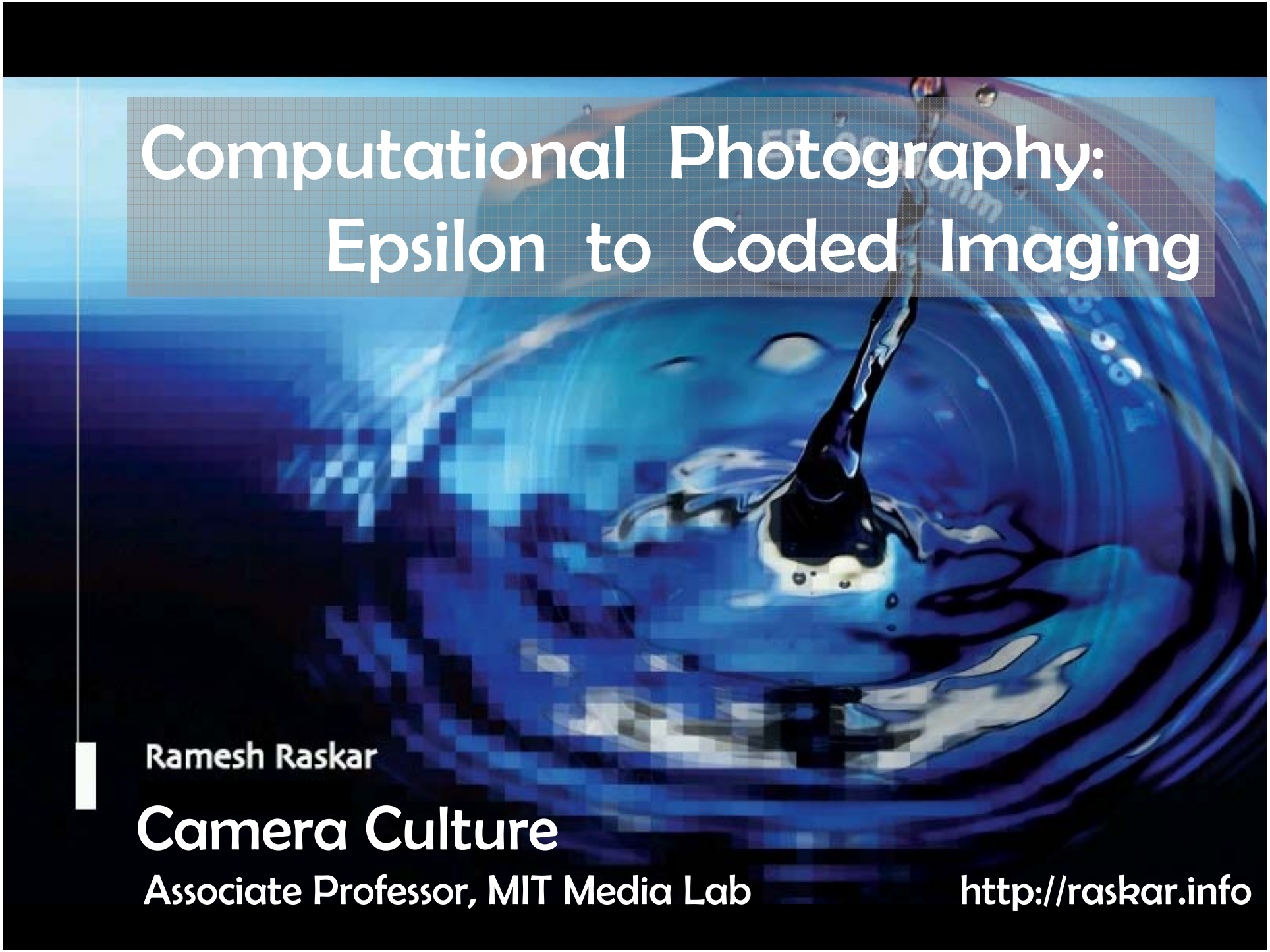


Computational Photography: Epsilon to Coded Imaging

Ramesh Raskar

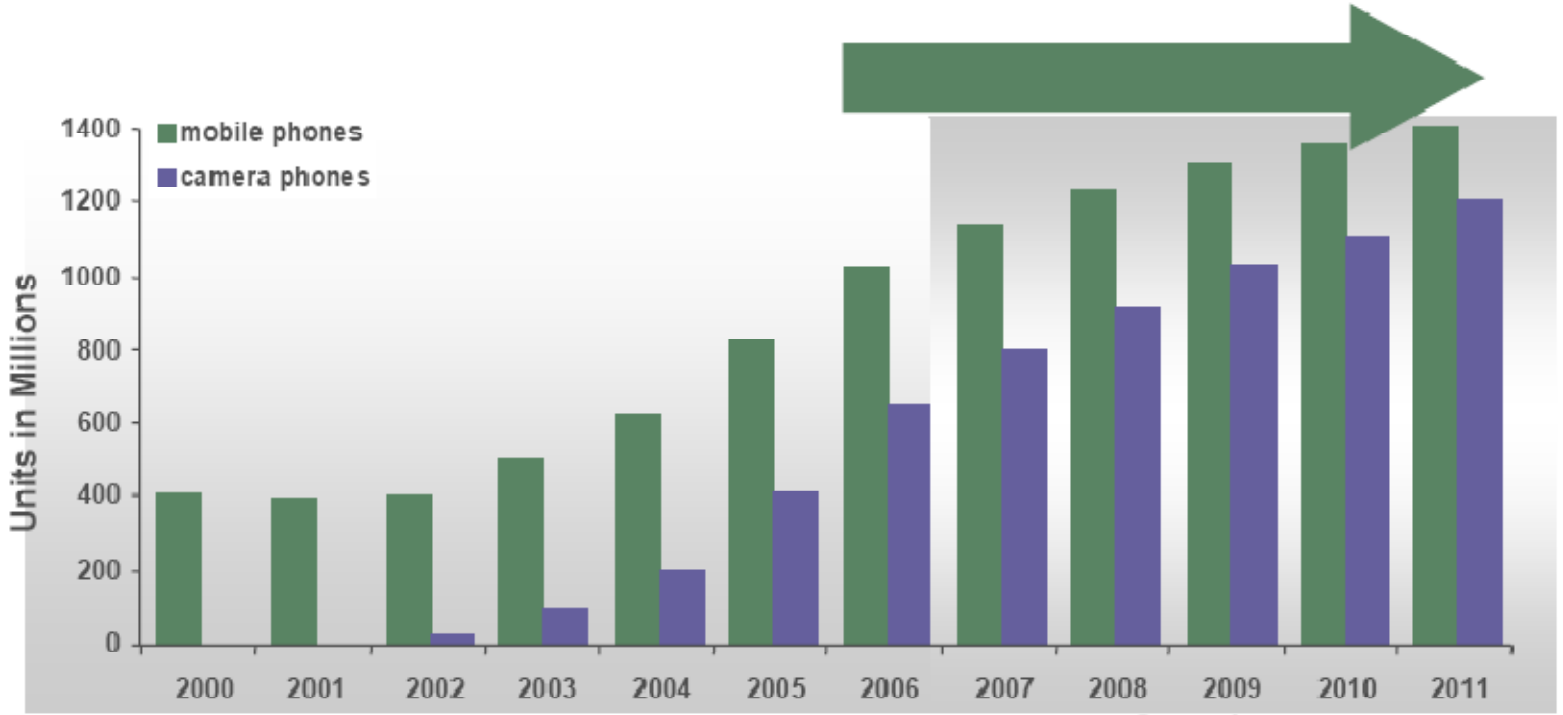
Camera Culture

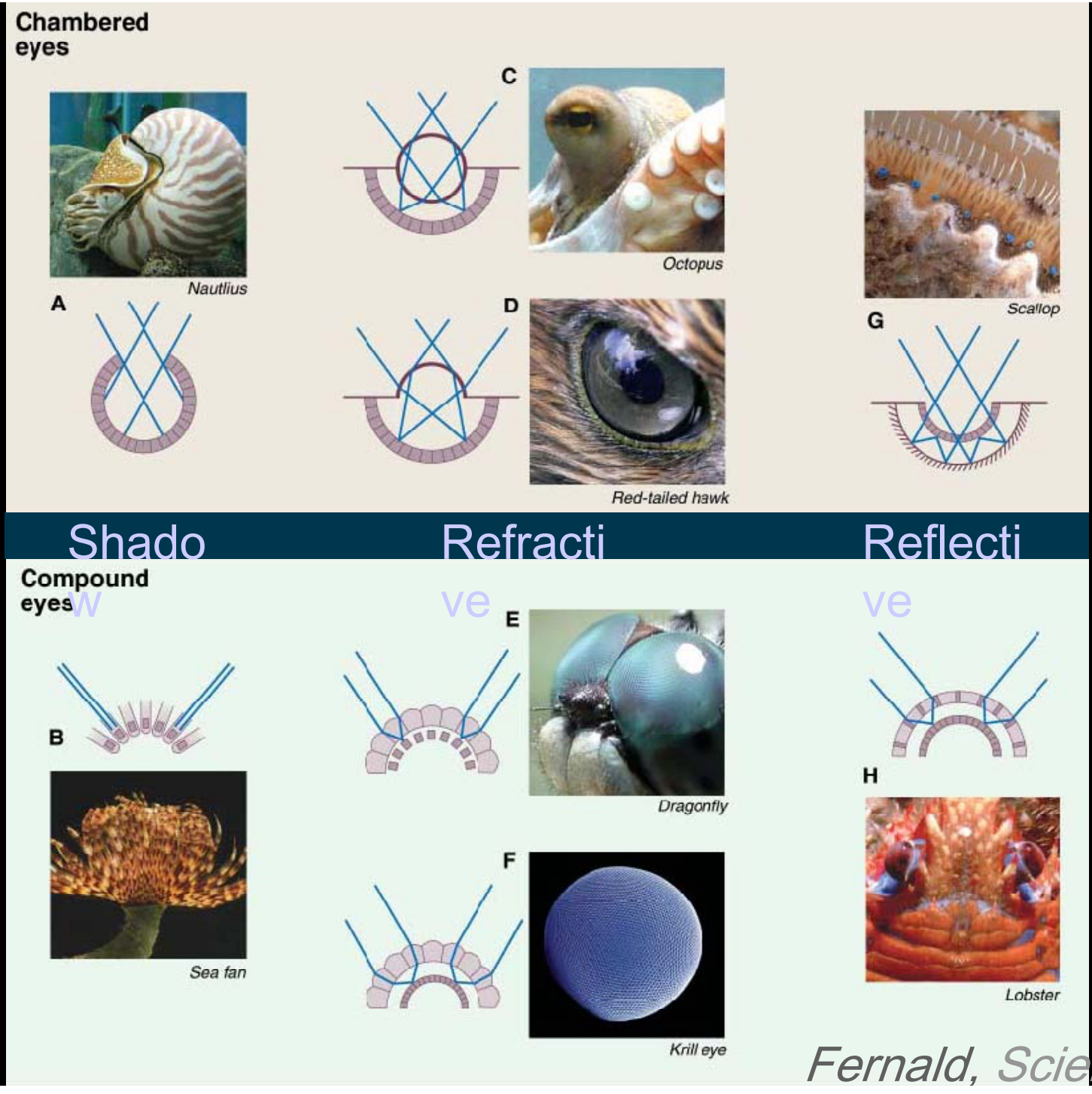
Associate Professor, MIT Media Lab

http://raskar.info

Integration of Cameras in Mobile Phones

TESSERA





Tools

for

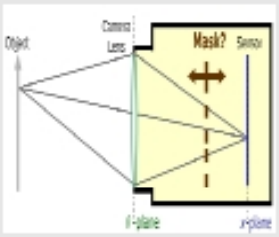
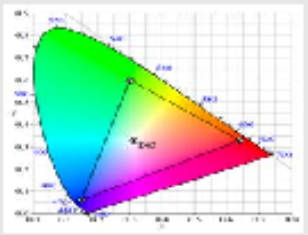
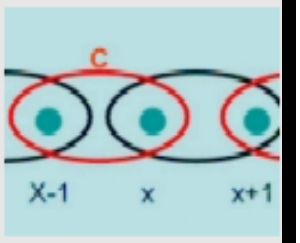
Visual

Computing

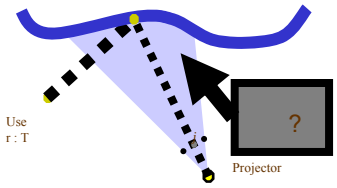
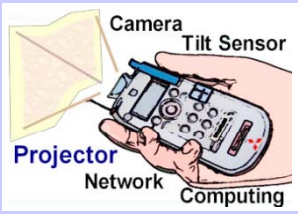
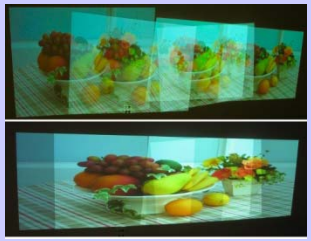
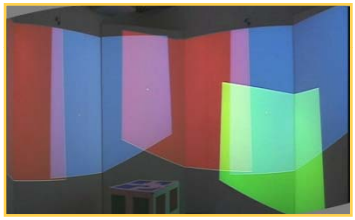
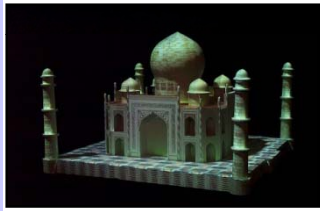
Fernald, Science [Sept 2006]

Camera Culture
MIT Media Lab

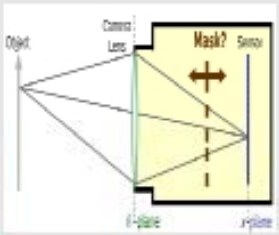
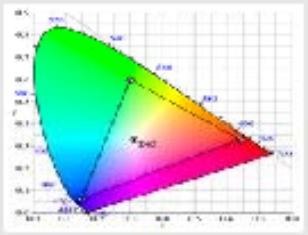
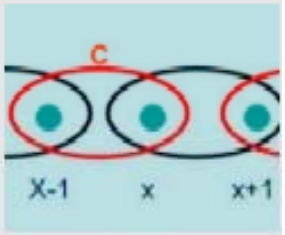
How can we create an entirely
new class of imaging platforms
that have an understanding of the world that far exceeds human ability
and produce meaningful abstractions that are well within human comprehensibility ?

Coded Time (Exposure)	Coding in Space		Coded Illumination	Coded Wavelength	Coded Sensing
Flutter Shutter Cam	Coded Aperture	Optical Heterodyning	Multi-flash Camera	Agile Spectrum	Gradient Processing
					
2006	2007	2007	2004	2008	2005

Computational Illumination

	Planar	Non-planar	Curved	Objects	Pocket-Proj
Single Projector	1998 	1997 		2002 	2002 
Multiple Projectors	1998 	1998 	2002 	1999 	2003 

Computational Camera and Photography

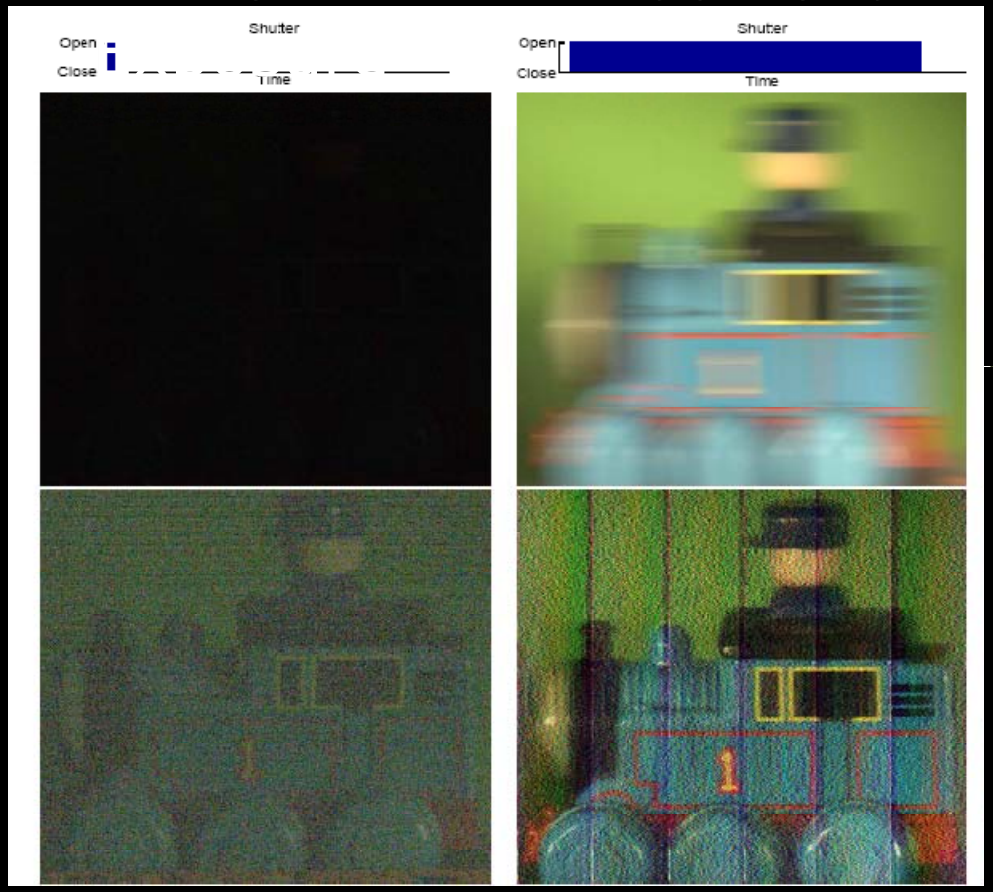
Coded Time (Exposure)	Coding in Space		Coded Illumination	Coded Wavelength	Coded Sensing
Flutter Shutter Cam	Coded Aperture	Optical Heterodyning	Multi-flash Camera	Agile Spectrum	Gradient Processing
					
2006	2007	2007	2004	2008	2005

Motion Blurred Photo


TOP CAB
286-4888

Short

Traditional



← Shutter

← Captured Single Photo

← Deblurred Result

Dark and noisy

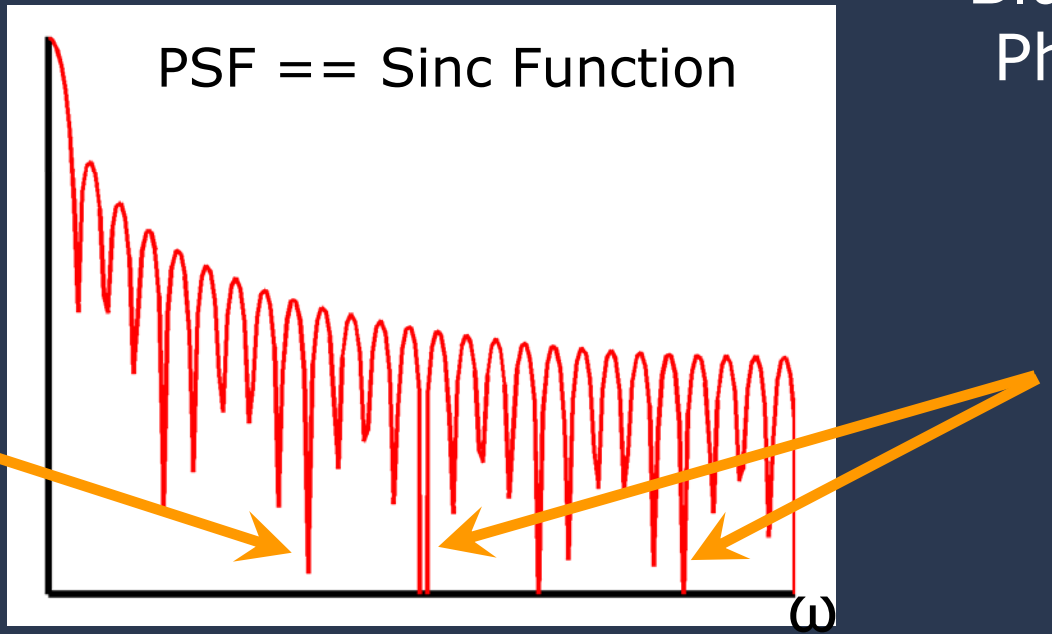
Banding Artifacts and some spatial frequencies are lost

Blurring == Convolution

Sharp Photo

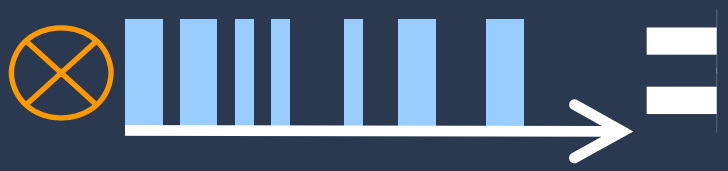
Fourier Transform

Blurred Photo

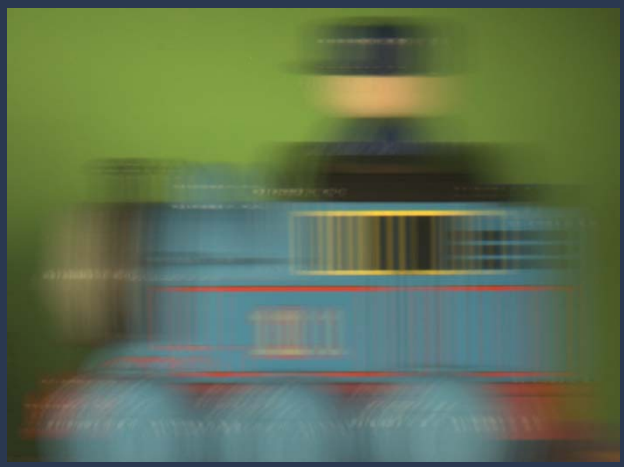


Traditional Camera: Shutter is OPEN: Box Filter

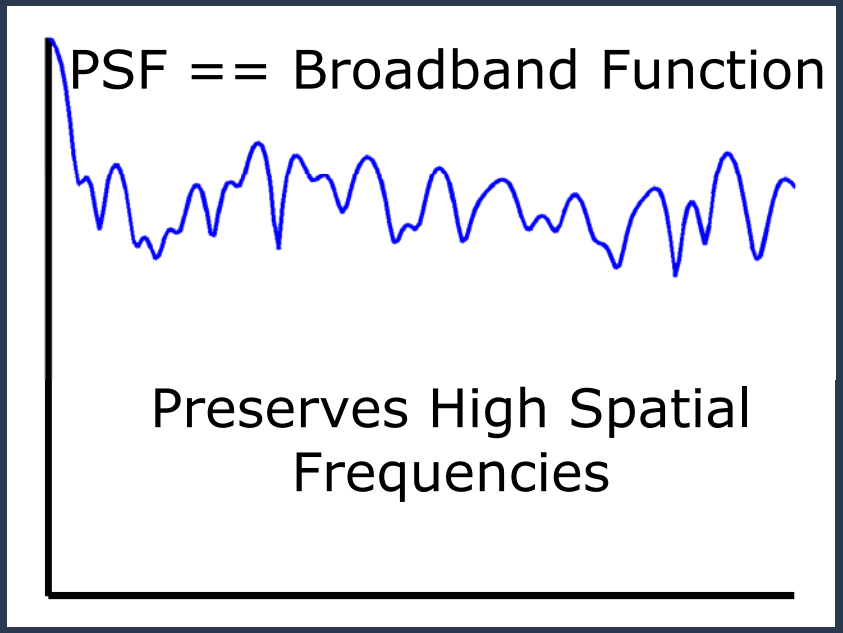
Sharp Photo



Fourier Transform



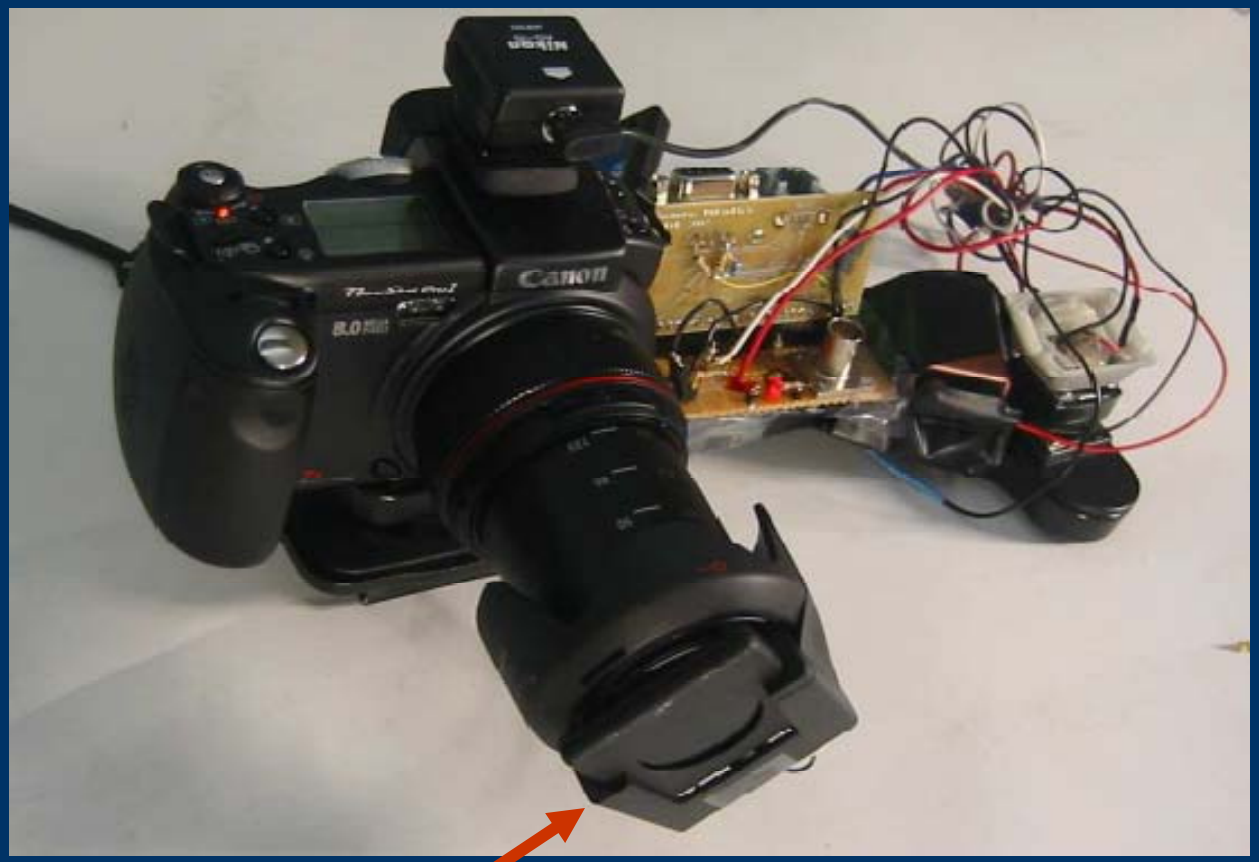
Blurred Photo



Flutter Shutter: Shutter is OPEN and CLOSED

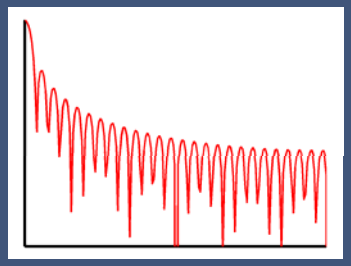
Flutter Shutter Camera

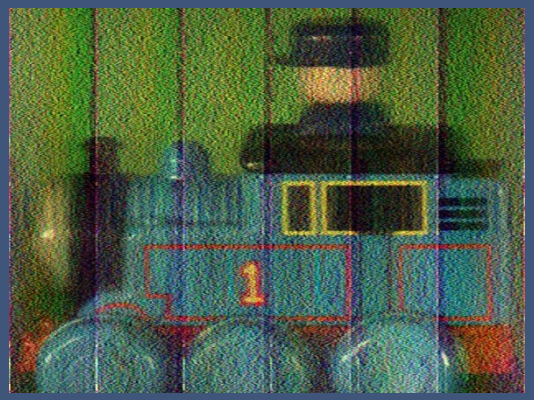
Raskar, Agrawal, Tumblin [Siggraph2006]



LCD opacity switched
in coded sequence

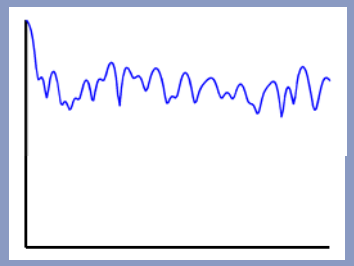
Traditio
nal

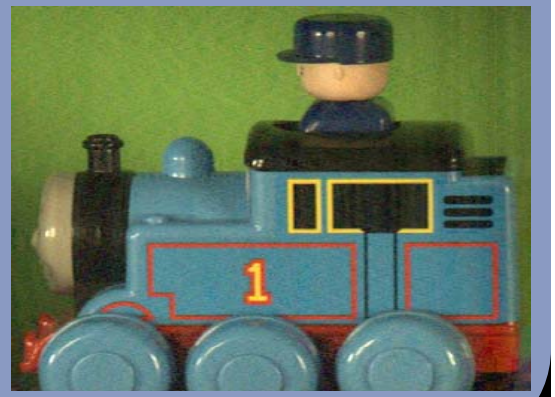




Deblurred
Image

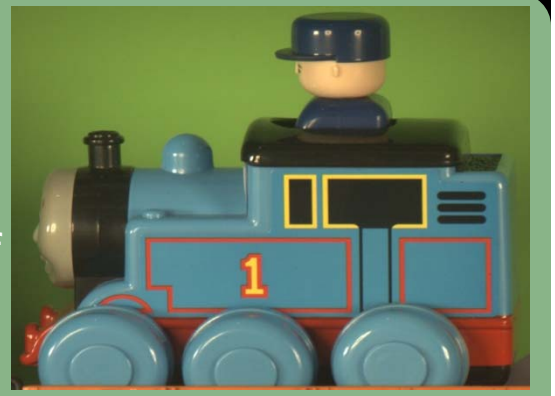
Coded
Exposu
re

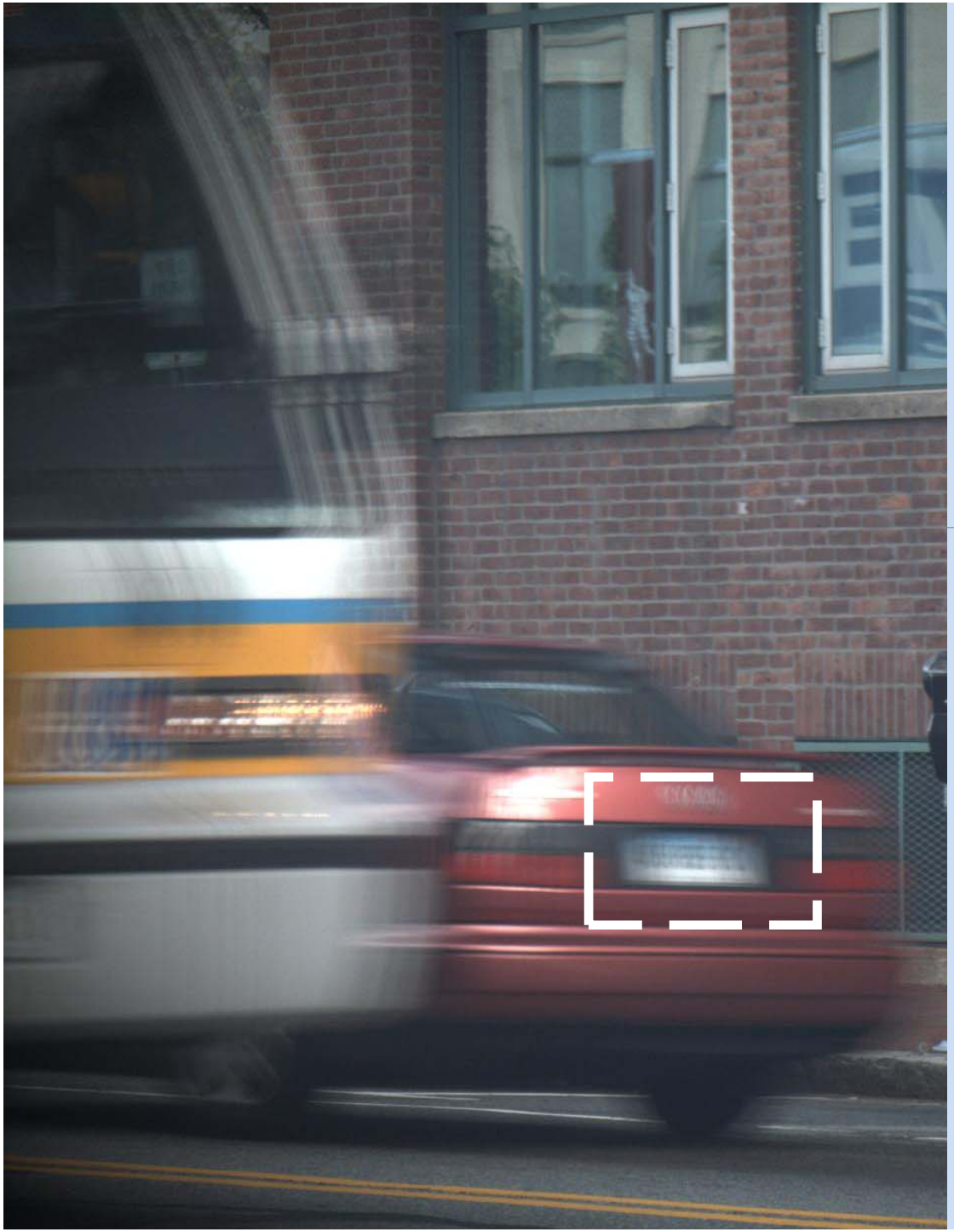




Deblurred
Image

Image of
Static
Object



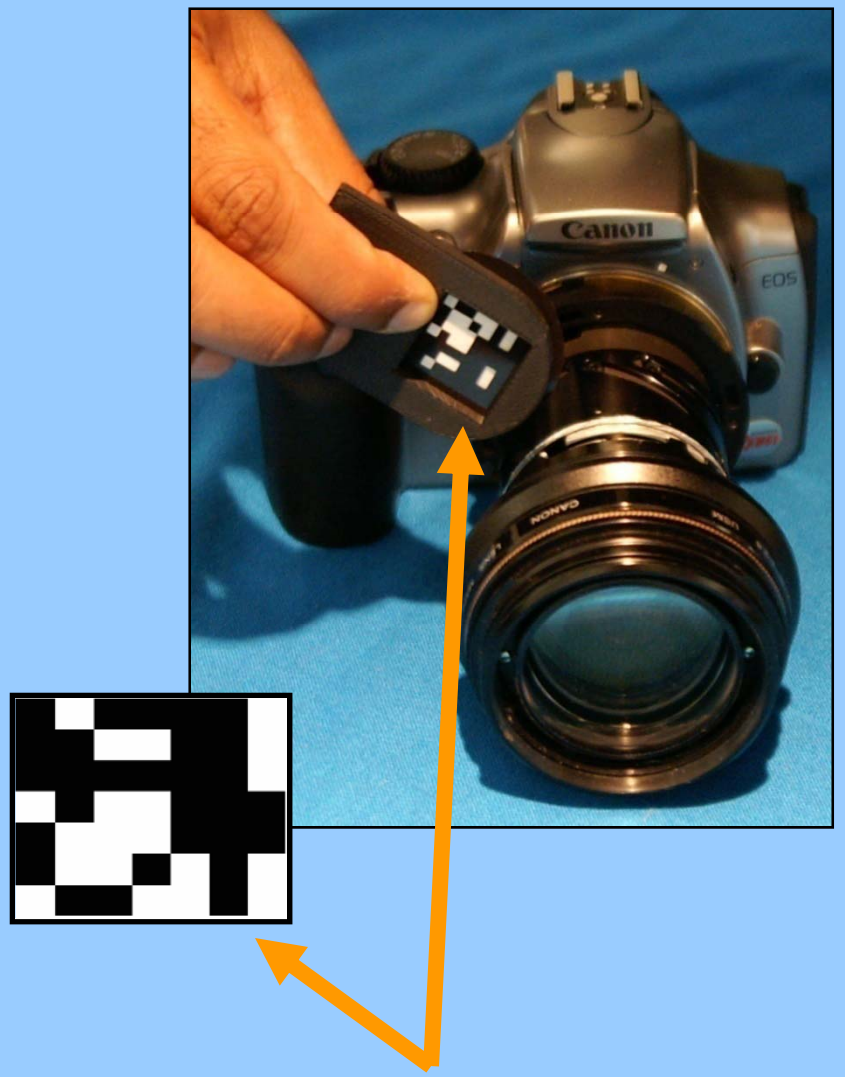



485-PCK

Coded Exposure

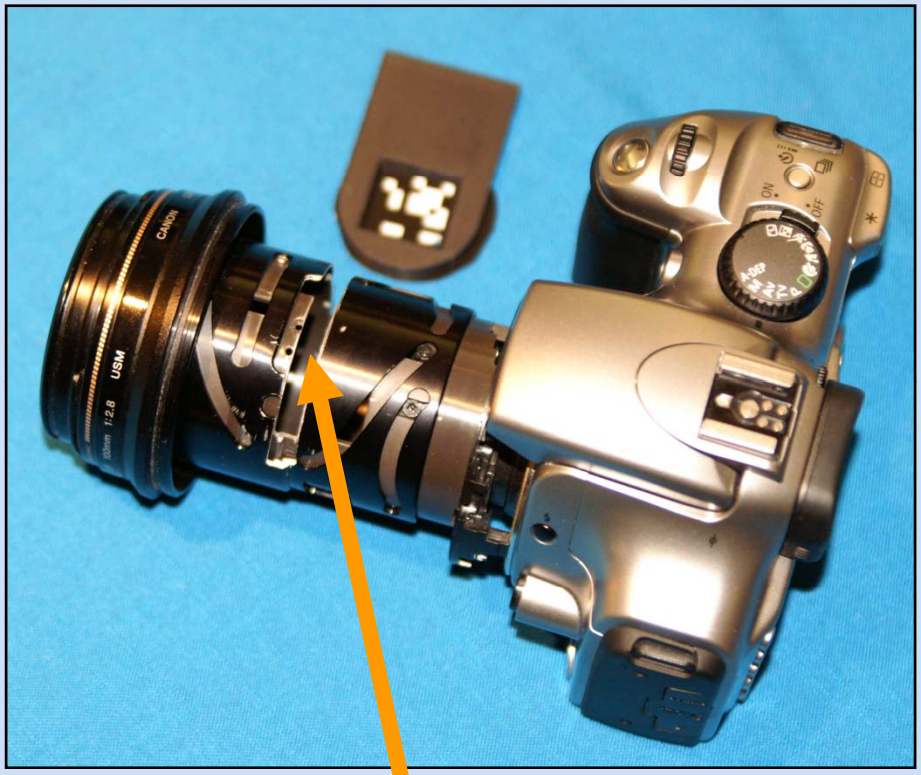
Temporal 1-D broadband code:
Motion Deblurring

Coded Aperture



Spatial 2-D broadband mask:
Focus Deblurring

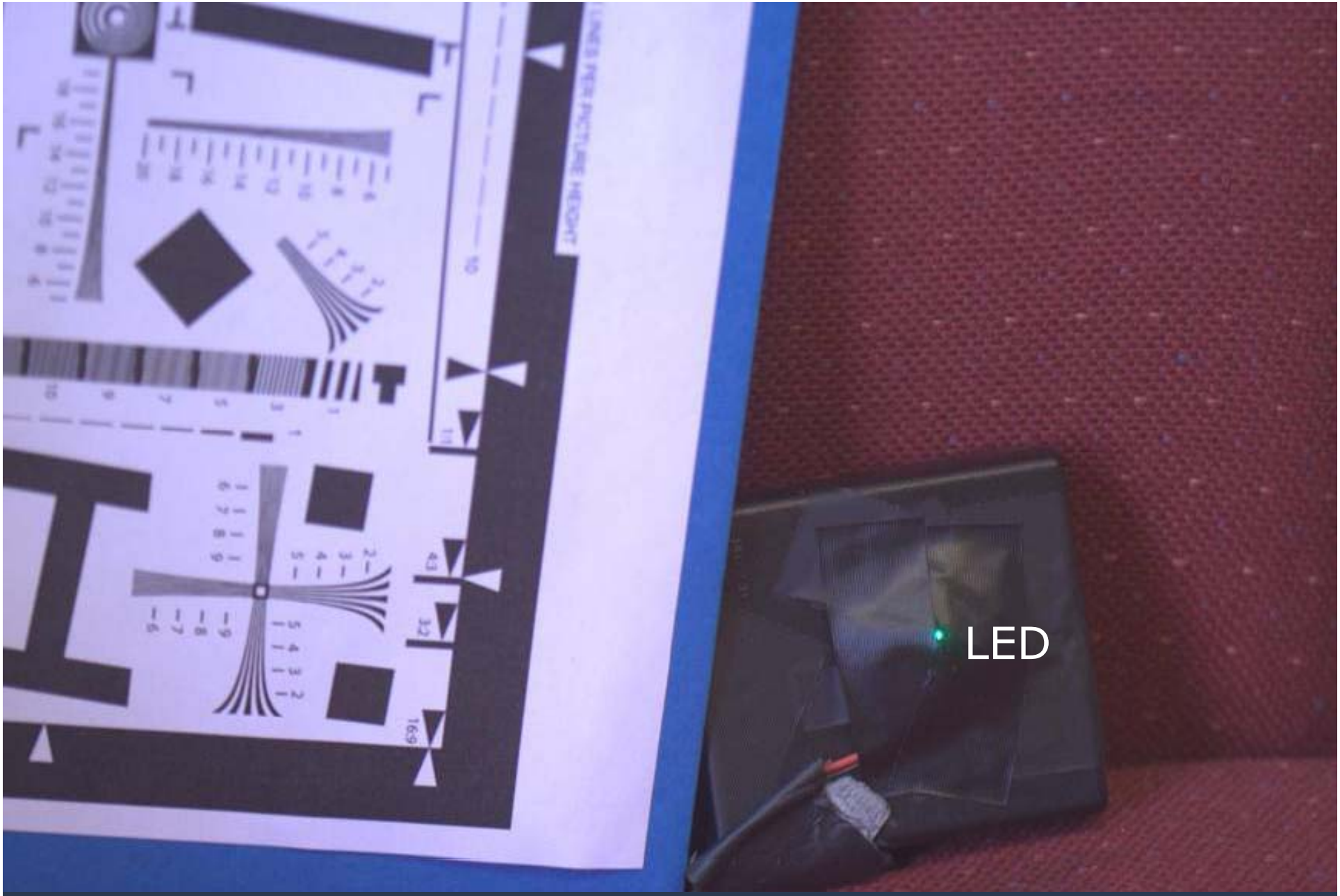
Coded Aperture Camera



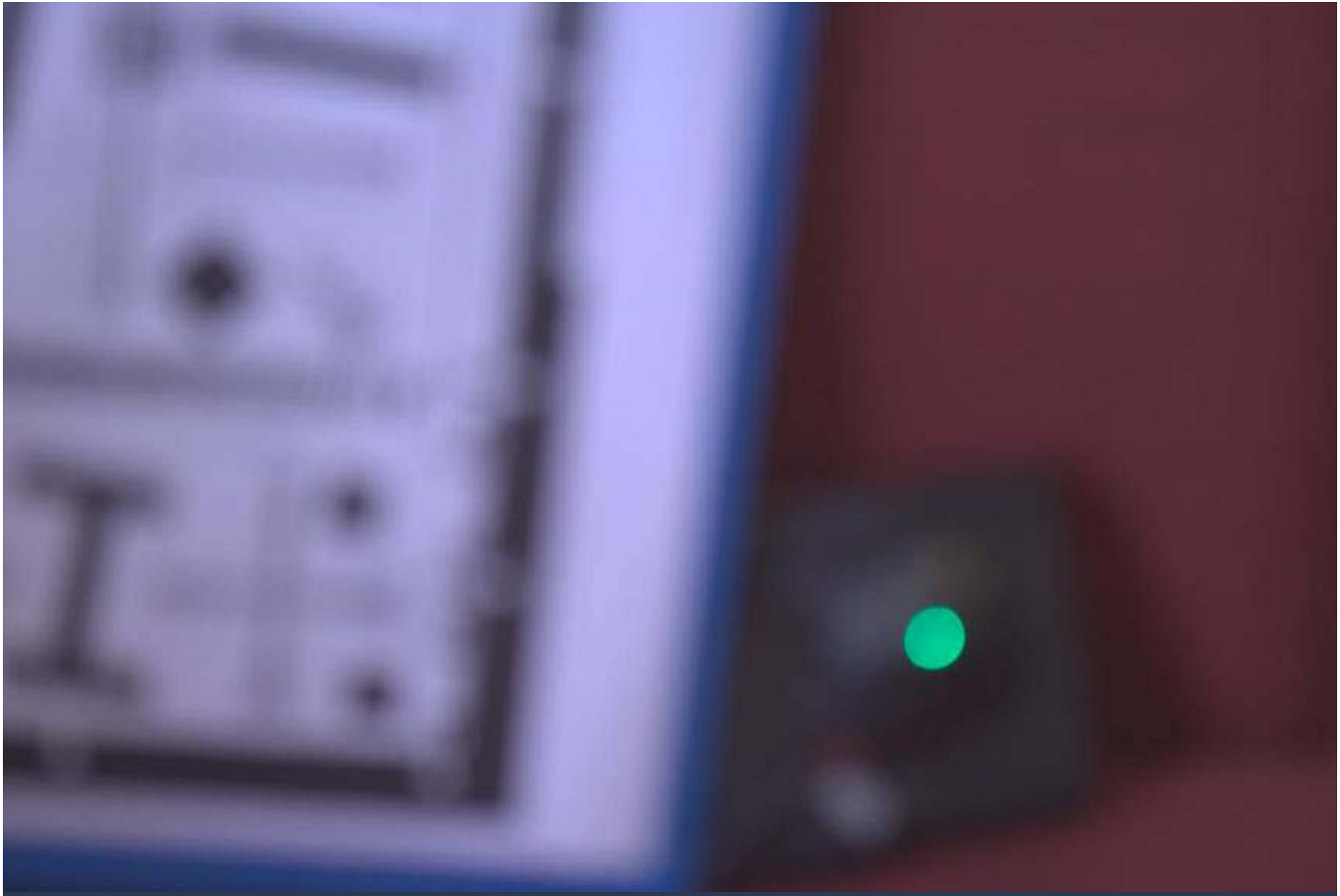
The aperture of a 100 mm lens is modified

Insert a coded mask with chosen binary pattern

Rest of the camera is unmodified



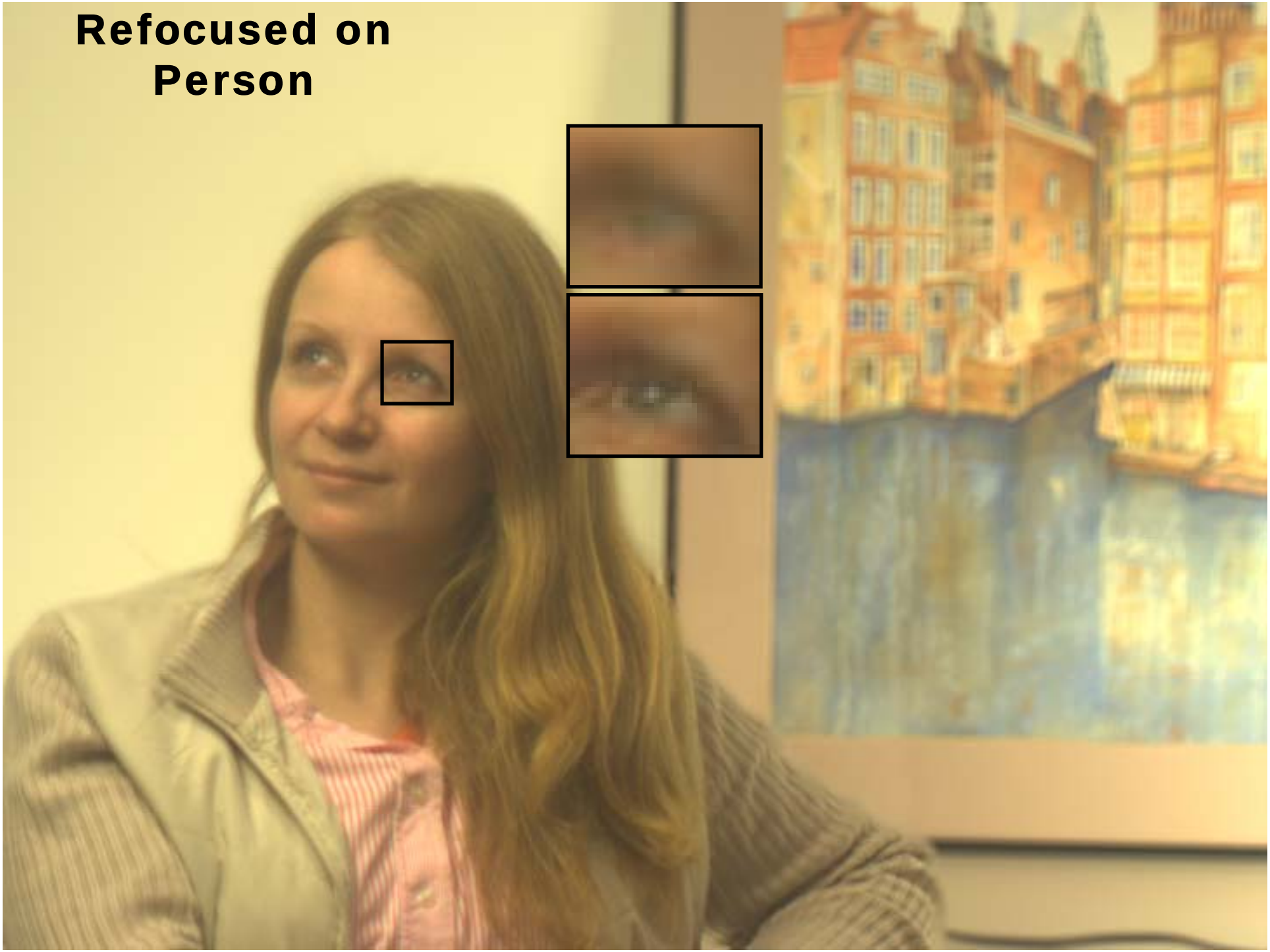
In Focus Photo



Out of Focus Photo: Open Aperture

Out of Focus Photo: Coded Aperture


Captured Blurred
Photo


Refocused on
Person

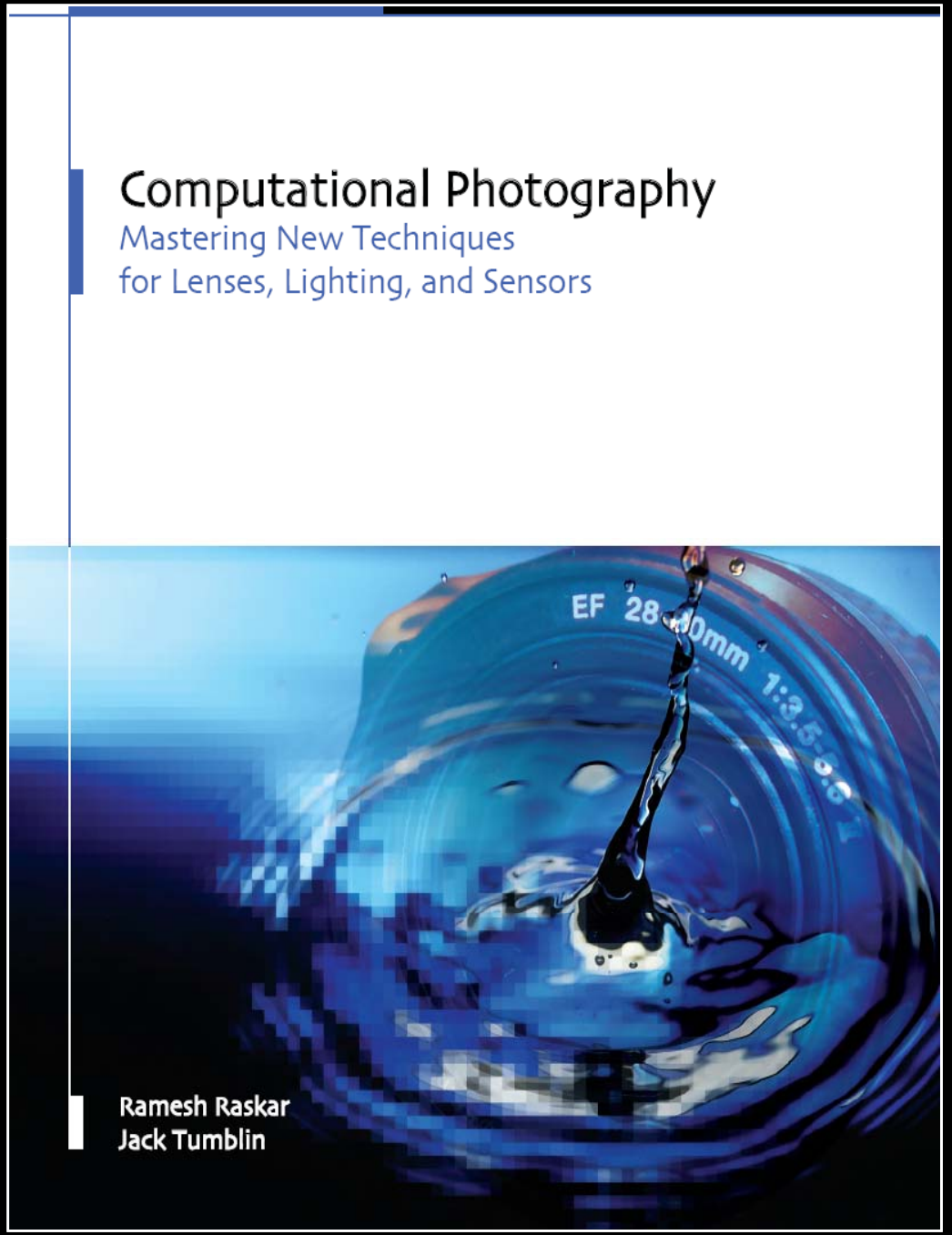
Computational Photography

1. Epsilon Photography
   - Low-level Vision: Pixels
   - Multiphotos by bracketing (HDR, panorama)
   - 'Ultimate camera'

2. Coded Photography
   - Mid-Level Cues:
     - Regions, Edges, Motion, Direct/global
   - Single/few snapshot
     - Reversible encoding of data
   - Additional sensors/optics/illum

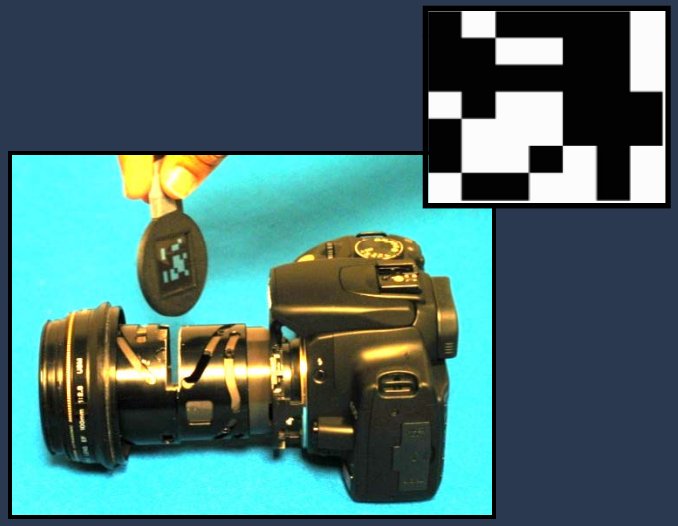
3. Essence Photography
   - Not mimic human eye
   - Beyond single view/illum
   - 'New artform'

- Ramesh Raskar and Jack Tumblin
- Book Publishers: A K Peters



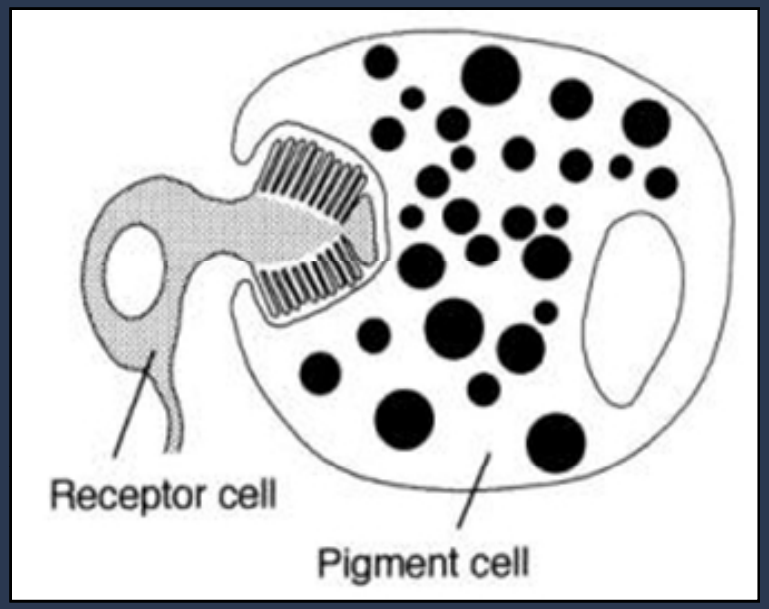
Less is More

Blocking Light == More Information

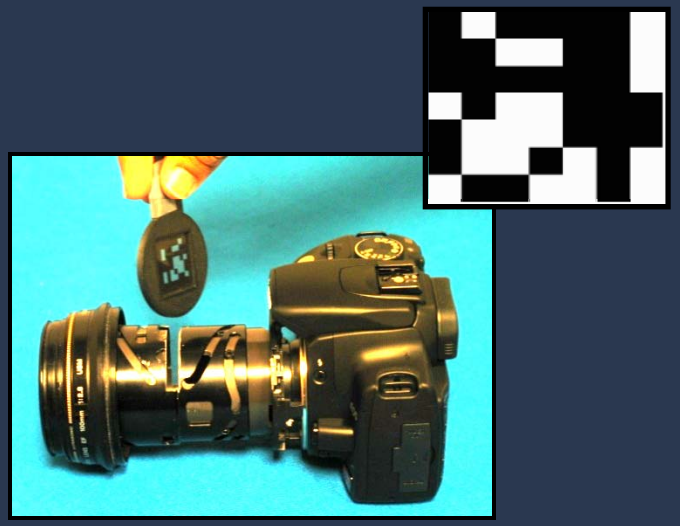


Coding in Time

Coding in Space

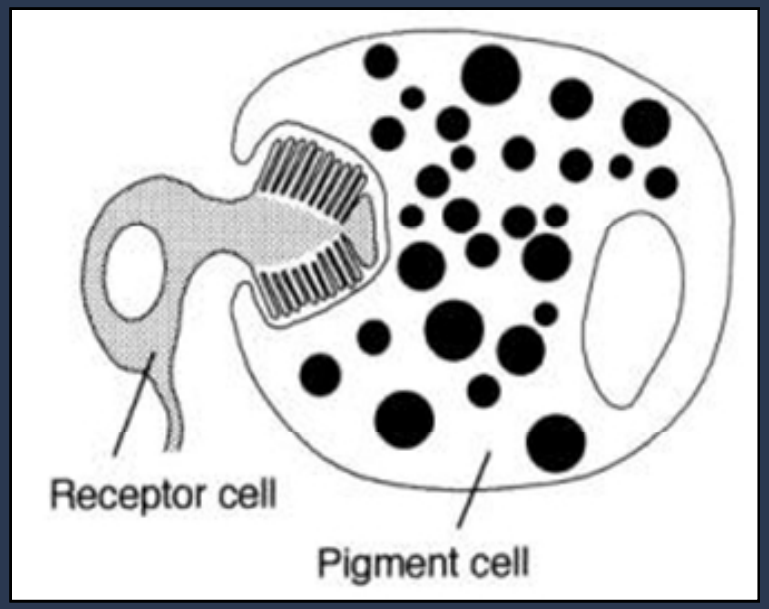


Larval Trematode Worm

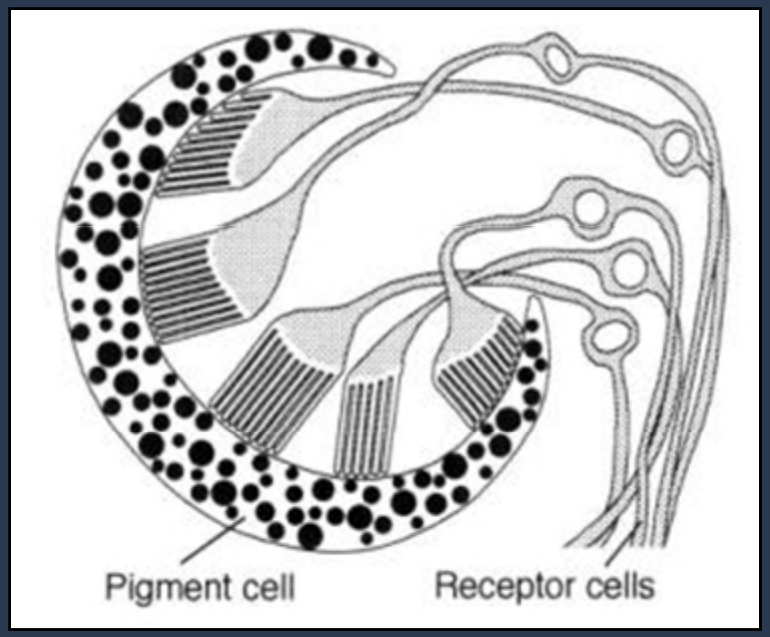


Coded Aperture Camera

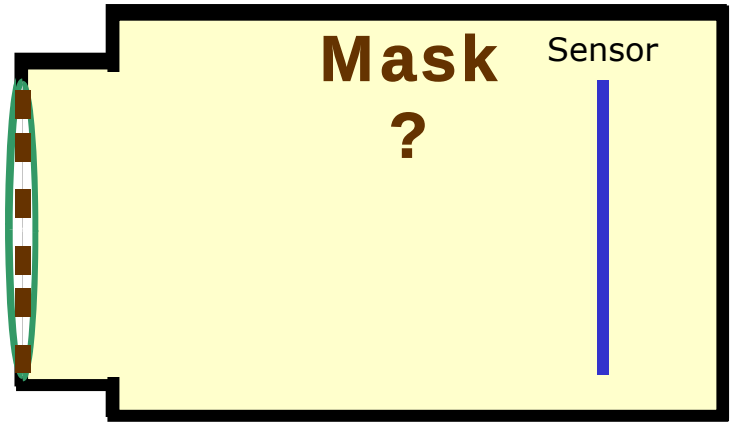
Shielding Light …

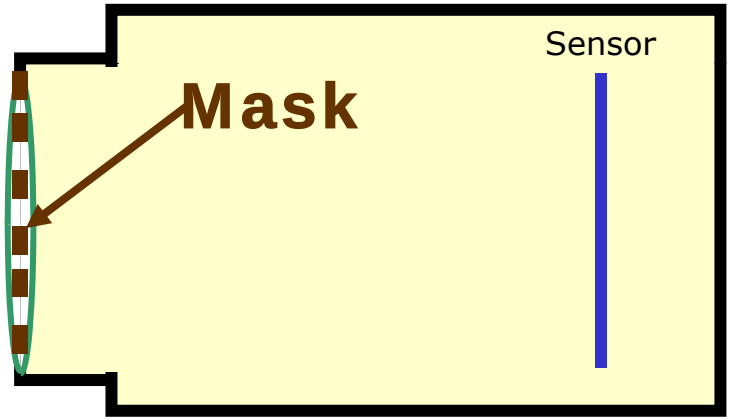


Larval Trematode Worm



Turbellarian Worm





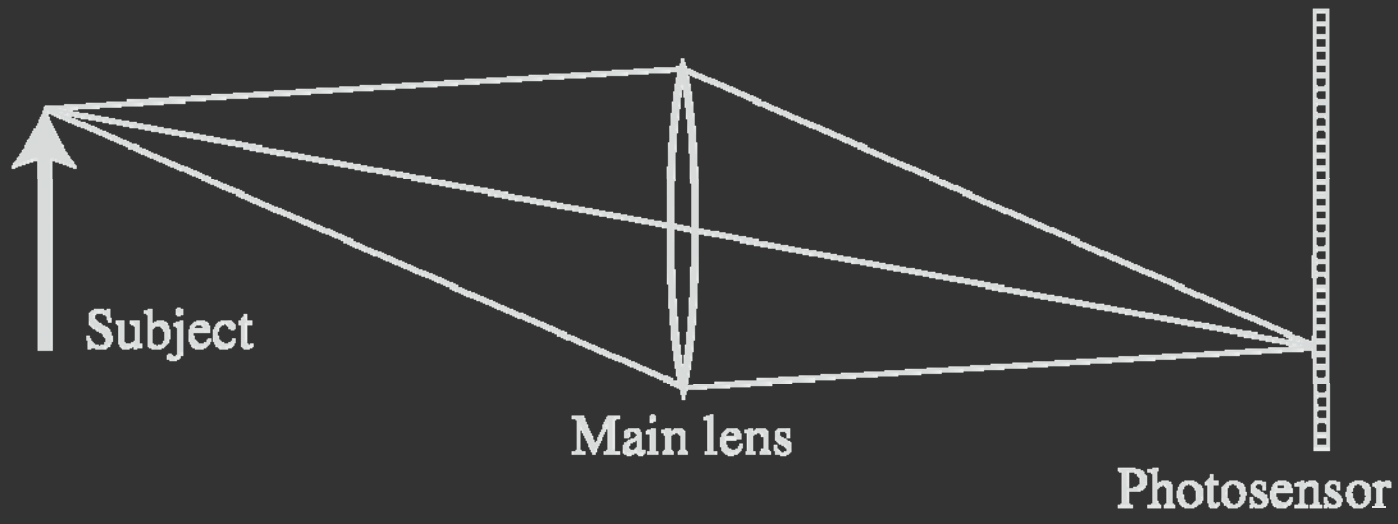
Full Resolution Digital Refocusing:

Coded Aperture Camera

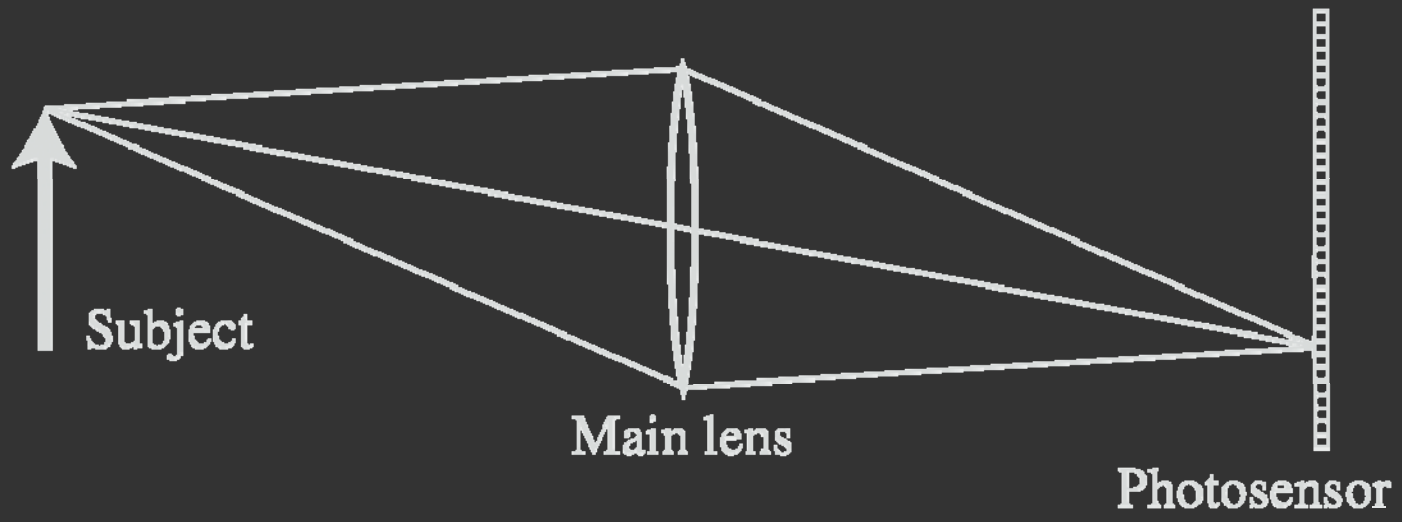
4D Light Field from 2D Photo:

Heterodyne Light Field Camera

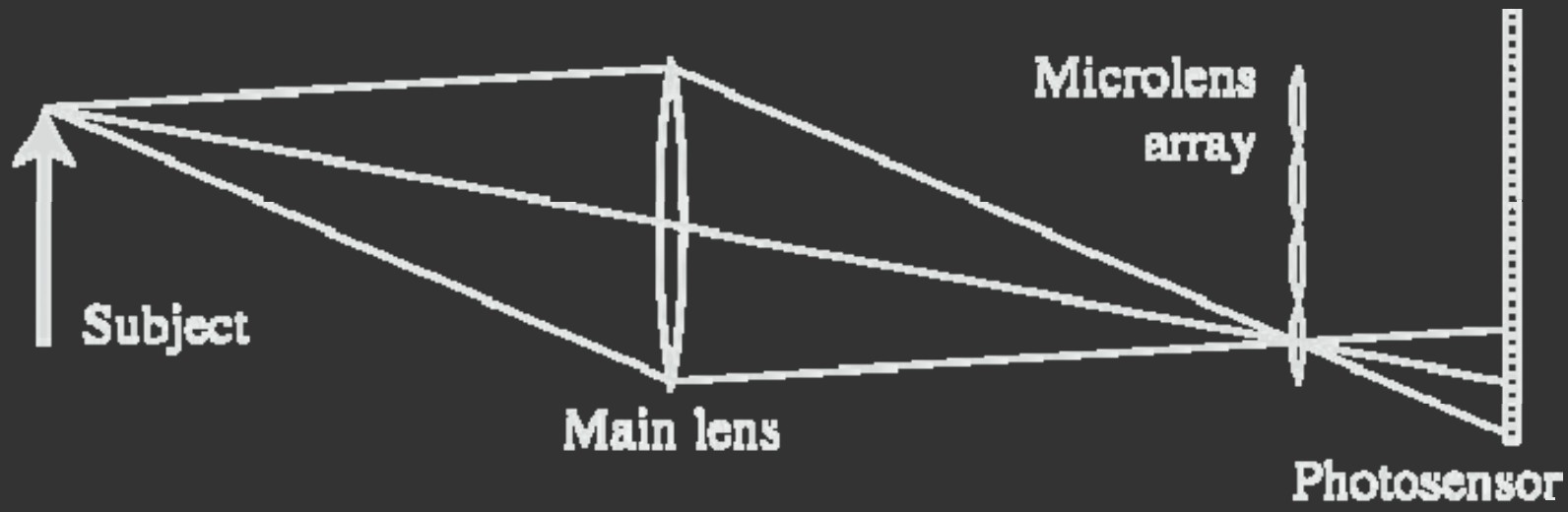
Light Field Inside a Camera



Light Field Inside a Camera



Lenslet-based Light Field camera

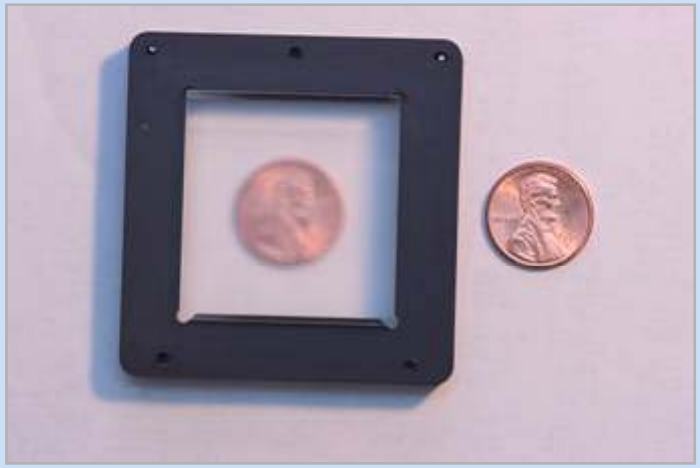


[Adelson and Wang, 1992, Ng et al. 2005]

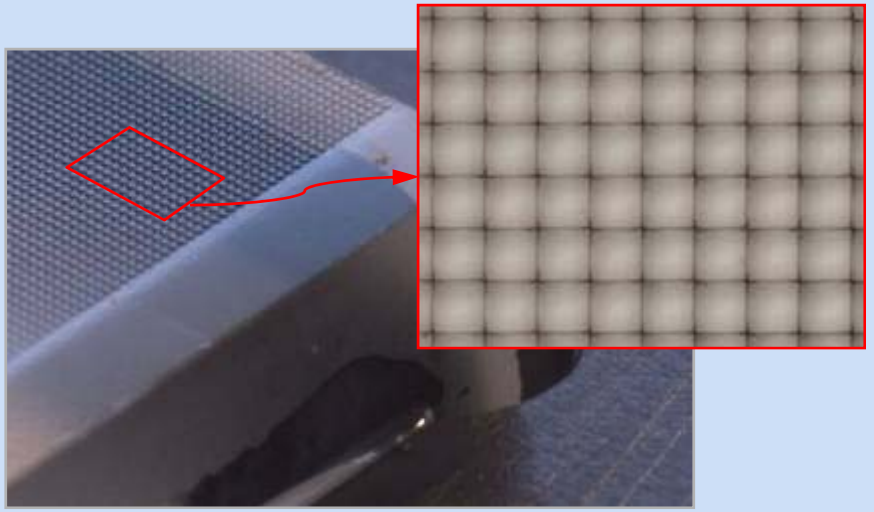
Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor



Adaptive Optics microlens array



125µ square-sided microlenses

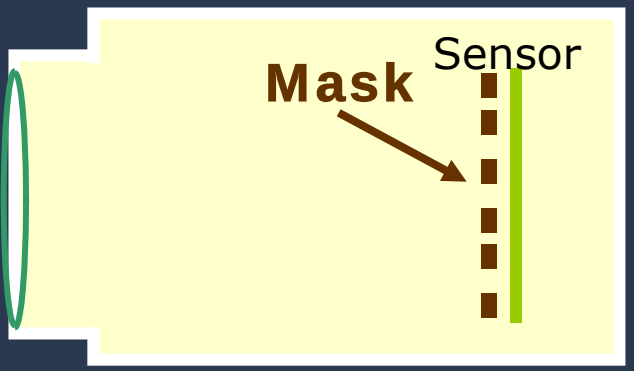
4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens

Digital Refocusing

[Ng et al 2005]

Can we achieve this with a Mask alone?

Mask based Light Field Camera

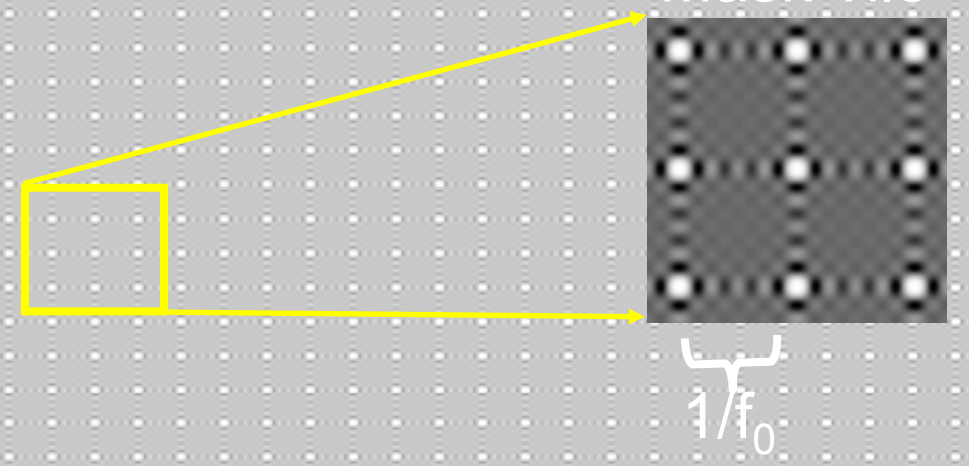


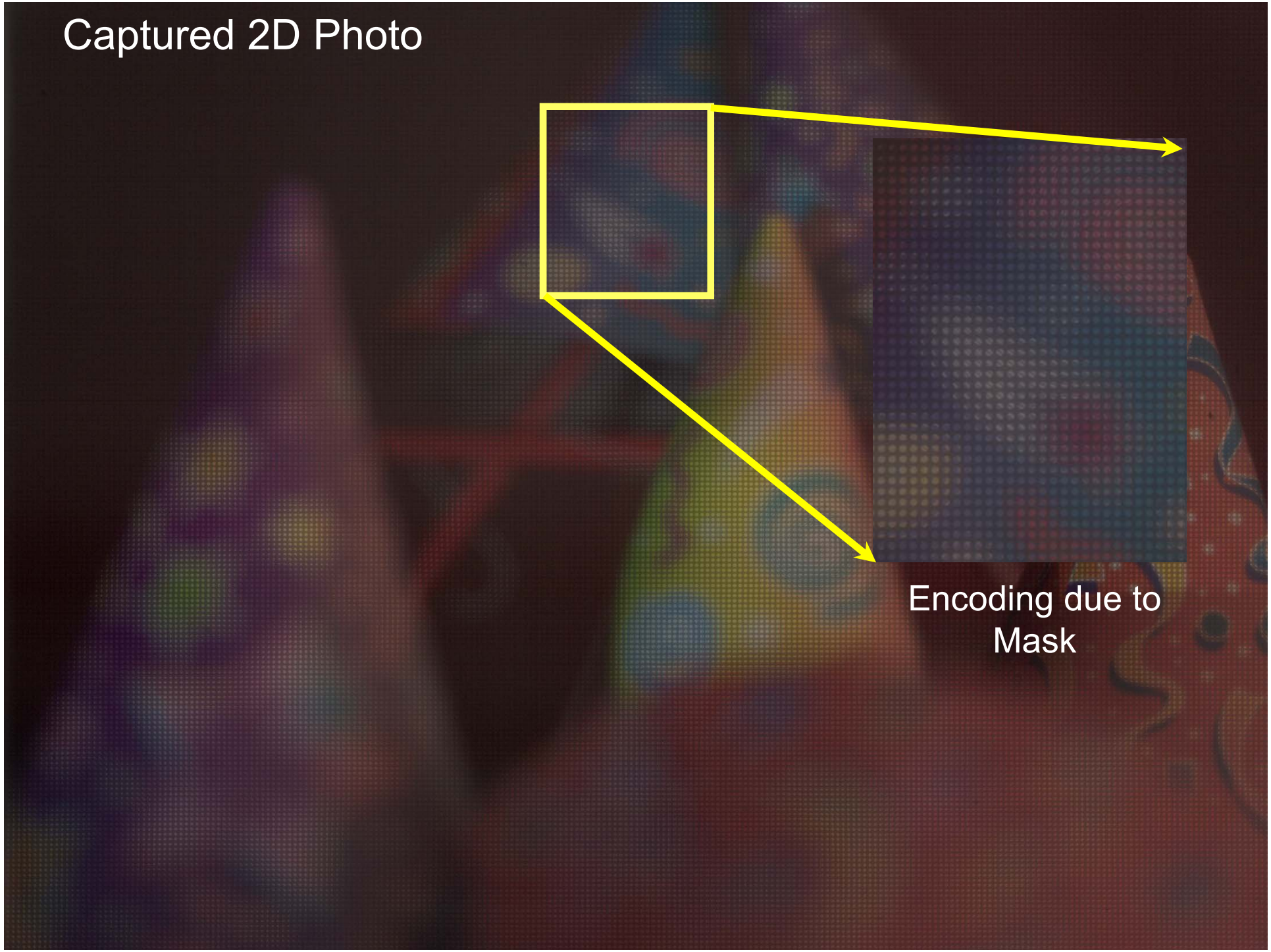
[Veeraraghavan, Raskar, Agrawal, Tumblin, Mohan, Siggraph 2007]

How to Capture 4D Light Field with 2D Sensor ?

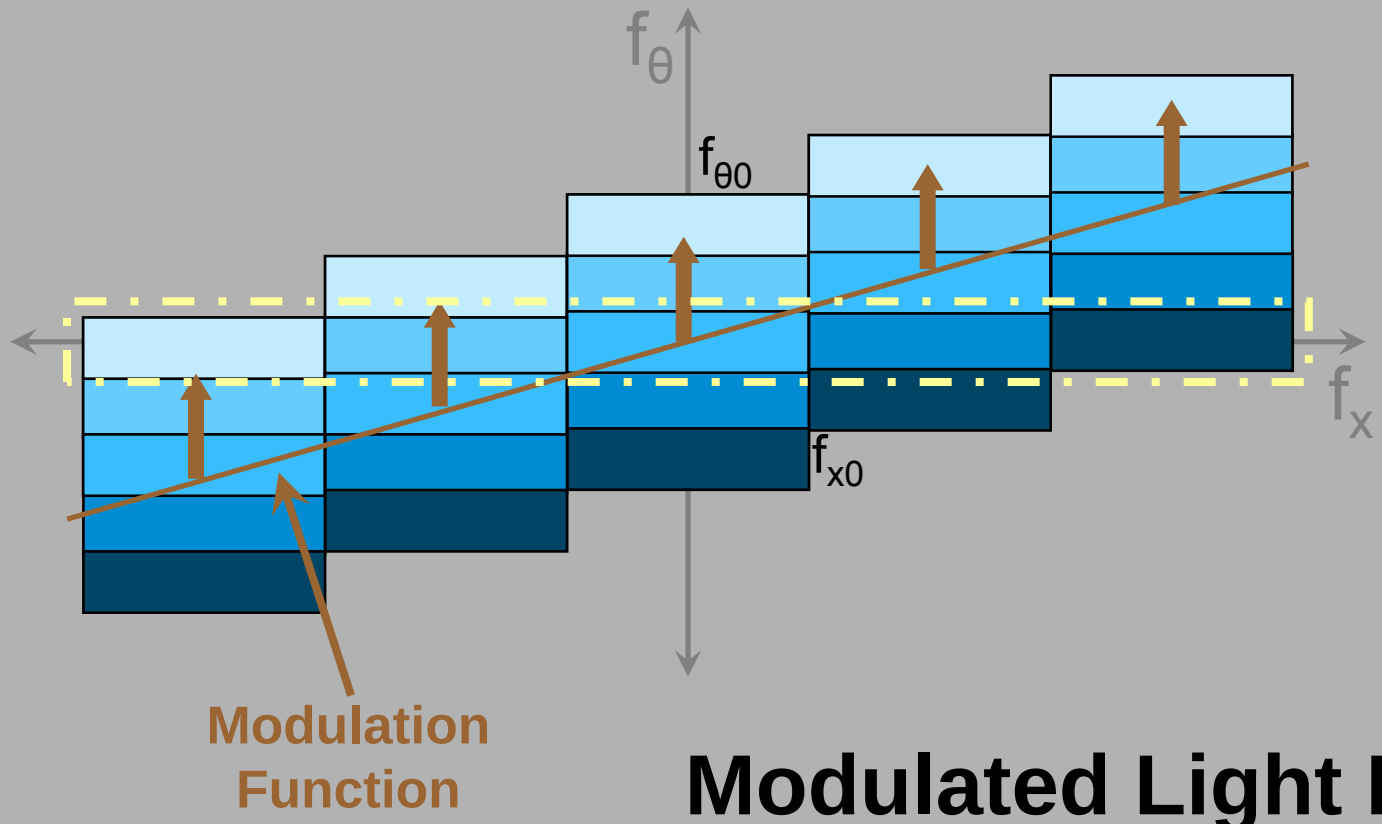
What should be the pattern of the mask ?

Cosine Mask Used




Captured 2D Photo
Encoding due to Mask

Sensor Slice captures entire Light Field



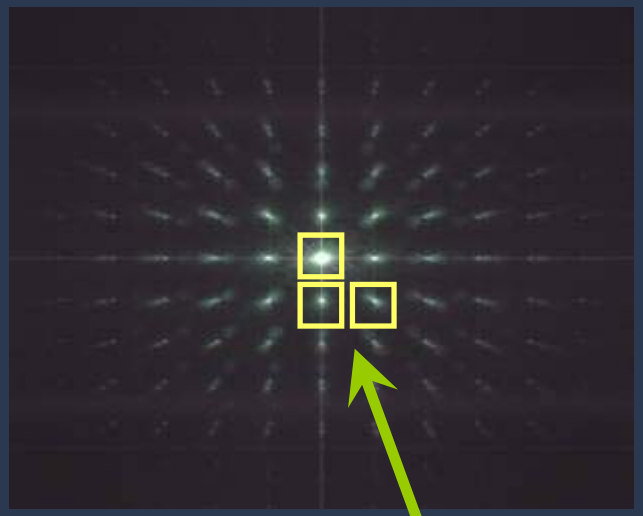
Modulated Light Field

Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D
FFT

2D Fourier Transform, 1800*1800



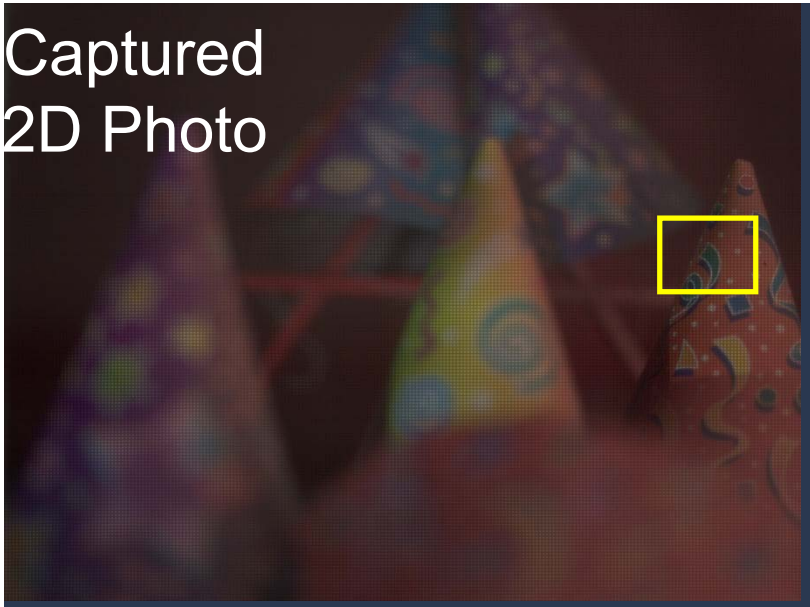
9*9=81 spectral copies

Rearrange 2D tiles into 4D
200*200*9*9
planes

4D IFFT

4D Light Field
200*200*9*9

Captured
2D Photo



divide

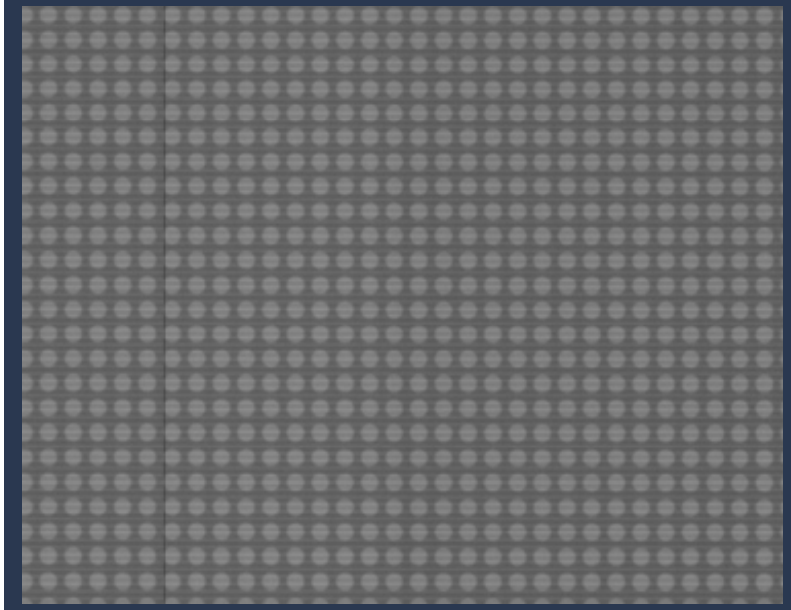
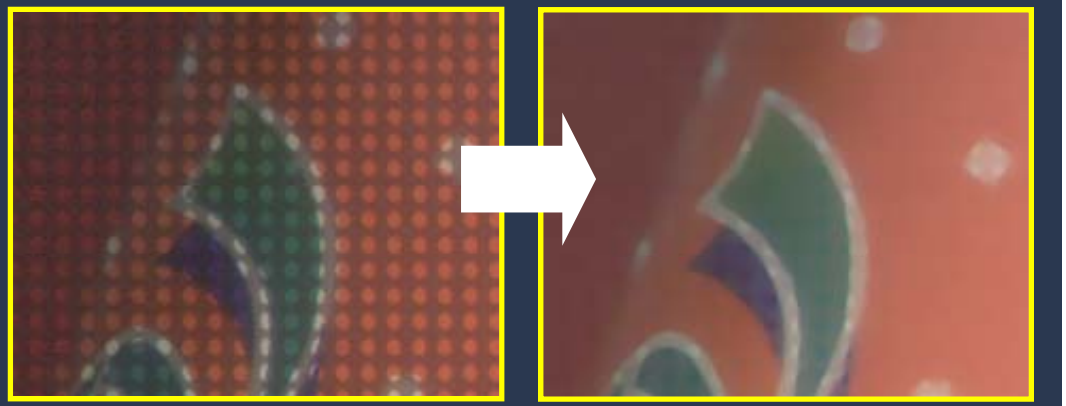


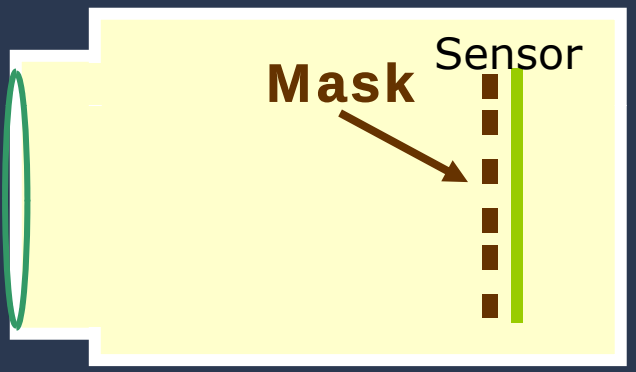
Image of White Lambertian Plane

=

Full resolution 2D image of Focused Scene Parts



Wavefront Sensing in Any Wavelength !



[Veeraraghavan, Raskar, Agrawal, Tumblin, Mohan, Siggraph 2007]

Lens Flare Reduction / Enhancement using 4D Ray Sampling

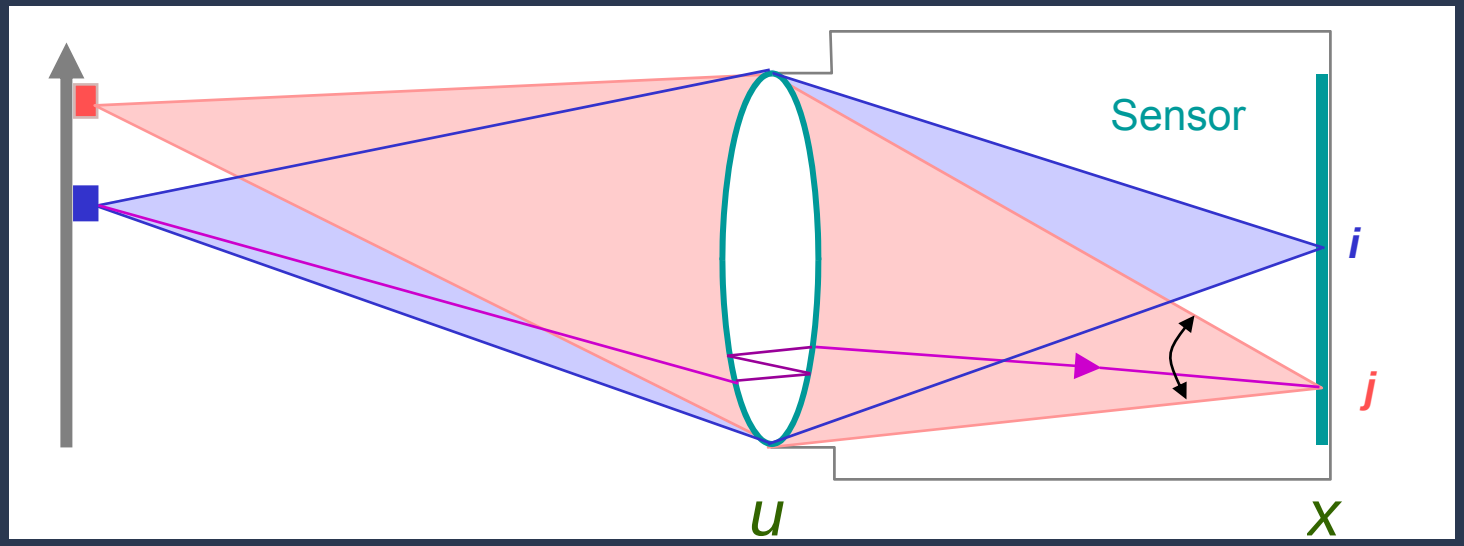
Glare Enhanced

Captured

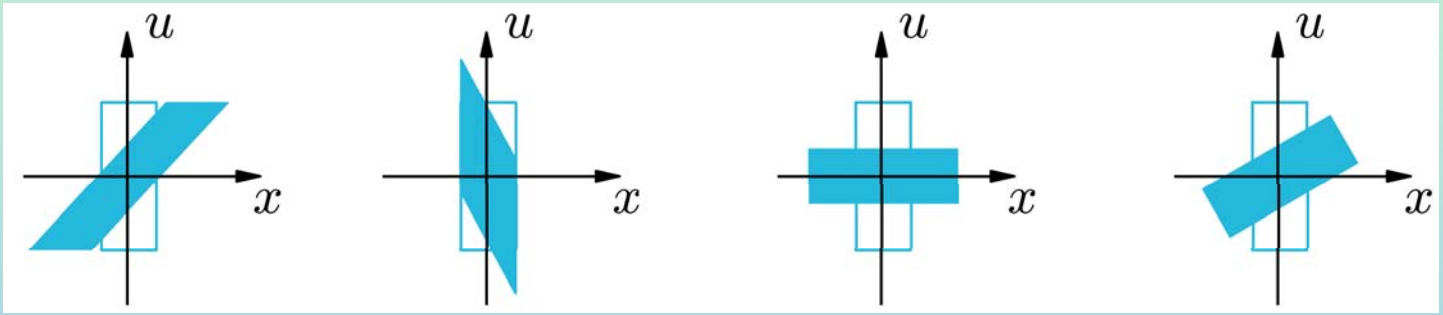
Glare Reduced

Glare = low frequency noise in 2D

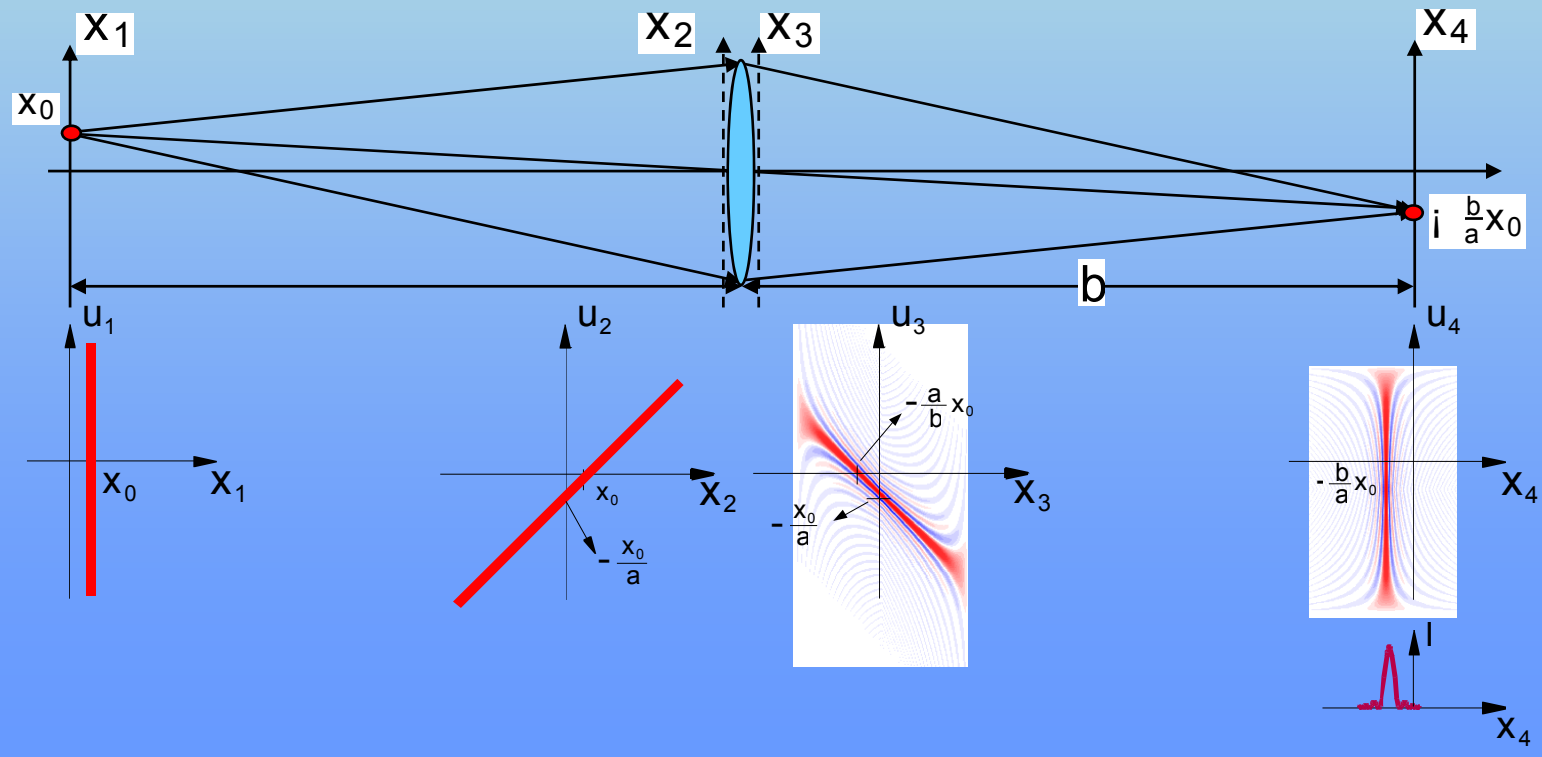
- But is high frequency noise in 4D
- Remove via simple outlier rejection



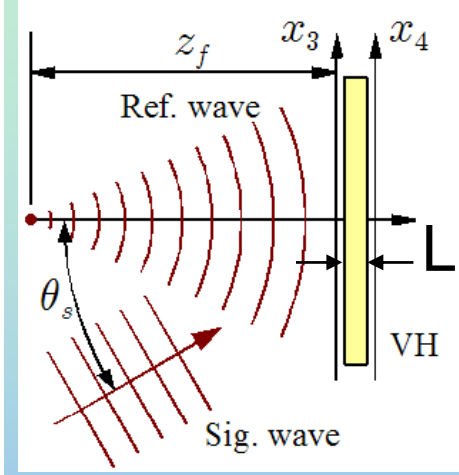
Rays = Waves for Propagation and Interface

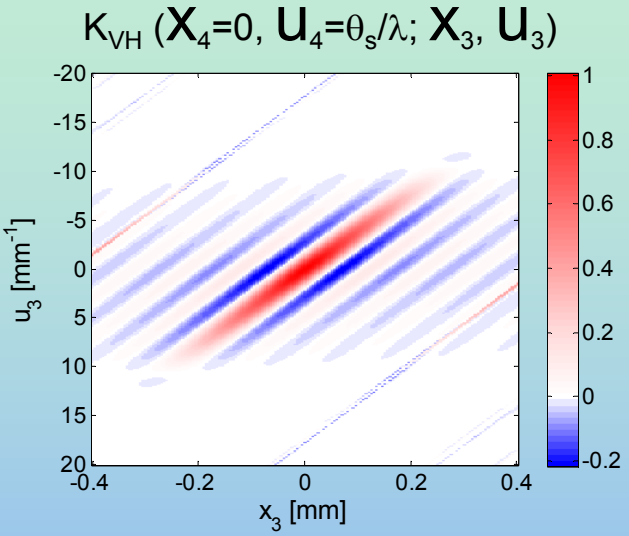


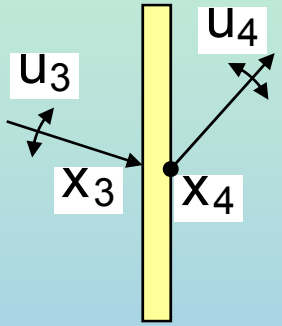
Fresnel propagation | Chirp (Lens) | Fourier transform | Fractional Fourier transform



Imaging via volume hologram (Depth-specific Imaging)







$$K_{VH}(x_4;u_4;x_3;u_3) = \iint dx_3^0 dx_4^0 e^{-i2\pi(u_4^0 x_4 - u_3^0 x_3)} \exp\left[-i2\pi z_f\,(u_3^0+u_4^0) - i\,u_3 + u_4 - \frac{\mu_s}{\lambda}\right]$$
$$\left\{\mathrm{sinc}\left[L\left(-i\,u_3+u_4+\frac{u_3^0+u_4^0}{2}\right)\left(u_4+\frac{u_4^0}{2}-\frac{\mu_s}{\lambda}\right)\right]\right.$$
$$\left.\mathrm{sinc}\left[L\left(-i\,u_3+u_4-\frac{u_3^0+u_4^0}{2}\right)\left(u_4-\frac{u_4^0}{2}-\frac{\mu_s}{\lambda}\right)\right]\right\}$$

Derivation: $h(x_2;x_1) = \exp\left[-i\frac{\pi z_f}{f^2}(x_1+x_2-f\mu_s)^2\right]\mathrm{sinc}\left[\frac{L}{f^2}(x_1+x_2)(x_2-f\mu_s)\right]$

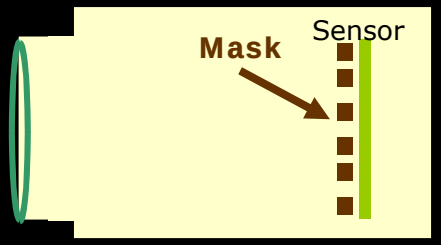
$K_{VHI}(x_2;u_2;x_1;u_1)$

$K_{VH}(x_4;u_4;x_3;u_3)$

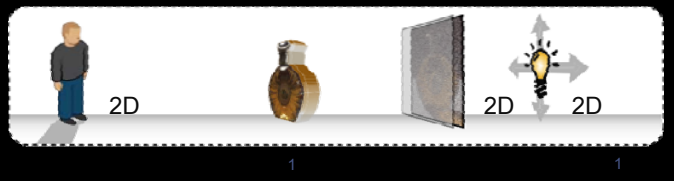
Parameters:
λ = 0.5 μm
μ_s= 30°
L = 1 mm
z_f = 50 mm

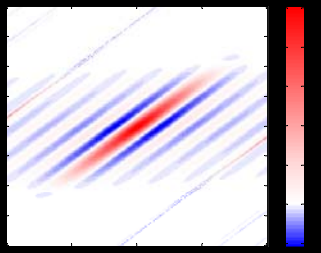
Computational Photography

1. Epsilon Photography
   - Low-level Vision: Pixels
   - Multiphotos by bracketing (HDR, panorama)
   - 'Ultimate camera'
2. Coded Photography
   - Mid-Level Cues:
     - Regions, Edges, Motion, Direct/global



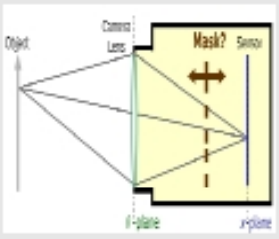
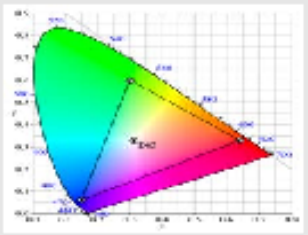
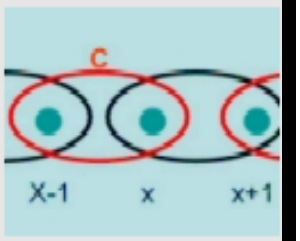
- Coded Exposure
  - Flutter Shutter Motion Deblurring
- Coded Aperture
  - Defocus
- Optical Heterodyning
  - Lightfield or Wavefront sensing
- Coded Glare
- 6D Display
- Femto-second Imaging
- Rays = Waves





Camera Culture
MIT Media Lab

How can we create an entirely
new class of imaging platforms
that have an understanding of the world that far exceeds human ability
and produce meaningful abstractions that are well within human comprehensibility ?

Coded Time (Exposure)	Coding in Space		Coded Illumination	Coded Wavelength	Coded Sensing
Flutter Shutter Cam	Coded Aperture	Optical Heterodyning	Multi-flash Camera	Agile Spectrum	Gradient Processing
					
2006	2007	2007	2004	2008	2005