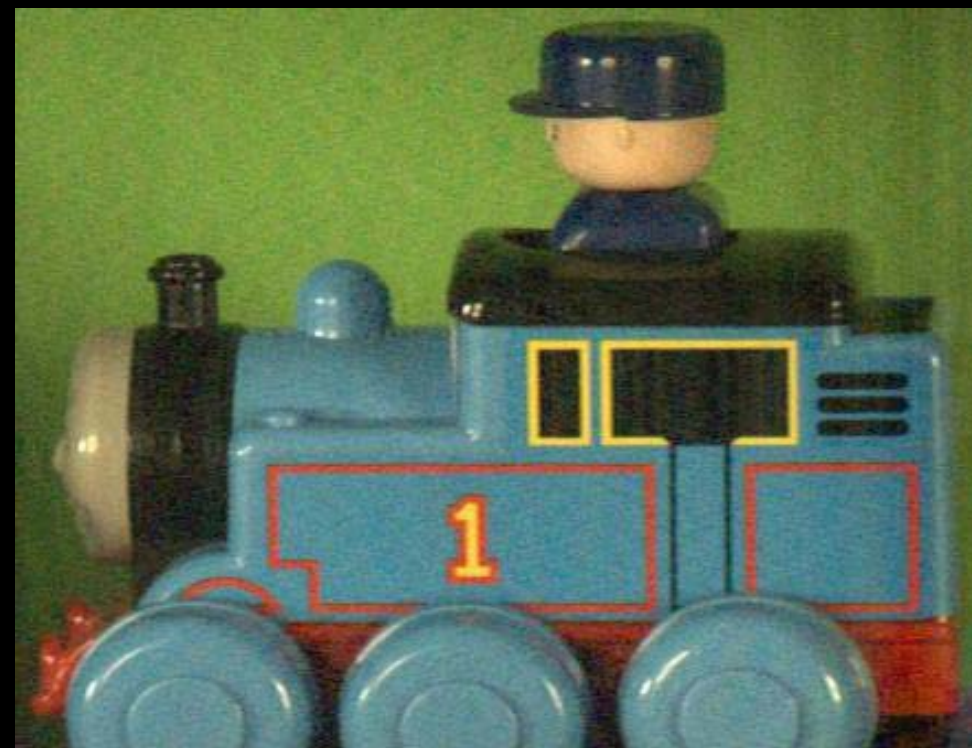
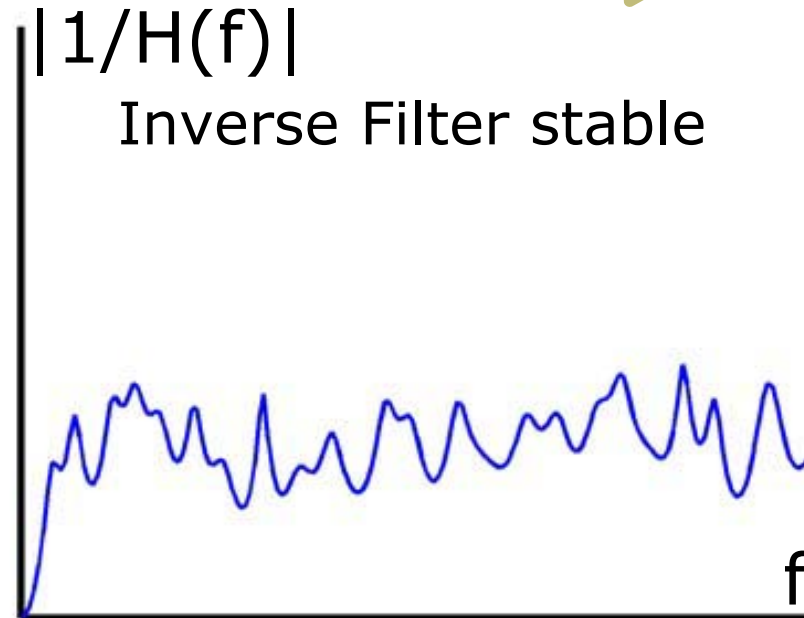
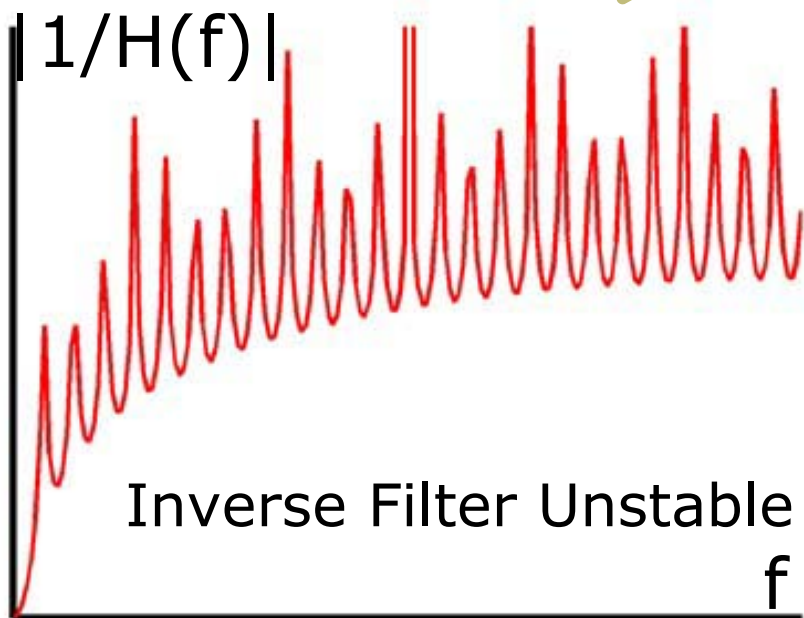
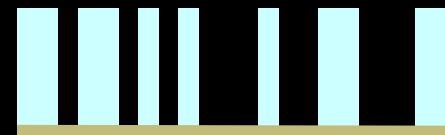
Traditional Camera: Box Filter



## Flutter Shutter: Coded Filter

# Comparison



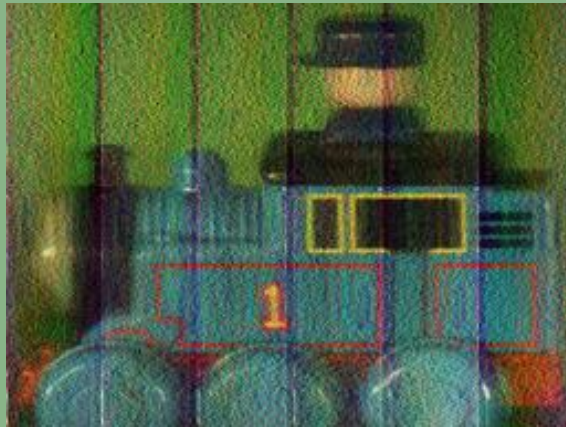




Short Exposure

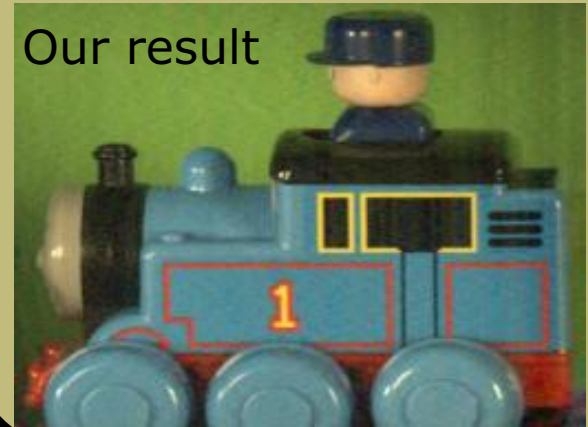


Long Exposure

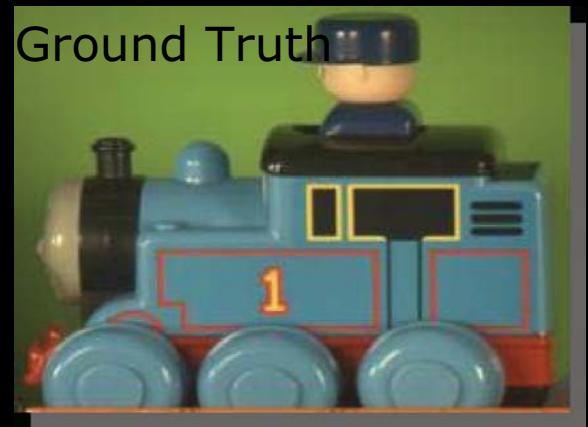


Matlab Lucy

Coded Exposure

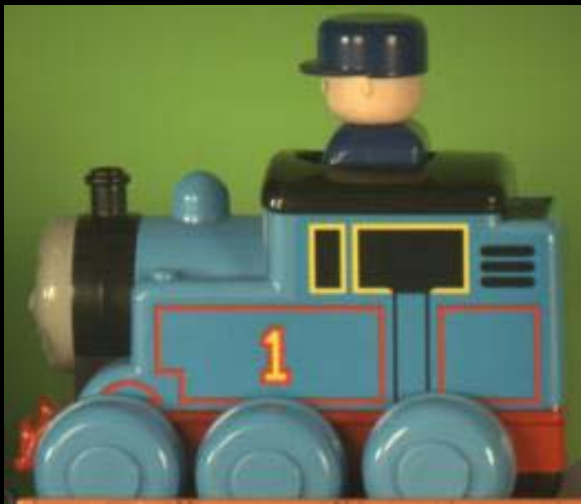


Our result



Ground Truth

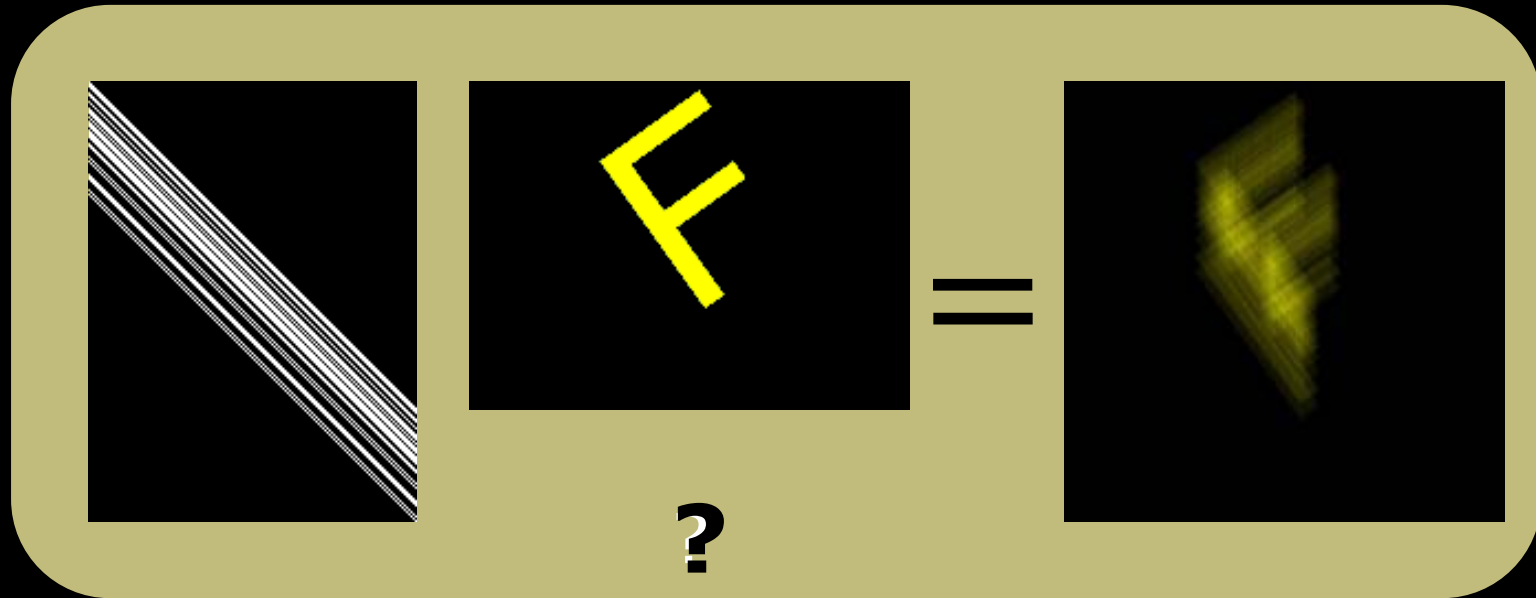
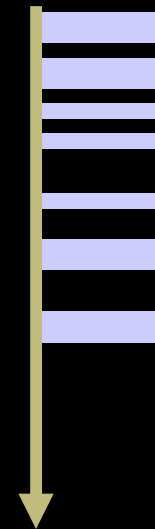
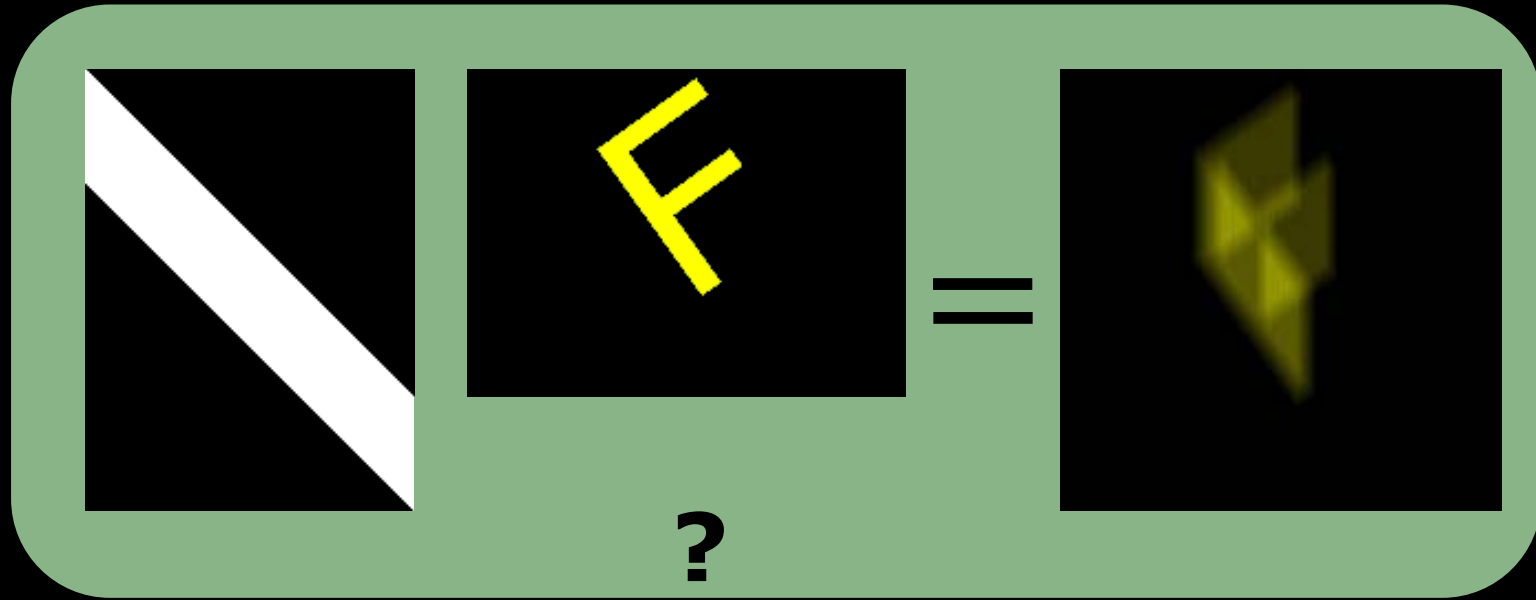
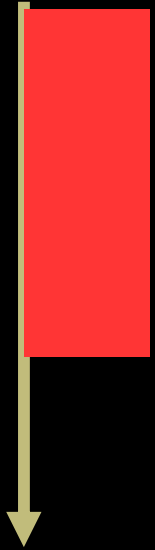
Source: Raskar, Agrawal and Tumblin. "Coded Exposure  
Photography: Motion Deblurring via Fluttered Shutter."  
Proceedings of SIGGRAPH 2006.



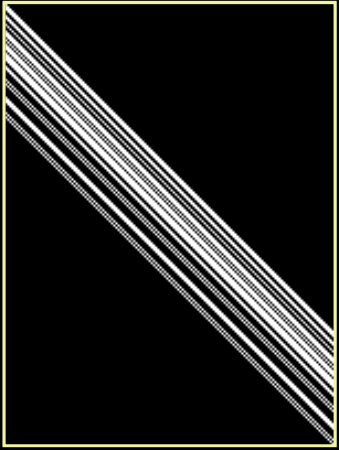
Motion Blur as Convolution



# Convolution == Linear System

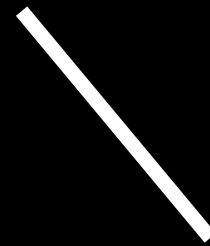
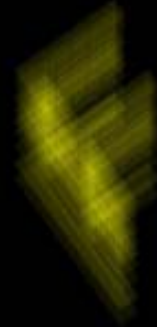


# Solving

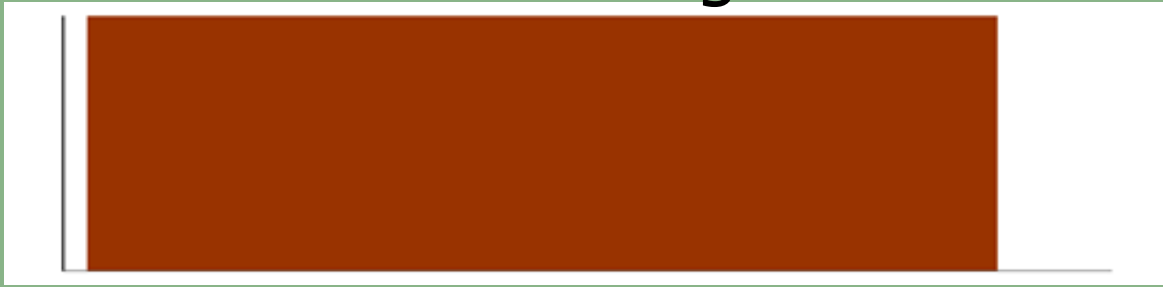


**F**

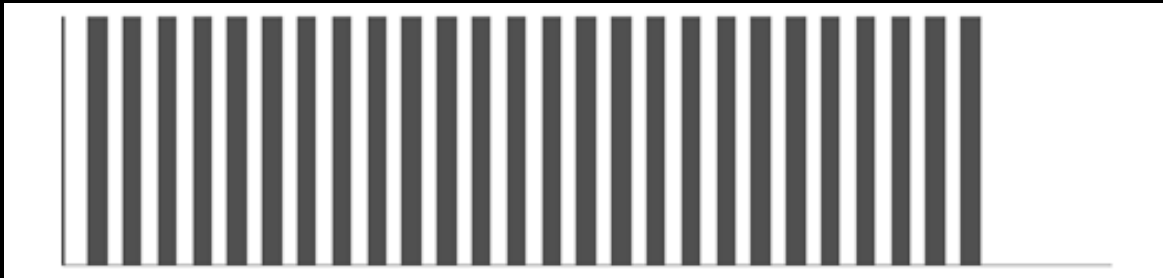
=



Are all codes "good"?



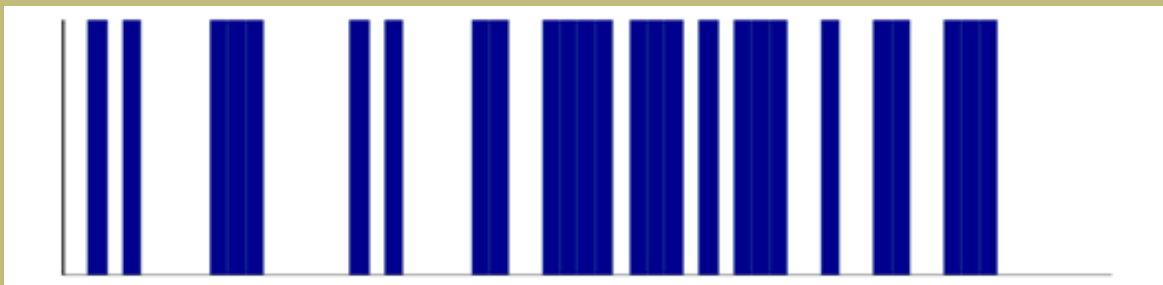
All ones



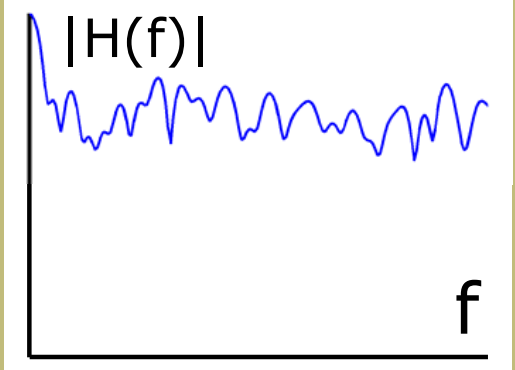
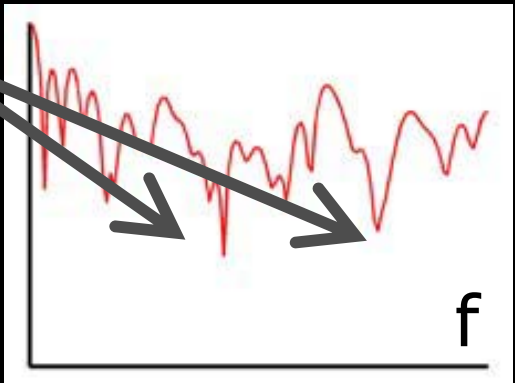
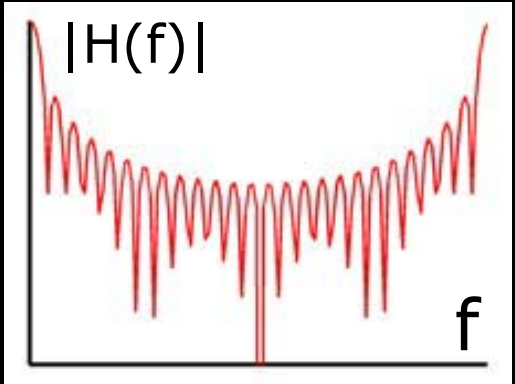
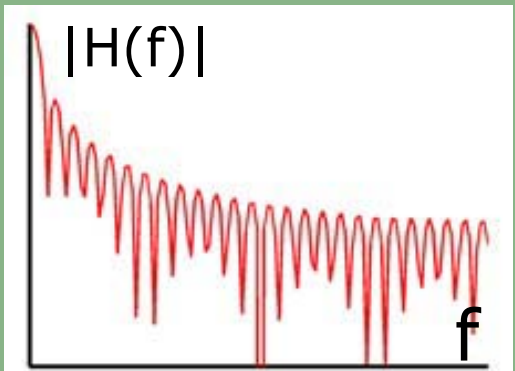
Alternate



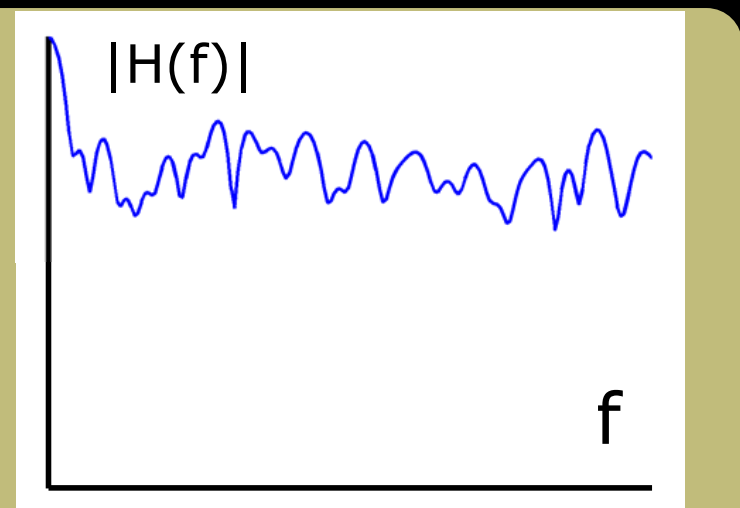
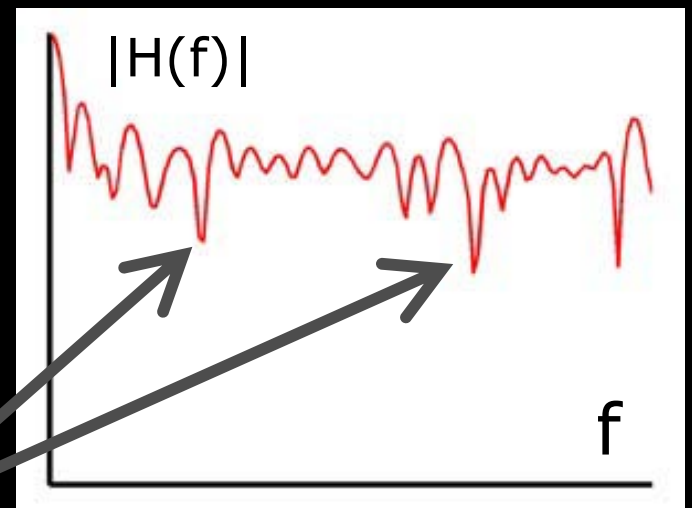
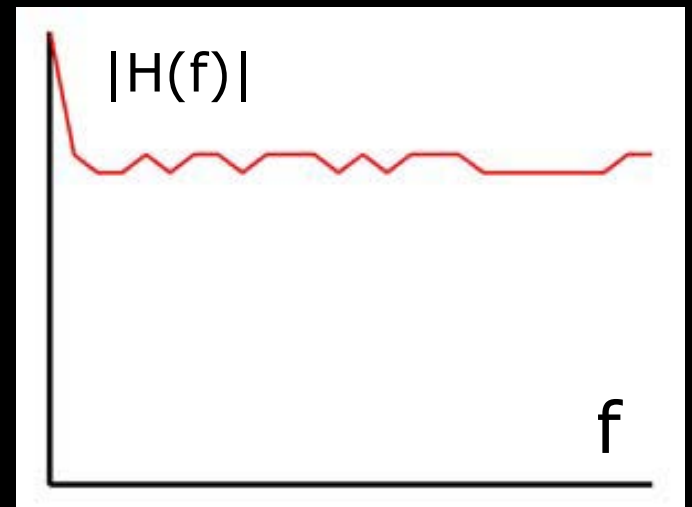
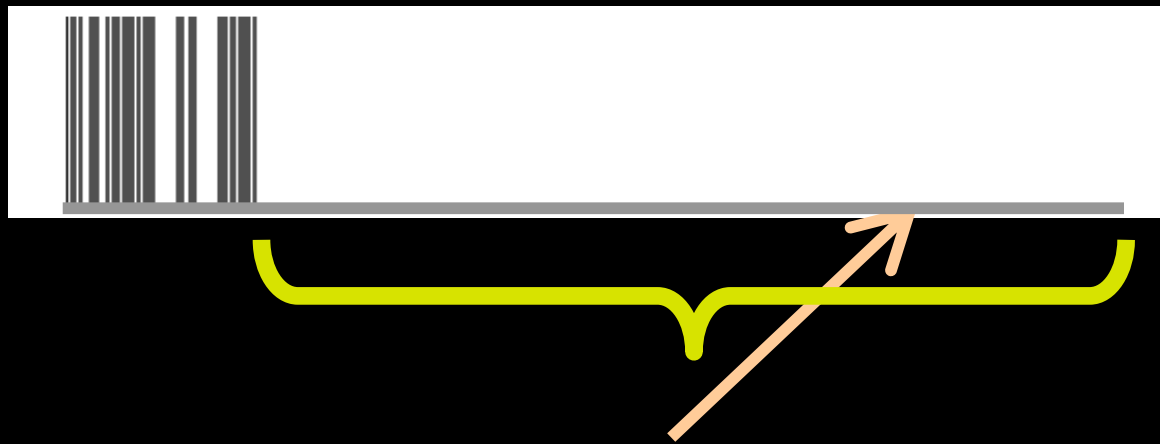
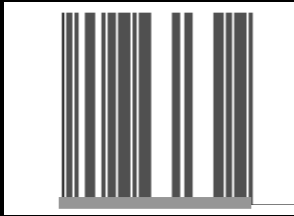
Random

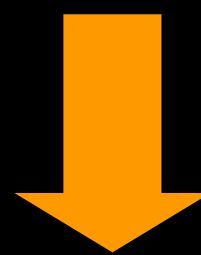


Our Code



Need to consider zero padded codes





License Plate Retrieval



# Camera Limitations and Tradeoffs

- Low dynamic range
- Resolution vs Noise
- Motion blur
  - Reduce shutter speed, but lose light
- Limited depth of field
  - Reduce aperture, but lose light
  - Increase shutter time, but motion blur





# Changing Aperture Size

Images removed due to copyright restrictions.

- Samuel Hasinoff and Kiriakos Kutulakos, 'A Layer-Based Restoration Framework for Variable-Aperture Photography' ICCV 2007

# How to handle focus blur?



Source: Veeraraghavan, Raskar, Agarwal, Mohan, and Tumblin. "Dappled Photography: Mask Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing." *Proceedings of SIGGRAPH 2007*.

## Coded Exposure (Flutter Shutter)

Raskar, Agrawal, Tumblin  
SIGGRAPH 2006



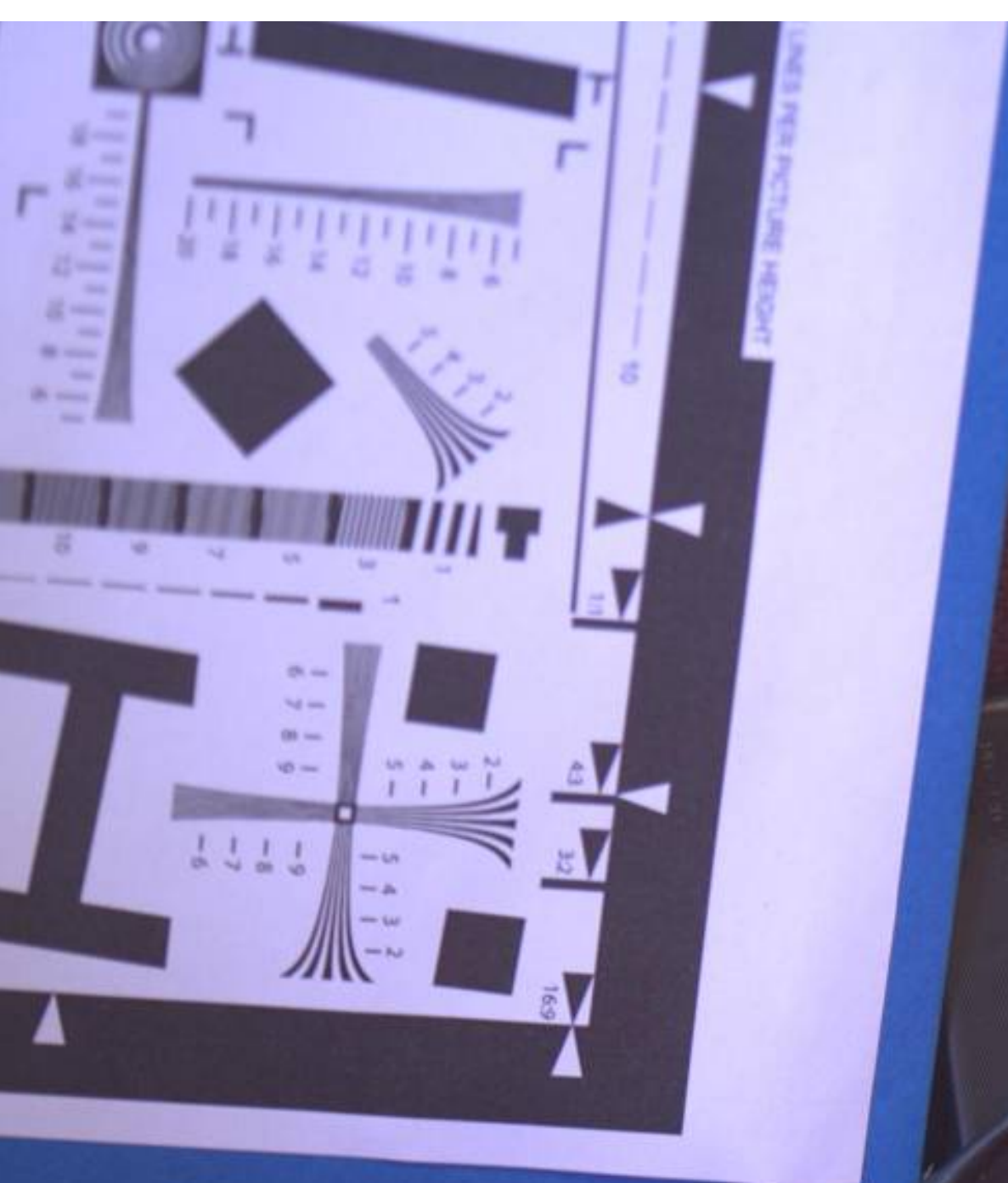
Temporal 1-D broadband code:  
**Motion** Deblurring

## Coded Aperture

with Veeraraghavan, Raskar, Tumblin, & Mohan,  
SIGGRAPH 2007

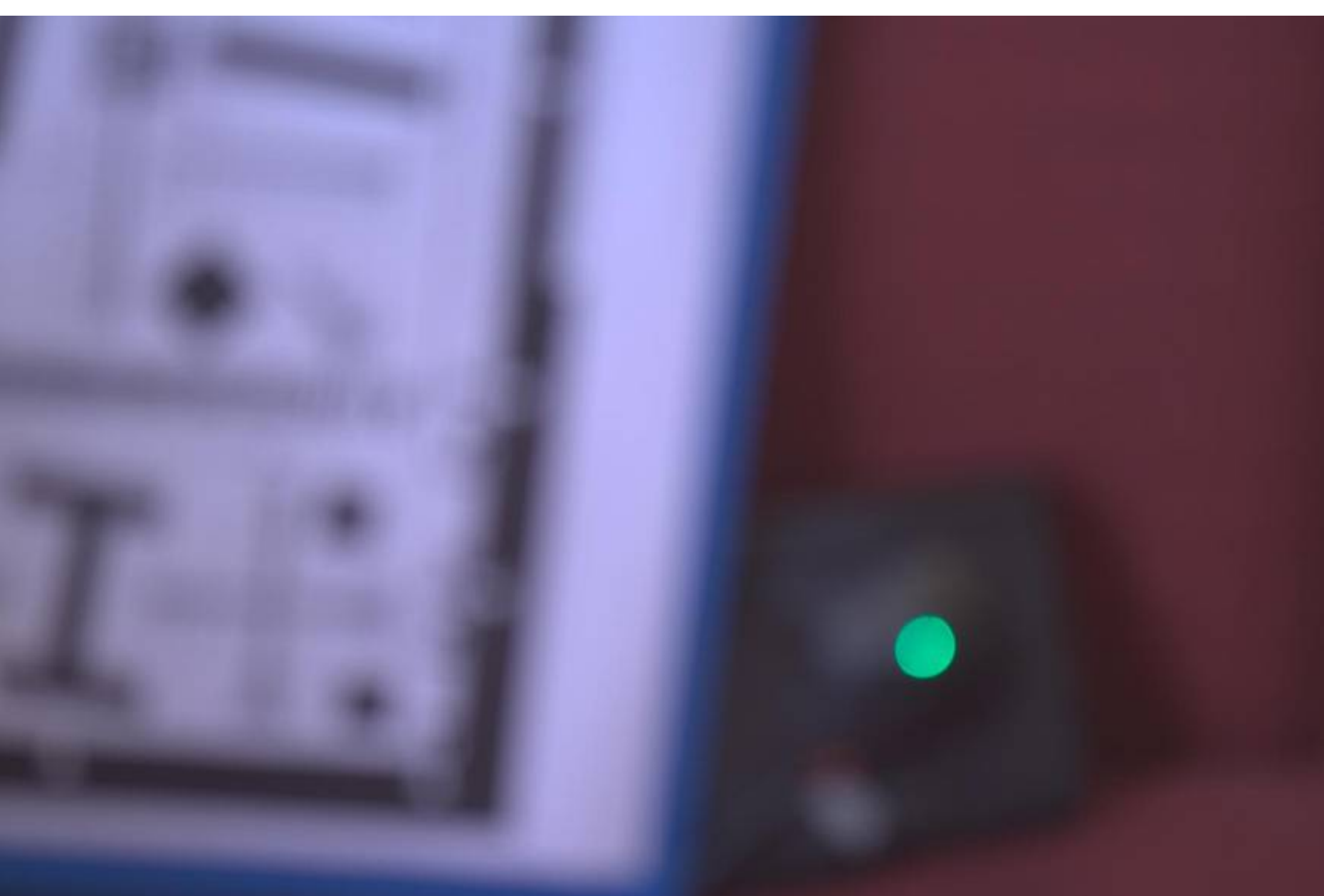


Spatial 2-D broadband code:  
**Focus** Deblurring



LED

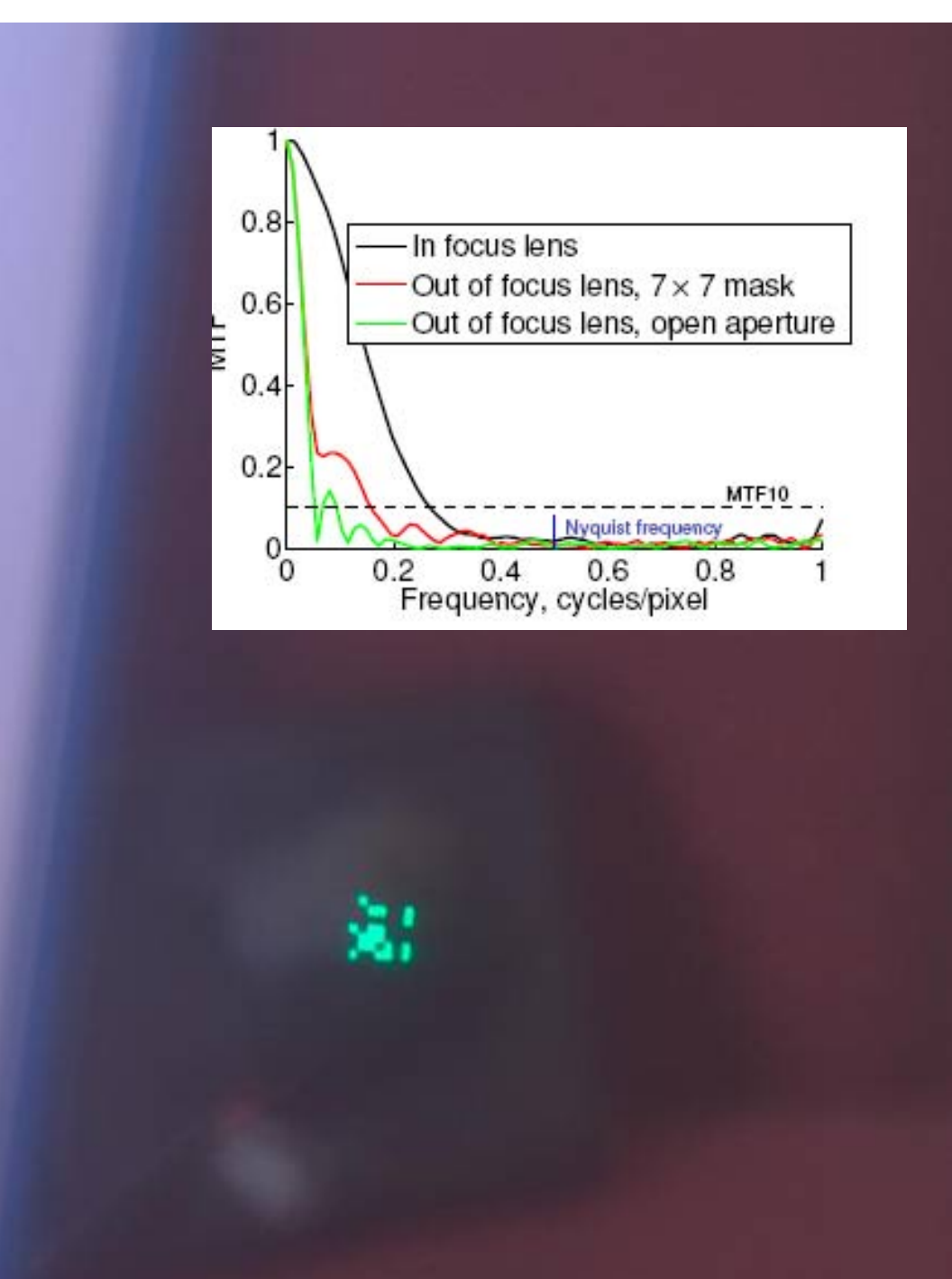
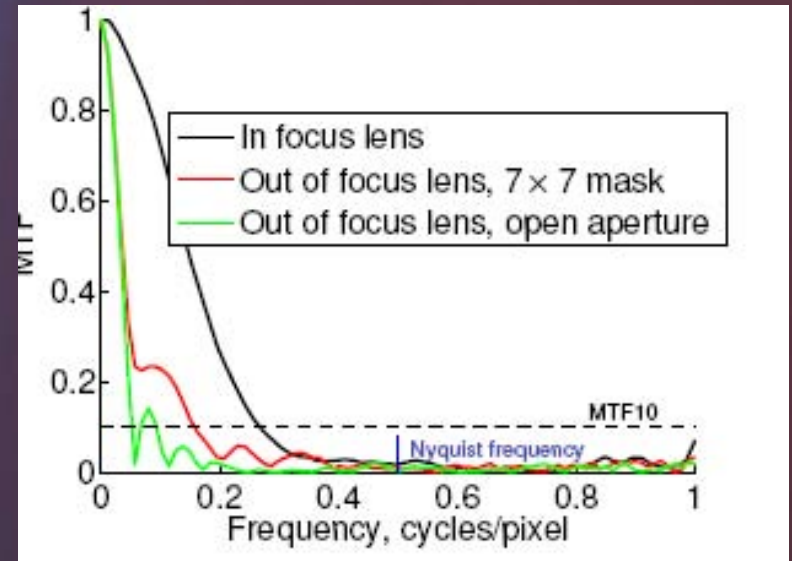
In Focus Photo



Out of Focus Photo: Open Aperture



Out of Focus Photo: Coded Aperture



# Out of Focus Photo: Coded Aperture

# Blurred Photos



Open Aperture



Coded Aperture, 7 \* 7 Mask

Source: Veeraraghavan, Raskar, Agarwal, Mohan, and Tumblin. "Dappled Photography: Mask Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing." *Proceedings of SIGGRAPH 2007*.



# Deblurred Photos



Open Aperture



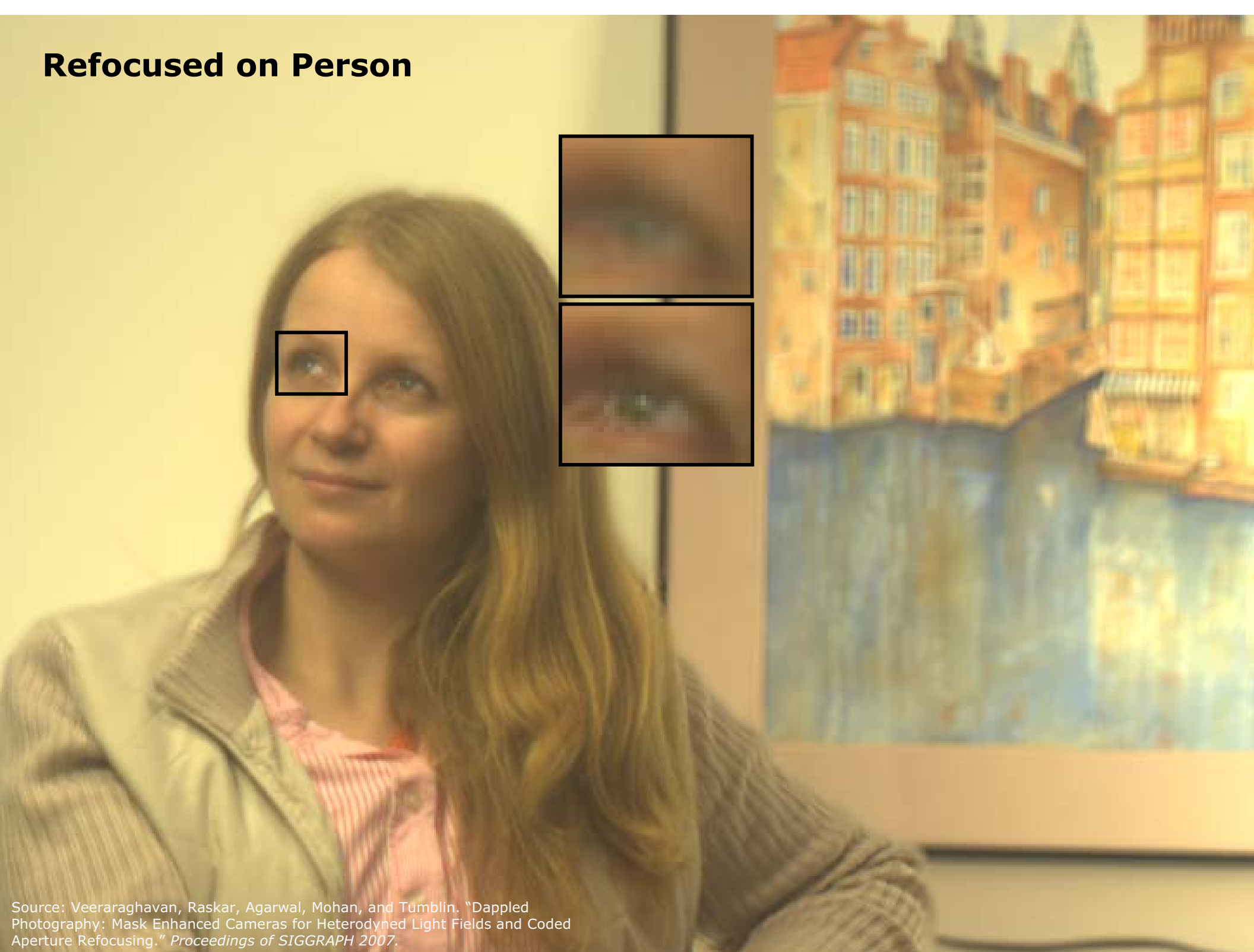
Coded Aperture, 7 \* 7 Mask

# Captured Blurred Photo



Source: Veeraraghavan, Raskar, Agarwal, Mohan, and Tumblin. "Dappled Photography: Mask Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing." *Proceedings of SIGGRAPH 2007*.

## Refocused on Person



Source: Veeraraghavan, Raskar, Agarwal, Mohan, and Tumblin. "Dappled Photography: Mask Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing." *Proceedings of SIGGRAPH 2007*.

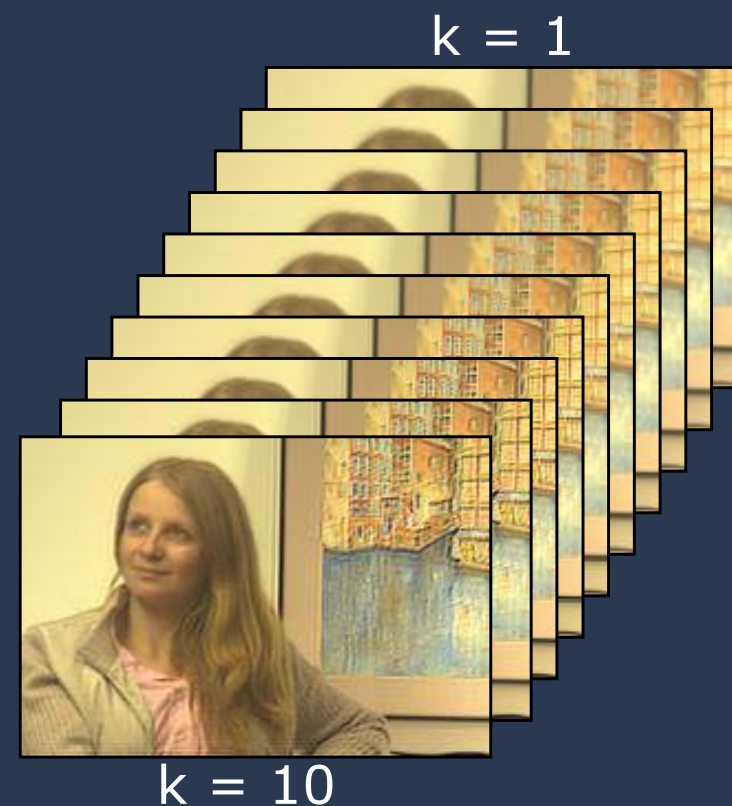
# Blur Estimation & Segmentation

- Defocus blur dependent on depth
- Assumptions
  - Layered Lambertian Scene
  - Constant blur within each layer

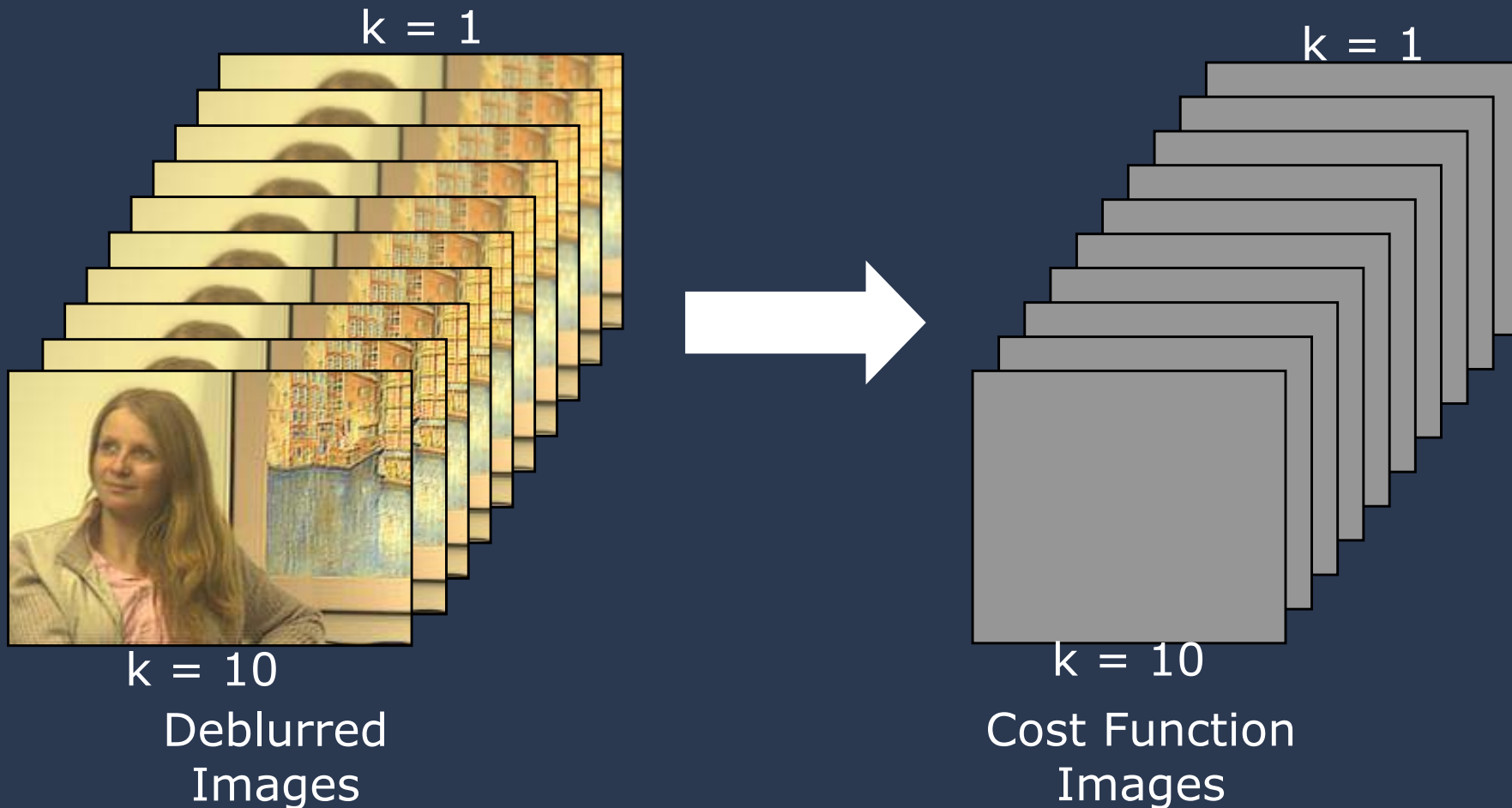


Captured Blurred Photo

Deblur at  
different blur  
sizes  $k$



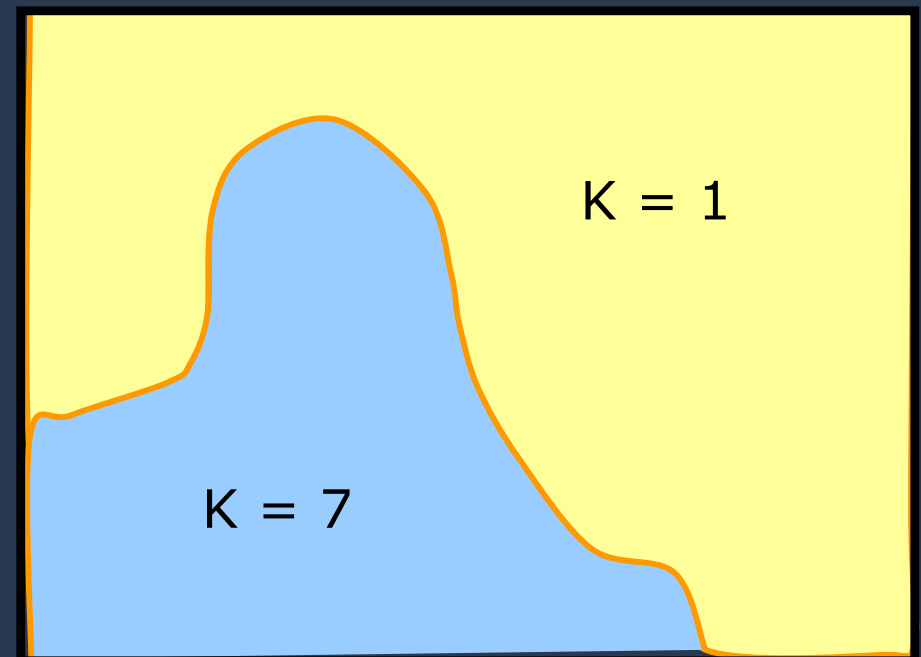
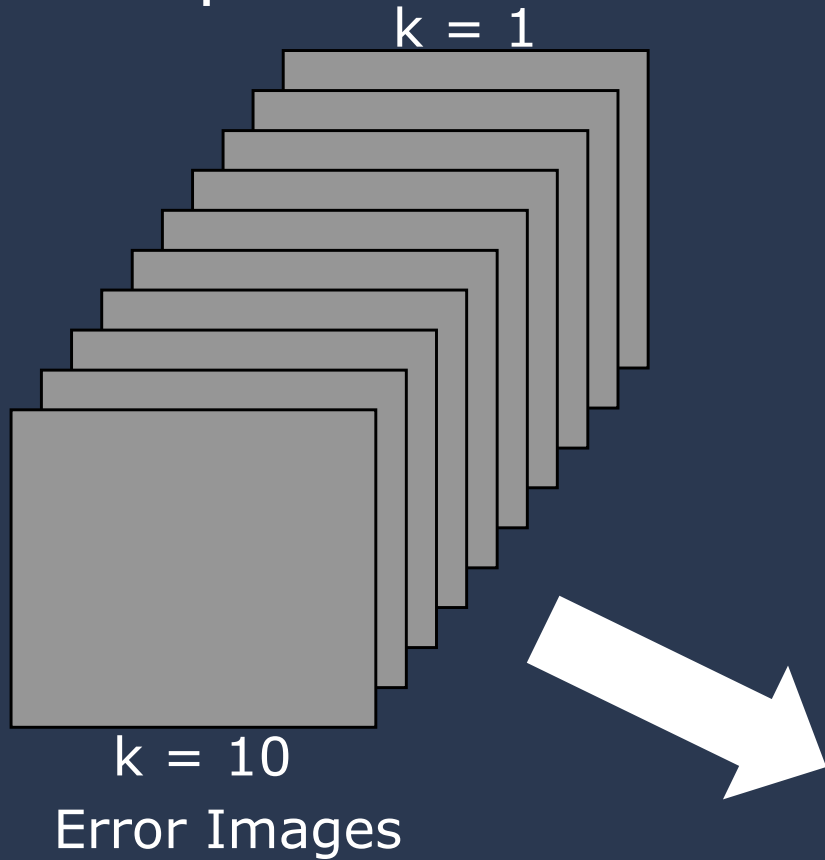
# Define Cost Function



Likelihood Error:  $(\text{Blurred image} - \text{Sharp Image} * \text{PSF}_k)^2$   
Gradient Error: Natural Image Statistics, Gradient Kurtosis

# Blur Estimation & Segmentation == Labeling

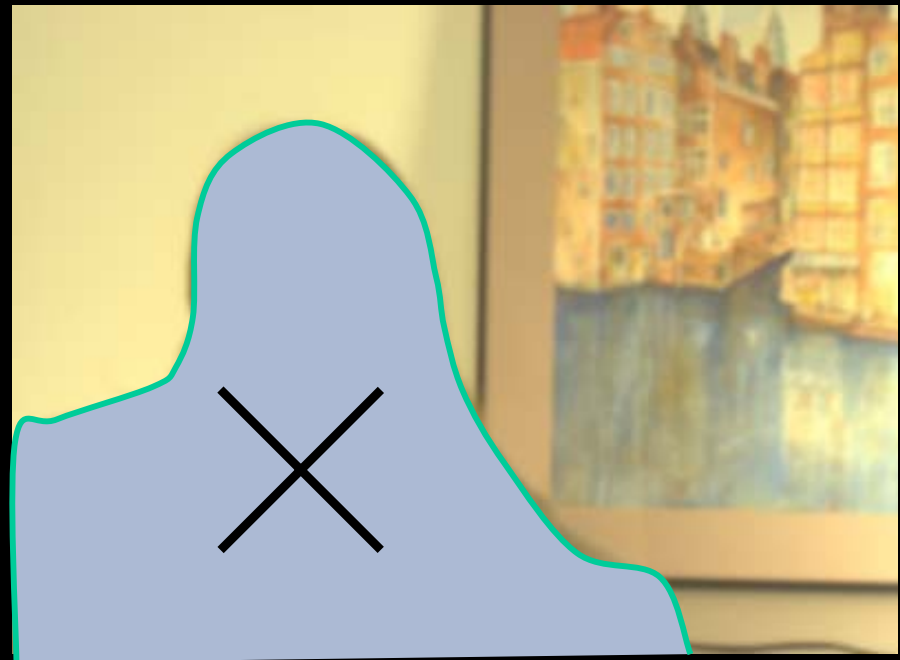
- Graph cuts for labeling



Captured  
Photo



Reblur

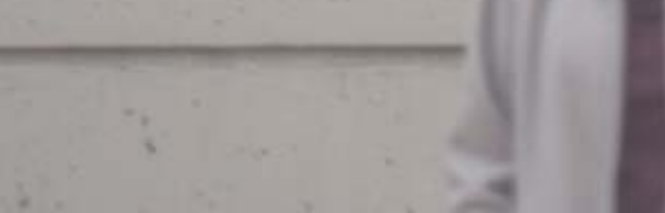
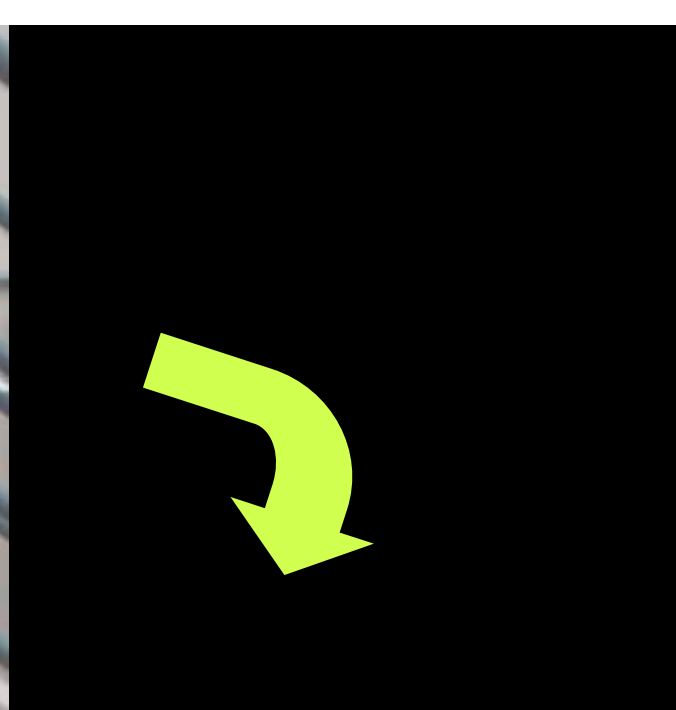
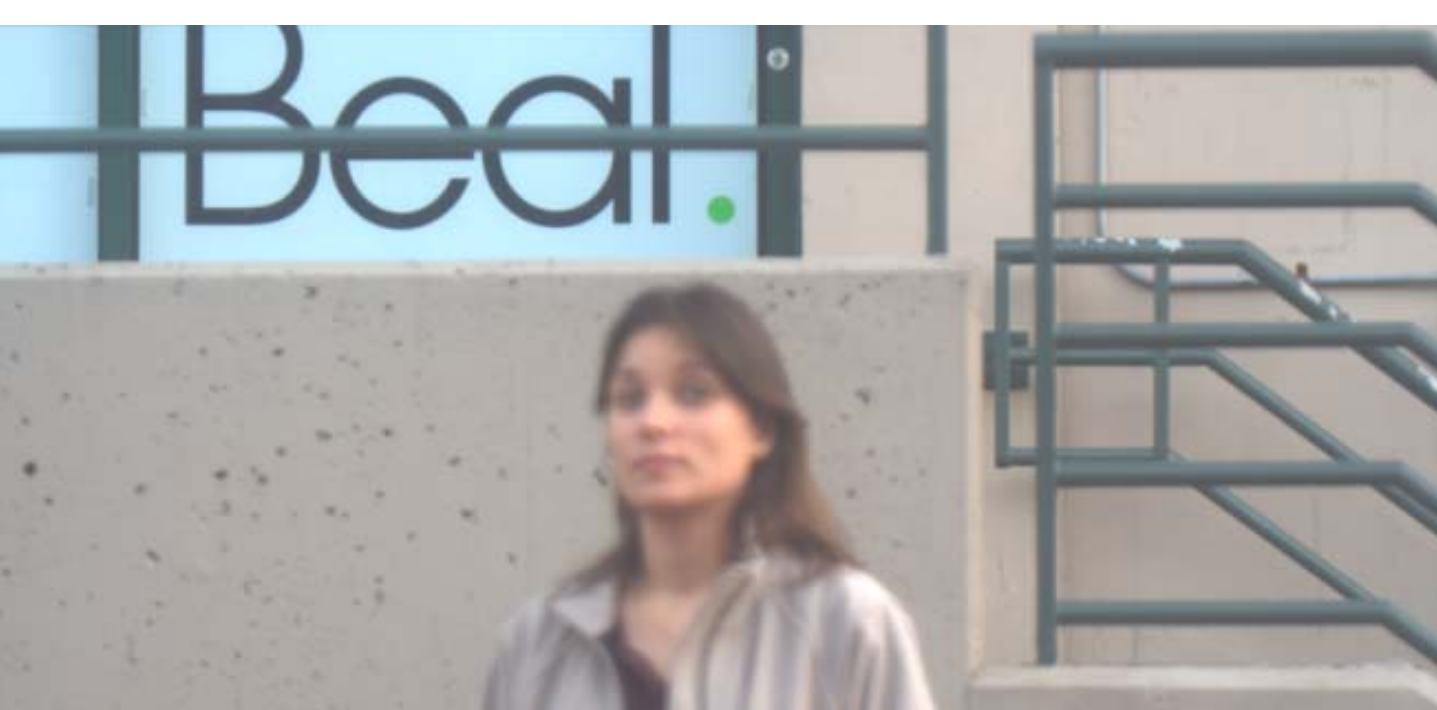


Deblur,  $k = 7$



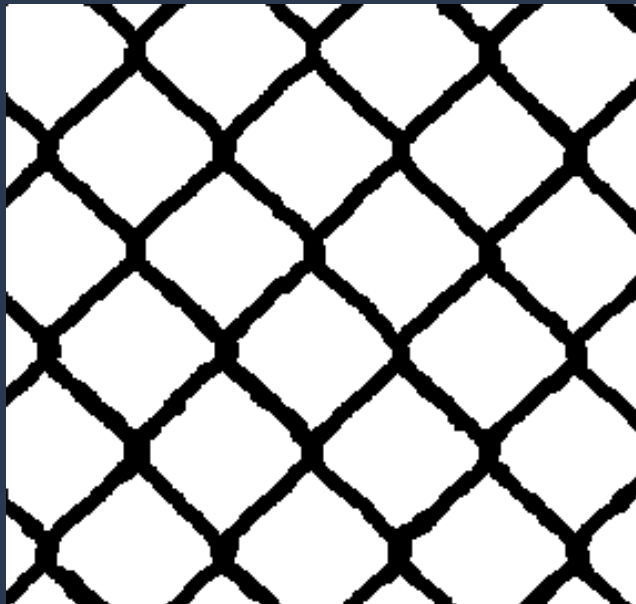
Fusion

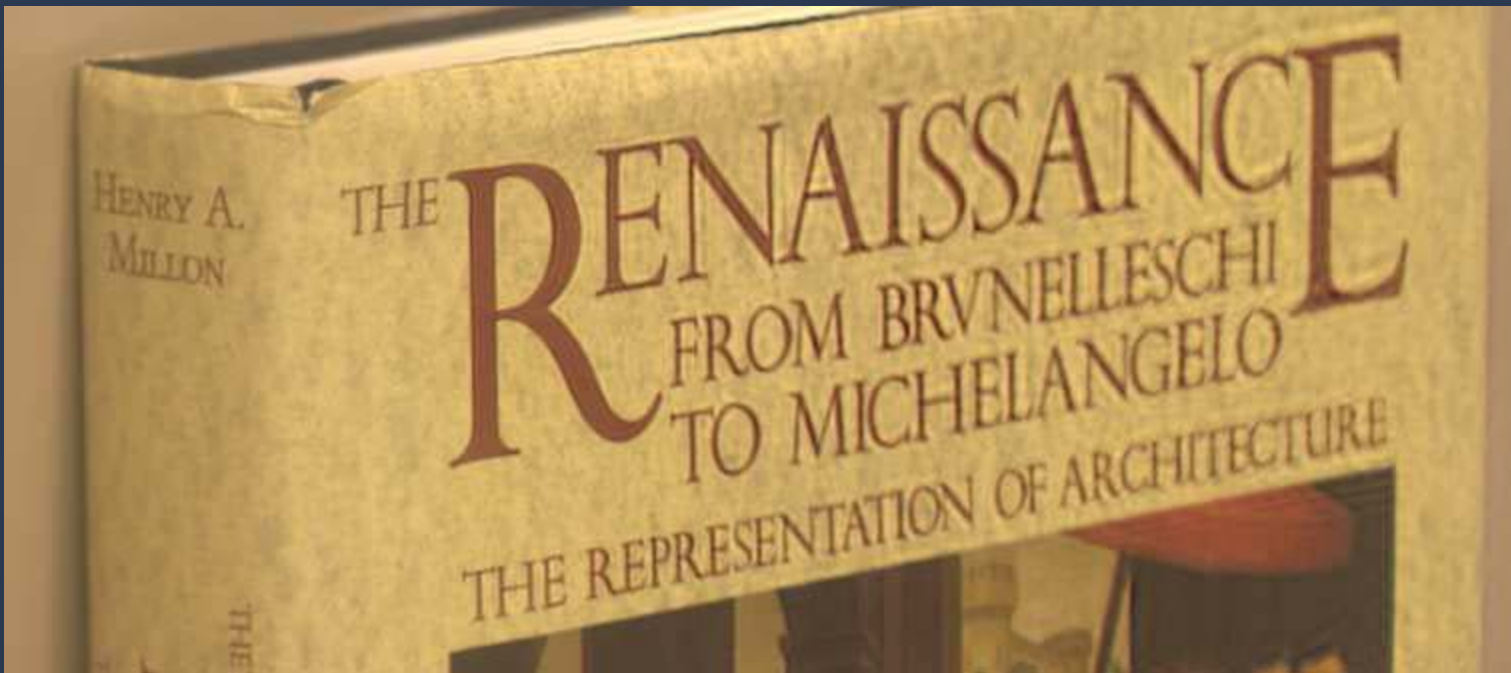






# Weighted Deconvolution





Source: Veeraraghavan, Raskar, Agarwal, Mohan, and Tumblin. "Dappled Photography: Mask Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing." *Proceedings of SIGGRAPH 2007*.

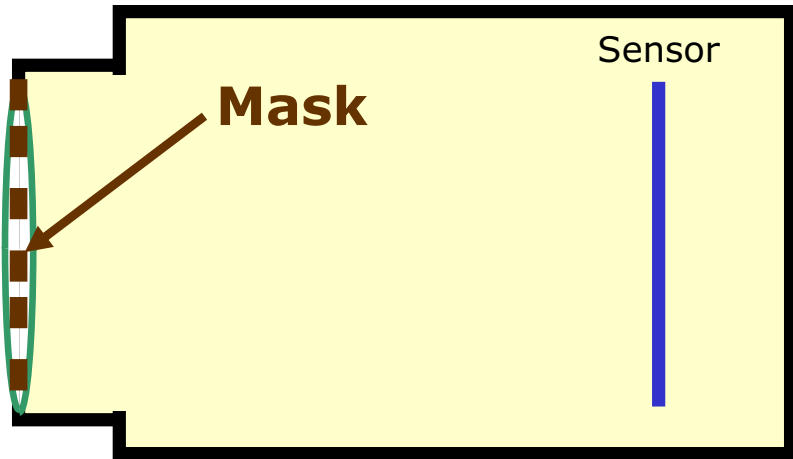
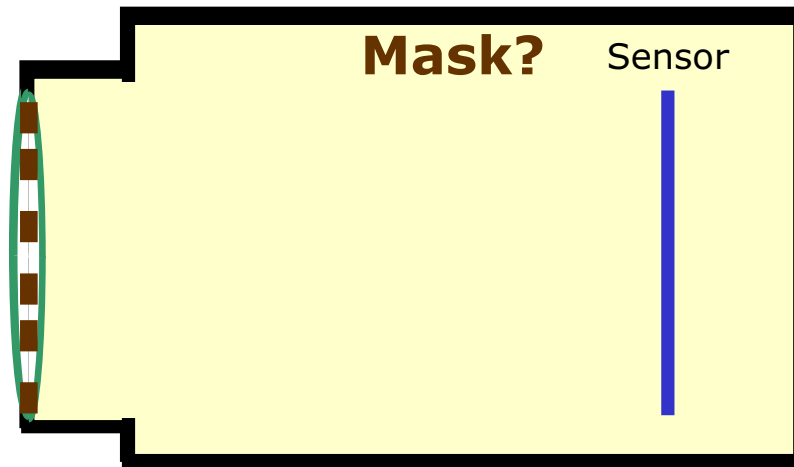


# Blocking Light == More Information



Coded Exposure  
Coding in Time

Coded Aperture  
Coding in Space



Full Resolution Digital  
Refocusing:

Coded Aperture Camera

4D Light Field from 2D  
Photo:

Heterodyne Light Field  
Camera

# Conventional Lens: Limited Depth of Field

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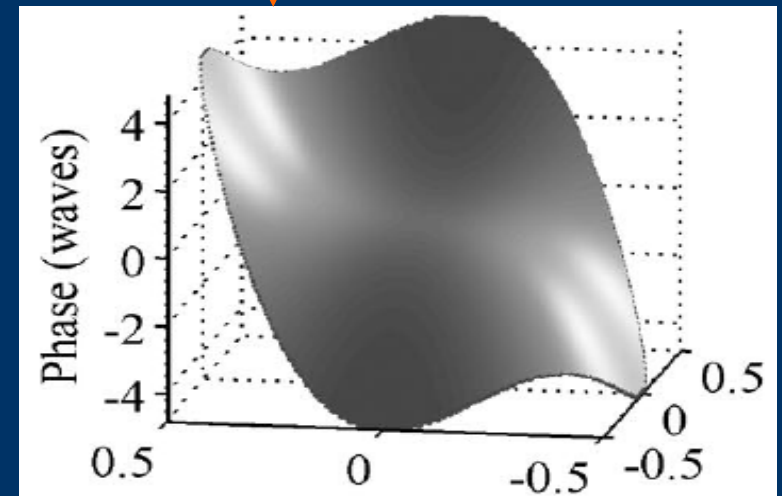
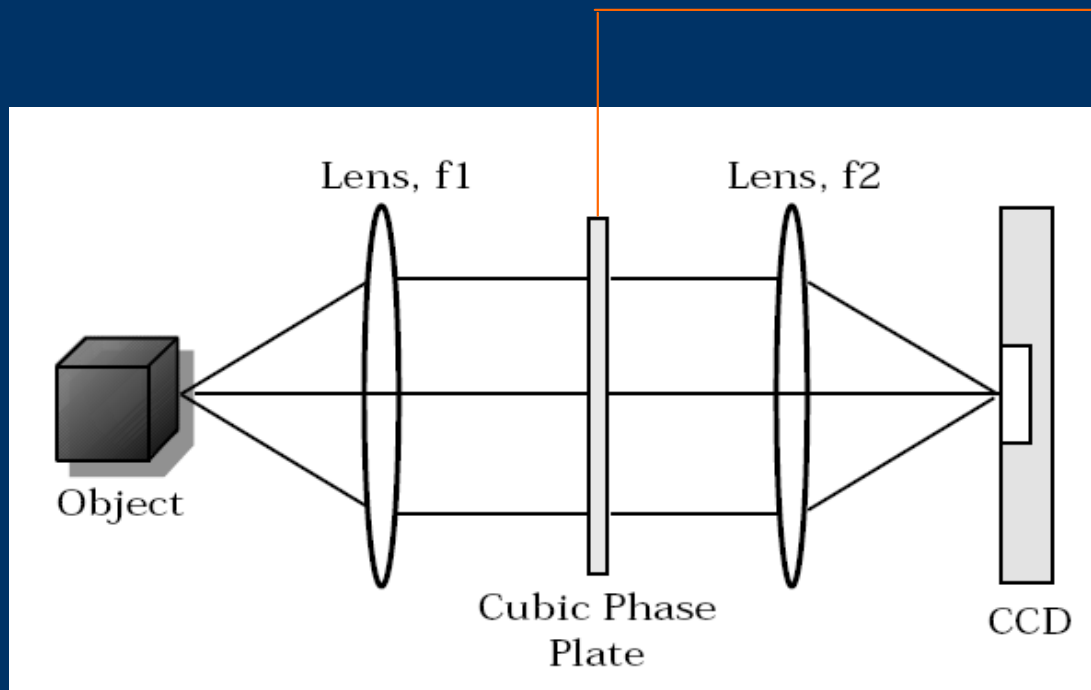
Open  
Aperture



Smaller  
Aperture



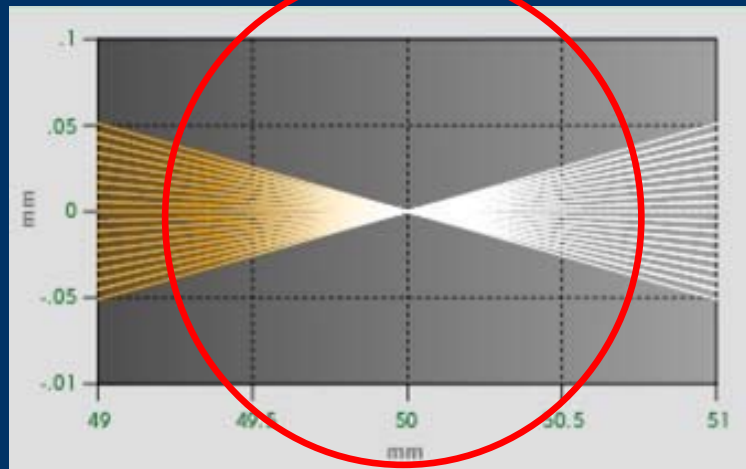
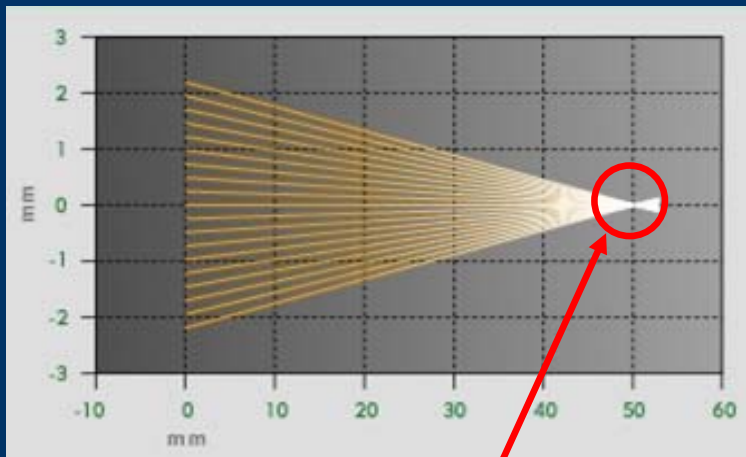
# Wavefront Coding using Cubic Phase Plate



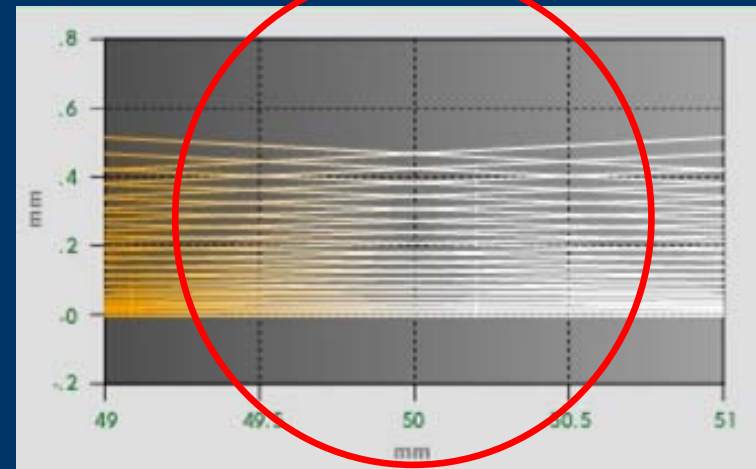
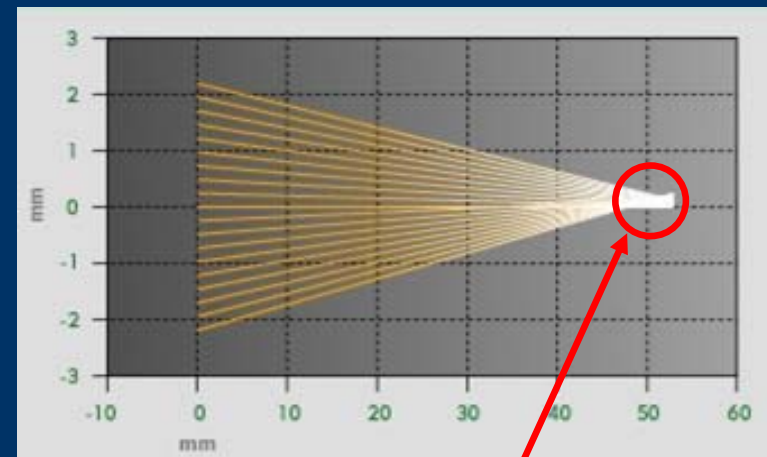
*"Wavefront Coding: jointly optimized optical and digital imaging systems",  
E. Dowski, R. H. Cormack and S. D. Sarama,  
Aerosense Conference, April 25, 2000*

# Depth Invariant Blur

## Conventional System



## Wavefront Coded System



# Decoding depth via defocus blur

- Design PSF that changes quickly through focus so that defocus can be easily estimated
- Implementation using phase diffractive mask

(Sig 2008, Levin et al used amplitude mask)

Phase mask

Image removed due to copyright restrictions.

Typical PSF changes slowly

Images removed due to copyright restrictions.

Designed PSF changes fast

Images removed due to copyright restrictions.



# Rotational PSF

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Images removed due to copyright restrictions.  
Two sequences showing rotating and standard PSF.

R. Piestun, Y. Schechner, J. Shamir, "Propagation-Invariant Wave Fields with Finite Energy," JOSA A 17, 294-303 (2000)

R. Piestun, J. Shamir, "Generalized propagation invariant wave-fields," JOSA A 15, 3039 (1998)

# Single Pixel Camera

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MAS.531 / MAS.131 Computational Camera and Photography  
Fall 2009

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