Coding and Modulation in Cameras

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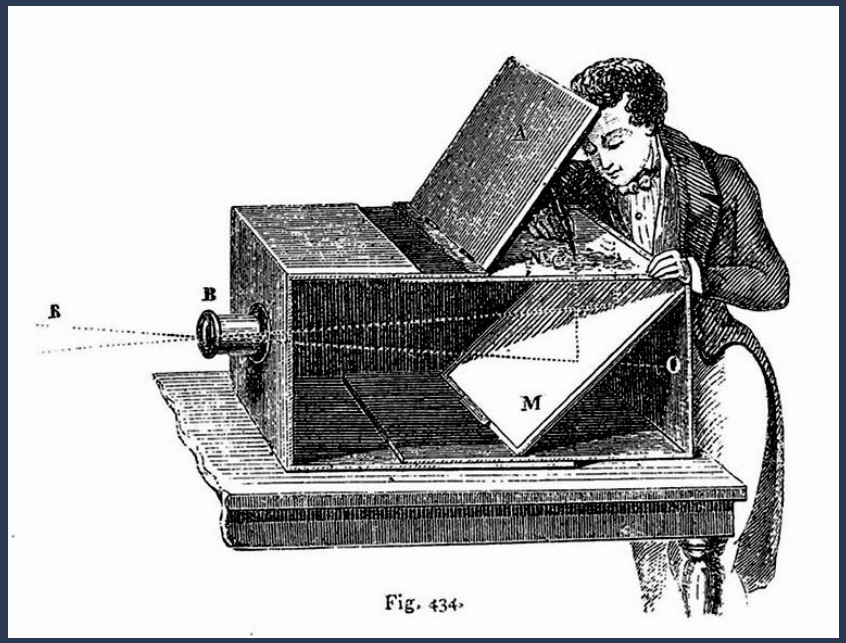
June 2010

Mitsubishi Electric Research Labs (MERL)
Cambridge, MA, USA

Schedule

Introduction	Srinivasa, 10 mins
Assorted Pixels	Srinivasa, 20 mins
Coding and Modulation in Cameras	Amit, 45 mins
Break	10 min
Light Fields and Applications	Ankit, 60 mins
Break	10 min
Computational Illumination	Srinivasa, 45 mins
Future Trends	Amit, 15 mins
Discussion	

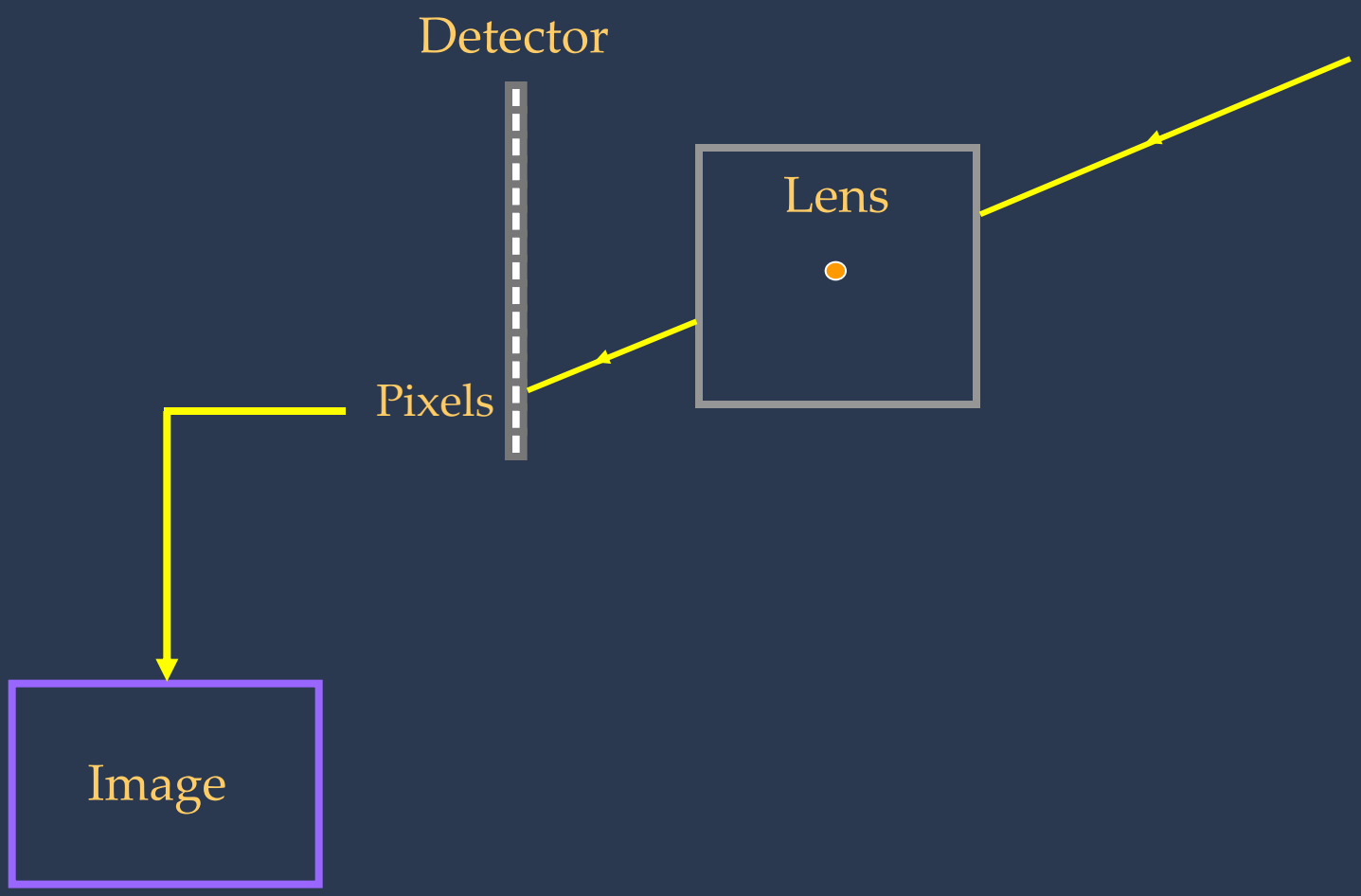
Have Cameras Evolved?



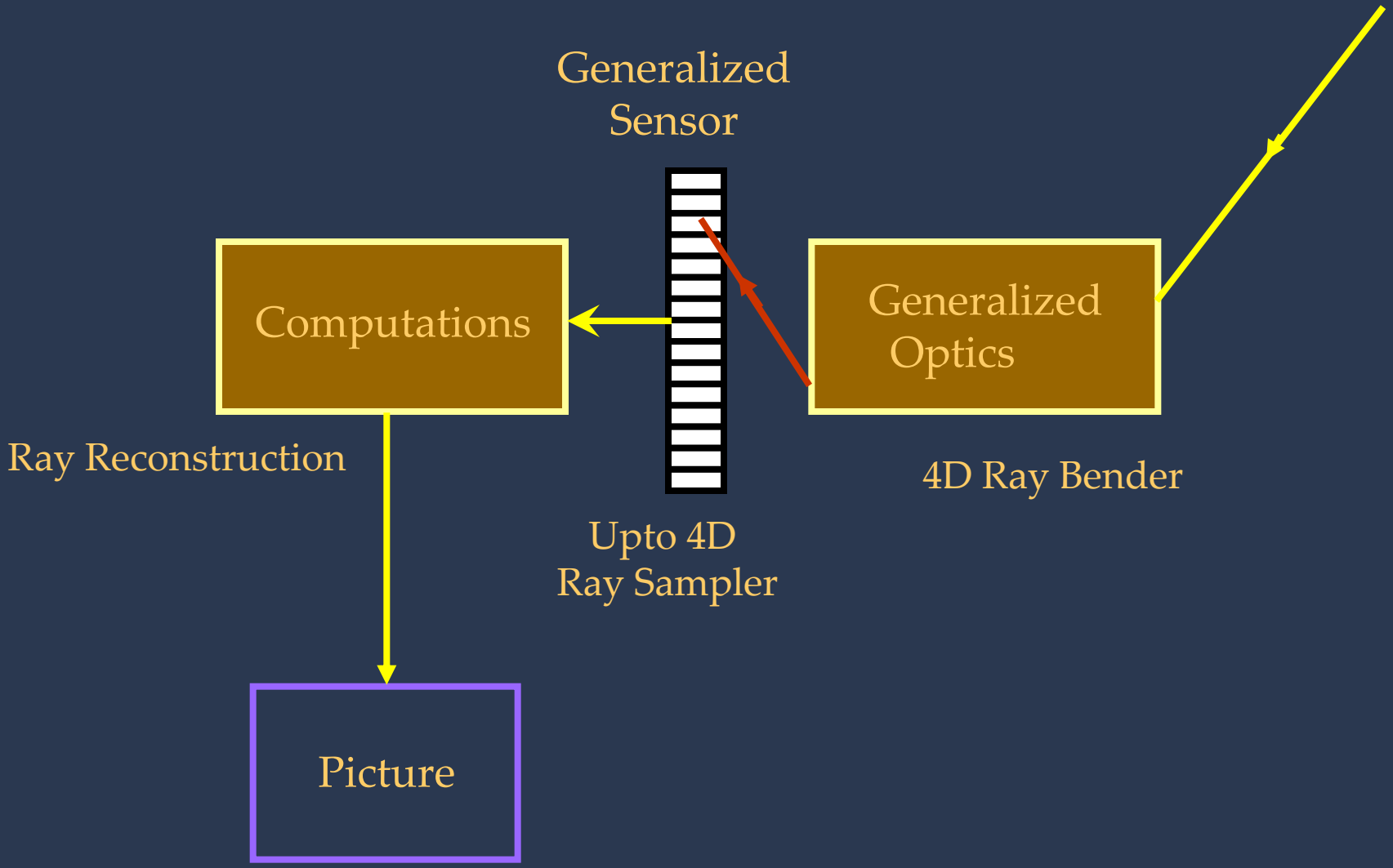
Lens Based Camera Obscura, 1568

Digital Cameras

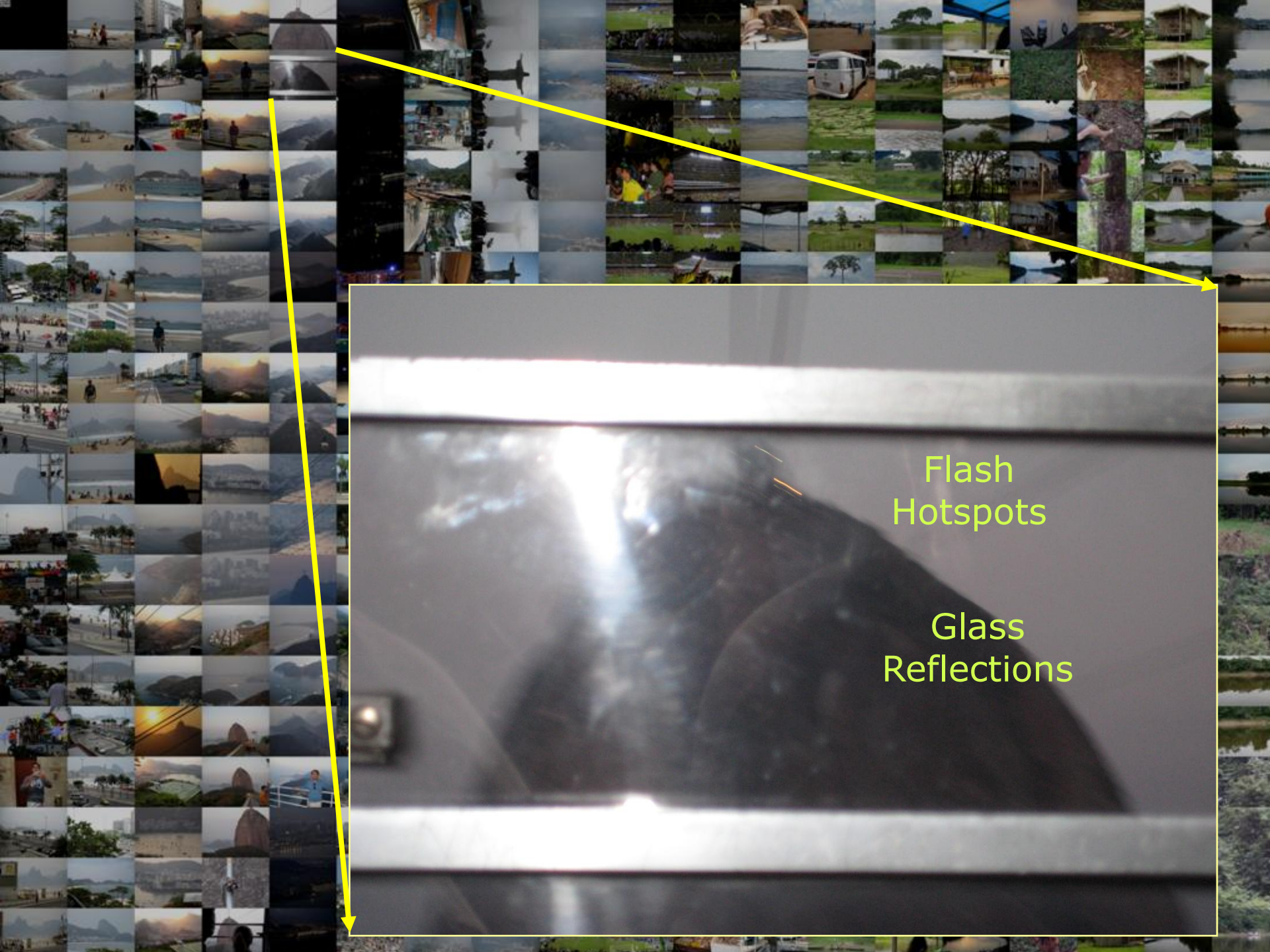
Traditional Photography



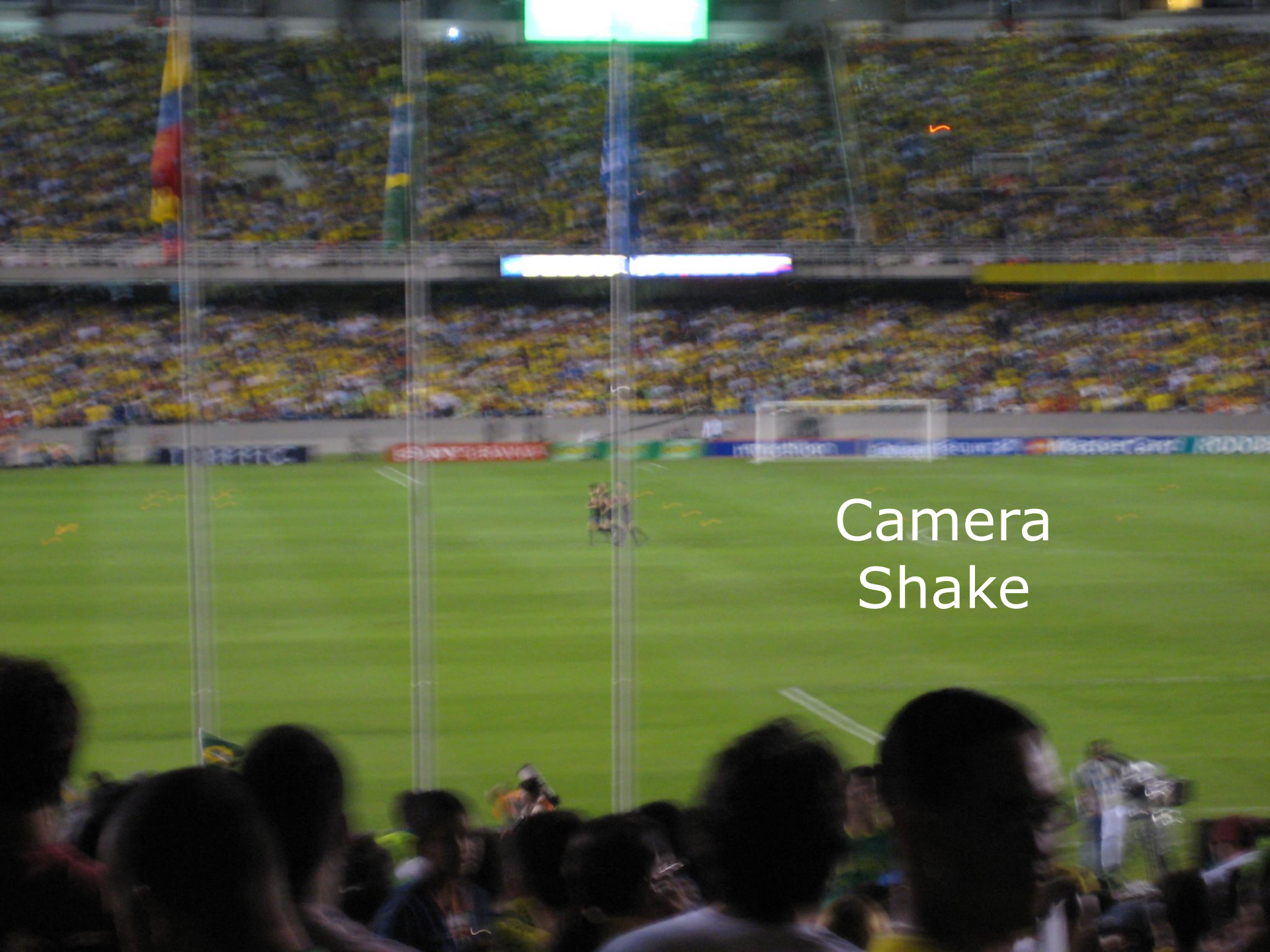
Computational Imaging:
Optics, Sensors and Computations



Slide Courtesy Ramesh Raskar


Flash
Hotspots
Glass
Reflections


Motion
Blur


Camera
Shake

High Dynamic Range

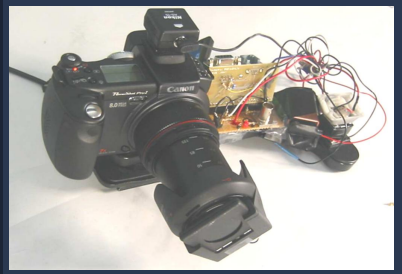

Out of
Focus

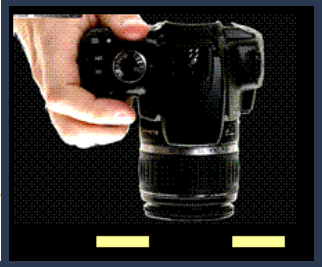
Fog, Haze, Bad Weather

Computational Imaging

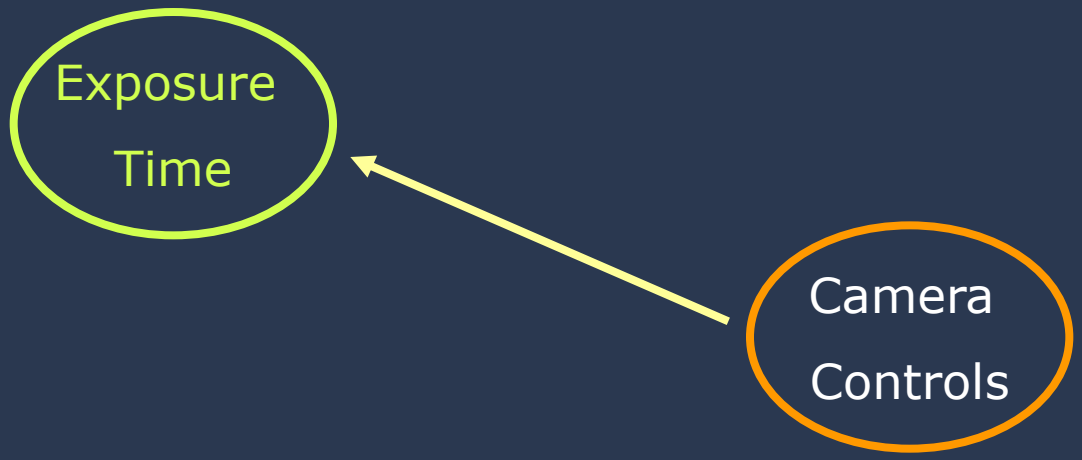
- Photo Manipulations
  - Two photos are better than one!!
  - Combine two+ photos
  - Change camera parameters

- Coding and Modulation
  - Capture relevant information
  - Decode in software





Two photos are better than one



Changing Exposure Time

- High dynamic range imaging
  - Mann and Picard, 95
  - Devebec and Malik, 97

Photo 1

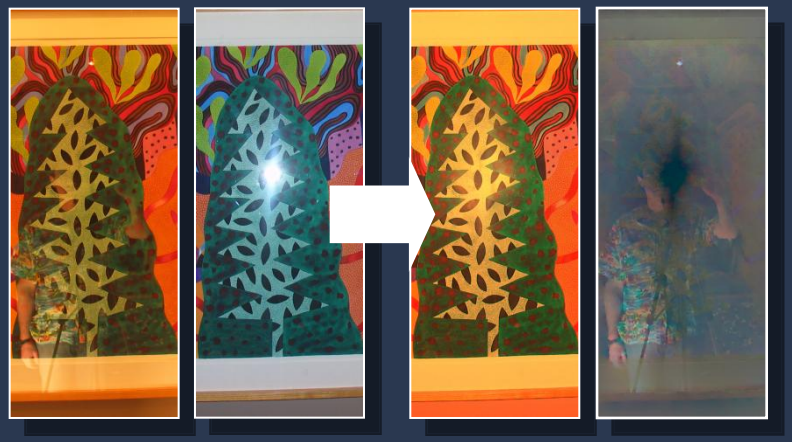
Photo 2

Photo 3

Epsilon Photography

- Dynamic Range
  - Multiple exposures
- Noise Reduction
  - Flash/No-flash images, Mutiple Images
- Motion Blur
  - Short + Long exposure
- Focus Blur
  - Focal Stack (Images focused at different depths)
- Spectrum
  - Visible + Near-IR
- Field of View
  - Panaromas
- Resolution
  - Multi-image super-resolution methods

Computational Imaging



- Photo Manipulations
  - Two photos are better than one!!
  - Combine two+ photos
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- Coding and Modulation
  - Capture relevant information
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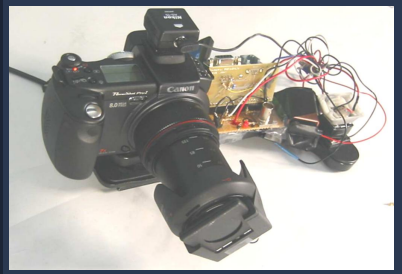
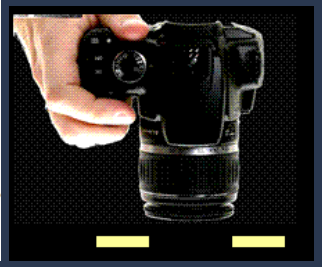
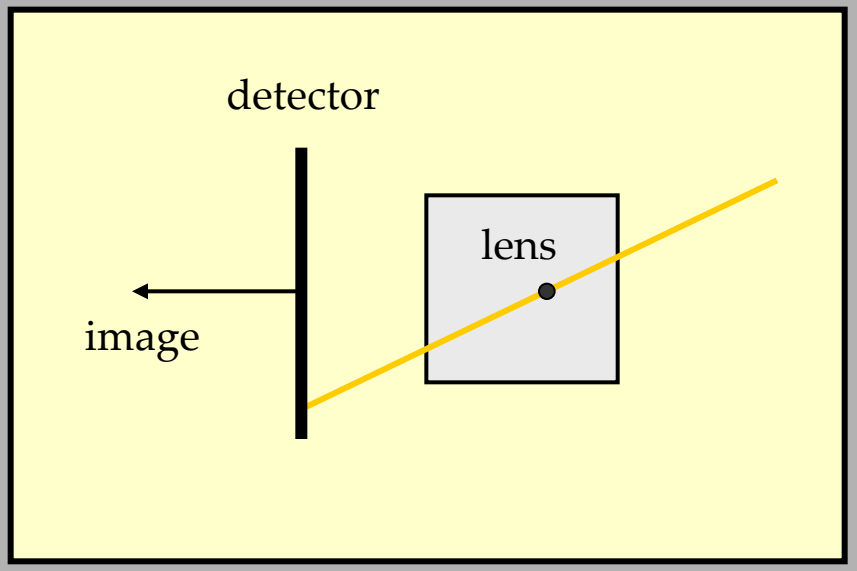
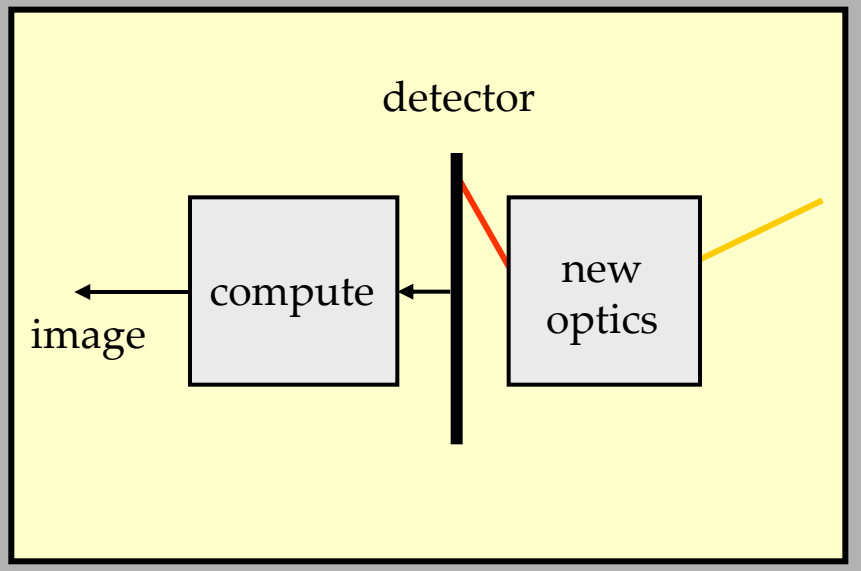






Traditional Camera



Computational Camera

Slide: Courtesy Shree Nayar

Computational Cameras

- Adaptive Dynamic Range Imaging, Nayar & Branzoi, ICCV 2003
- Omnidirectional Cameras, Gluckman & Nayar, ICCV 98
- Folded Catadioptric Cameras, Nayar & Peri, CVPR 99
- Catadioptric Imaging, Nayar 88
- Flexible Field of View, Kuthirummal & Nayar, 07
- Cata-Fisheye Camera for Panoramic Imaging," Krishnan & Nayar, 08
- Generalized Mosaicing, Schechner & Nayar, ICCV 01
- Motion Deblurring using Hybrid Imaging, Ben-Ezra & Nayar
- Jitter Camera, Ben-Ezra et al CVPR 04
- Programmable Imaging, Nayar et al 2004
- Single Lens Depth Camera, Gao & Ahuja, 2006
- Omnidirectional Stereo Vision System, Yi and Ahuja, 06
- Omnifocus Nonfrontal Imaging Camera, Aggarwal et al
- Split Aperture Imaging, Aggarwal and Ahuja, 2001
- Plenoptic Cameras, Adelson & Wang, Ng et al., Stanford
- Multi-Aperture Photography, Green et al. SIGGRAPH 07
- Coded Apertures, Wavefront Coding (CDM Optics)
- Assorted Pixels, Narasimhan & Nayar

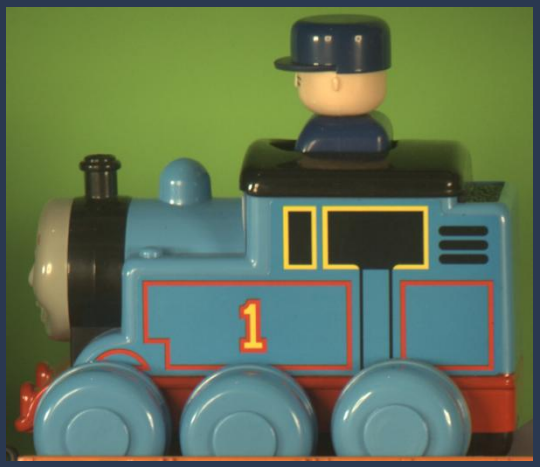
Coded Exposure [Raskar, Agrawal, Tumblin SIGGRAPH 2006]

Coded Exposure (Flutter Shutter) Camera

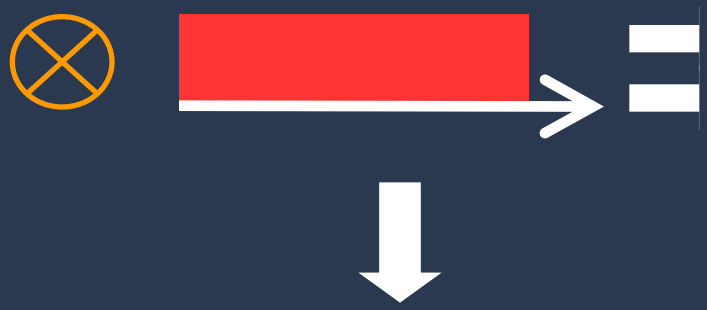
Raskar, Agrawal, Tumblin [Siggraph2006]

Coding in Time: Shutter is opened and closed

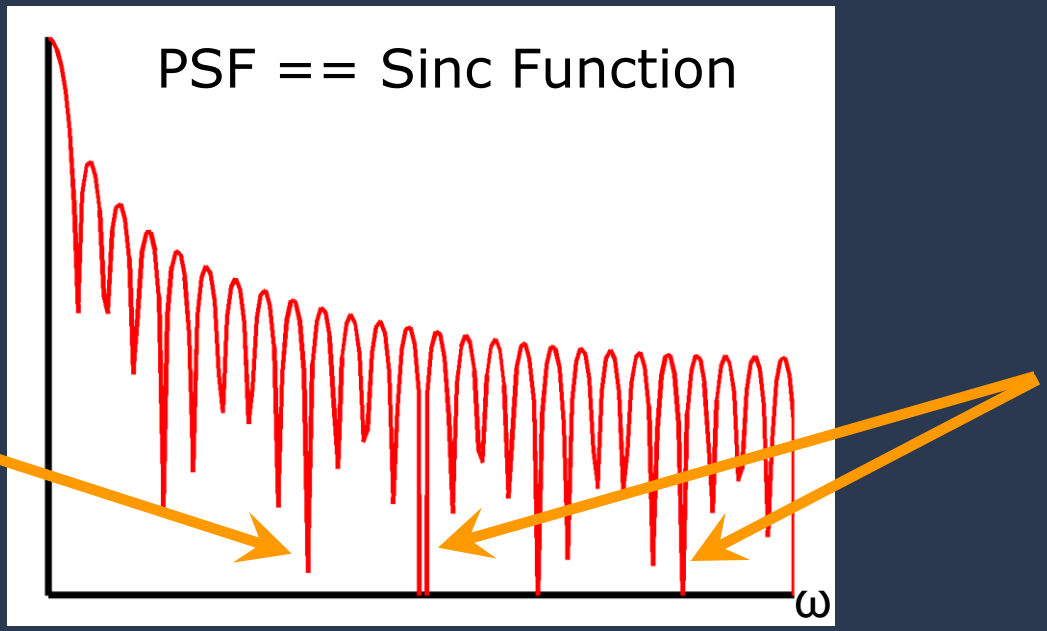
Blurring == Convolution



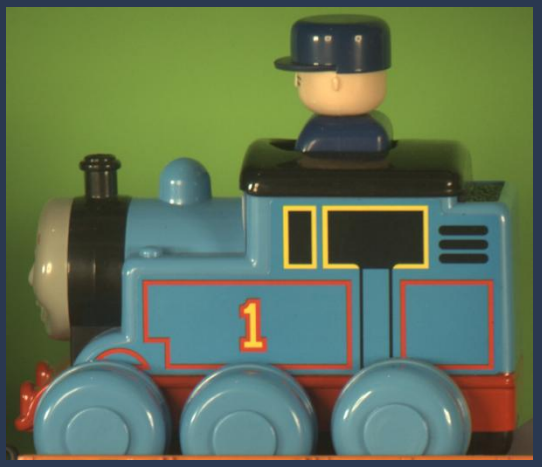
Sharp Photo



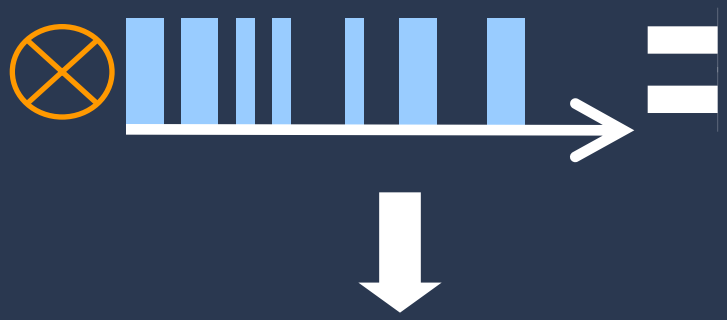
Blurred Photo

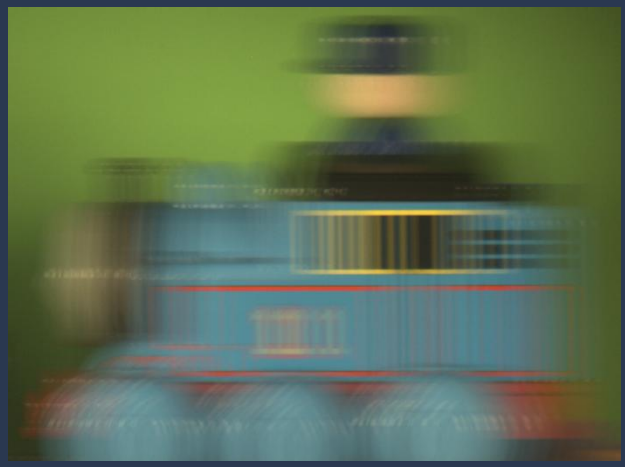


Traditional Camera: Shutter is OPEN: Box Filter

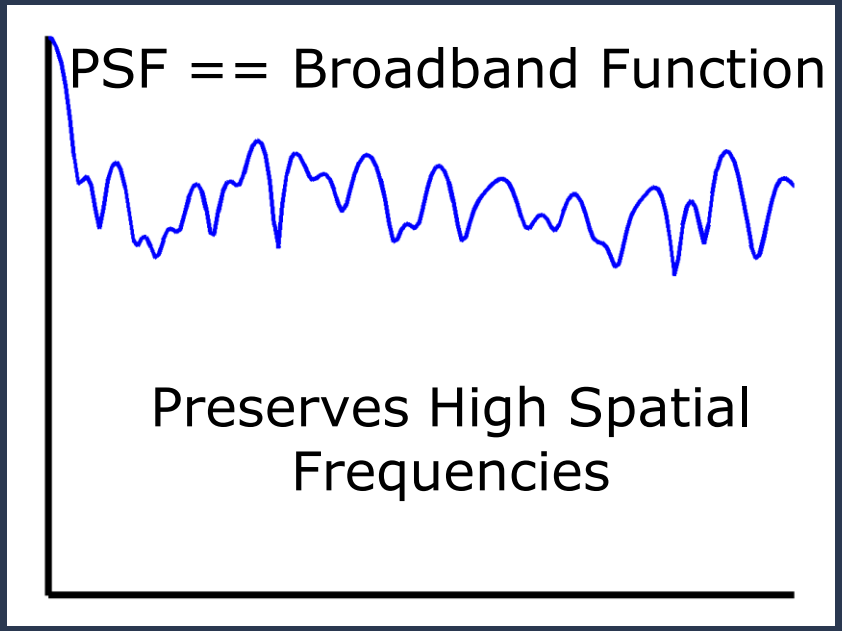


Sharp Photo



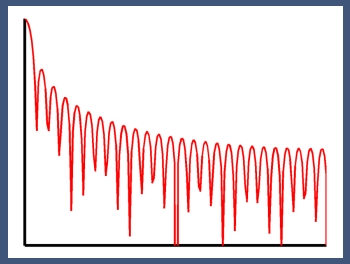


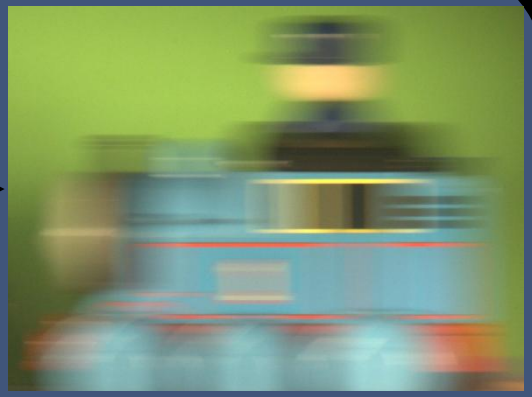
Blurred Photo

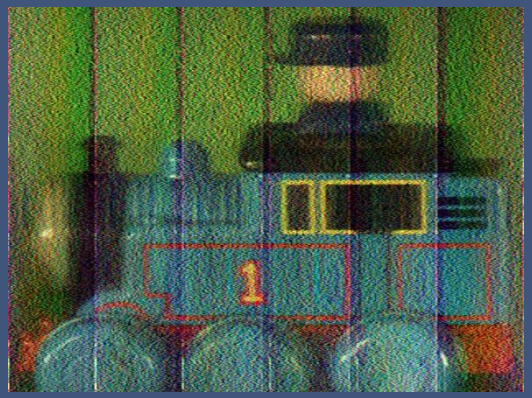


Flutter Shutter: Shutter is OPEN and CLOSED

Traditional

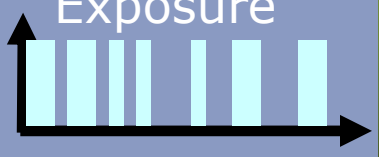


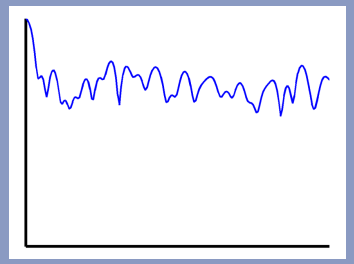


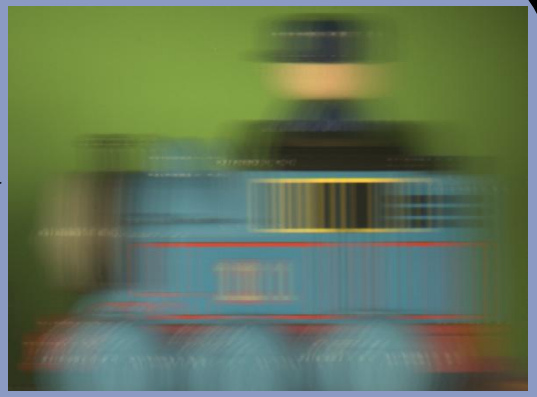


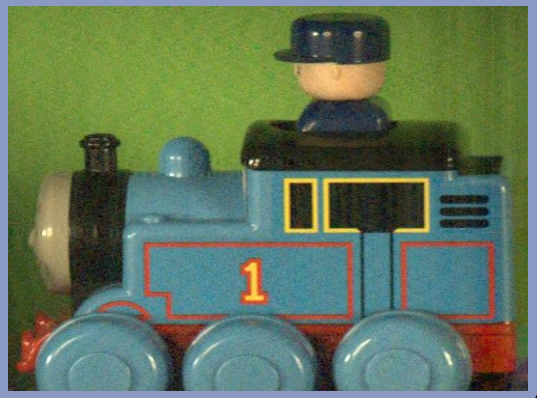
Deblurred Image

Coded Exposure



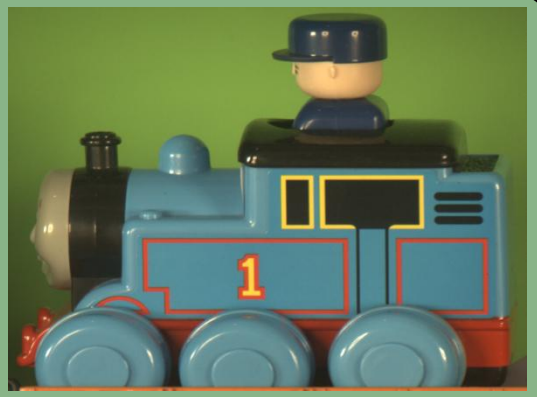






Deblurred Image

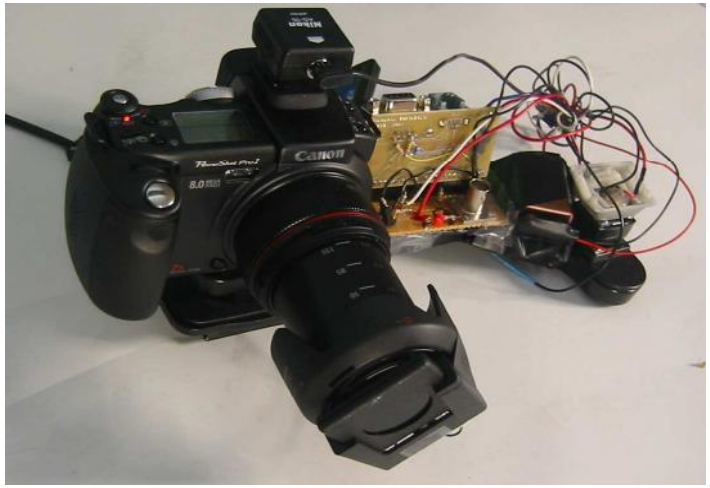
Image of Static Object



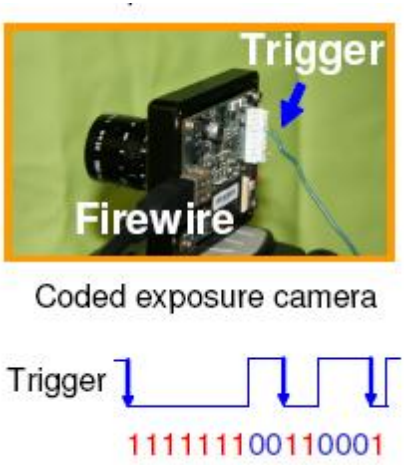

485·PCK

Coded Exposure (Flutter Shutter) Camera

Raskar, Agrawal, Tumblin [Siggraph2006]



External Shutter
with SLR Camera



PointGrey Camera
No additional Cost

Coding in Time: Shutter is opened and closed

How to handle focus blur?

Coded Exposure (Flutter Shutter)

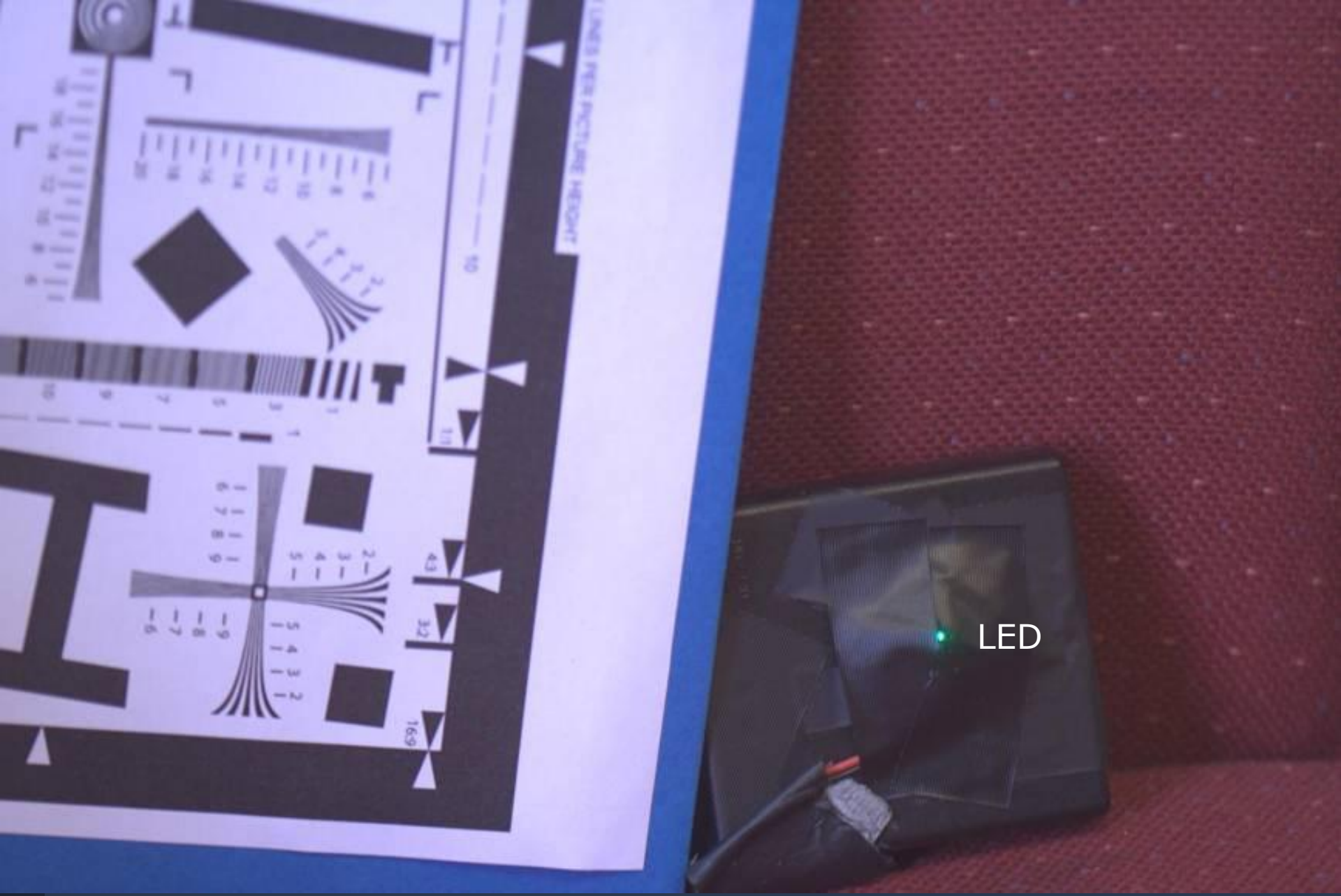
Raskar, Agrawal, Tumblin
SIGGRAPH 2006

Temporal 1-D broadband code:
Motion Deblurring

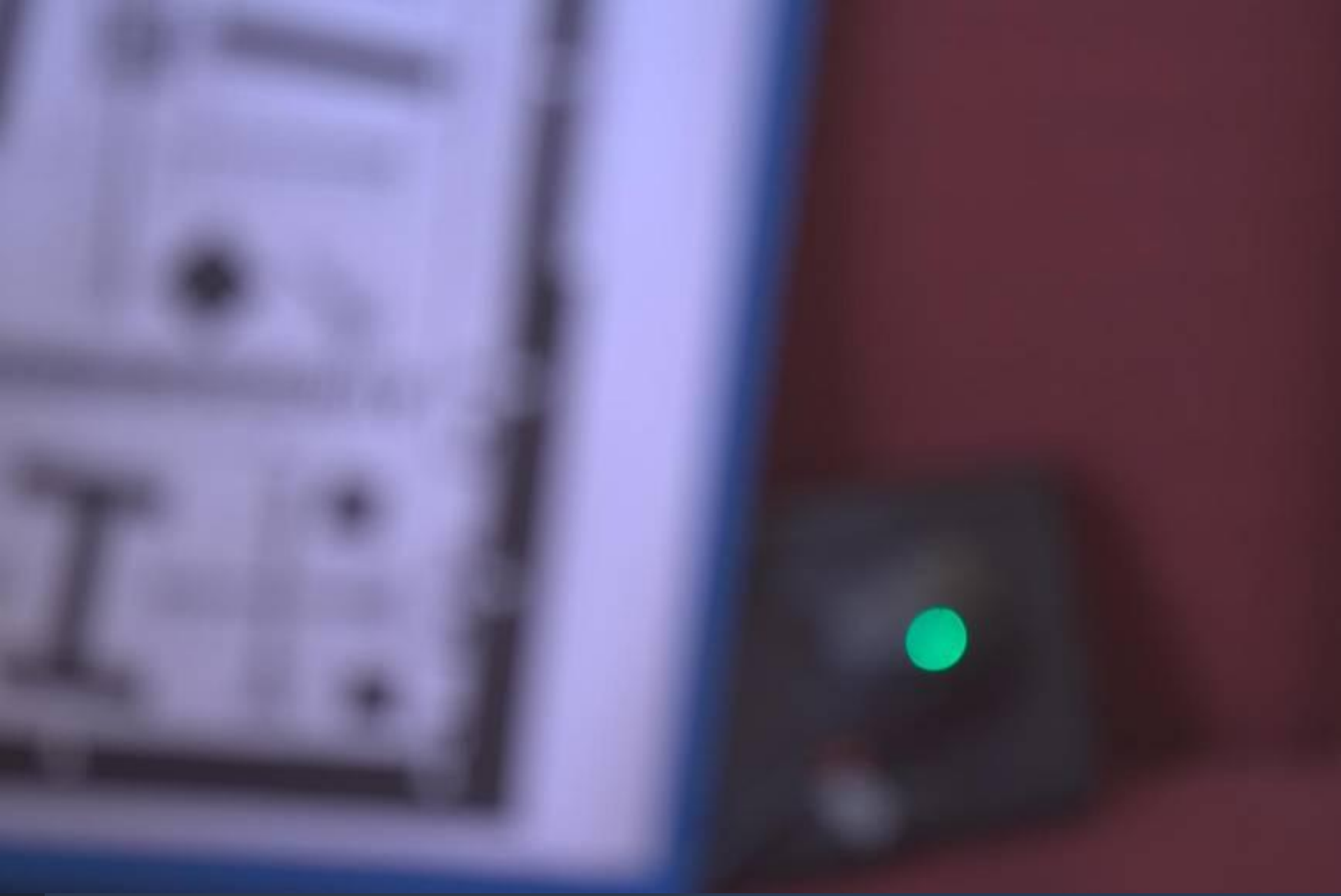
Coded Aperture

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

Spatial 2-D broadband code:
Focus Deblurring



In Focus Photo



Out of Focus Photo: Open Aperture

Out of Focus Photo: Coded Aperture

Blurred Photos

Open Aperture

Coded Aperture, 7 * 7 Mask

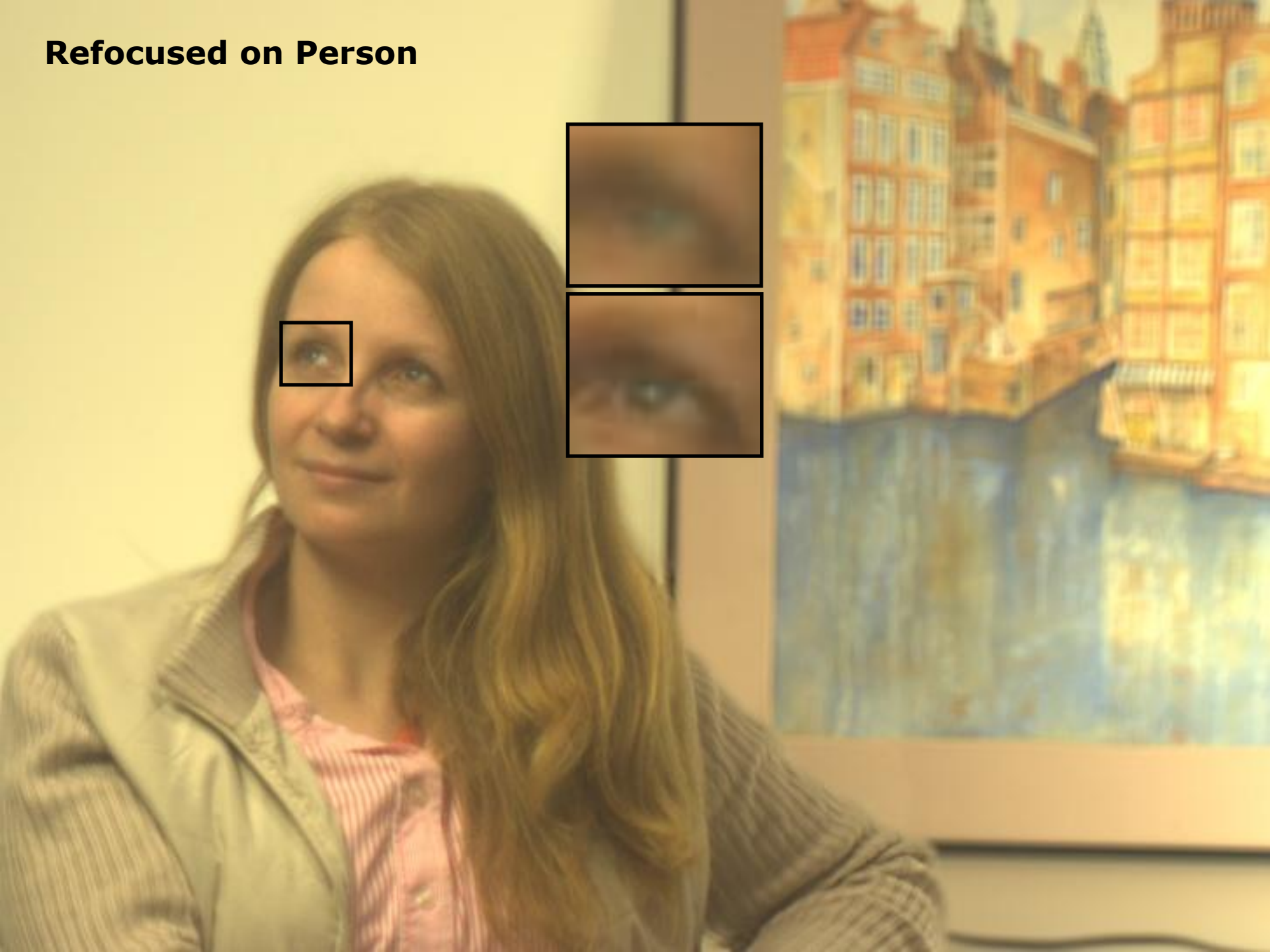
Deblurred Photos

Open Aperture

Coded Aperture, 7 * 7 Mask


Captured Blurred
Photo

Refocused on Person




Beal.


Beal

Blocking Light == More Information

Coded Exposure
Coding in Time

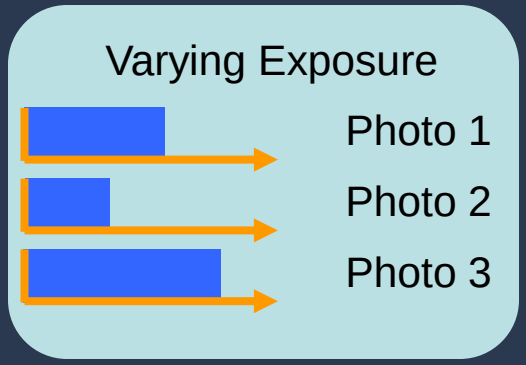
Coded Aperture
Coding in Space

Key Concept 1: PSF Invertibility

- Modify the PSF to be invertible
  - PSF == Impulse Response
- Traditional Camera
  - Non-invertible PSF (loses information)
- Coding in Camera
  - Invertible PSF
- Coding in Time == Coded Exposure
- Coding in Space == Coded Aperture

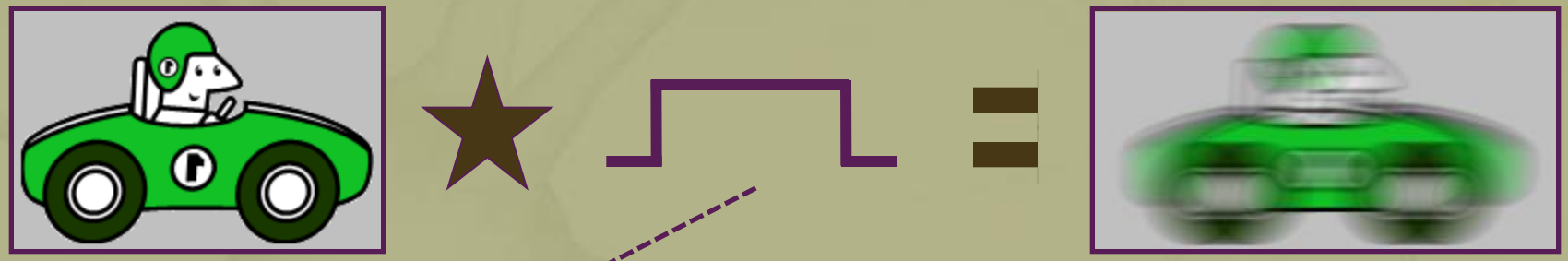
Key Concept: PSF Null-Filling

- PSF invertibility using multiple photos
- No camera modification required
- Can do it on available SLR's
  - Using Exposure Bracketing mode (AEB)



"Invertible Motion Blur in Video", Agrawal, Xu and Raskar, SIGGRAPH 2009

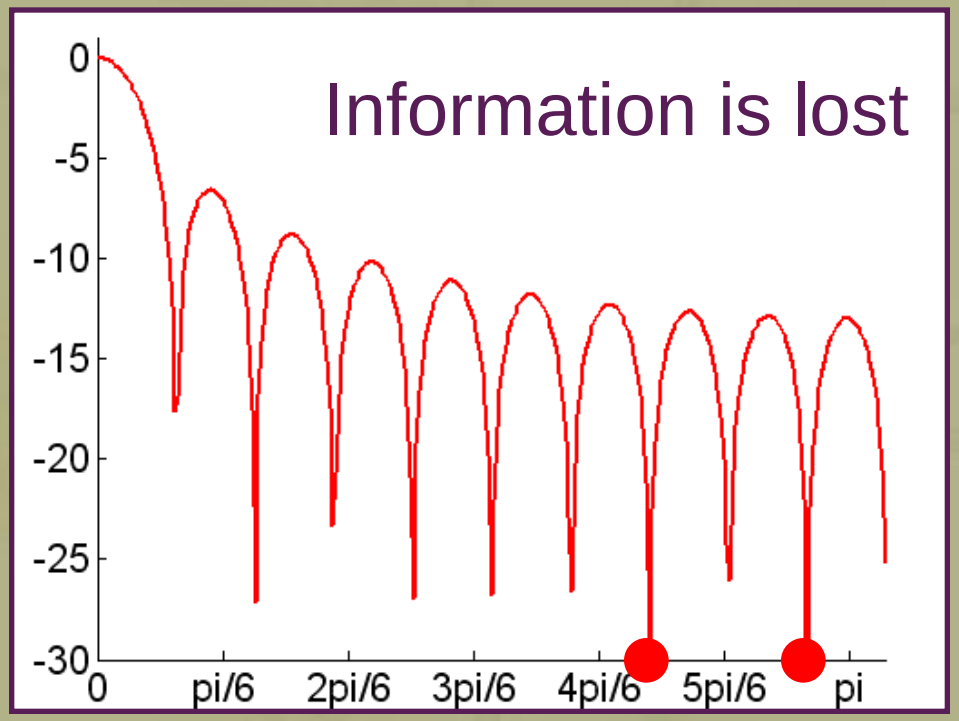
Traditional Exposure Video



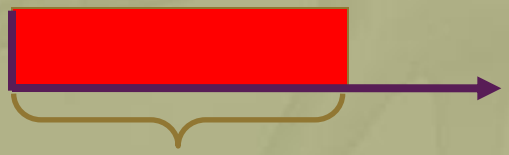
Motion PSF
(Box Filter)

Exposure Time

Fourier
Transform

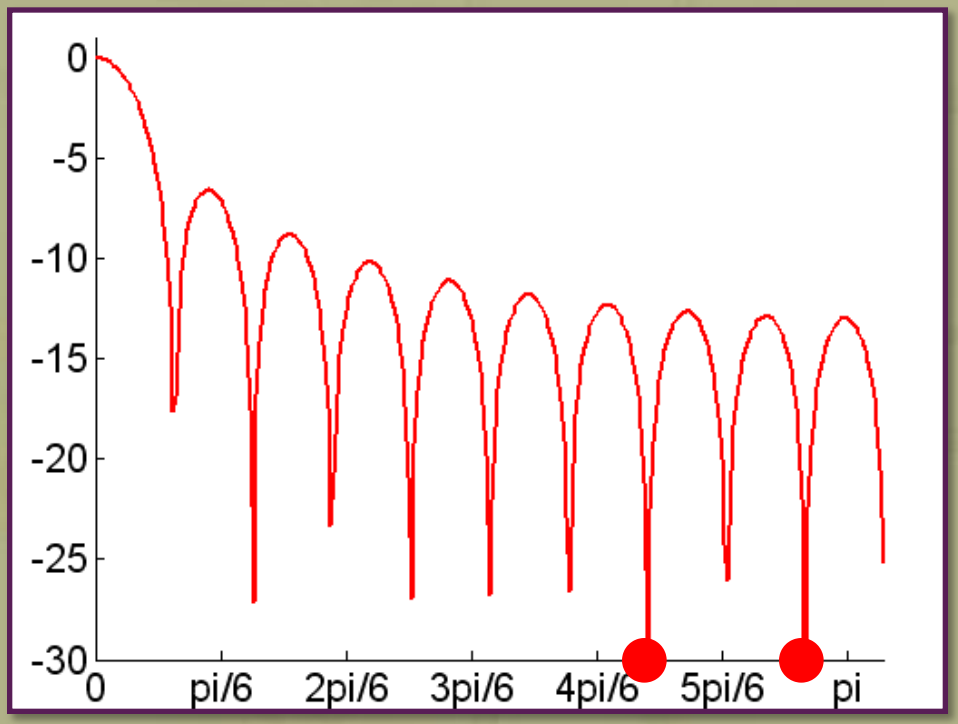


Varying Exposure Video

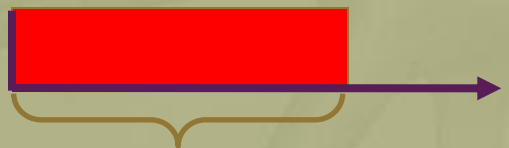


Exposure Time

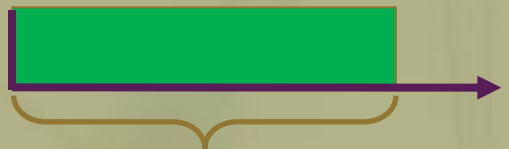
Fourier Transform



Varying Exposure Video

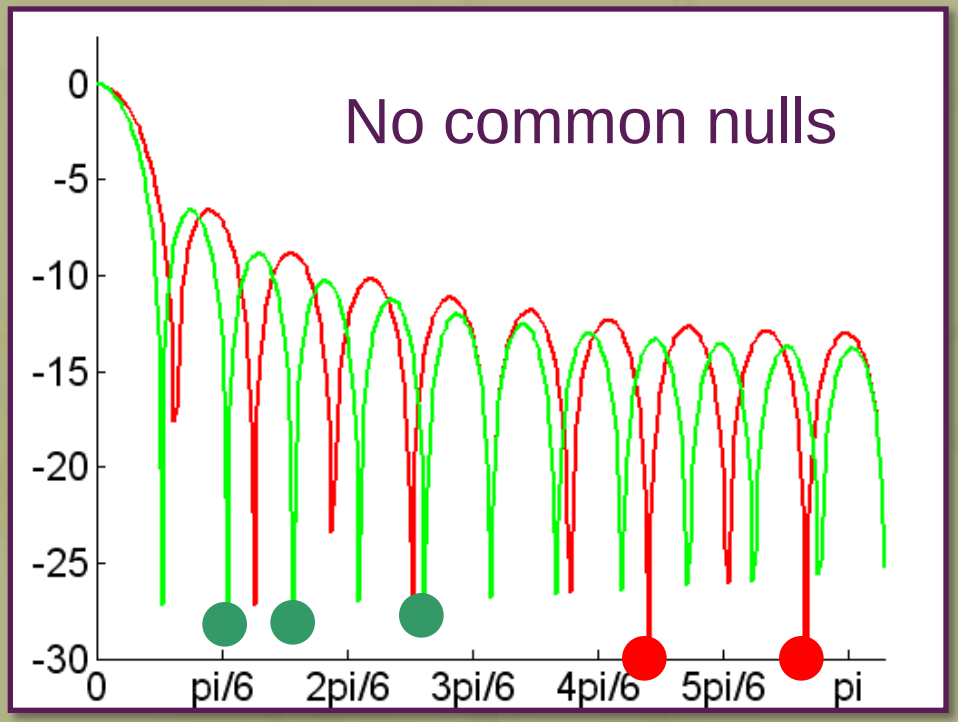


Exposure Time

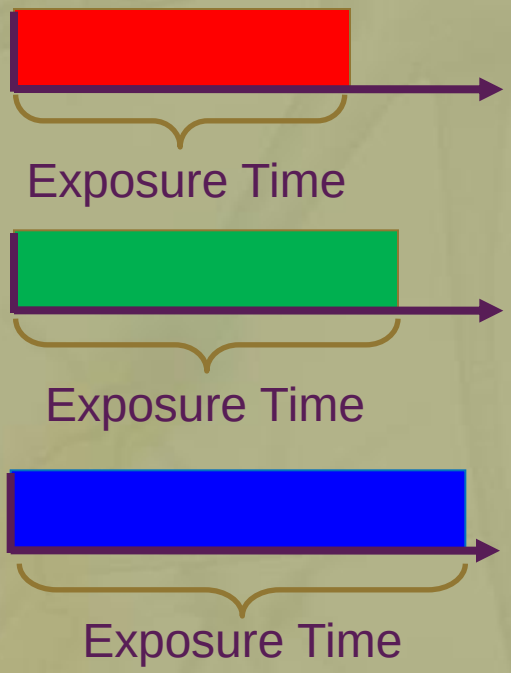


Exposure Time

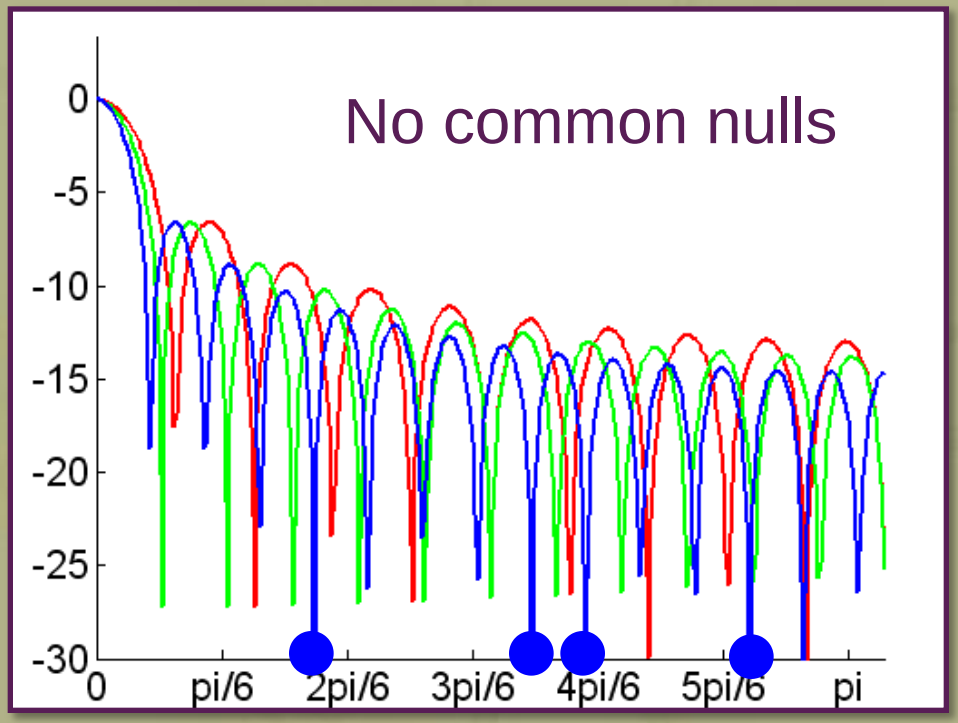
Fourier Transform



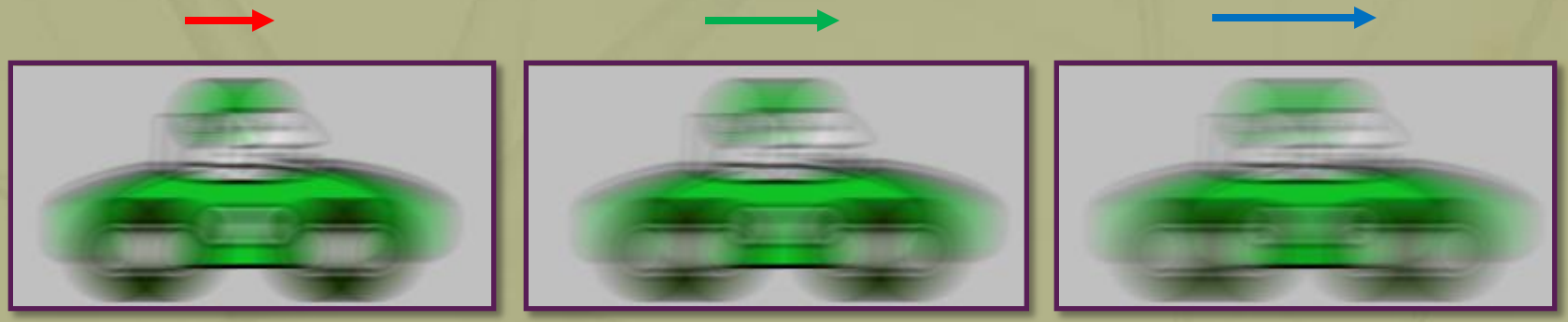
Varying Exposure Video



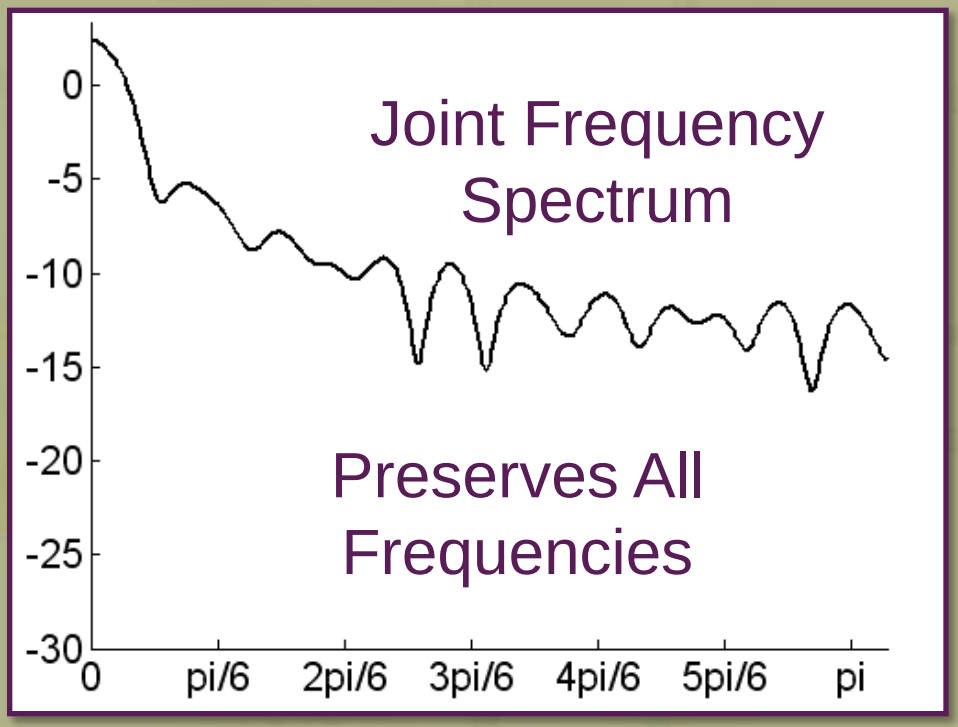
Fourier Transform



Varying Exposure Video = PSF Null-Filling

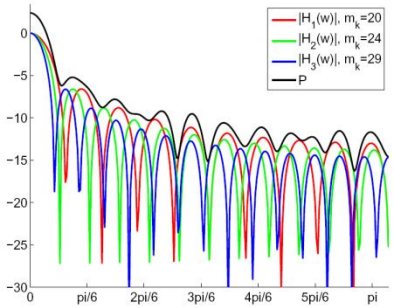


Fourier Transform

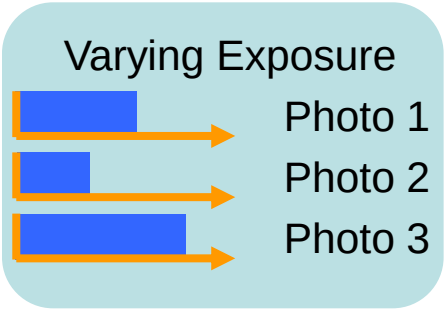


Key Idea: PSF Null-Filling

- Individual non-invertible PSF's combined into jointly-invertible PSF
  - Information lost in any single photo is captured in some other photo



- For motion deblurring
  - Achieve PSF null-filling by varying the exposure time of successive photos



Varying Exposure Video



Blurred Photos

Deblurred Result

Outdoor Car

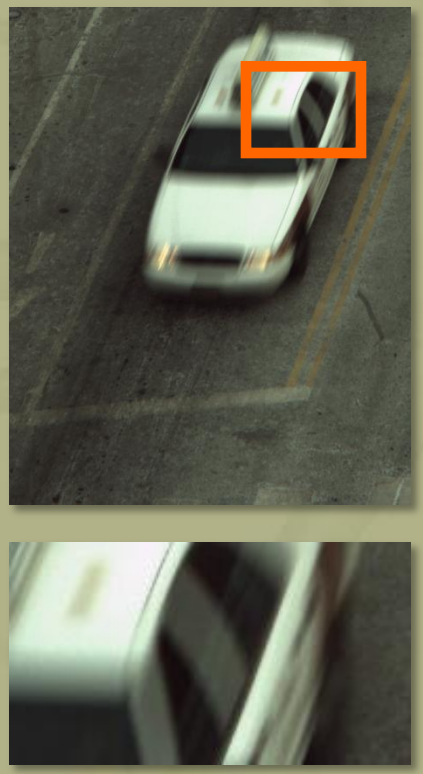


Photo 1

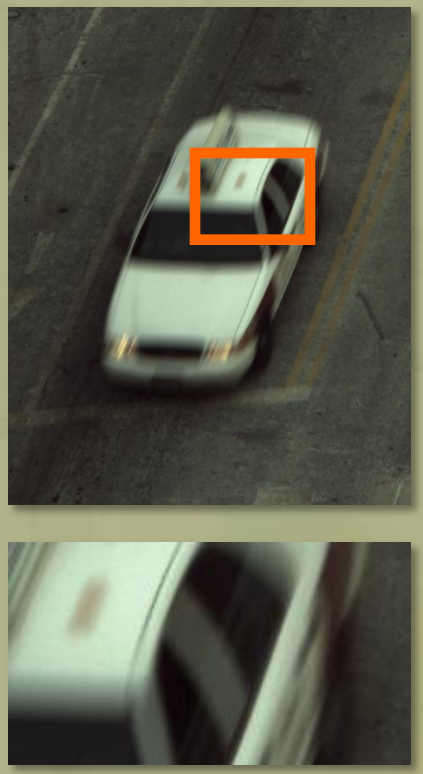


Photo 2

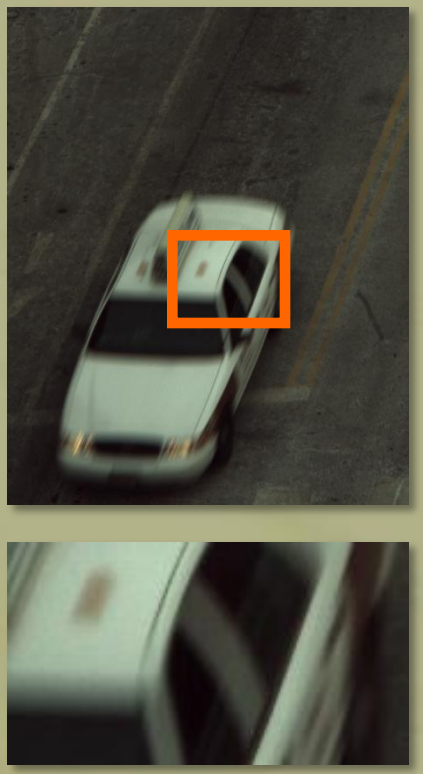
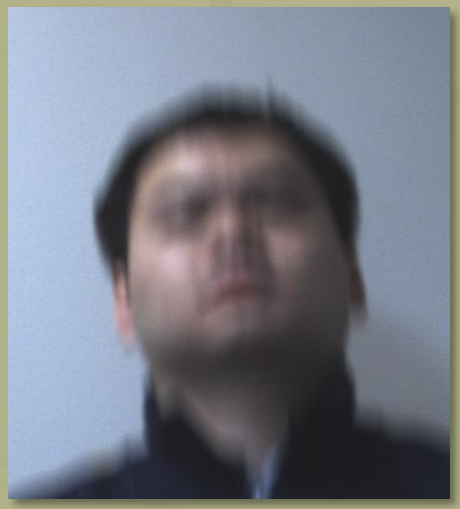


Photo 3

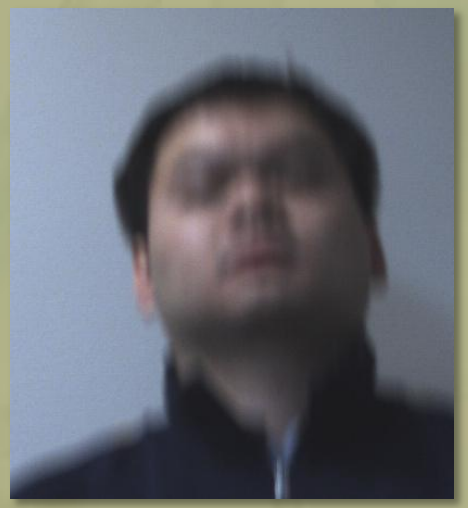
Deblurring

Face

Blurred Photo 1



Blurred Photo 2



Blurred Photo 3

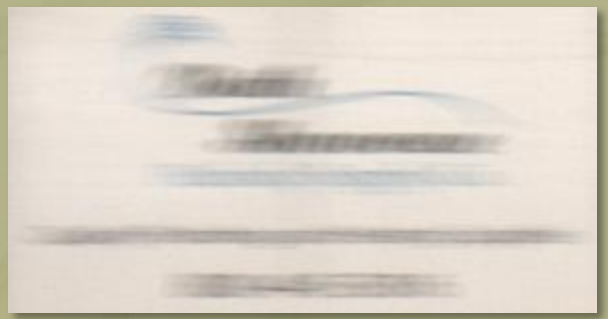
Deblurred

Auto Exposure Bracketing (AEB) for Varying Exposure Deblurring

1/50s

1/80s

1/30s



Blurred Photos

Deblurred Result

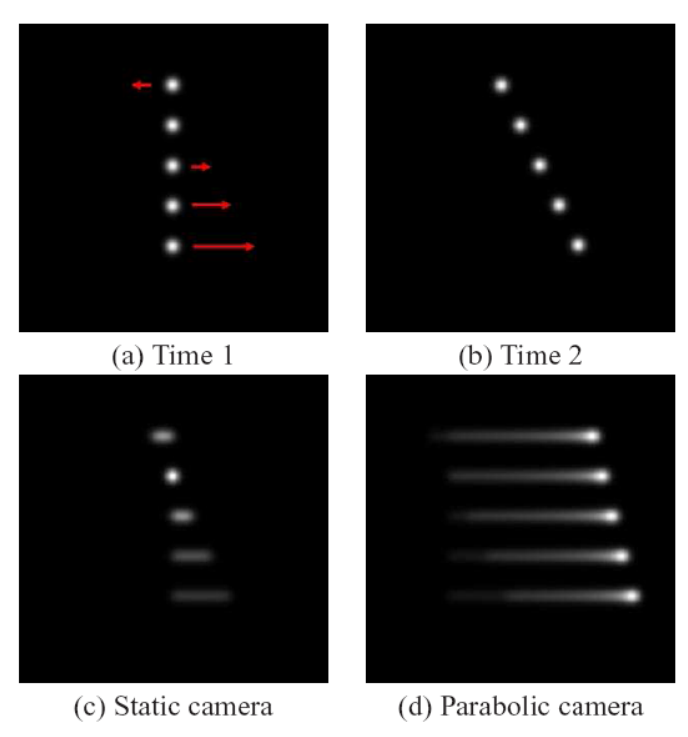
Key Concept 2: PSF Invariance

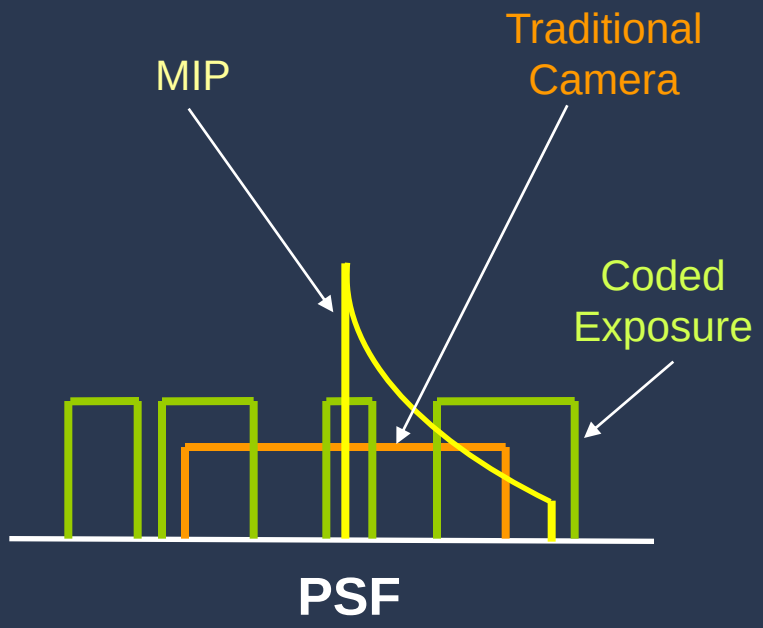
- But…
  - Need to estimate depth or velocity for deblurring
- Modify the PSF to be invariant
- Motion Blur
  - Motion invariant Photography (MIP), Levin et al SIG08
- Focus Blur
    - Wavefront coding
    - Focus Sweep Camera
    - Spectral Sweep Camera
    - Diffusion coding

PSF Invariance: Motion Blur

- Move the camera while taking photo
  - Constant Camera Acceleration

- Leads to similar PSF for object velocity in a range
- But requires knowledge of motion direction





Comparison

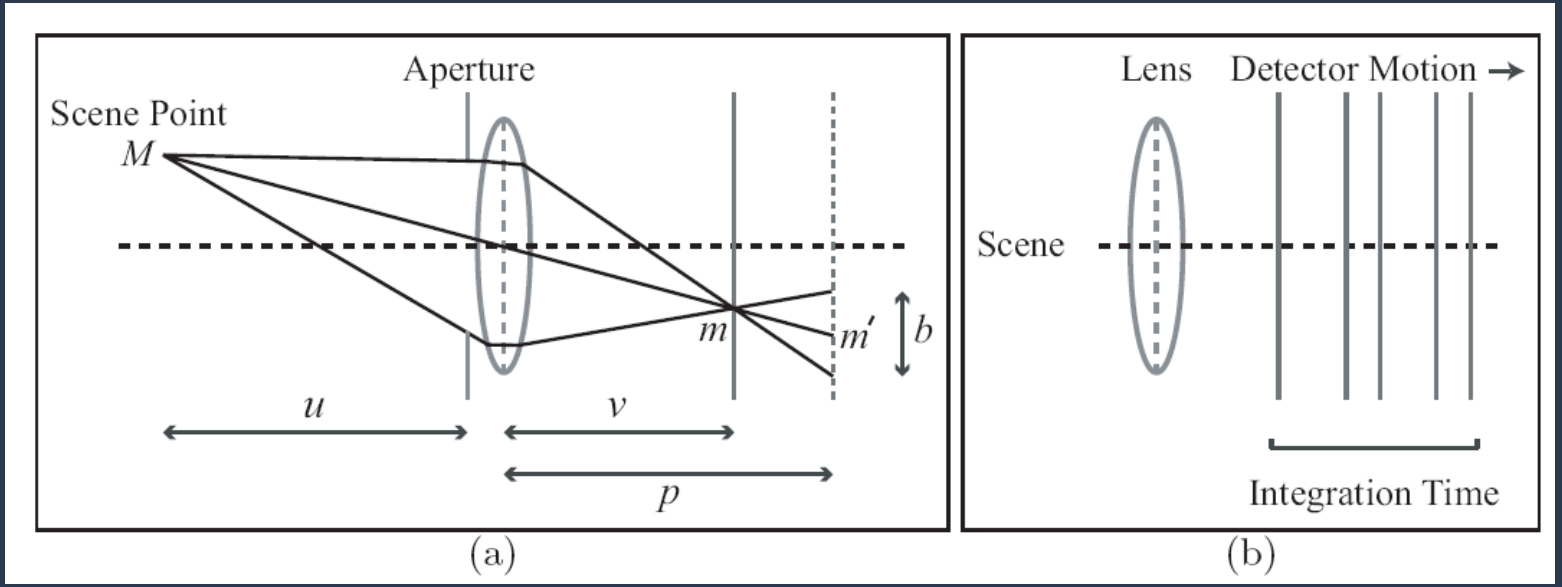
- Coded Exposure
  - Requires motion magnitude for deblurring
  - But works for any motion direction

- PSF Invariance
  - Requires motion direction to move the camera
  - But invariant PSF for motion magnitude within a range

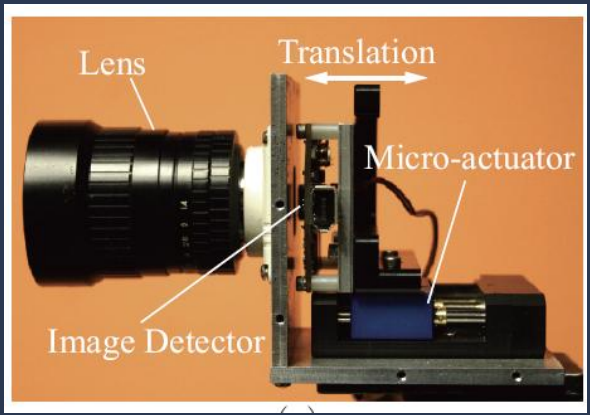
Optimal Single Image Capture for Motion Deblurring, Agrawal and Raskar, CVPR 2009

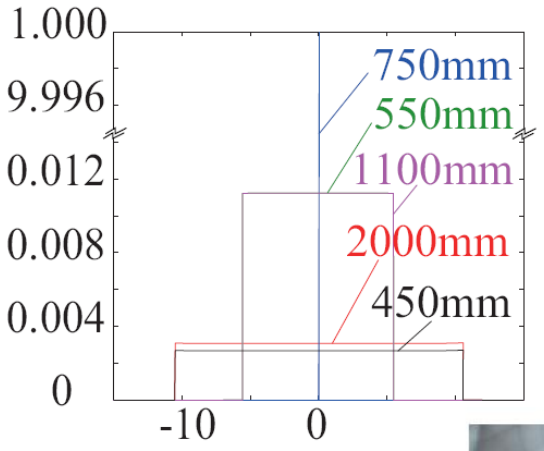
PSF Invariance: Focus Blur

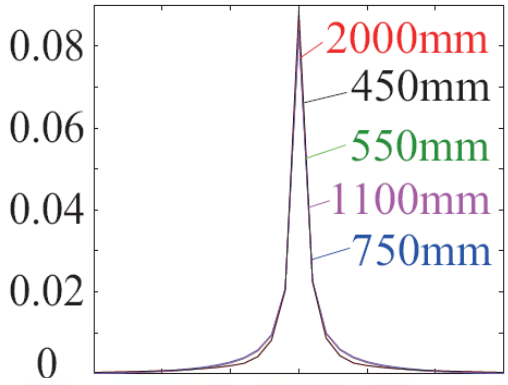
- Defocus PSF should be invariant of depth



Nagahara et al.
ECCV 2008

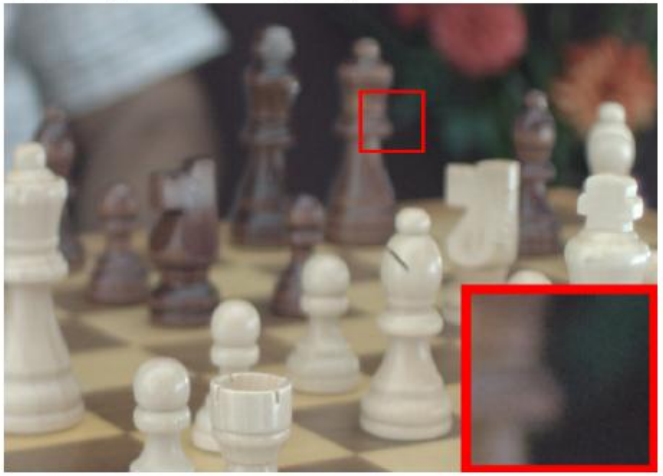


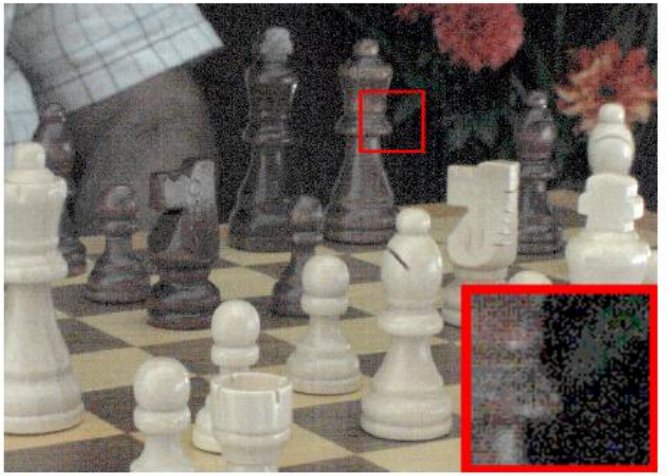




(a) Captured Image (f/ 1.4, T=0.36sec)

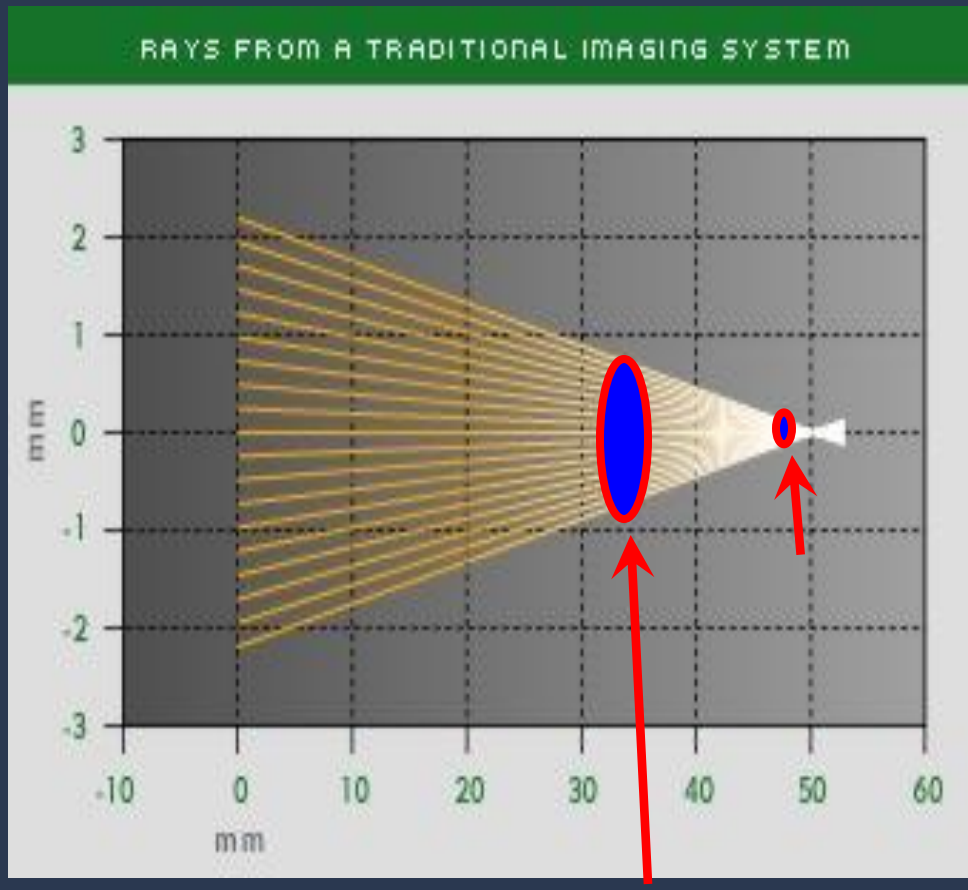
(b) Computed EDOF Image





Wavefront Coding

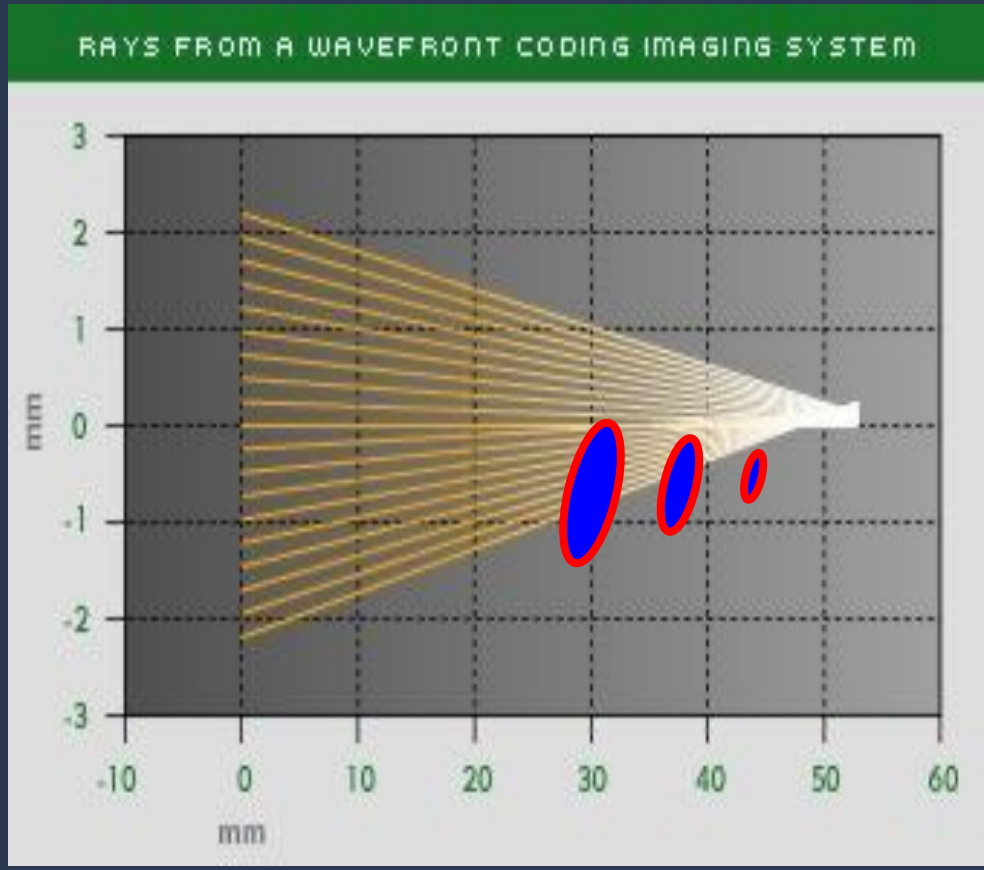
- Traditional Lens:
  - Defocus (‘circle of confusion) dependent on distance from plane of focus



http://www.cdm-optics.com

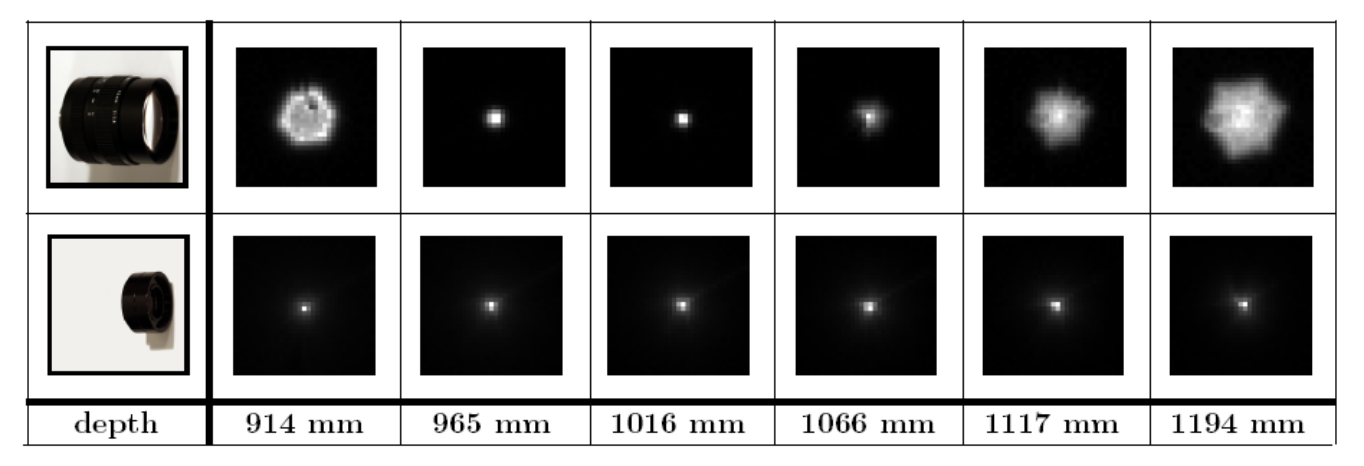
Wavefront Coding

- Traditional Lens:
  - Defocus dependent on distance from plane of focus
- Cubic Phase Plate
  - Defocus nearly independent of distance
  - All points 'blurred'
  - Deconvolve to get sharper image

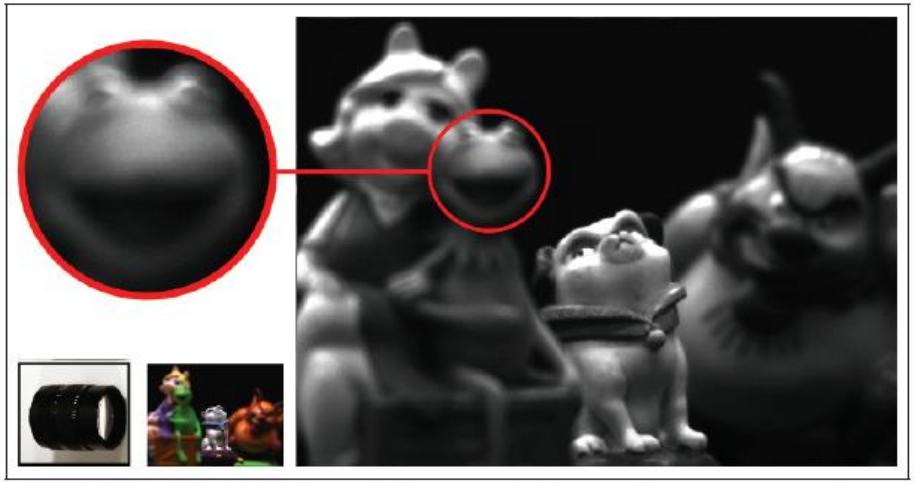


http://www.cdm-optics.com

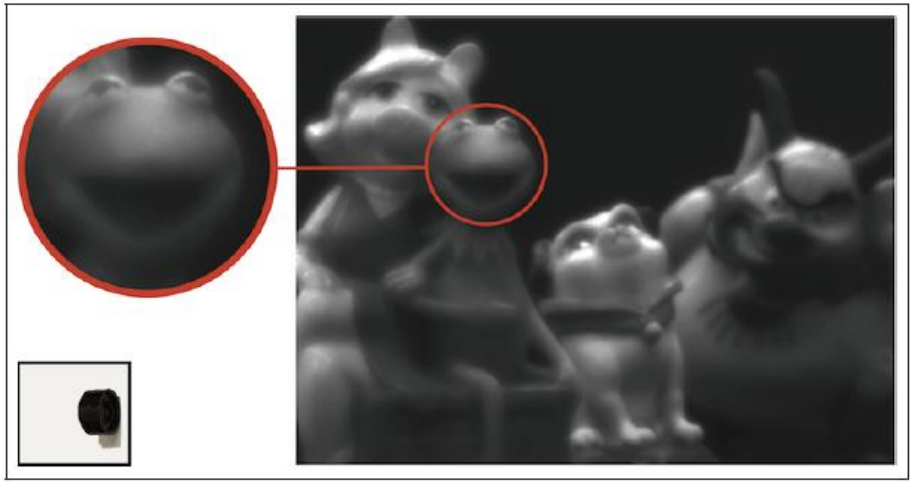
Spectral Focal Sweep Lens



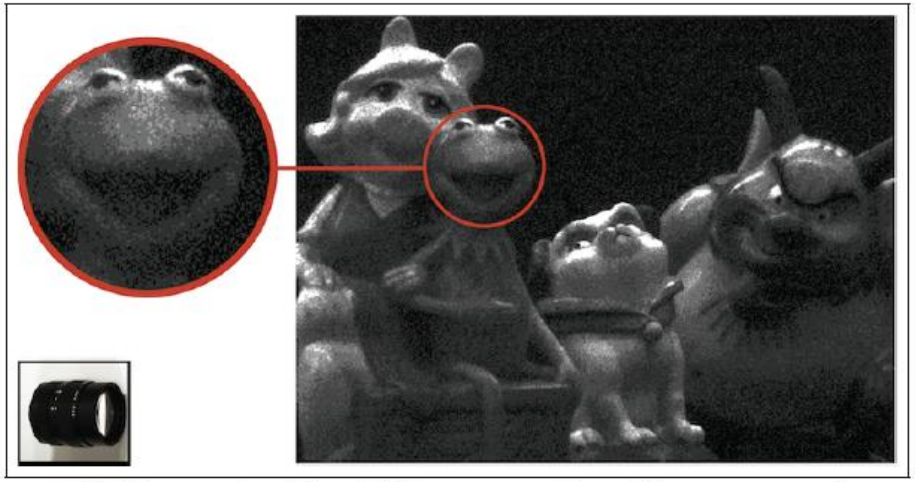
Cossairt and Nayar, ICCP 2010



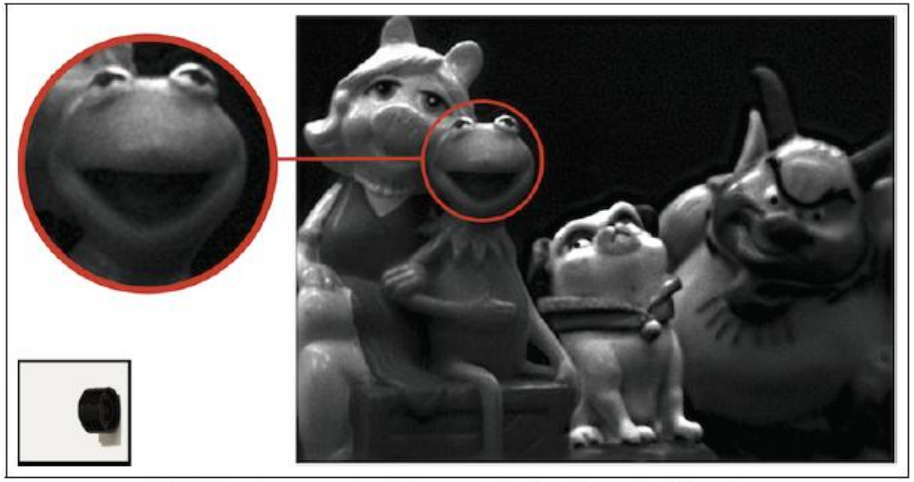
(a) Captured with a F/4 corrected lens (8ms exposure)



(b) Captured with our SFS lens (8ms exposure)



(c) Captured with a F/16 corrected lens (8ms exposure)



(d) The image in Figure 8(c) after deblurring

Cossairt and Nayar, ICCP 2010

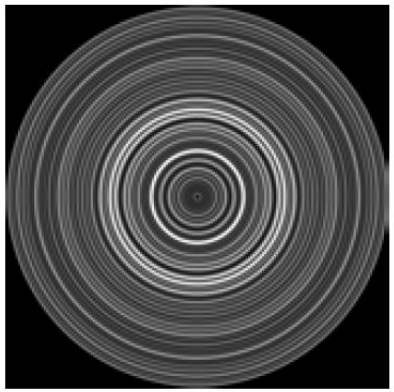
PSF Invariance: Focus Blur

- Vary focal length in captured photo

Focal Length Variation	Hardware Implementation	Reference
Time	Sensor Motion	Nagahara et al. ECCV 2008
Phase/Angle	Cubic Phase Plate	Wavefront Optics
Wavelength	Lens with Chromatic Aberrations	Cossairt and Nayar, ICCP 2010
Aperture	Divide the aperture into different lens	Ben-Eliezer, Applied Optics 2005, Levin et al SIGGRAPH 2009

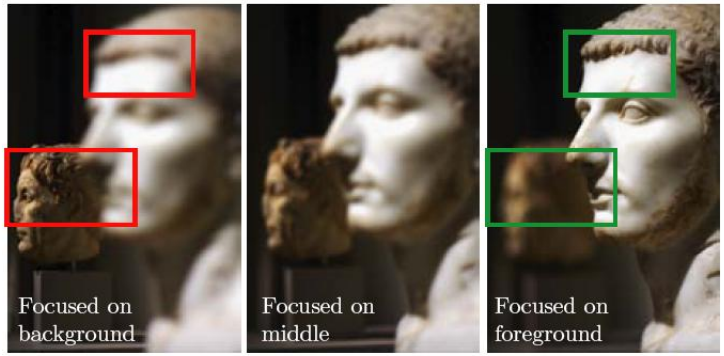
PSF Invariance: Diffusion Coding

- Use a radially symmetric diffuser in aperture
- Cossairt and Nayar, SIGGRAPH 2010

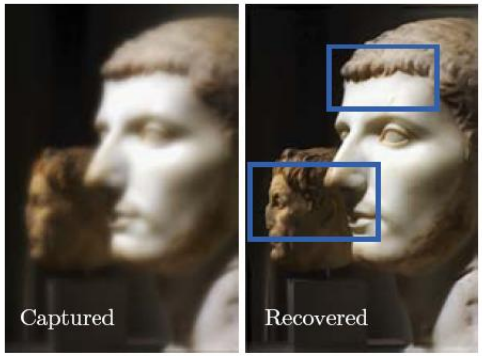


(b) Diffuser height map

(d) The diffuser



(a) Normal camera



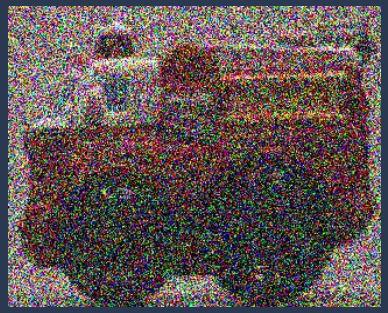
(b) Diffusion coded camera

High Speed Imaging

- High speed cameras
  - Expensive
  - Require on-board memory
  - Fundamental Light Loss

30 fps

500 fps
-24.5 dB

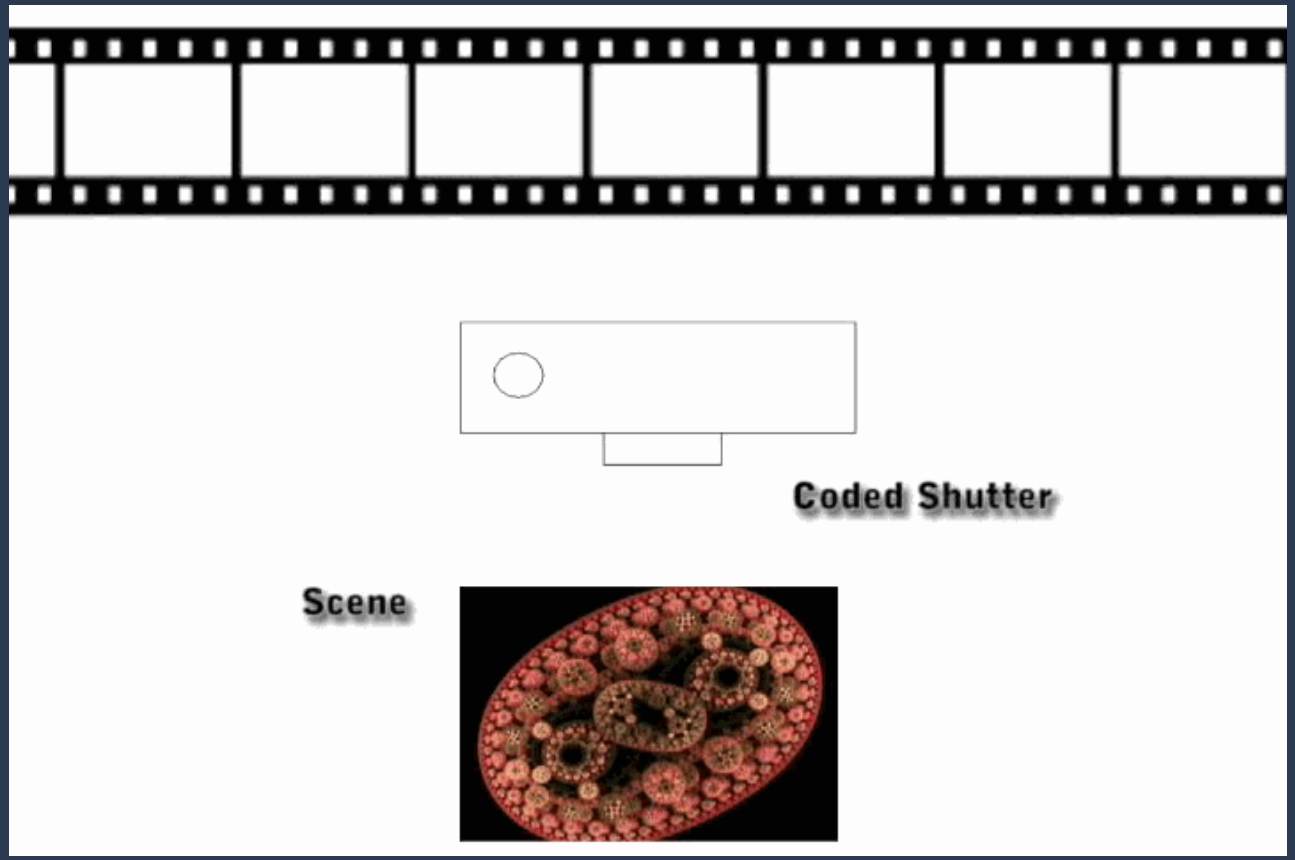


2000 fps
-36.5 dB

4000 fps
-42.5 dB

Coded Strobing Camera: 100x Temporal Super-Resolution

- For Periodic Signals
- Coded Exposure Video
  - Every frame is coded differently



Battery powered Toothbrush

20fps normal camera

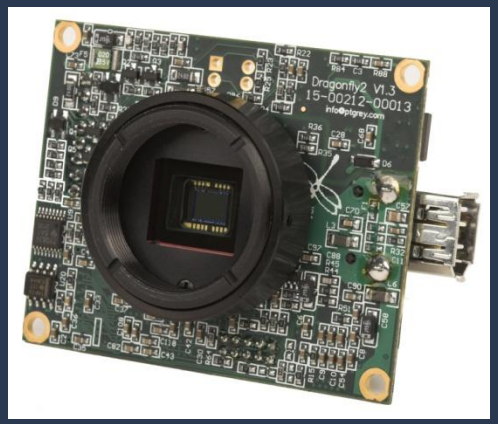
20fps coded strobing camera

Reconstructed frames

1000fps hi-speed camera

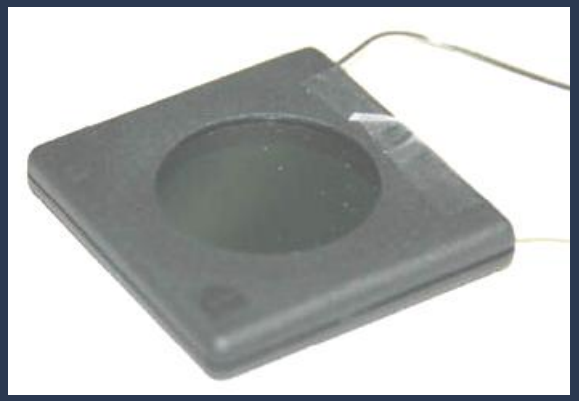
Implementation

Can strobed at 1ms



Captured at 10fps PGR Dragonfly2

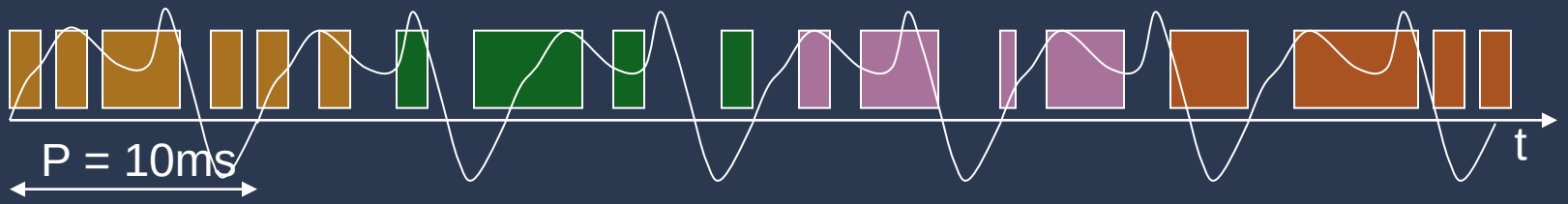
Can strobe at 250us



External FLC Shutter

Temporally at a pixel

observe different linear combinations of the periodic signal

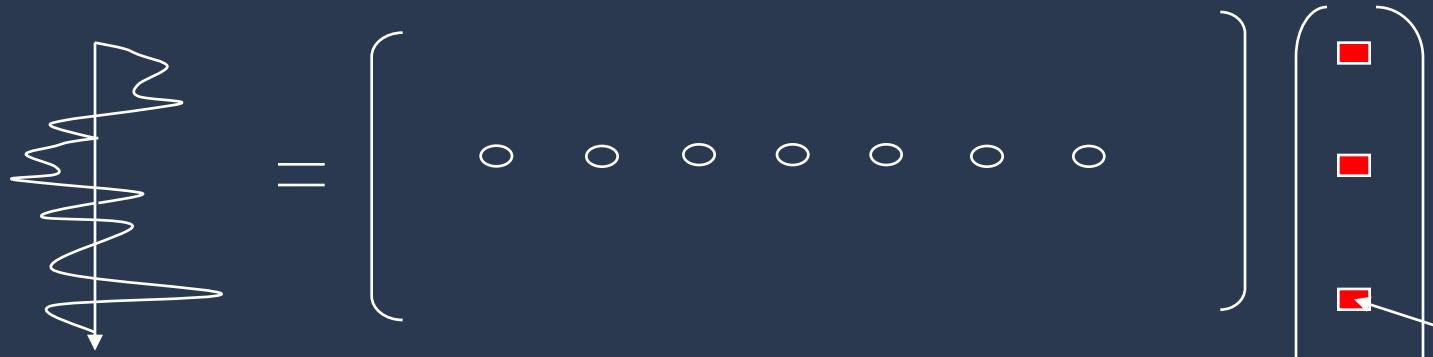


Advantage of the design:

Exposure coding is independent of the frequency periodic signal.

50% light throughput, far greater than traditional strobing.

Compressive sensing Reconstruction



y = **A** **s**

Observed low rate frames

Mixing matrix

Sparse Basis Coeff

Basis Pursuit De-noising

$$\min \|s\|_1 \; s.t. \|y - As\|_2 \leq \varepsilon$$

Battery powered Toothbrush

20fps normal camera

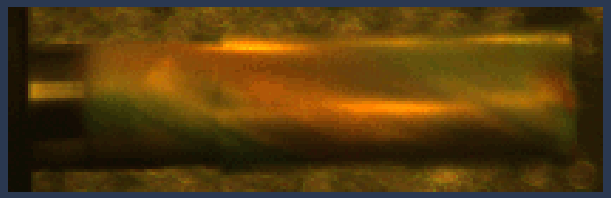
20fps coded strobing camera

Reconstructed frames

1000fps hi-speed camera

Rotating Mill Tool captured by PointGrey Dragonfly2

Normal Video: 25fps



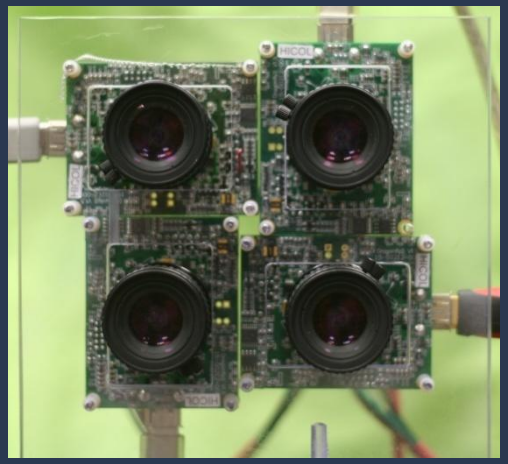
Coded Strobing Video: 25fps

Reconstructed Video at 2000fps

High Speed Imaging

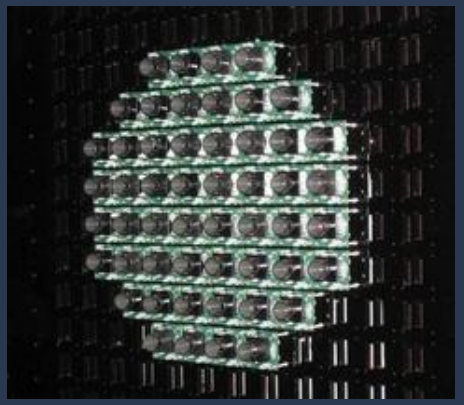
- Coded Strobing Camera for Periodic Signals
- For General Scenes?

Camera Arrays

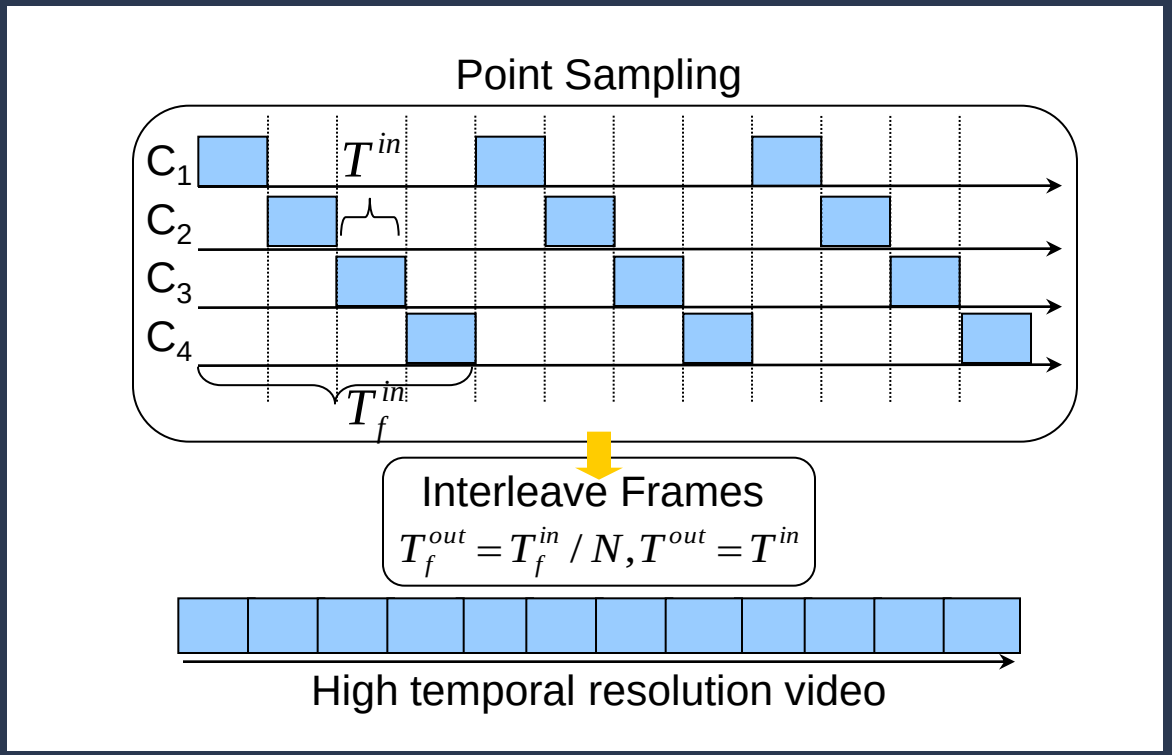


Agrawal et al. CVPR 2010, Wilburn et al. CVPR 2004, Shechtman et al. ECCV 2002

Camera Arrays

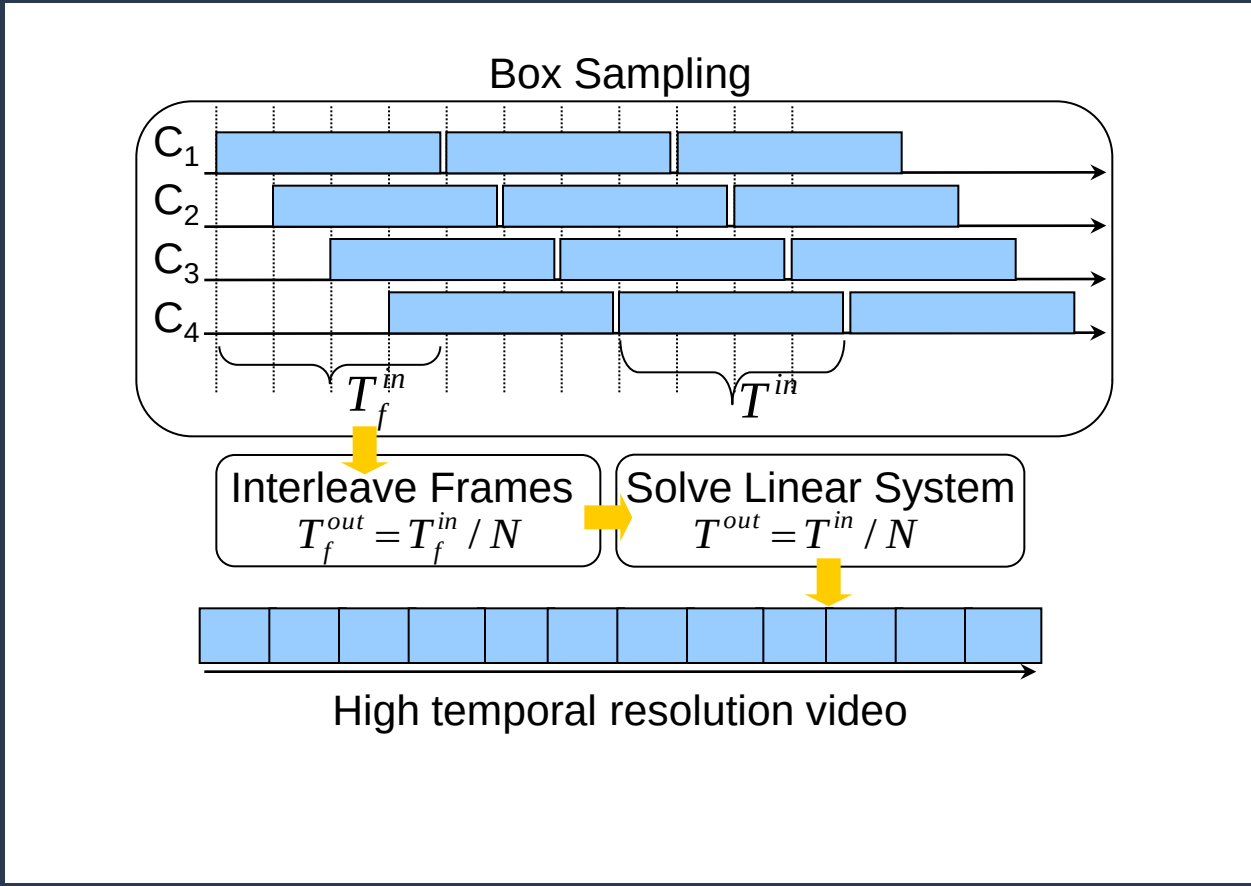


- Point Sampling
  - Wilburn et al CVPR 2004
  - Each camera captures independent sample of high speed video



Camera Arrays

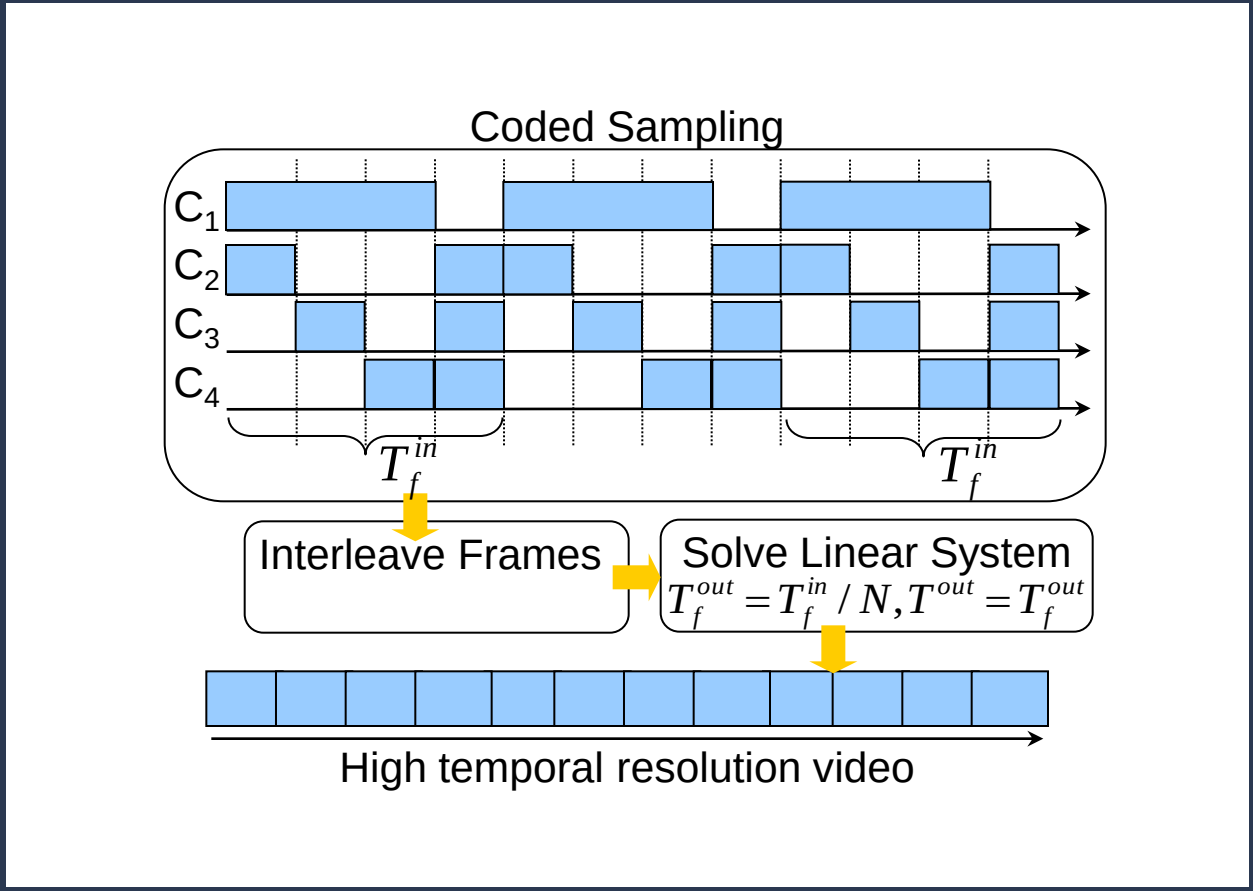
- Box Sampling



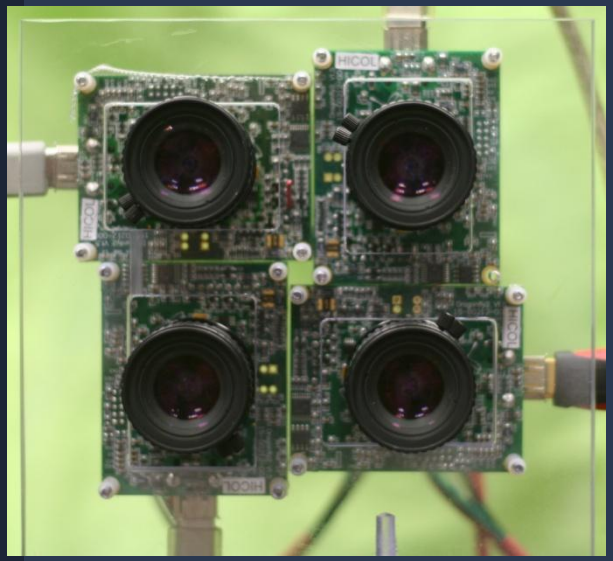
Space-Time Super-Resolution, Shechtman et al. ECCV 2002

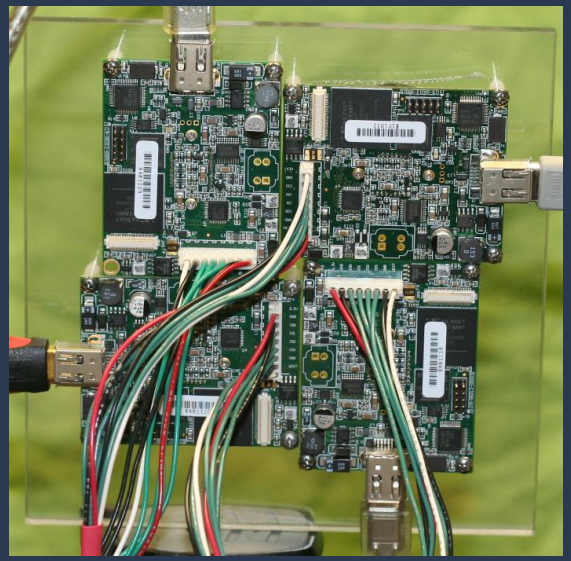
Camera Arrays

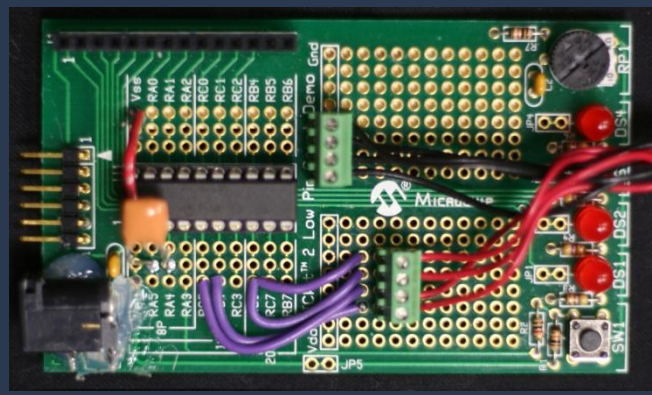
- Coded Sampling
- Agrawal, Gupta, Veeraraghavan and Narasimhan CVPR 2010



Implementation







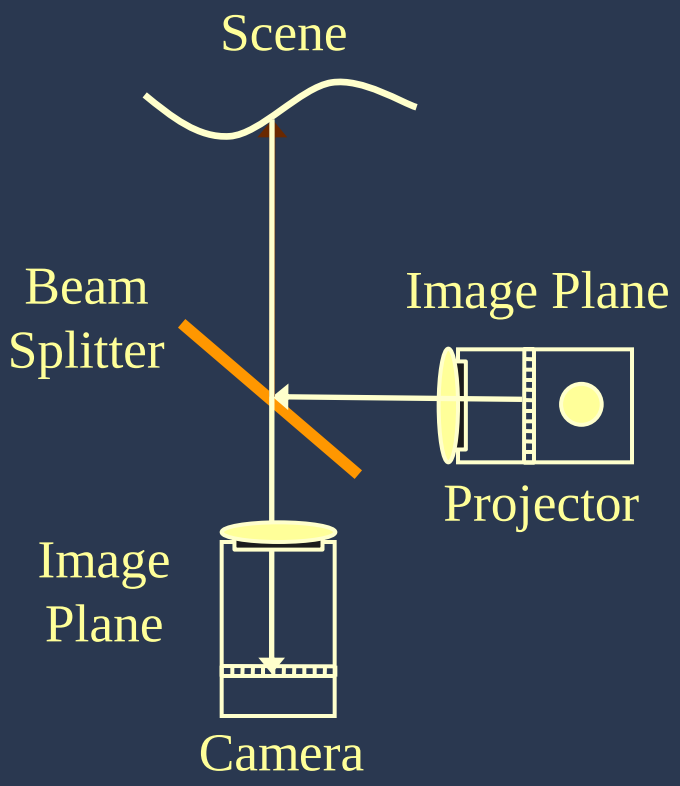
Flexible Videography

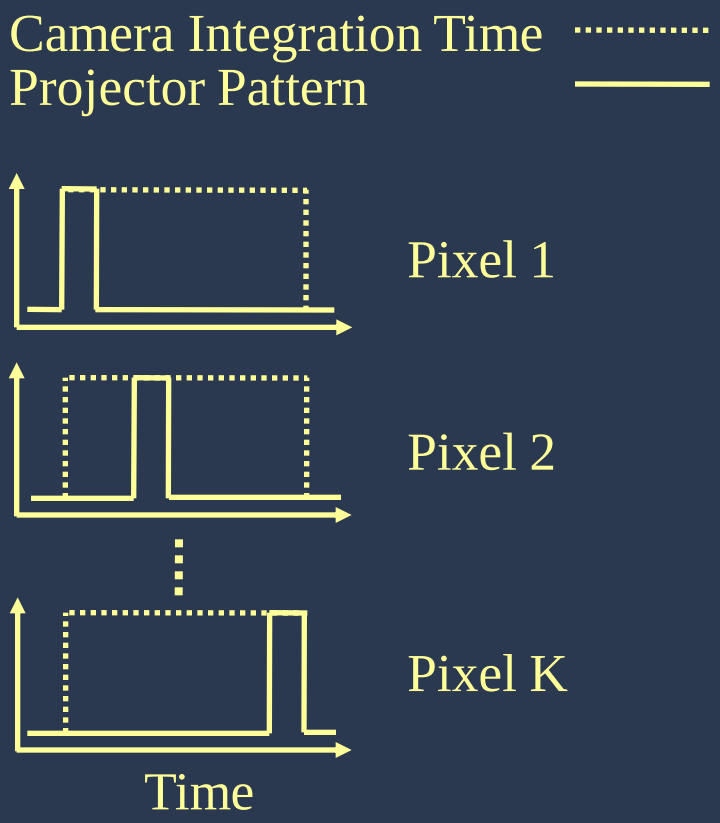
[Gupta, Agrawal, Veeraraghavan and Narasimhan, ECCV 2010]

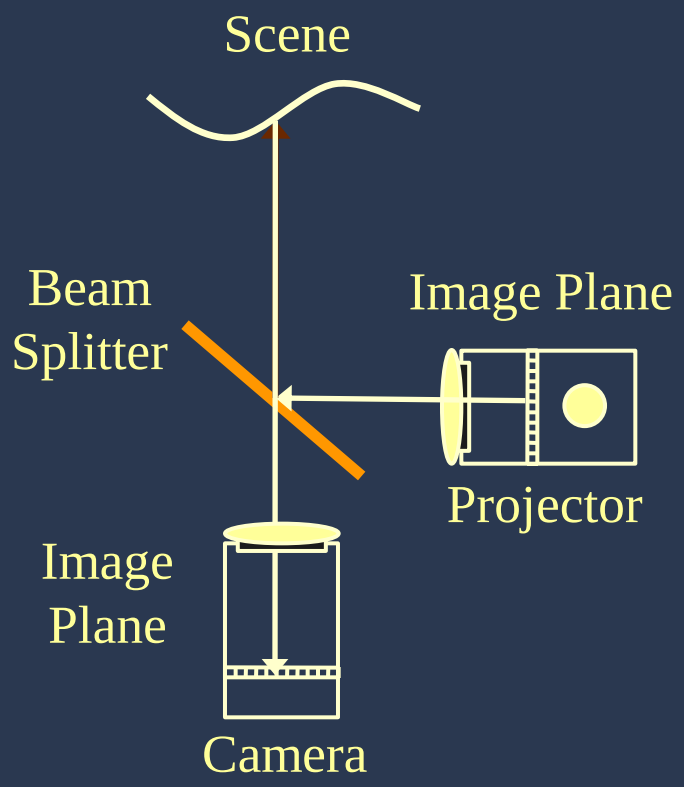
- Resolution Tradeoff: Traditional Video Camera
  - Fixed Space-Time Resolution
  - Independent of the scene
  - Same all over the image
- Flexible Videography
  - Change space-time resolution in post capture
  - Scene dependent Resolution
  - Different for different parts of the image

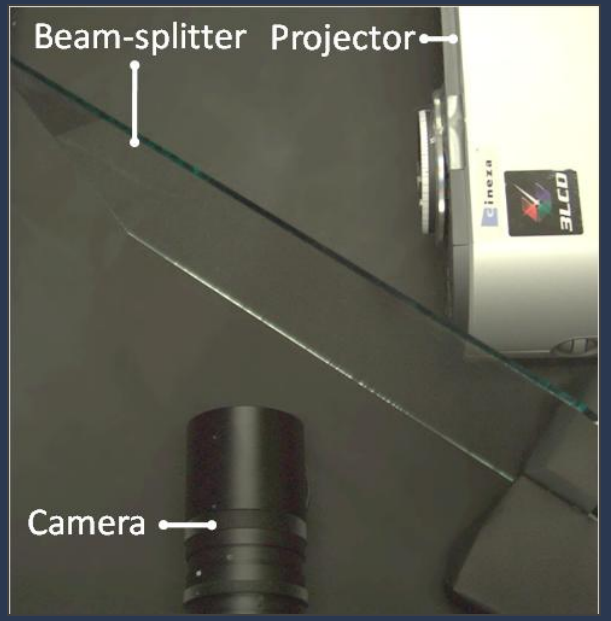
Flexible Voxels

- Per pixel coded exposure
  - Different temporal modulation per pixel

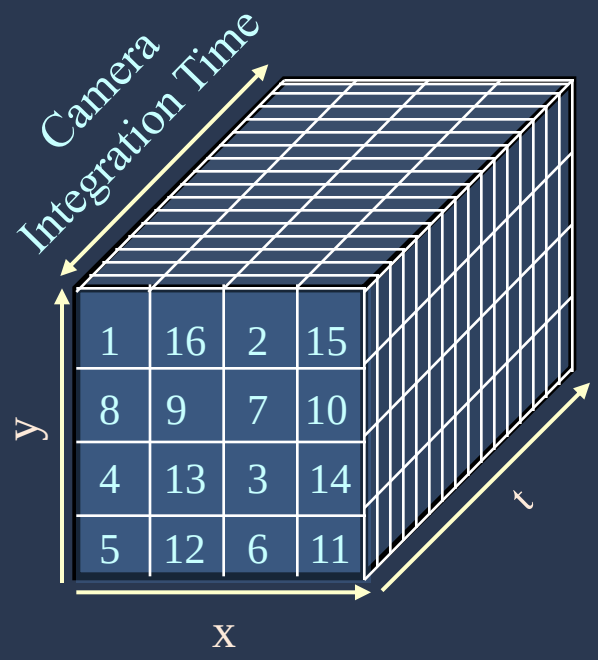





Scene
Beam Splitter
Image Plane
Projector
Image Plane
Camera

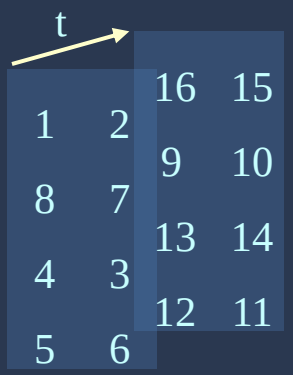

Beam-splitter
Projector
Camera

Sampling Strategy for 1-16x

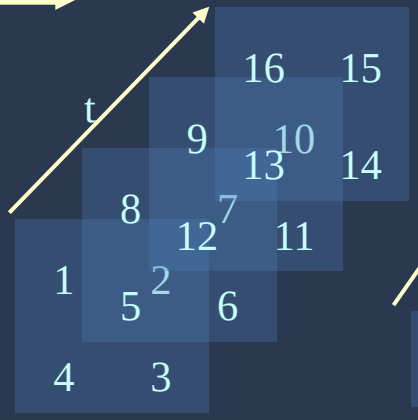


1 16 2 15
8 9 7 10
4 13 3 14
5 12 6 11

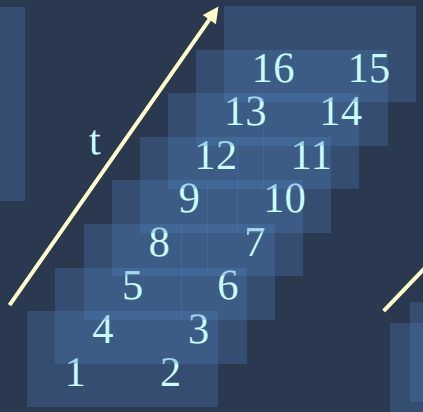
TR = 1, SR = 1/1



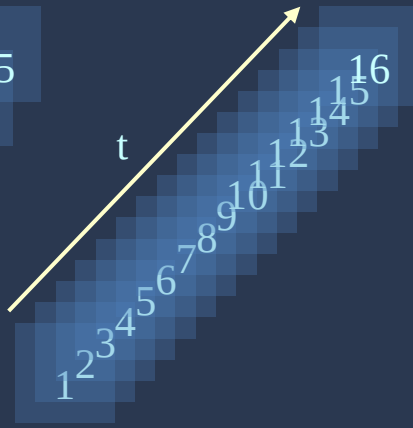
TR = 2, SR = 1/2



TR = 4, SR = 1/4



TR = 8, SR = 1/8



TR = 16, SR = 1/16

Captured Video

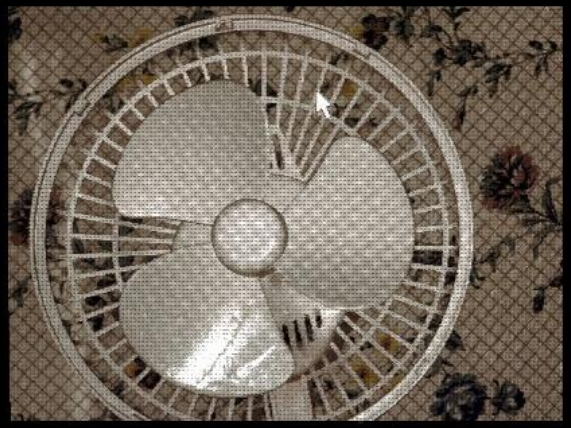
Naïve Reconstruction

8X Temporal Super-res, but 8 times lower spatial resolution

Optical Flow Magnitudes

Motion Aware Reconstruction

8X Temporal Super-res on moving fan, same spatial resolution on static parts



Captured Video

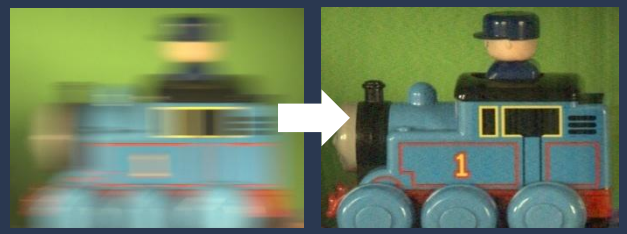
Naïve Reconstruction

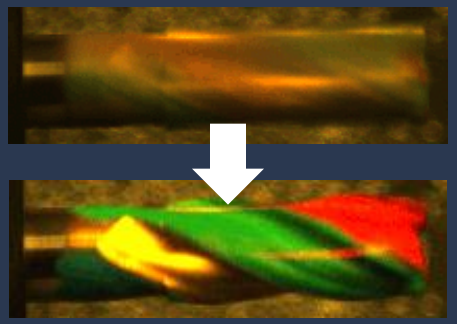
Optical Flow

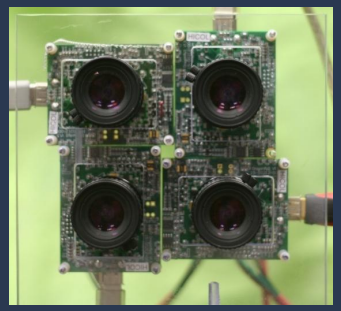
Motion Aware Reconstruction

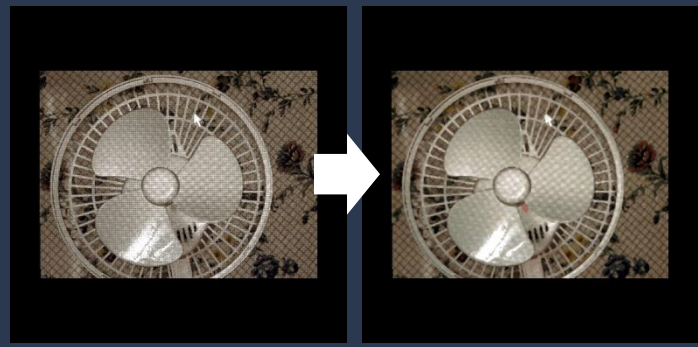
Summary: Temporal Modulations

- Coded Exposure (Photo)
  - Same for all pixels
  - Motion deblurring
- Strobe Camera (Video)
  - Same for all pixels in a frame
  - Different across frames
  - Temporal Super-Resolution (100x)
- Multi-Camera Arrays (Video)
  - Same for all pixels in a frame
  - Same across frames, different across cameras
  - High Speed Imaging
- Flexible Voxels (Motion Aware Video)
  - Different for pixels in a frame
  - Same across frames
  - Post Capture Space Time Resolution Tradeoff

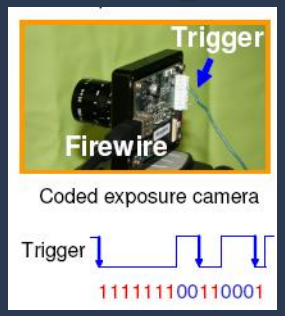


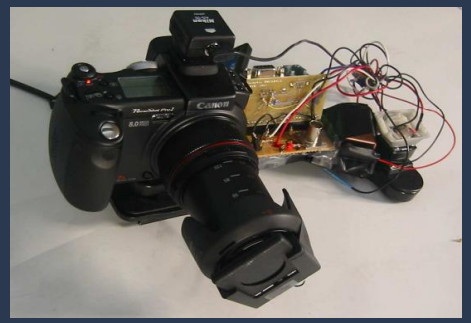




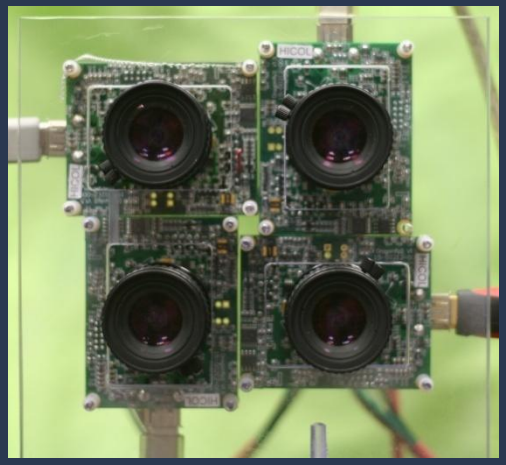


Section Summary





- Coding and Modulation
  - Beyond Photo Manipulations
- Key Concepts
  - PSF Invertibility and PSF Invariance
- Motion Blur and Defocus blur
  - Coded exposure, Coded aperture, Wavefront coding etc.
- High Speed Imaging
  - Strobing Camera
  - Coded Sampling for Camera Arrays
- Flexible Videography
  - Post-capture Resolution Tradeoff



Schedule

Introduction	Srinivasa, 10 mins
Assorted Pixels	Srinivasa, 20 mins
Coding and Modulation in Cameras	Amit, 45 mins
Break	10 min
Light Fields and Applications	Ankit, 60 mins
Break	10 min
Computational Illumination	Srinivasa, 45 mins
Future Trends	Amit, 15 mins
Discussion	