

# Near-Invariant Blur for Depth and 2D Motion via Time-Varying Light Field Analysis

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Yosuke Bando<sup>1,2</sup>

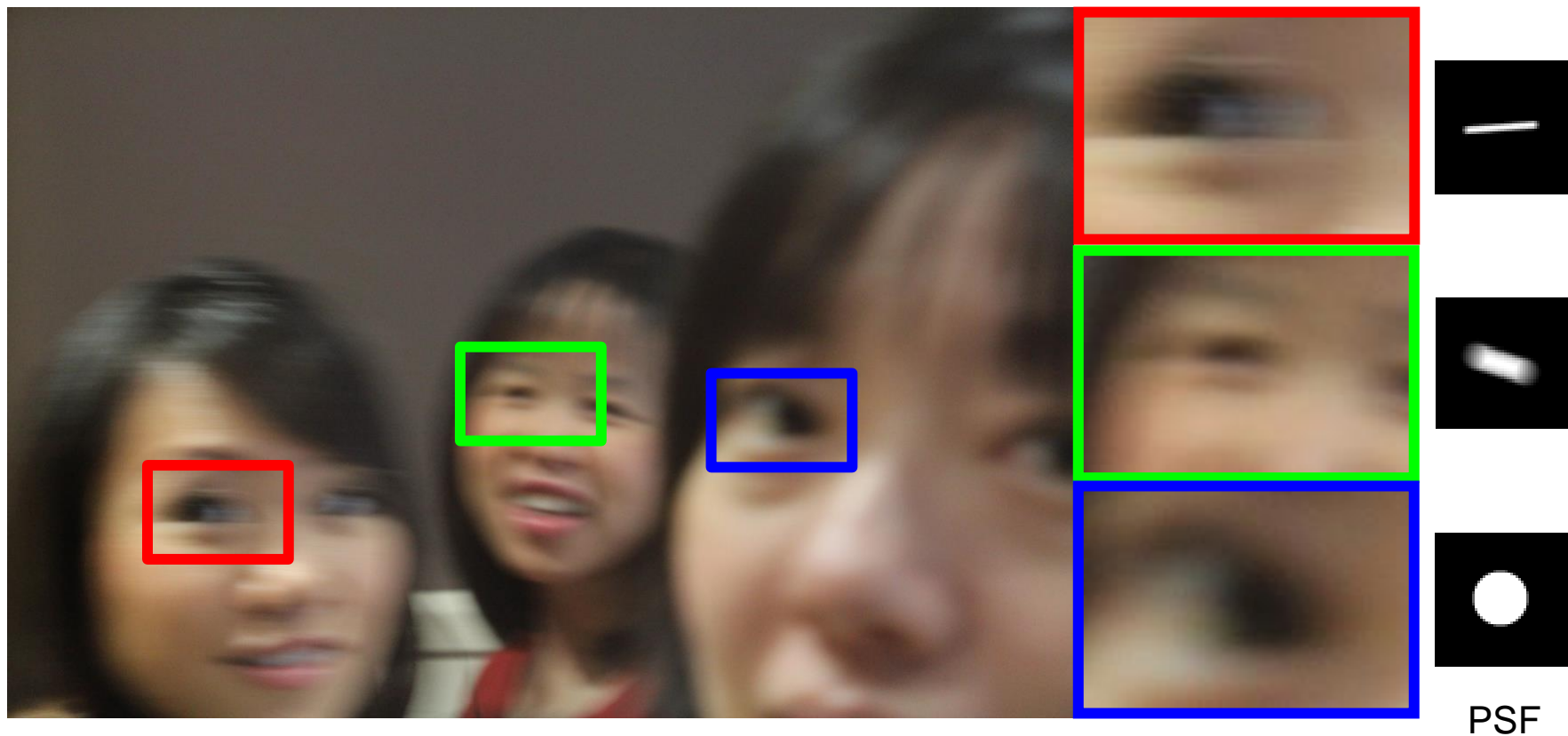
Henry Holtzman<sup>2</sup>

Ramesh Raskar<sup>2</sup>

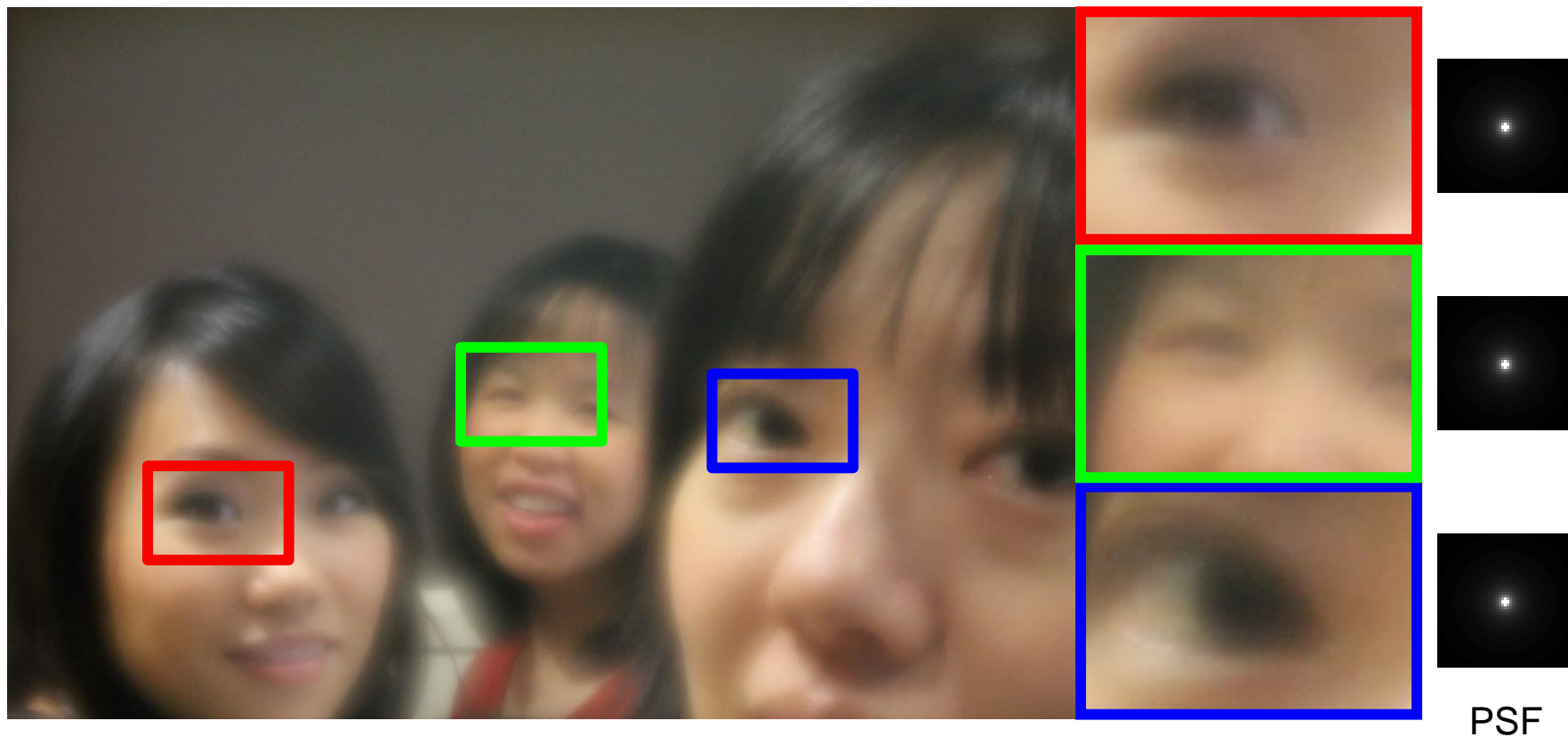
<sup>1</sup>Toshiba Corporation

<sup>2</sup>MIT Media Lab

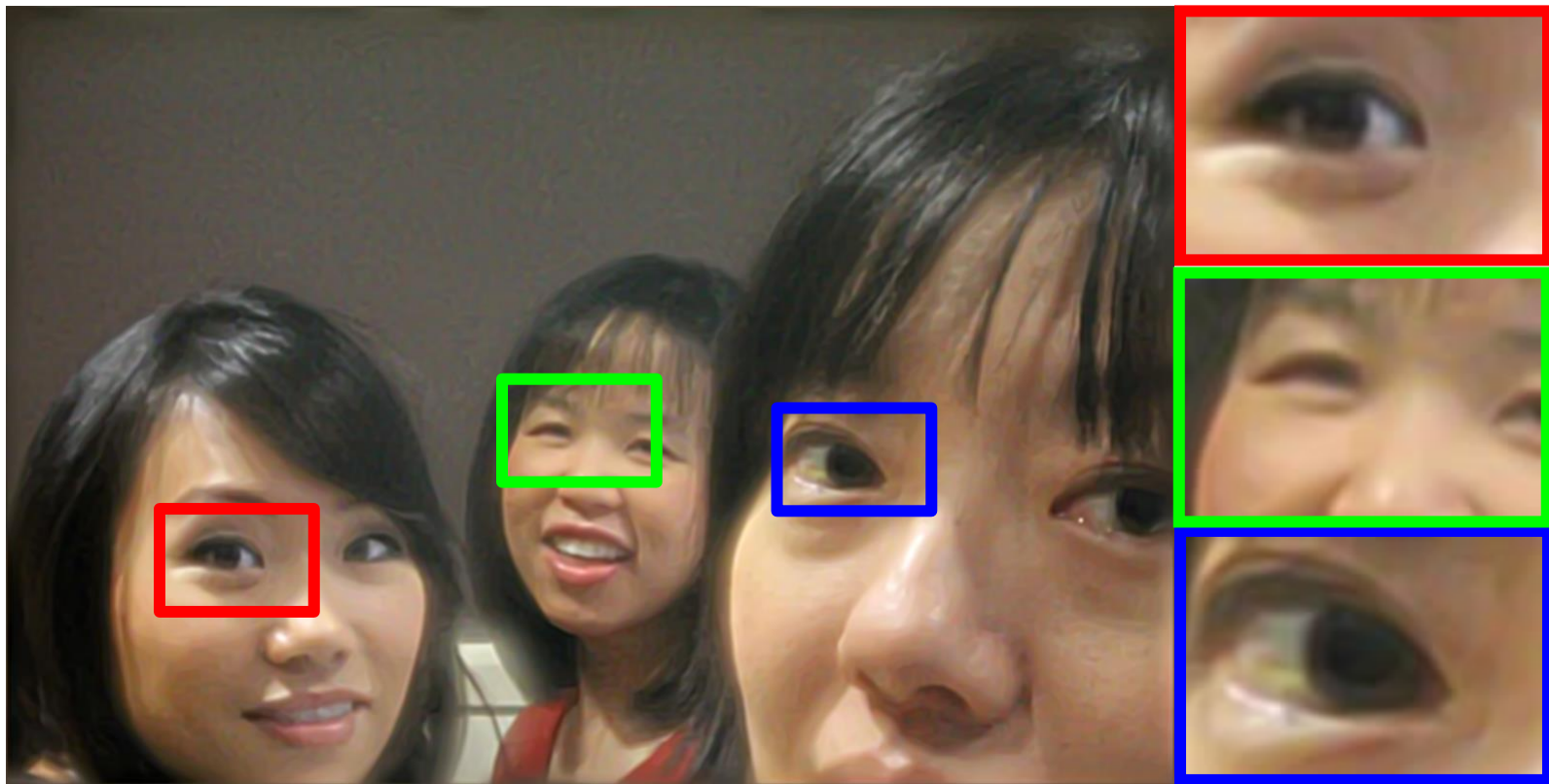
# Defocus & Motion Blur



# Depth and Motion-Invariant Capture



# Deblurring Result



# Outline

- Motivation
- Related Work
- Intuitions
- Analysis
- Results
- Conclusions

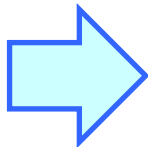
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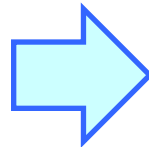
# Joint Defocus & Motion Deblurring

Standard approach

Image  
capture



Local blur  
estimation



Non-uniform  
deblurring



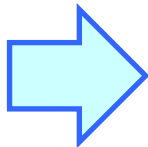
**Extremely difficult**

- Estimate depth and motion from a single image
- Recover lost high-frequency content

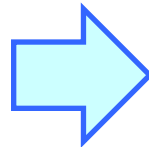
# Joint Defocus & Motion Deblurring

## Standard approach

Image capture



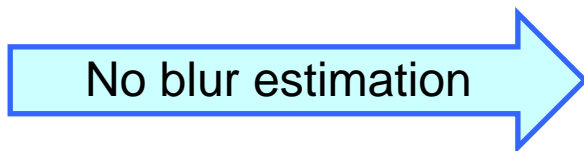
Local blur estimation



Non-uniform deblurring

## Proposed approach

Depth and 2D motion-invariant image capture



**Uniform**  
deconvolution

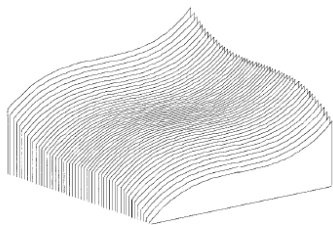
**Well-studied problem**



# Outline

- Motivation
- **Related Work**
- Intuitions
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# Depth-Invariant Capture



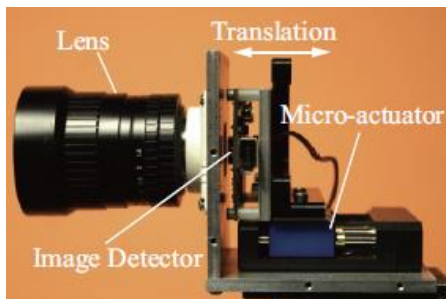
## Wavefront coding

[Dowski and Cathey 1995]



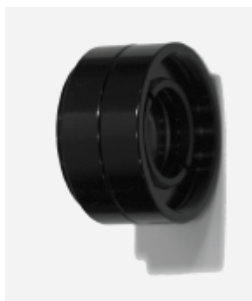
## Diffusion coding

[Cossairt et al. 2010]



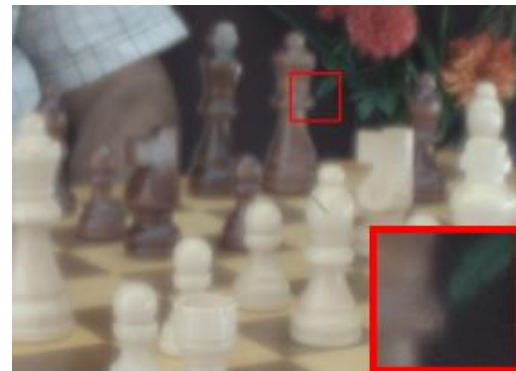
## Focus sweep

[Hausler 1972;  
Nagahara et al. 2008]



## Spectral focus sweep

[Cossairt and Nayar 2010]



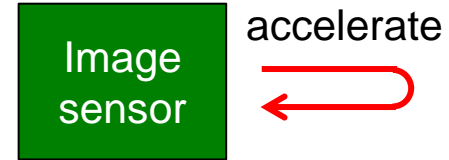
Depth-invariant image



Deblurred

# 1D Motion-Invariant Capture

- Invariant to object speed
- Motion direction must be fixed
  - Horizontal, for example



[Levin et al. 2008]



Normal camera



Motion-invariant image



Deblurred

# Computational Cameras for Deblurring

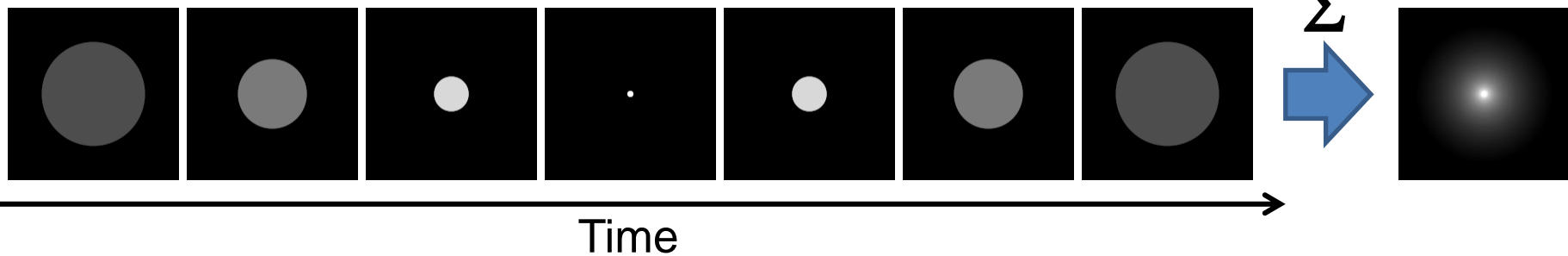
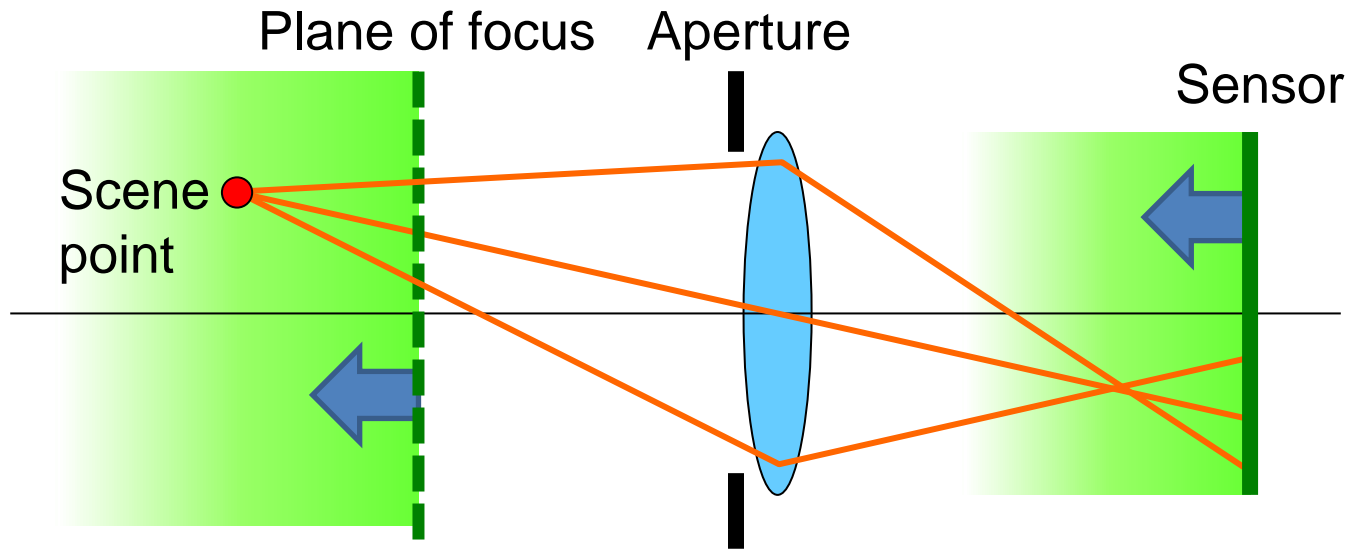
	Defocus deblurring	Motion deblurring
H p (r	No joint defocus and motion deblurring	
	No 2D motion-invariant capture	
Invariant capture	<b>Wavefront coding</b> [Dowski and Cathey 1995] <b>Focus sweep</b> [Hausler 1972; Nagahara et al. 2008] <b>Diffusion coding</b> [Cossairt et al. 2010] <b>Spectral focus sweep</b> [Cossairt and Nayar 2010]	<b>Motion-invariant photography</b> (for 1D motion) [Levin et al. 2008]

Also nearly  
2D motion-invariant

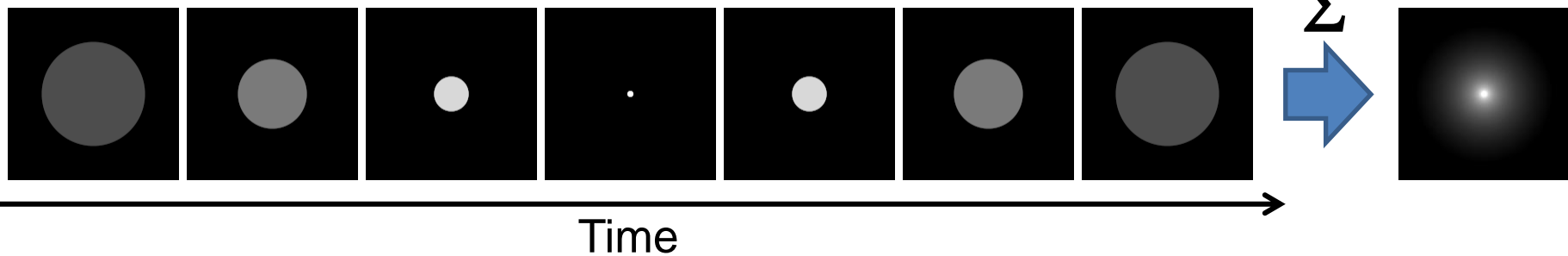
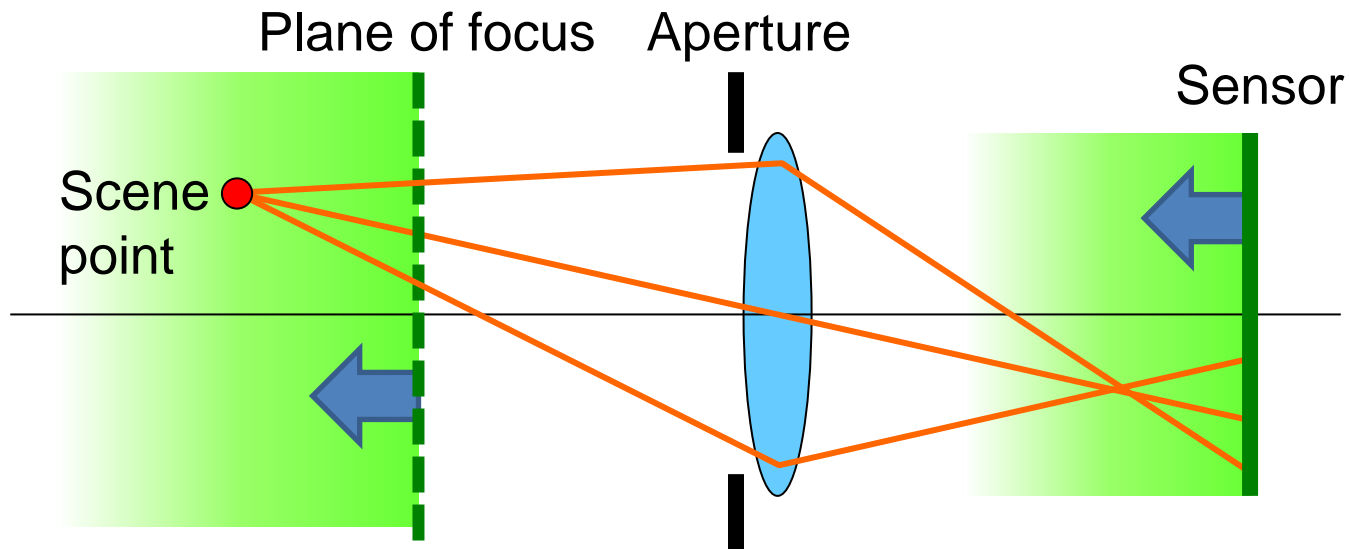
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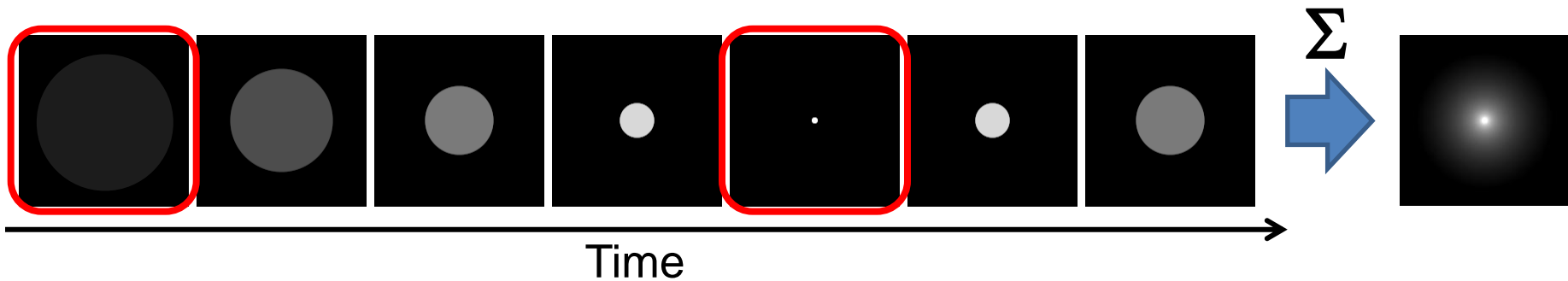
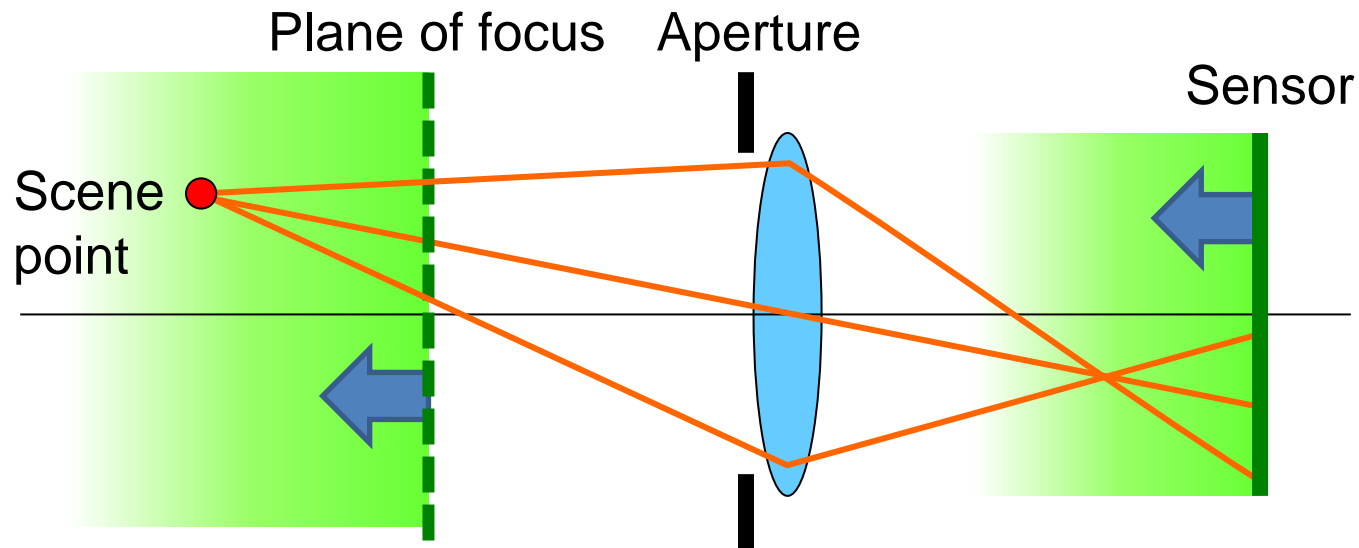
# Depth-Invariance for Static Point



# Depth-Invariance for Static Point

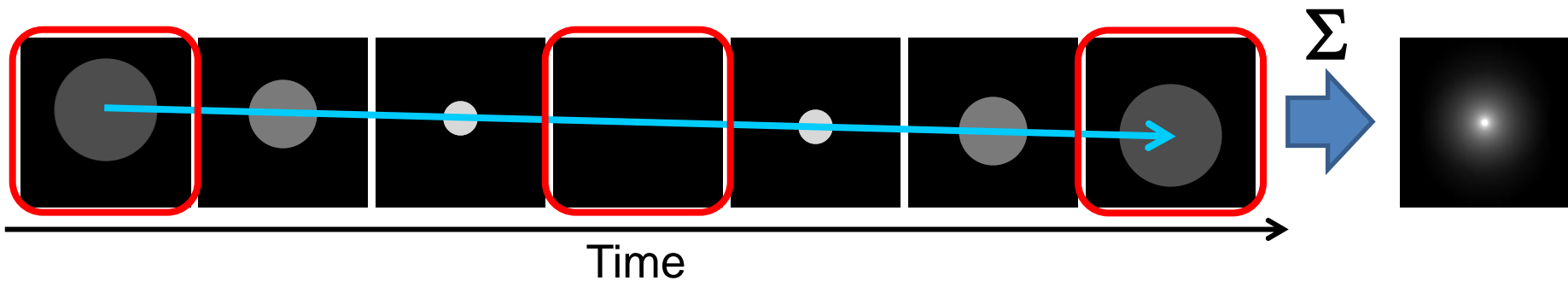
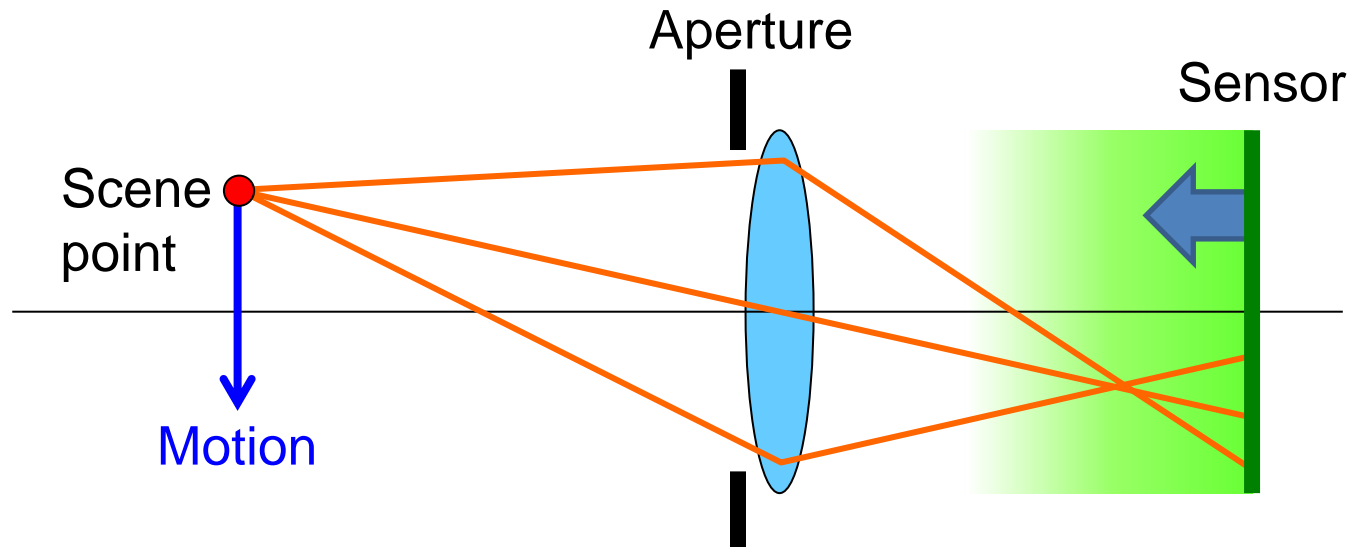


# Depth-Invariance for Static Point





# Motion-Invariance for Moving Point



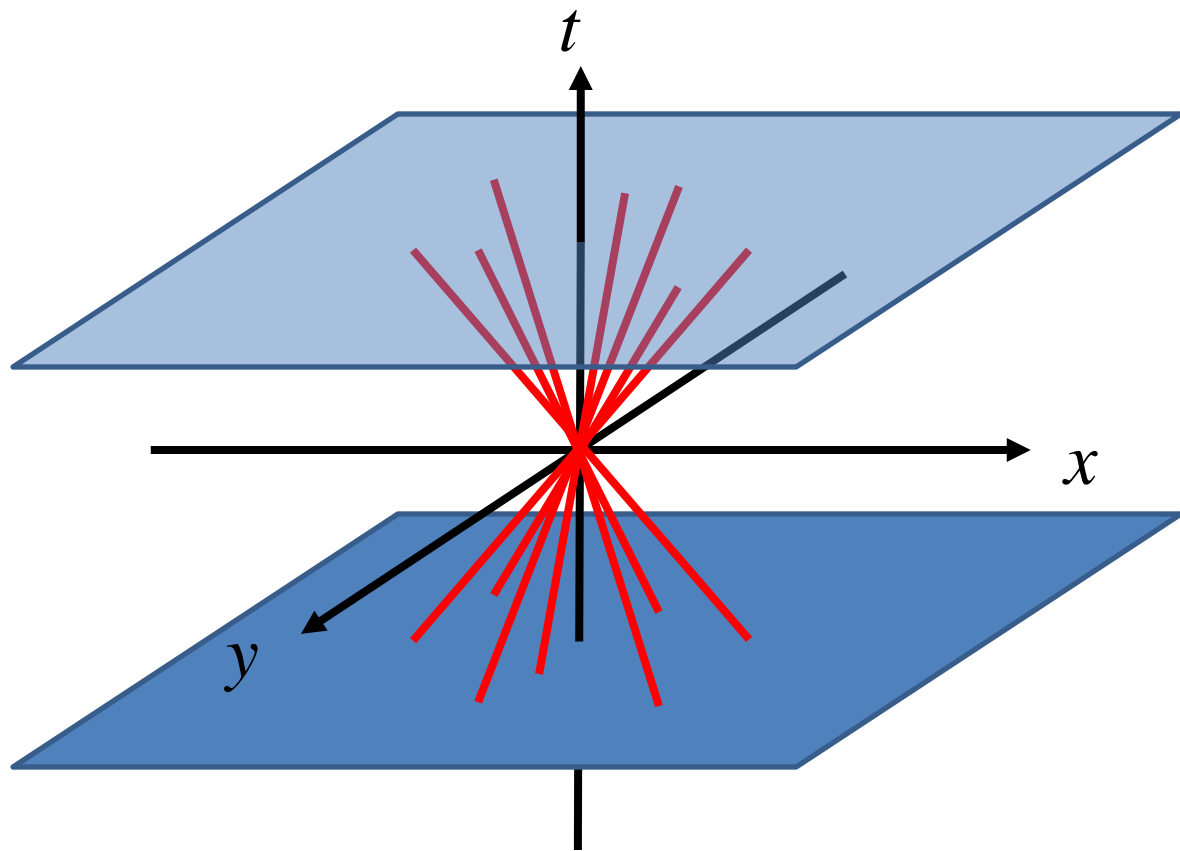
# Follow Shot



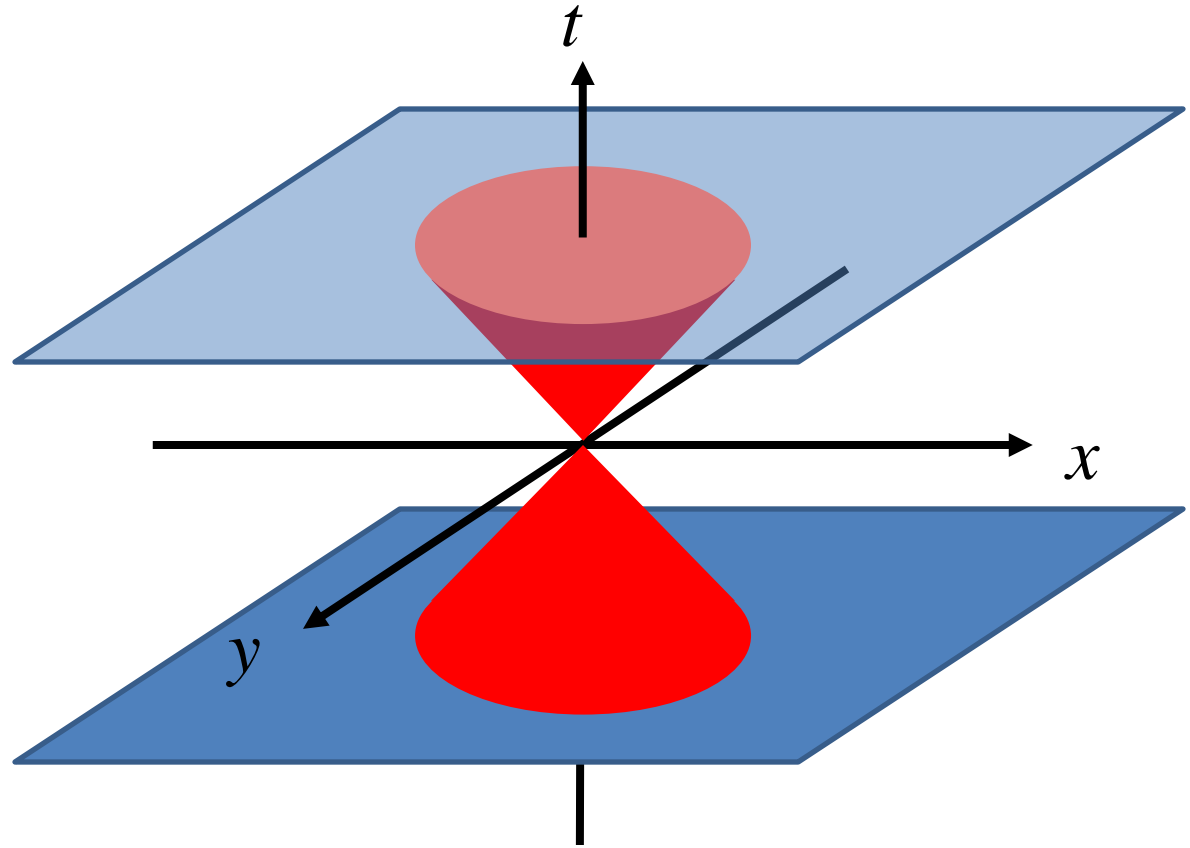
[http://commons.wikimedia.org/wiki/File:Bruno\\_Senna\\_2006\\_Australian\\_Grand\\_Prix-3.jpg](http://commons.wikimedia.org/wiki/File:Bruno_Senna_2006_Australian_Grand_Prix-3.jpg)



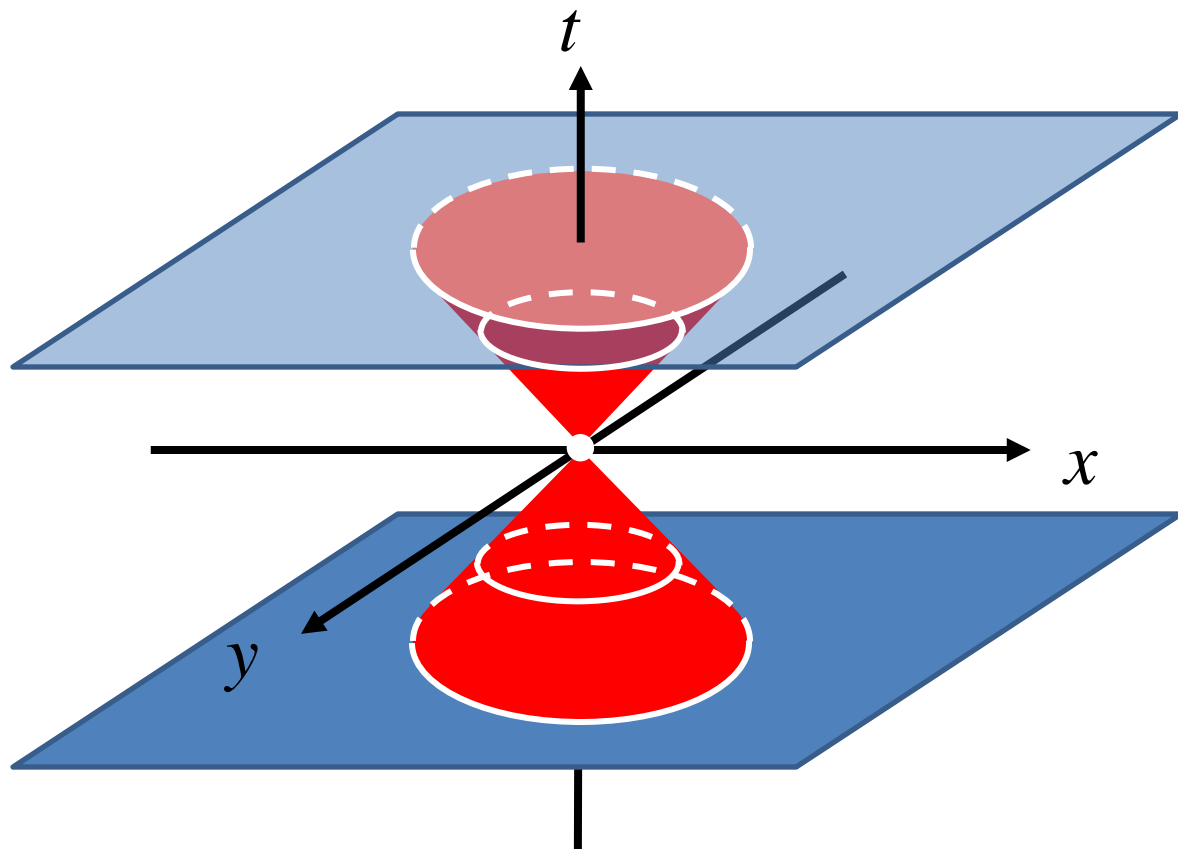
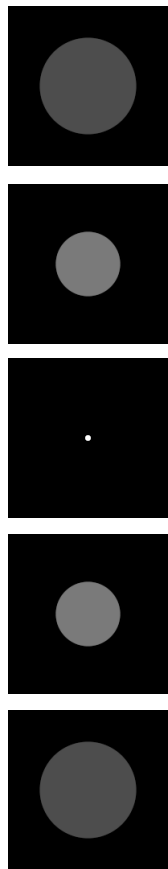
# Follow Shots for Various Motions



# Follow Shots for Various Motions



# Follow Shots for Various Motions



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# Analysis

- Photo is a projection of a light field [Ng 2005]

$$D(\mathbf{x}_0) = \iint k(\mathbf{x}_0 - \mathbf{x}, -\mathbf{u}) \cdot l(\mathbf{x}, \mathbf{u}) d\mathbf{x}d\mathbf{u}$$

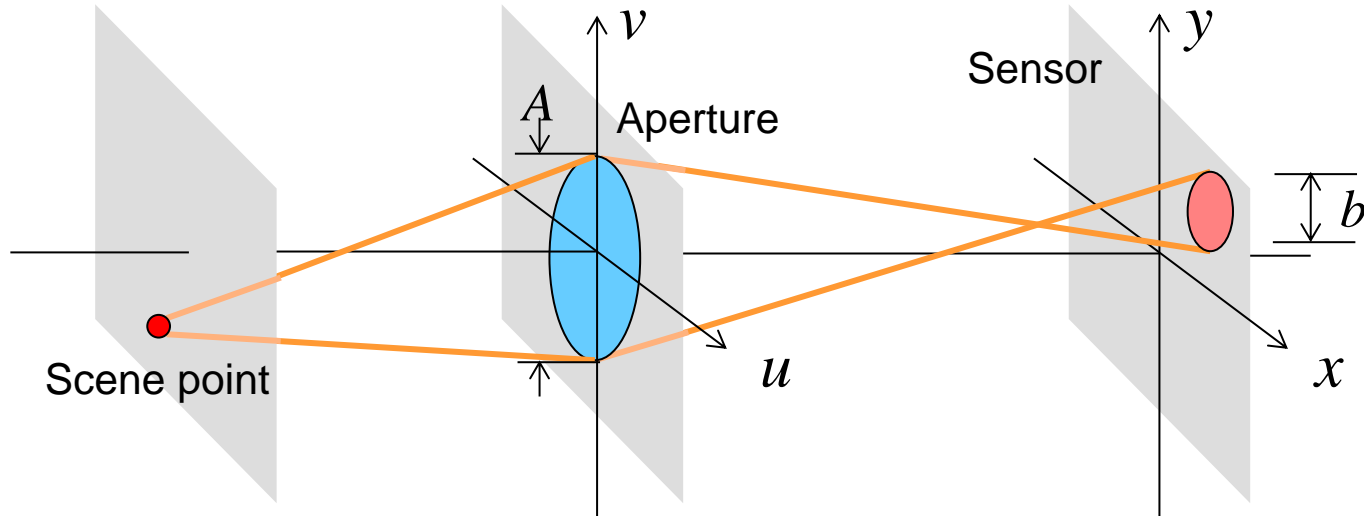
Defocus-blurred  
image

Light field  
kernel

Light field

$\mathbf{x} = (x, y)$

$\mathbf{u} = (u, v)$



# Analysis

- Photo is a projection of a **time-varying** light field

$$D(\mathbf{x}_0) = \iint k(\mathbf{x}_0 - \mathbf{x}, -\mathbf{u}) \cdot l(\mathbf{x}, \mathbf{u}) dxdu$$

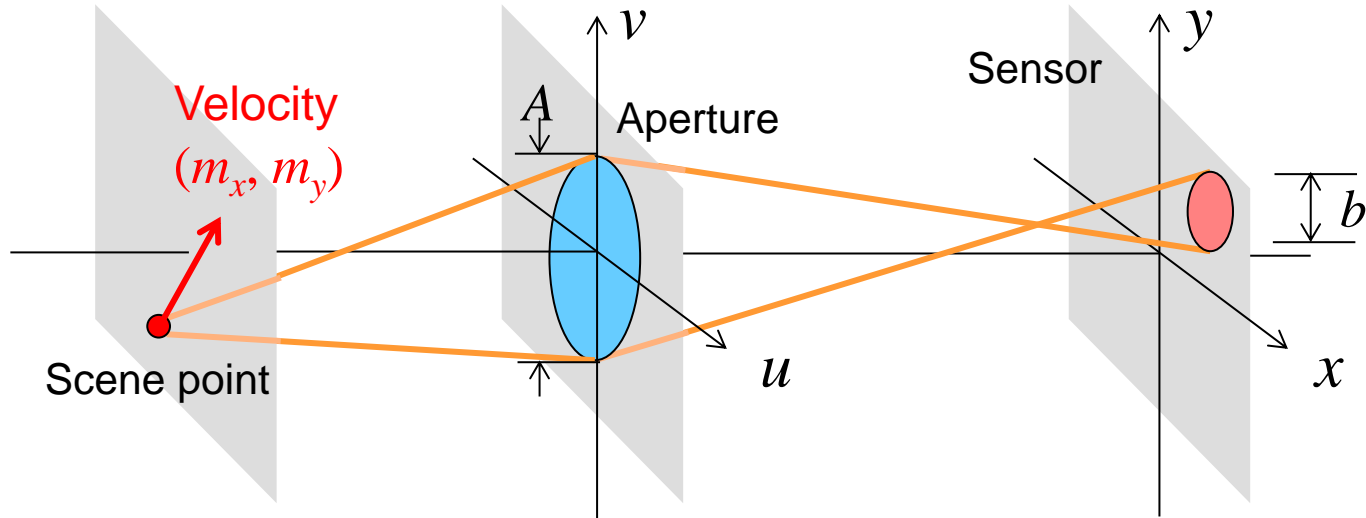
$$\mathbf{x} = (x, y)$$

$$\mathbf{u} = (u, v)$$

Defocus-blurred  
image

Light field  
kernel

Light field





# Analysis

- Photo is a projection of a **time-varying** light field

$$D(\mathbf{x}_0) = \iiint k(\mathbf{x}_0 - \mathbf{x}, -\mathbf{u}, -t) \cdot l(\mathbf{x}, \mathbf{u}, t) dx d\mathbf{u} dt$$

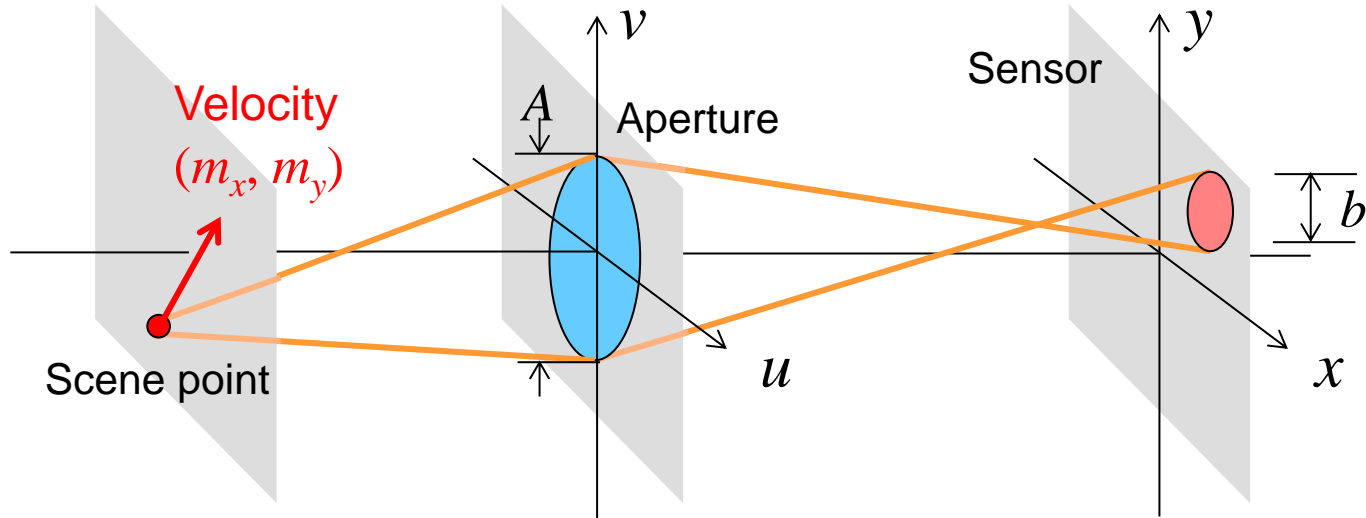
$$\mathbf{x} = (x, y)$$

$$\mathbf{u} = (u, v)$$

Defocus/motion-blurred image

Time-varying light field kernel

Time-varying light field



# Time-Varying Light Field Analysis

- Photo is a projection of a time-varying light field

$$D(\mathbf{x}_0) = \iiint k(\mathbf{x}_0 - \mathbf{x}, -\mathbf{u}, -t) \cdot l(\mathbf{x}, \mathbf{u}, t) dxdu dt \quad \begin{array}{l} \mathbf{x} = (x, y) \\ \mathbf{u} = (u, v) \end{array}$$

Defocus/motion-blurred image

Time-varying light field kernel

Time-varying light field



Lambertian scene at depth  $s$  with velocity  $\mathbf{m} = (m_x, m_y)$

$$\phi_{s,\mathbf{m}}(\mathbf{x}) = \iint k(\mathbf{x} + s\mathbf{u} + \mathbf{m}t, \mathbf{u}, t) du dt$$

Joint defocus & motion blur PSF



Magnitude of 2D Fourier transform

$$|\hat{\phi}_{s,\mathbf{m}}(\mathbf{f}_x)|^2 = |\hat{k}(\mathbf{f}_x, -s\mathbf{f}_x, -\mathbf{m} \cdot \mathbf{f}_x)|^2$$

Modulation transfer function (MTF)

# Analysis Procedure and Findings

- For each existing computational camera for deblurring
  - 1. derive a kernel equation describing the optical system
  - 2. calculate its Fourier transform to obtain the MTF
  - 3. compare it with the theoretical upper bounds

		3D kernel $k(\mathbf{x}, t)$		Emulated MTF		High freq. preserv.	MTF invariance
Camera design		High freq. preserv.		MTF invariance		$\hat{\phi}_m(\mathbf{f}_x)^2$	$\min  \hat{\phi}_m ^2 / \max  \hat{\phi}_m ^2$
$\mathbf{x} = (x, y)$ Spatial View $\mathbf{u} = (u, v)$ Time Scene $t$ Scene Object $s$ $\mathbf{m} = (m_x, m_y)$ Object Spatial $\mathbf{f}_x = (f_x, f_y)$	Camera design	$\min_{s, \mathbf{m}}  \hat{\phi}_{s, \mathbf{m}}(\mathbf{f}_x) ^2$		$\min  \hat{\phi}_{s, \mathbf{m}} ^2 / \max  \hat{\phi}_{s, \mathbf{m}} ^2$		1	1
Upper bound	Upper bound	$\frac{2A^3T}{3SM \mathbf{f}_x ^2}$		1		1	1
Standard lens	Narrow aperture	Focus sweep		$\frac{2A^3T}{3\sqrt{3}SM \mathbf{f}_x ^2}$		$\frac{2}{3}$	$\frac{2}{3}$
Coded aperture	$\sum_j \{\delta(\mathbf{x} - s_j)\}$	$\frac{A^2}{(sT)^2} \sum_j \{\delta(\mathbf{x} - s_j)\}$	$\frac{A^2}{s^2  f_x ^2}$	$\frac{A^2}{s^2  f_x ^2}$	1	1	1
Lattice-focal lens	$\sum_j \{\delta(\mathbf{x} - s_j)\}$	$\frac{A^2}{(sT)^2} \sum_j \{\delta(\mathbf{x} - s_j)\}$	$\frac{A^2}{s^2  f_x ^2}$	$\frac{A^2}{s^2  f_x ^2}$	1	1	1
Wavefront coding	$\delta(\mathbf{x} - (au^2, av^2))$	$\frac{A^2}{s^2  f_x ^2}$	$\frac{A^2}{s^2  f_x ^2}$	$\frac{A^2}{s^2  f_x ^2}$	1	1	1
Static focus sweep	$\frac{1}{2} \int_{-s/2}^{s/2} \{\delta(\mathbf{x} - s\mathbf{u})\} R( \mathbf{u} /A) ds$	$\frac{A^2}{s^2  f_x ^2}$	$\frac{A^2}{s^2  f_x ^2}$	$\frac{A^2}{s^2  f_x ^2}$	1	1	1

		3D kernel $k(\mathbf{x}, t)$		Emulated MTF		High freq. preserv.	MTF invariance
Camera design		High freq. preserv.		MTF invariance		$\hat{\phi}_m(\mathbf{f}_x)^2$	$\min  \hat{\phi}_m ^2 / \max  \hat{\phi}_m ^2$
Integration surface	Integration window	$\int_{\mathcal{S}} \int_{\mathcal{W}} \delta(\mathbf{x} - s\mathbf{u}) R( \mathbf{u} /A) R(t/T) dt$		$ \hat{k}(\mathbf{f}_x, -s\mathbf{f}_x, -\mathbf{m} \cdot \mathbf{f}_x) ^2$		$\min_{s, \mathbf{m}}  \hat{\phi}_{s, \mathbf{m}}(\mathbf{f}_x) ^2$	$\min  \hat{\phi}_s ^2 / \max  \hat{\phi}_s ^2$
Upper bound	Upper bound	$\frac{2A^3T}{3SM \mathbf{f}_x ^2}$		1		1	1
Combination of existing designs	Combination of existing designs	$k_a(\mathbf{x}, \mathbf{u}) * k_b(\mathbf{x}, \mathbf{u})$		$ \hat{k}(\mathbf{f}_x) ^2 \cdot  \hat{\phi}_m(\mathbf{f}_x) ^2$		$\min_s  \hat{\phi}_s ^2$	$(\min  \hat{\phi}_s ^2 / \max  \hat{\phi}_s ^2) \cdot (\min  \hat{\phi}_m ^2 / \max  \hat{\phi}_m ^2)$
Focus sweep	Focus sweep	$\delta(\mathbf{x} - (tu))$		$\frac{A^3T}{s^2  f_x ^2}$		$\frac{2A^3T}{3\sqrt{3}SM \mathbf{f}_x ^2}$	$\frac{2}{3}$

58%

66%

Better than any other existing computational cameras for deblurring

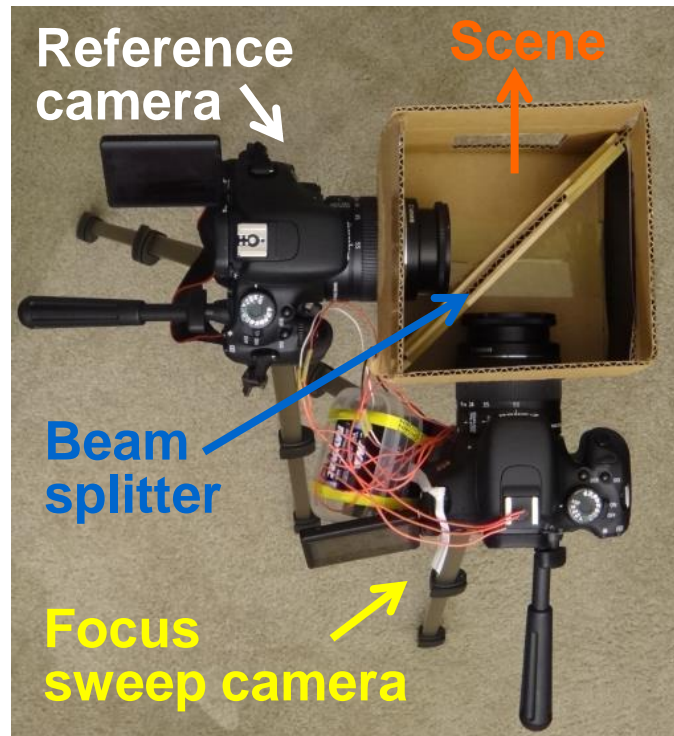
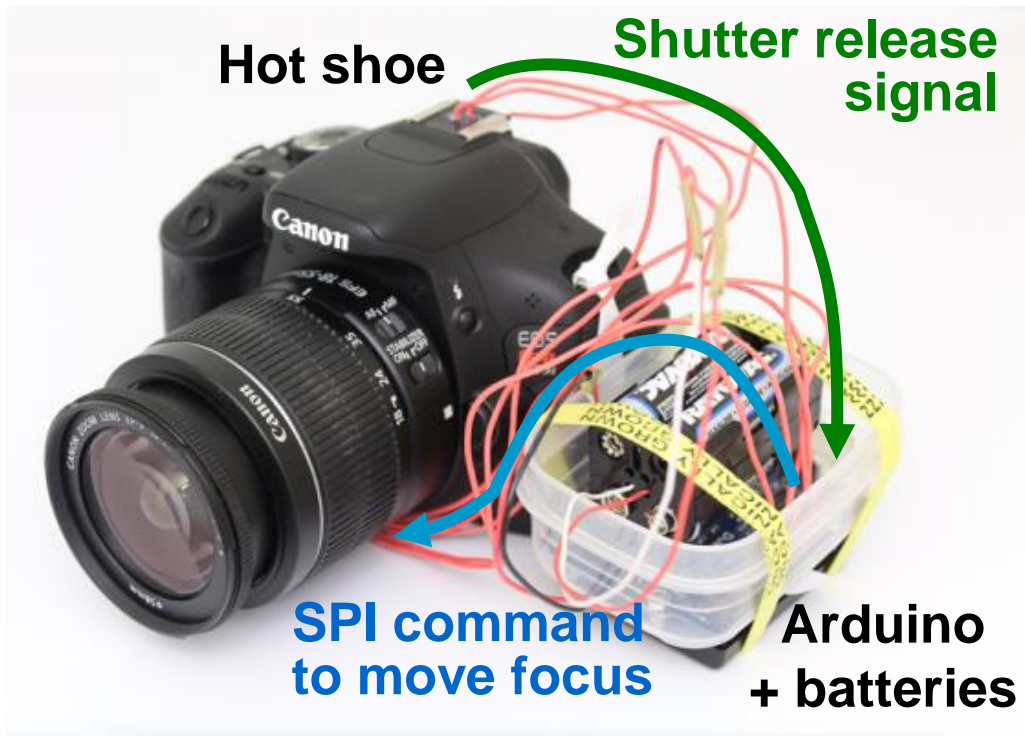
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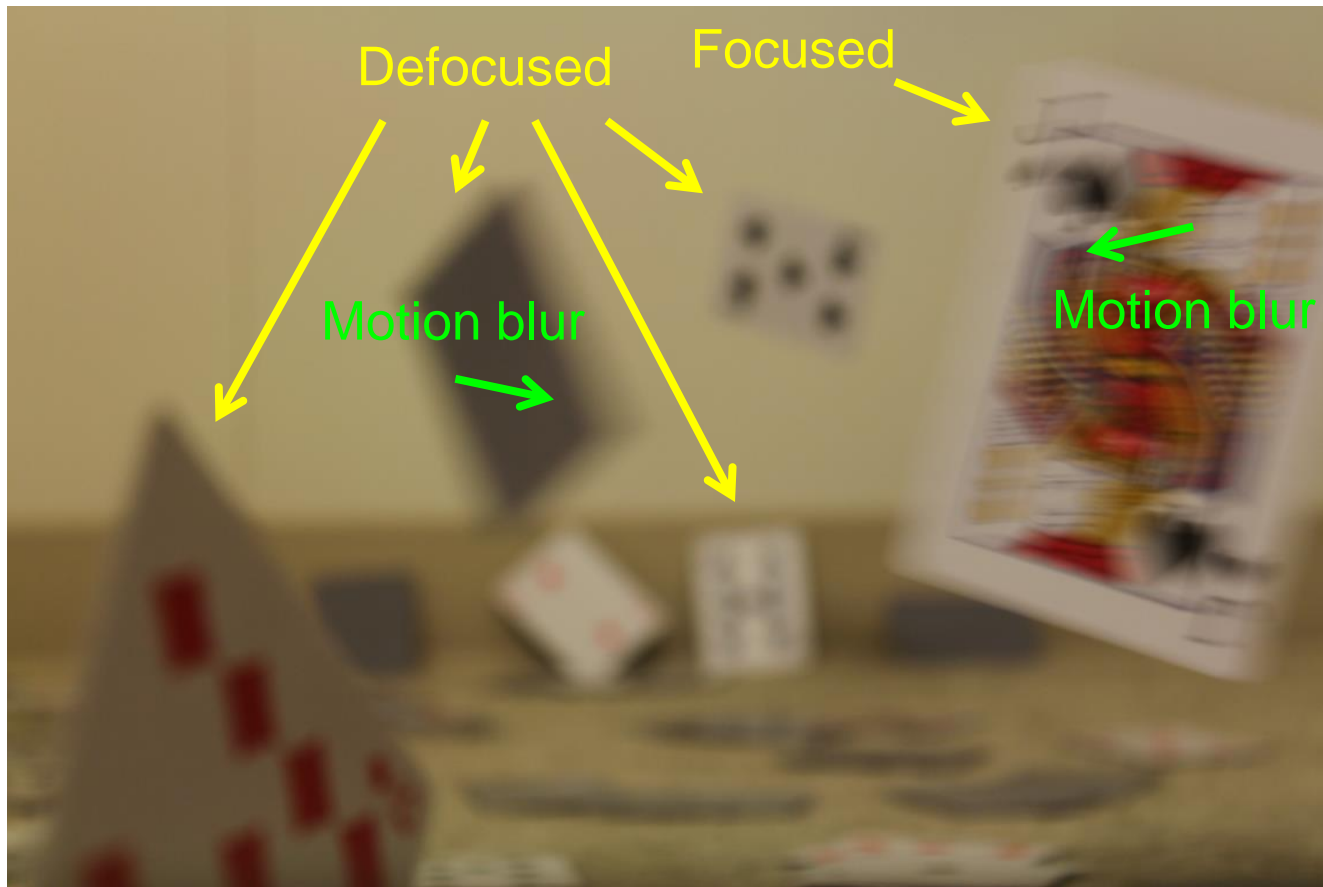
# Prototype Focus Sweep Camera



# Prototype Camera & Setup



# Normal Camera Image



# Focus Sweep Image





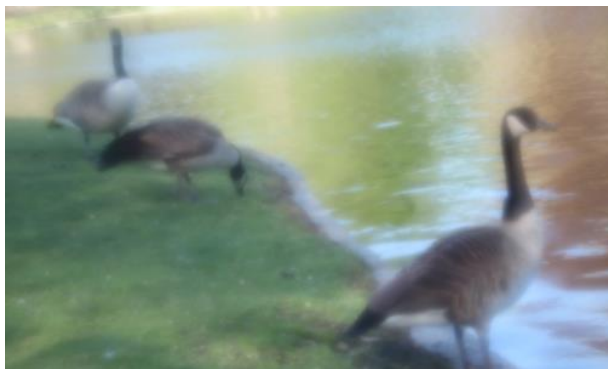
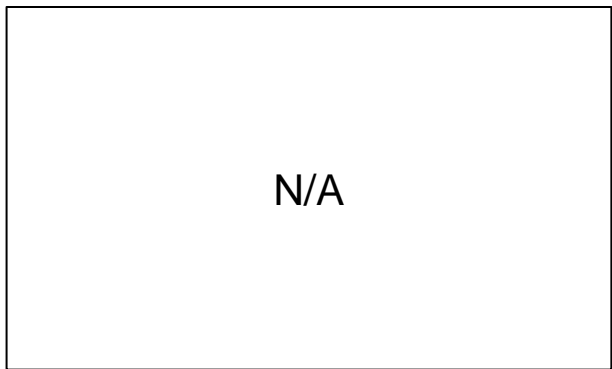
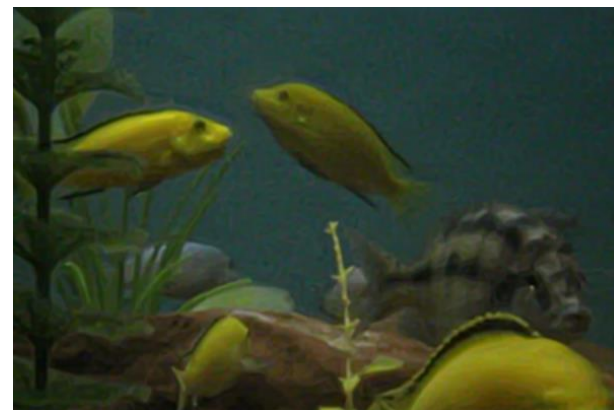
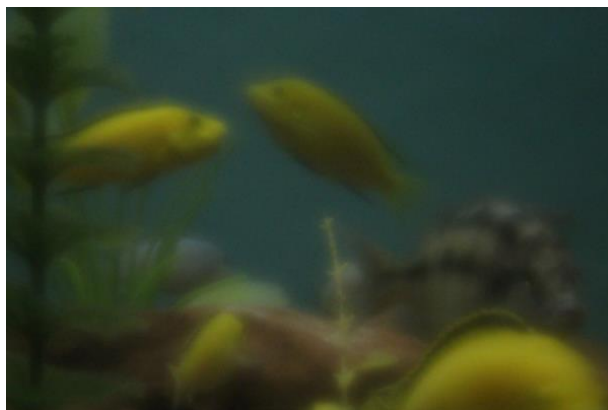
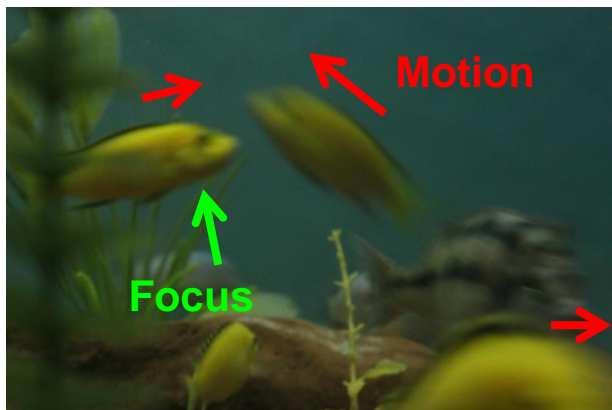
# Deconvolution Result



# Short Exposure Narrow Aperture Image



# More Examples



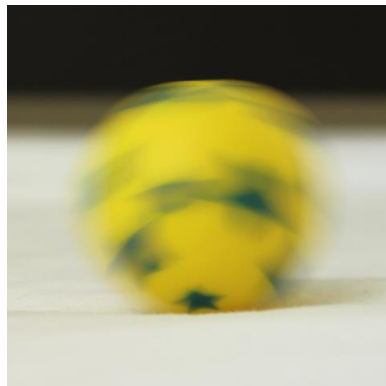
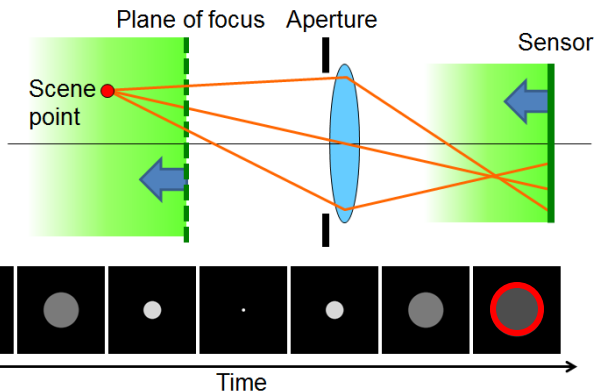
Standard camera

Focus sweep

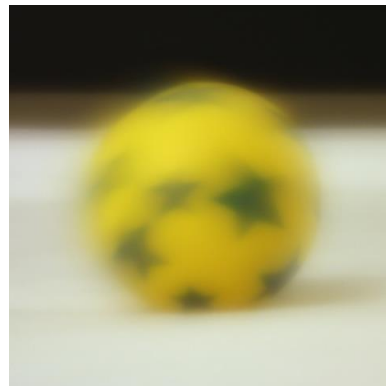
Deconvolution results

# Limitations

- Object depth and speed ranges must be bounded
- Depth and speed ranges cannot be adjusted separately
- Object motion must be in-plane linear
- Camera shake cannot be handled



Standard camera

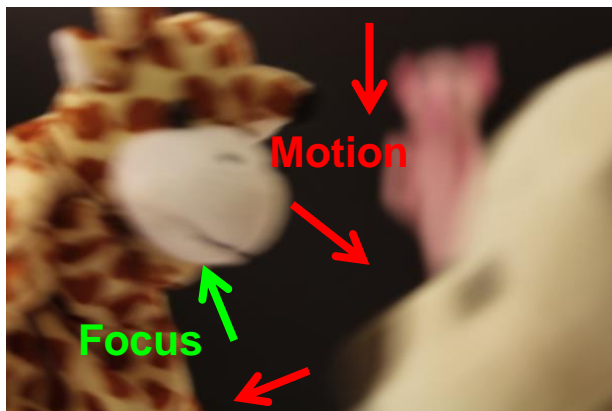
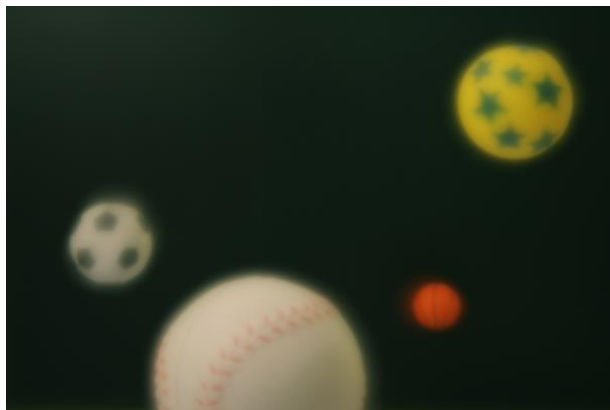
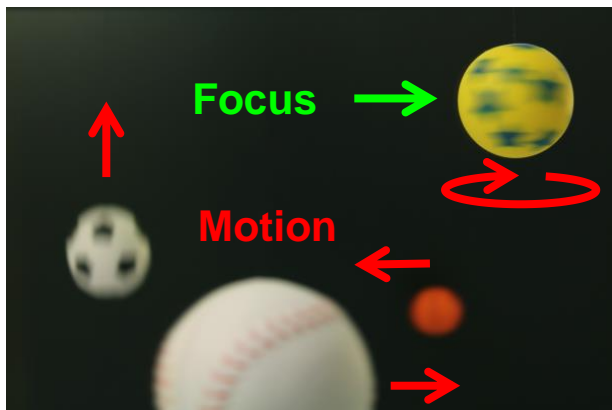


Focus sweep



Deconvolved

# Rotation & Z Motion



Standard camera

Focus sweep

Deconvolution results

# Summary

- Simple approach to joint defocus & motion deblurring
  - No need for estimating scene depth or motion
  - Also preserves high-frequency image content
  - Theoretically near-optimal
  - Has practical implementation (just firmware update)



Standard camera



Focus sweep



Deconvolution results



# Summary

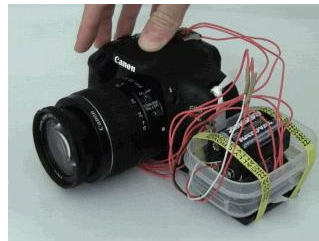
- Simple joint defocus & motion deblurring

- No depth or motion estimation
- Preserves high-frequency
- Theoretically near-optimal
- Practical implementation



- <http://www.media.mit.edu/~bandy/invariant/>

- How to control the lens
- How to achieve perfect invariance
  - Computational Cameras & Displays 2013



## Acknowledgments

- Yusuke Iguchi
- Noriko Kurachi
- Matthew Hirsch,
- Matthew O'Toole
- Douglas Lanman
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