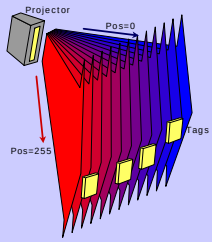
Less is More:
Coded Computational Photography

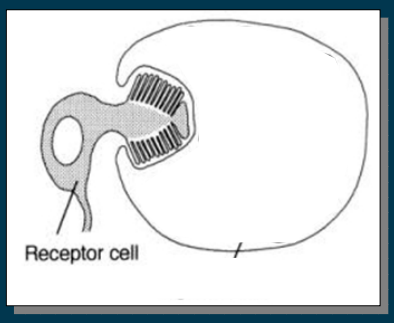




Ramesh Raskar

Mitsubishi Electric Research Labs (MERL)
Cambridge, MA

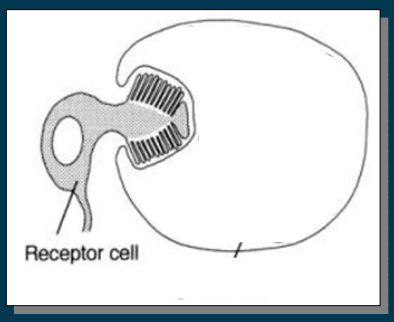
Simplest Visual Organs



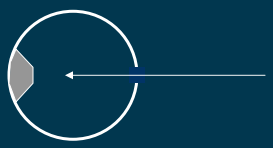
Larval Trematode Worm

'Single Pixel' Camera

Simplest Visual Organs

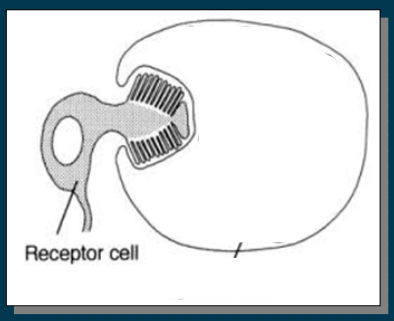


Larval Trematode Worm

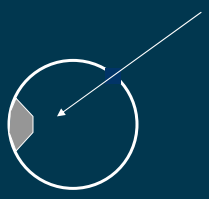


'Single Pixel' Camera

Simplest Visual Organs

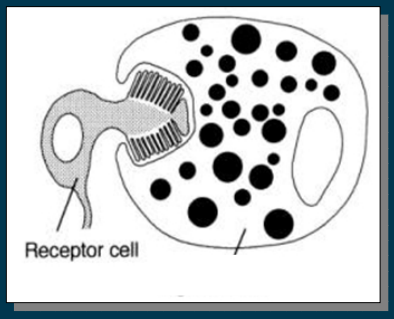


Larval Trematode Worm

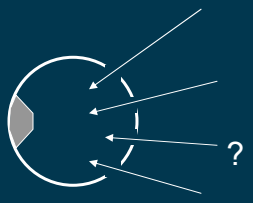


?

Special Aperture



Larval Trematode Worm

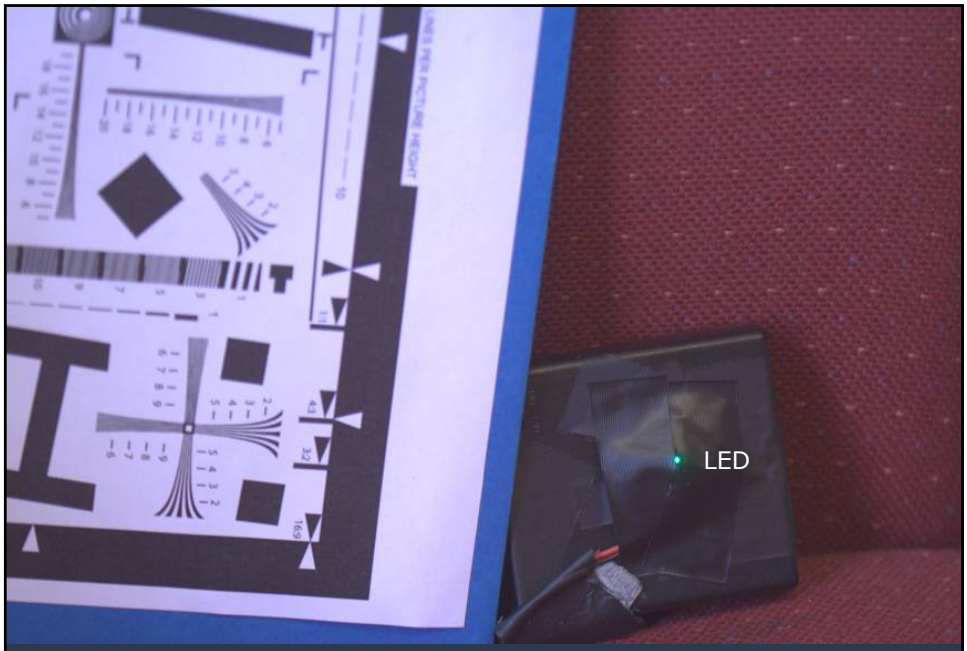


Special Aperture

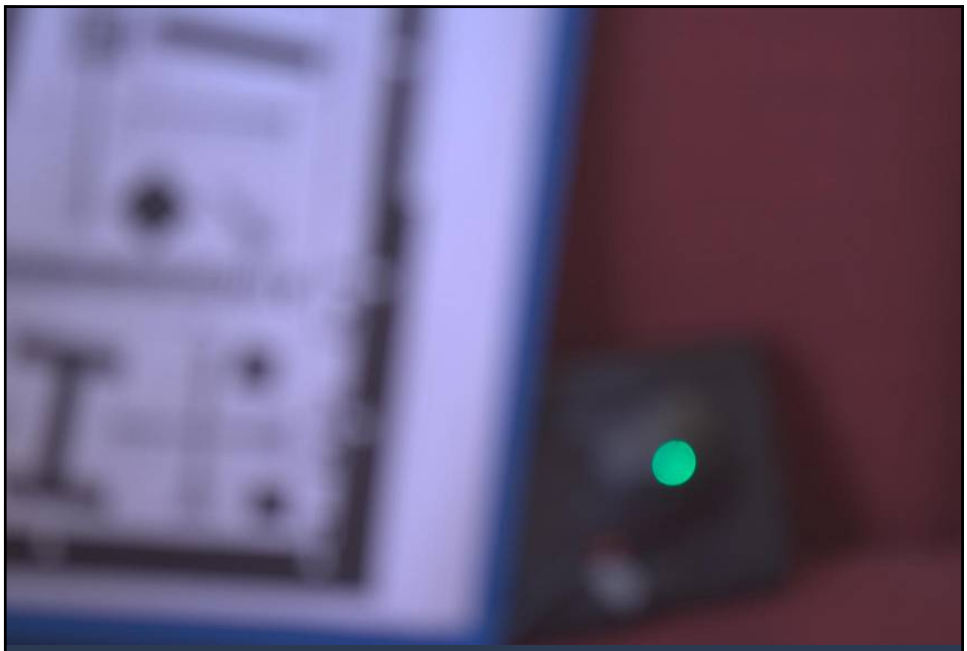
The aperture of a 100 mm lens is modified

Insert a coded mask with chosen binary pattern

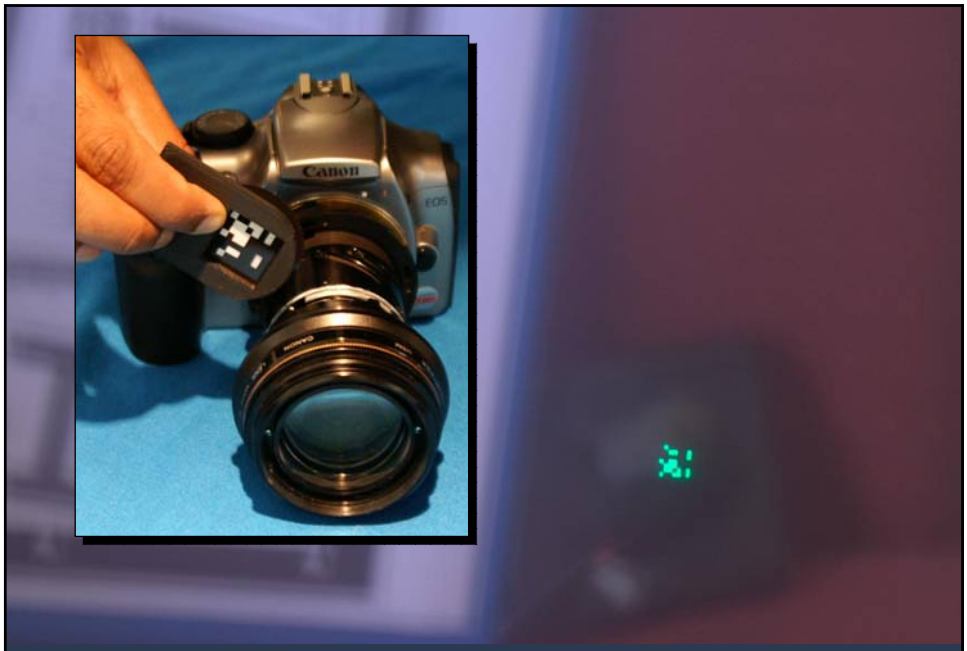
Rest of the camera is unmodified



In Focus Photo

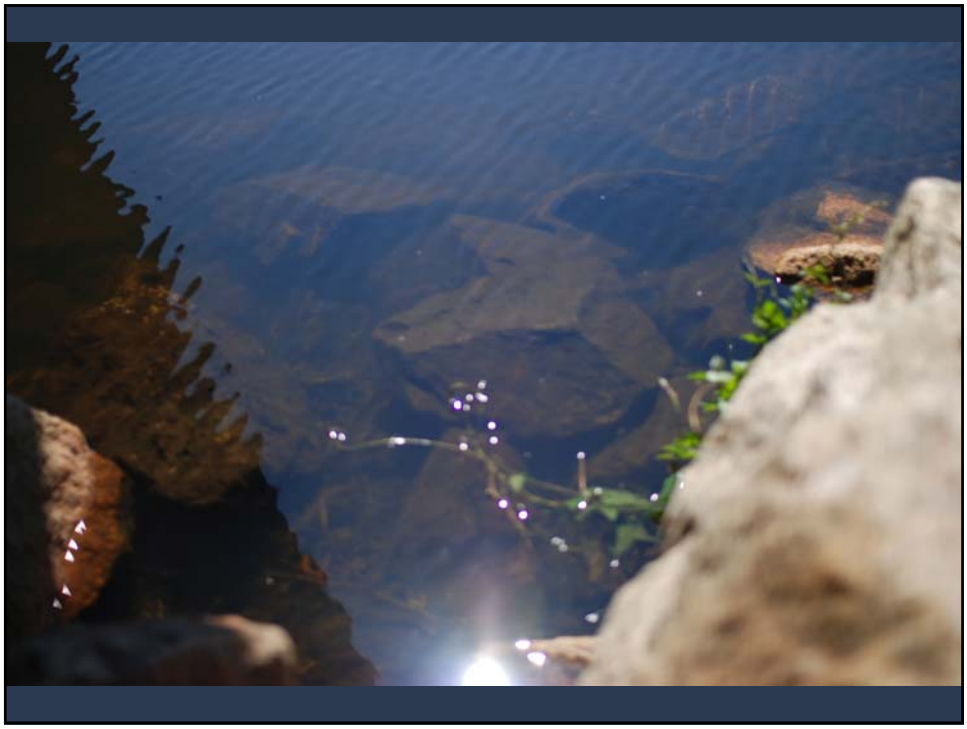


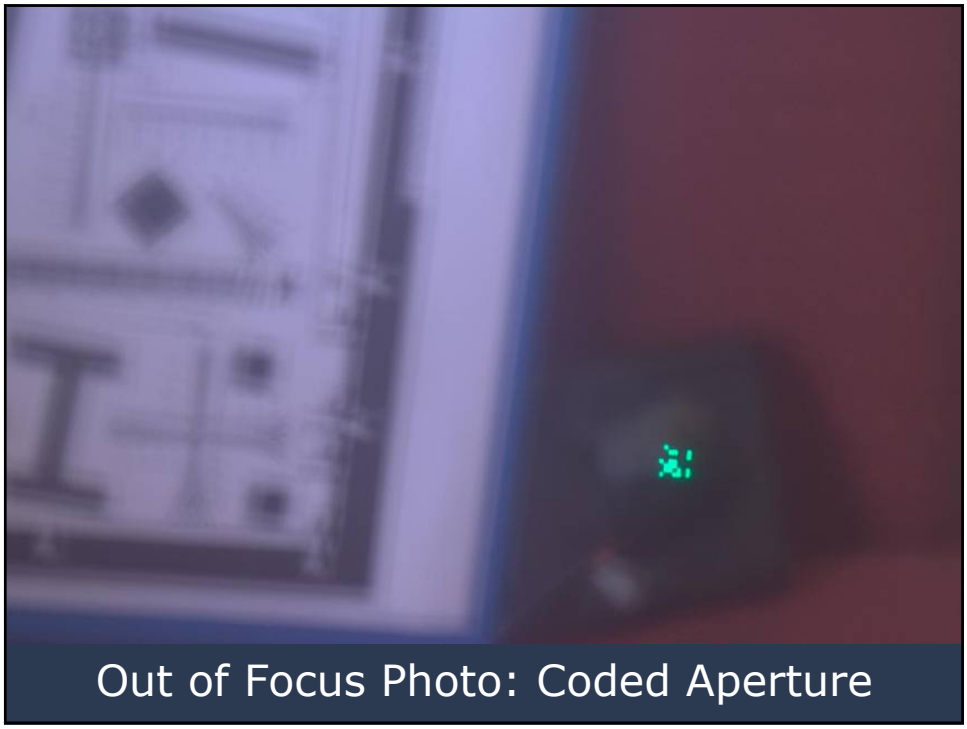
Out of Focus Photo: Open Aperture



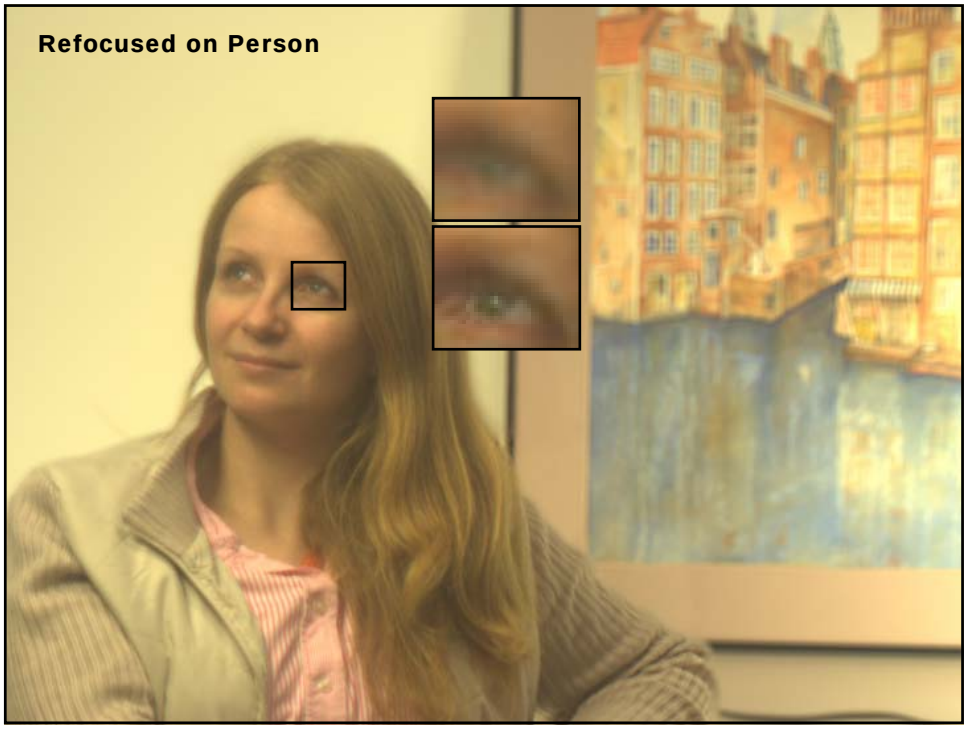
Out of Focus Photo: Coded Aperture

Bokeh





Out of Focus Photo: Coded Aperture


Refocused on Person

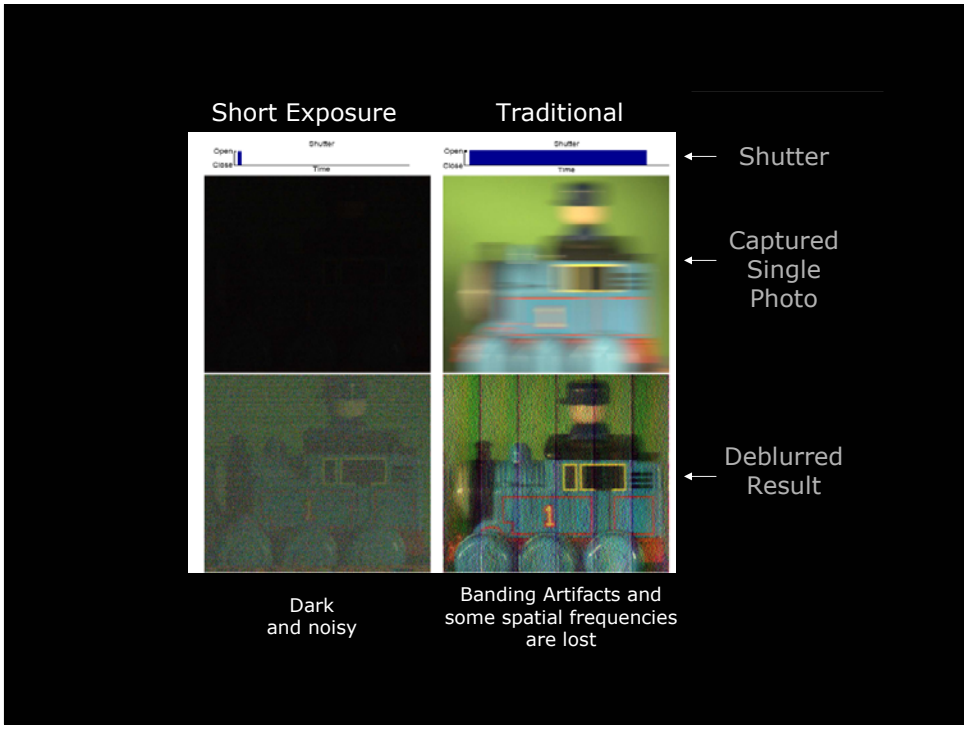

Blurred Photos
Open Aperture
Coded Aperture, 7 * 7 Mask

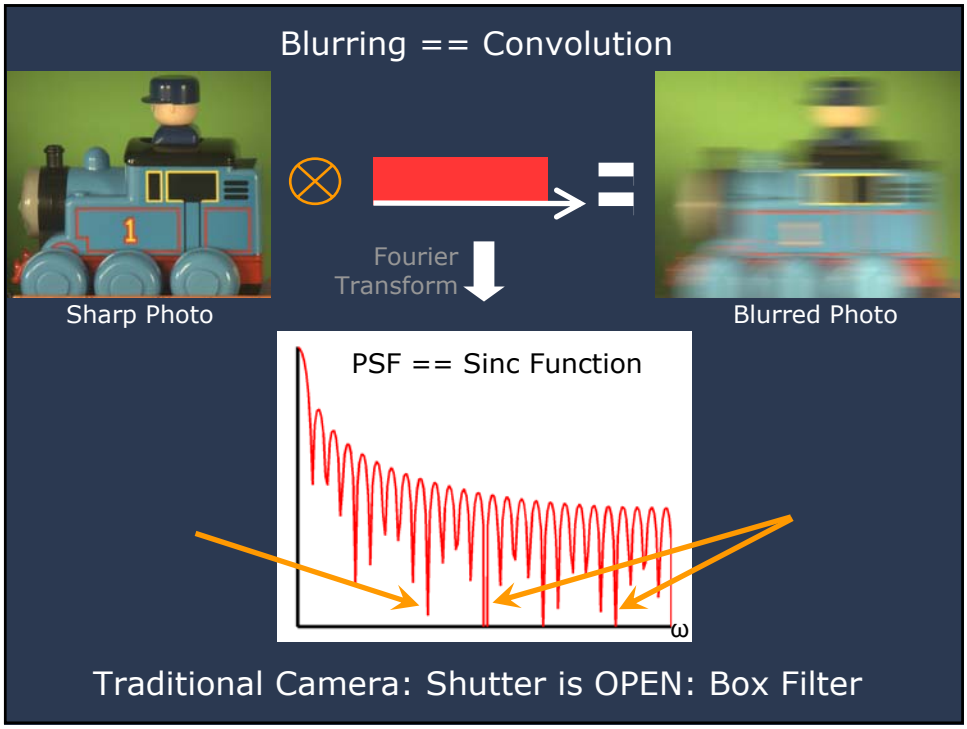
After Removing De-Focus Blur

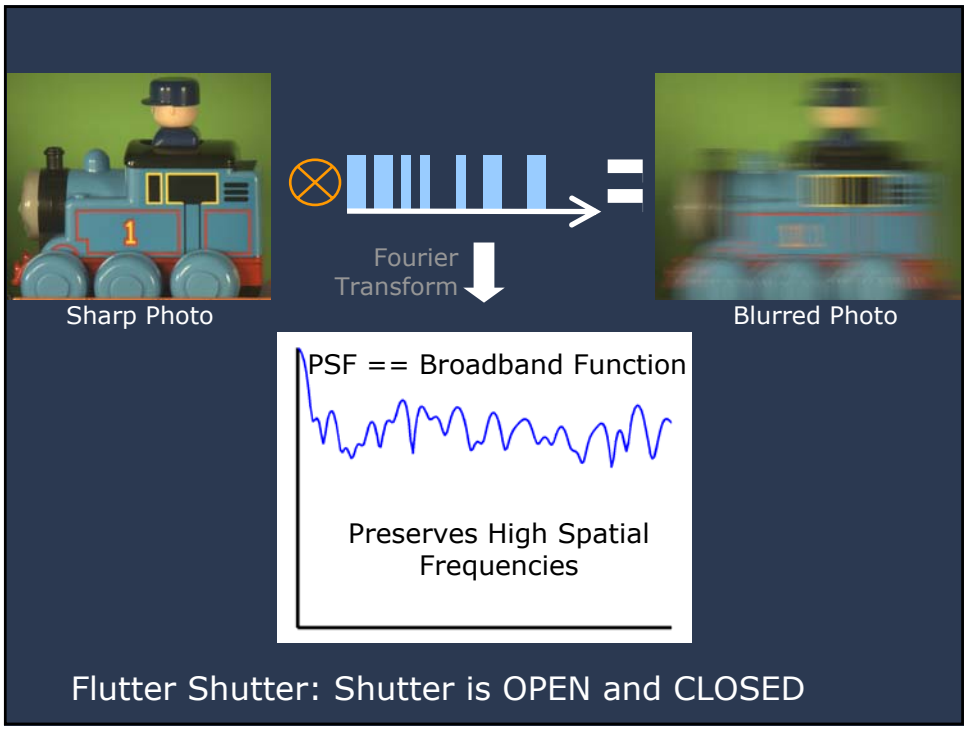
Open Aperture

Coded Aperture, 7 * 7 Mask


TOP A CAB

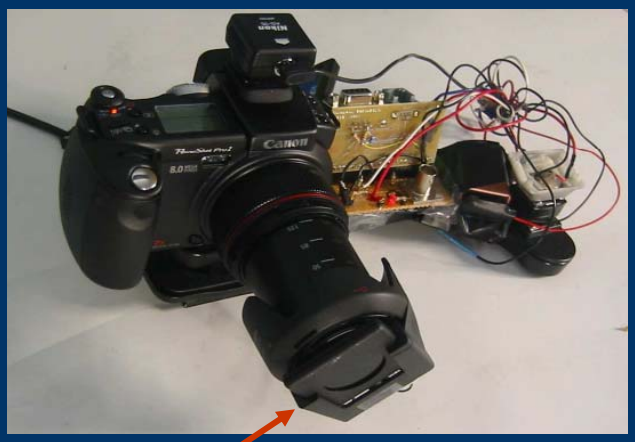

Short Exposure
Traditional
Shutter
Captured Single Photo
Deblurred Result
Dark and noisy
Banding Artifacts and some spatial frequencies are lost


Blurring == Convolution
Sharp Photo
Fourier Transform
Blurred Photo
PSF == Sinc Function
ω
Traditional Camera: Shutter is OPEN: Box Filter

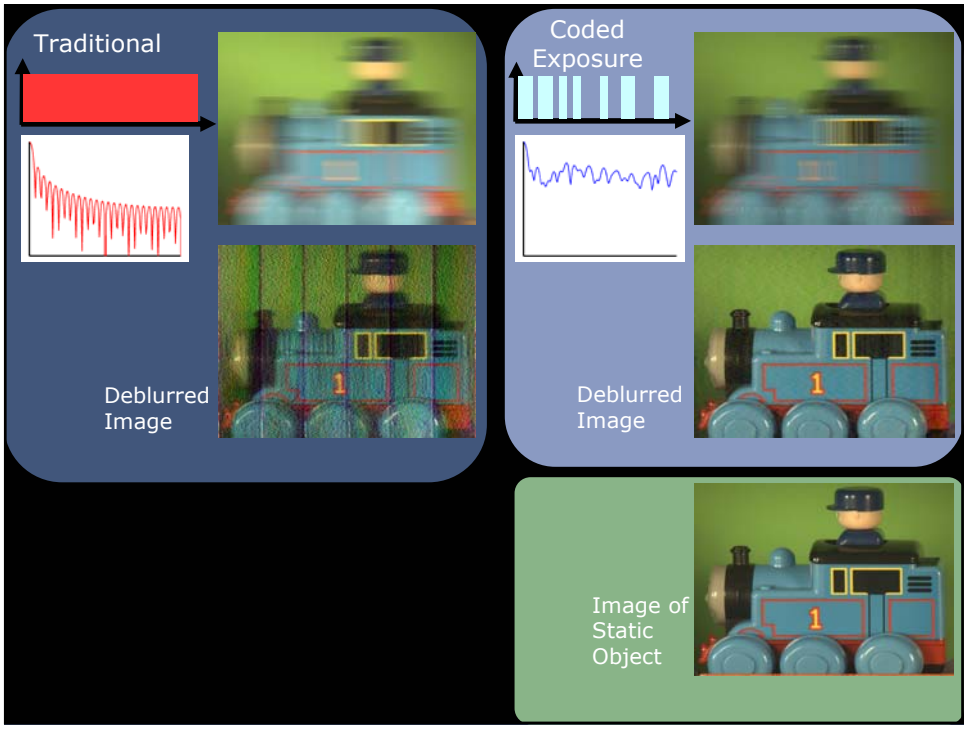

Sharp Photo
Fourier Transform
Blurred Photo
PSF == Broadband Function
Preserves High Spatial Frequencies
Flutter Shutter: Shutter is OPEN and CLOSED

Flutter Shutter Camera

Raskar, Agrawal, Tumblin [Siggraph2006]

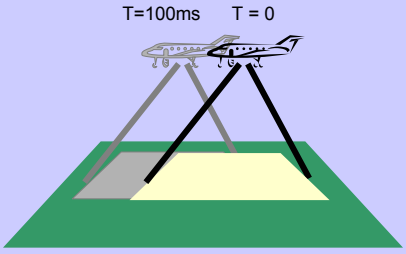


LCD opacity switched
in coded sequence



Application: Aerial Imaging

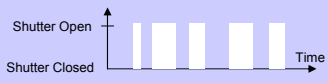
Sharpness versus Image Pixel Brightness



Long Exposure:

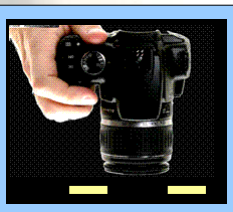
Short Explosure:

Flutter Shutter



<u>Sharp image</u> with sufficient <u>brightness</u>

Coded Exposure



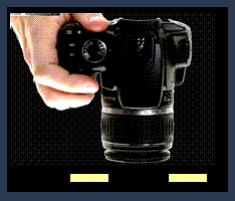
Temporal 1-D broadband code:
Motion Deblurring

Coded Aperture

Spatial 2-D broadband mask:
Focus Deblurring

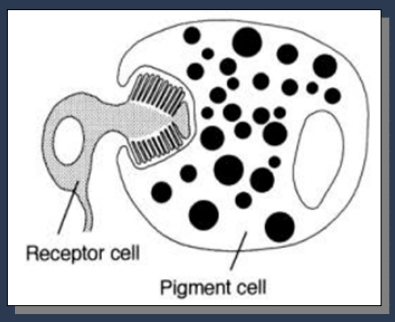
Less is More

Blocking Light == More Information



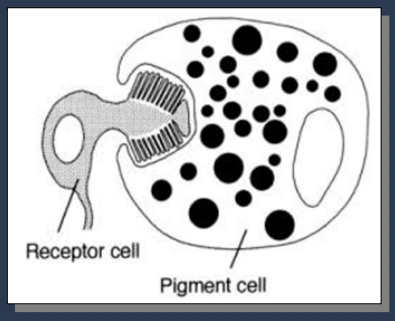
Coding in Time

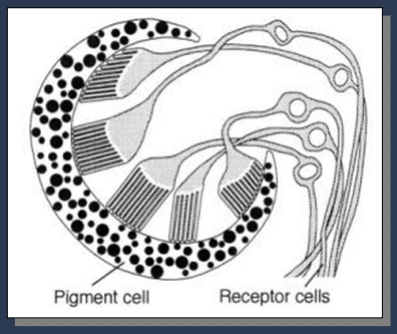
Coding in Space



Larval Trematode Worm

Coded Aperture in Nature ?



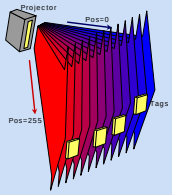


Larval Trematode Worm

Turbellarian Worm

Less is More ..

- Coded Exposure
  - Motion Deblurring
- Coded Aperture
  - Focus Deblurring
- Optical Heterodyning
  - Light Field Capture
- Coded Illumination
  - Motion Capture
  - Multi-flash: Cartoons



Computational Photography

1. Epsilon Photography
   - Multi-photos by perturbing camera parameters
   - HDR, panorama
   - 'Ultimate camera': (Photo-editors)
2. Coded Photography
   - Single/few snapshot
   - Reversible encoding of data
   - Additional sensors/optics/illum
   - 'Scene analysis' : (Consumer software?)
3. Impossible Photos
   - Beyond single view/illum
   - Not mimic human eye
   - 'New art form'

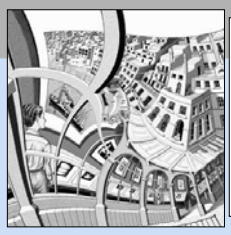
Computational Photography

1. Epsilon Photography
   - Multiphotos by varying camera parameters
   - HDR, panorama
   - 'Ultimate camera': (Photo-editor)
2. Coded Photography
   - Single/few snapshot
   - Reversible encoding of data
   - Additional sensors/optics/illum
   - 'Scene analysis' : (Next software?)

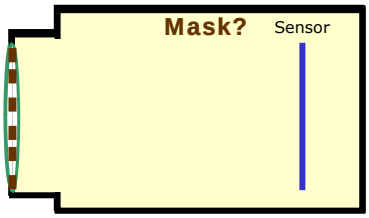

3. Impossible Photos
   - Not mimic human eye
   - Beyond single view/illum
   - 'New artform'

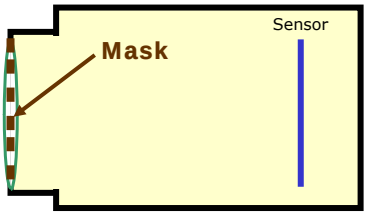
Computational Photography

1. Epsilon Photography
   - Multiphotos by varying camera parameters
   - HDR, panorama
   - 'Ultimate camera': (Photo-editor)
2.
   -
   -
   -
   -




3. Impossible Photos
   - Not mimic human eye
   - Beyond single view/illum
   - 'New artform'





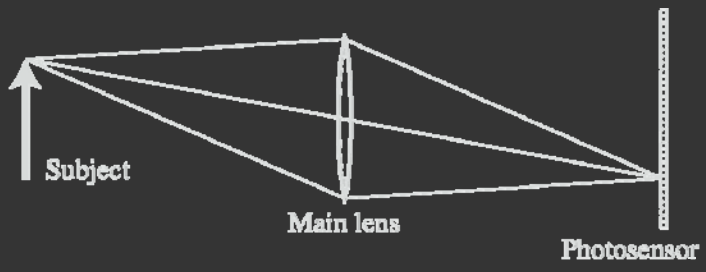
Full Resolution Digital Refocusing:

Coded Aperture Camera

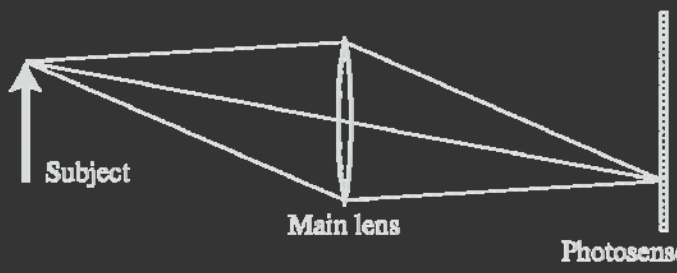
4D Light Field from 2D Photo:

Heterodyne Light Field Camera

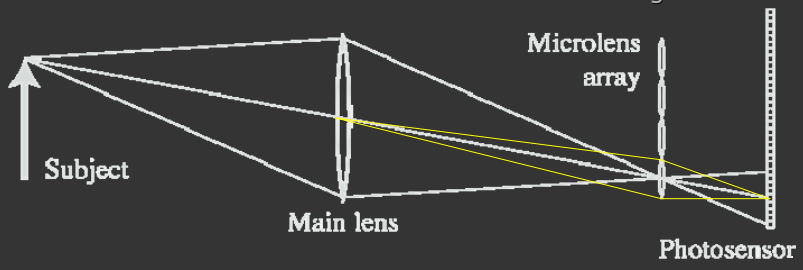
Capturing Light Field Inside a Camera



Capturing Light Field Inside a Camera



Lenslet-based Light Field camera

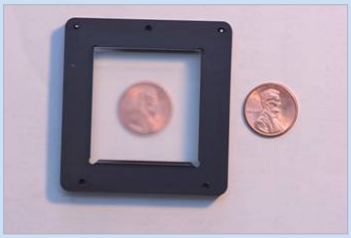


[Adelson and Wang, 1992, Ng et al. 2005]

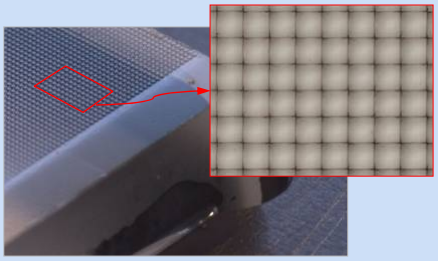
Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor



Adaptive Optics microlens array



125µ square-sided microlenses

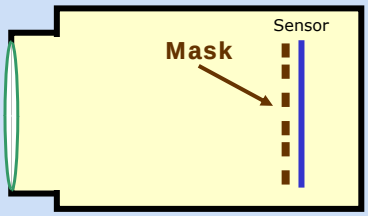
4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens

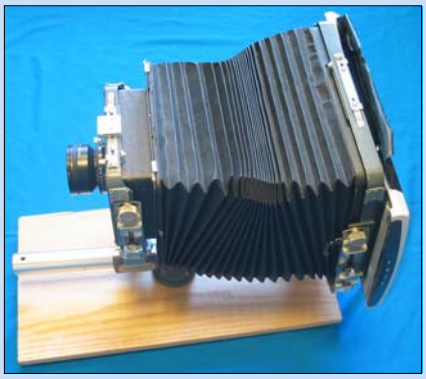
Digital Refocusing

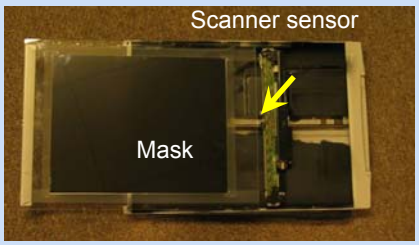
[Ng et al 2005]

Can we achieve this with a Mask alone?

Heterodyne Light Field Camera

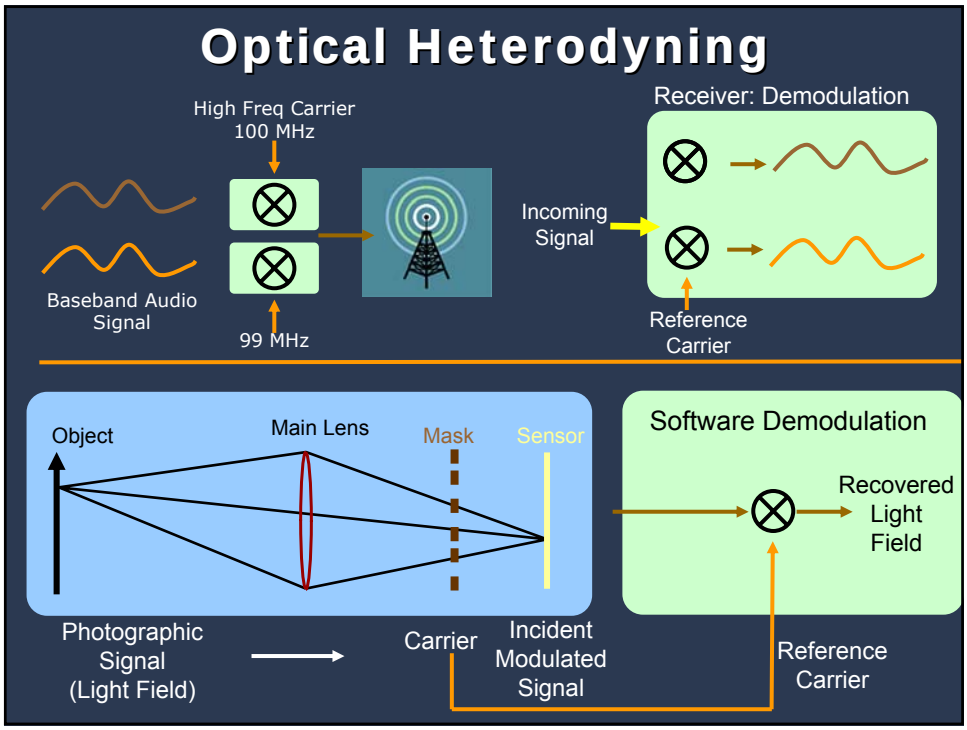


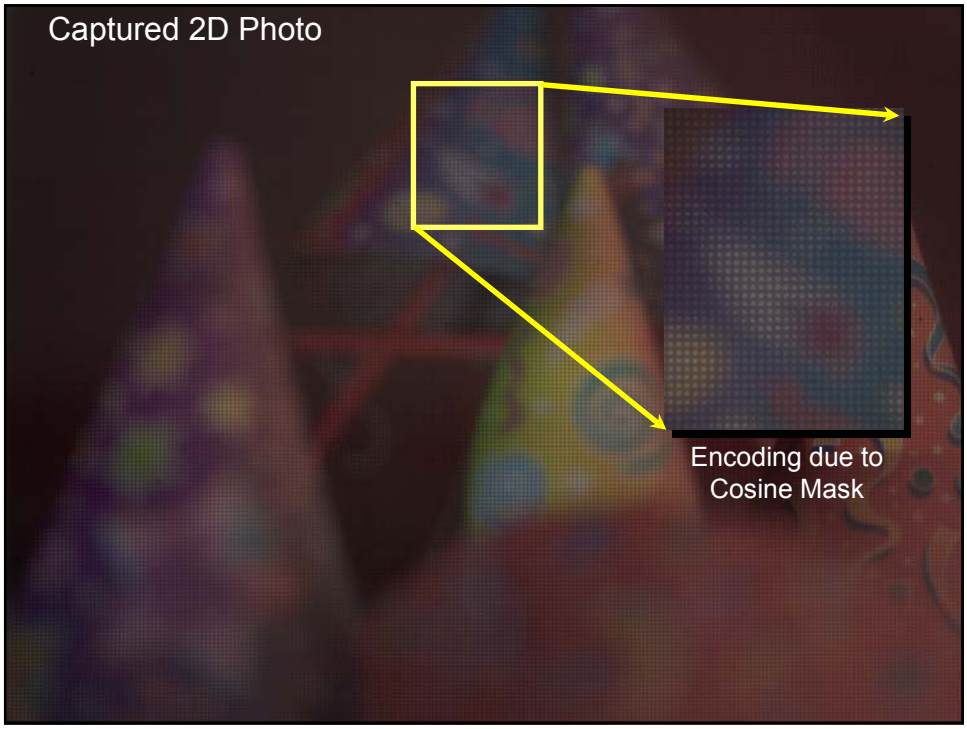


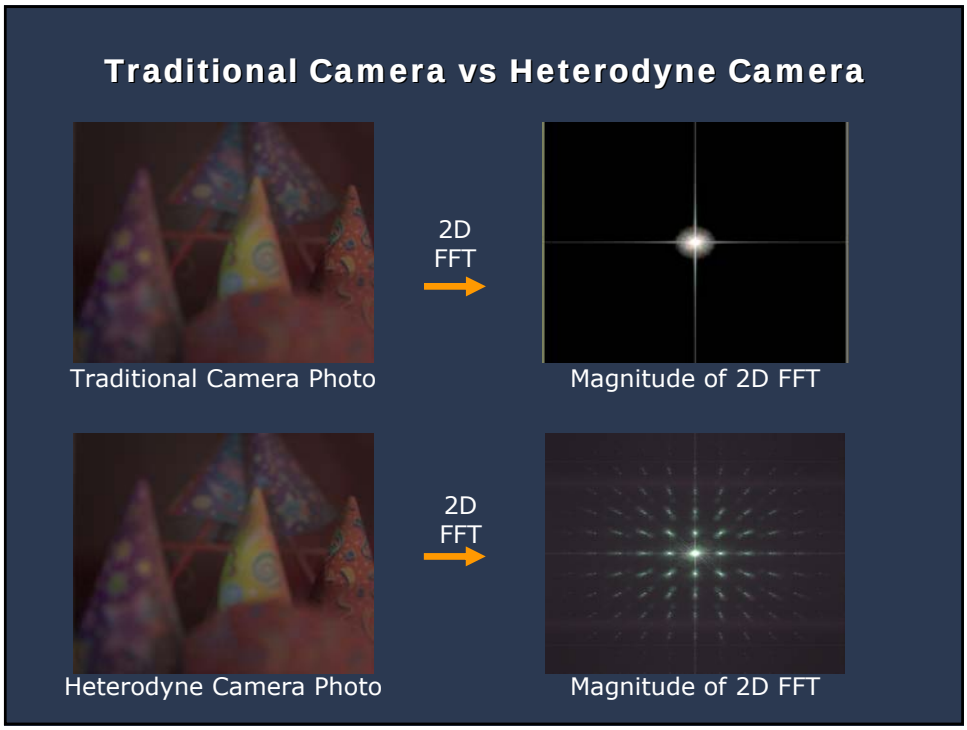


How to Capture 4D Light Field with 2D Sensor ?

What should be the pattern of the mask ?




Captured 2D Photo
Encoding due to
Cosine Mask

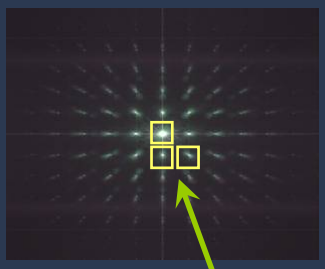

Traditional Camera vs Heterodyne Camera
2D
FFT
Traditional Camera Photo
Magnitude of 2D FFT
2D
FFT
Heterodyne Camera Photo
Magnitude of 2D FFT

Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D
FFT

2D Fourier Transform, 1800*1800



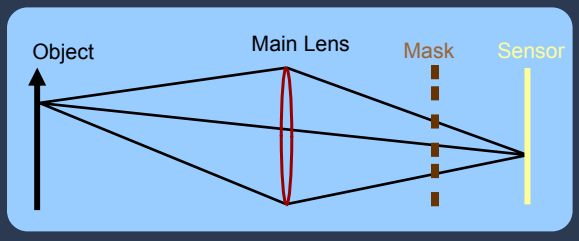
9*9=81 spectral copies

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

4D IFFT

4D Light Field
200*200*9*9

A Theory of Mask-Enhanced Camera



- Mask == Light Field Modulator
- Intensity of ray gets multiplied by Mask
- Convolution in Frequency domain

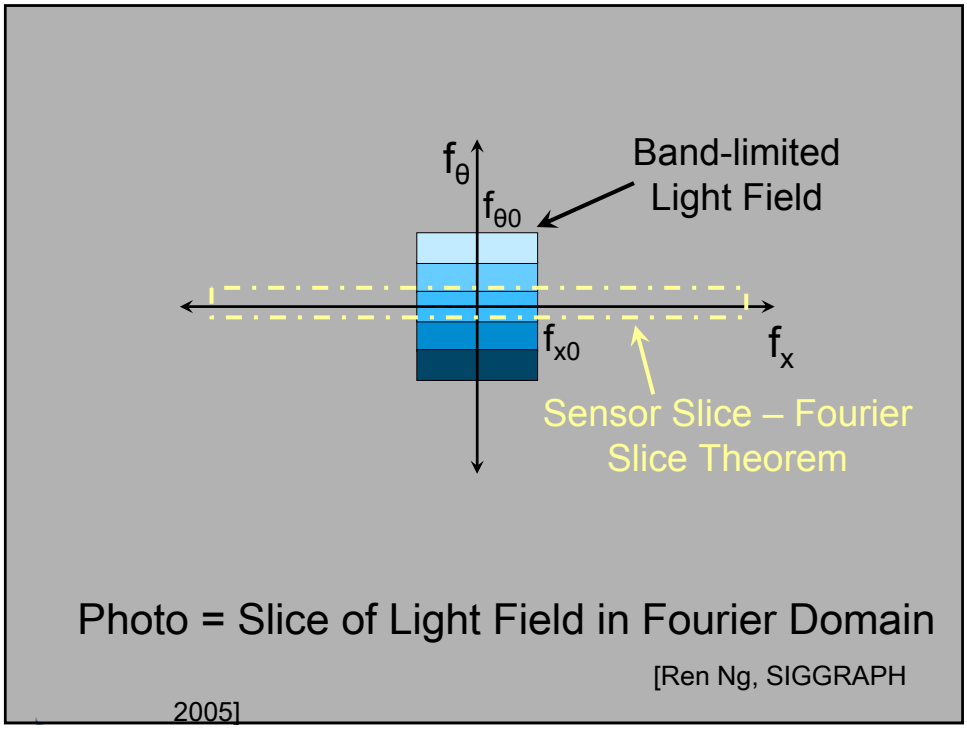
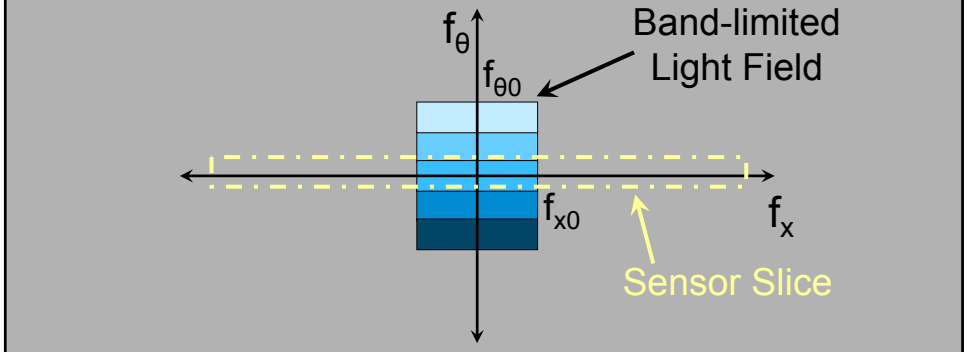


Photo = Slice of Light Field in Fourier Domain

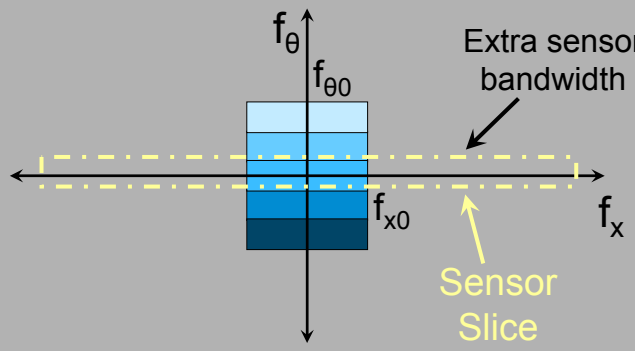
[Ren Ng, SIGGRAPH 2005]

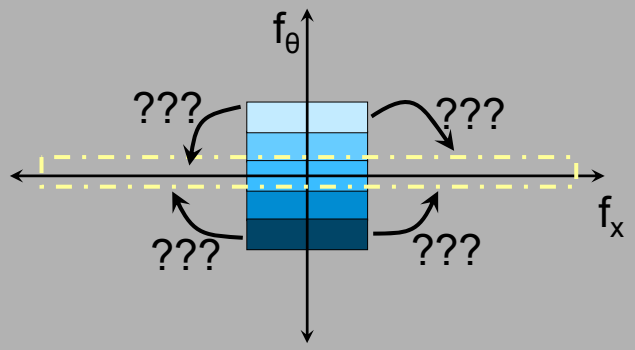
How to Capture 2D Light Field with 1D Sensor ?



Fourier Light Field Space

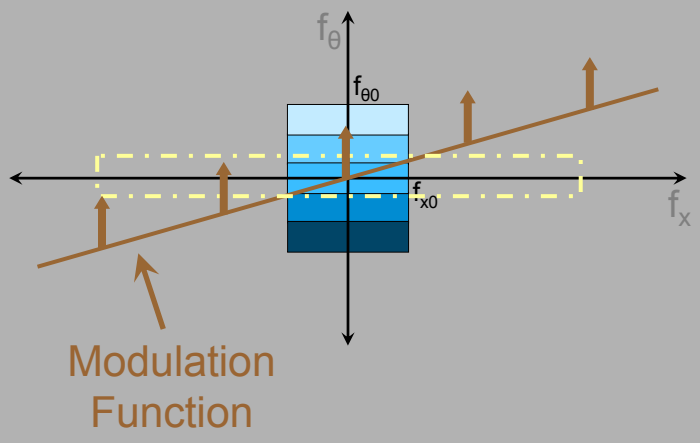
Extra sensor bandwidth cannot capture extra *dimension* of the light field



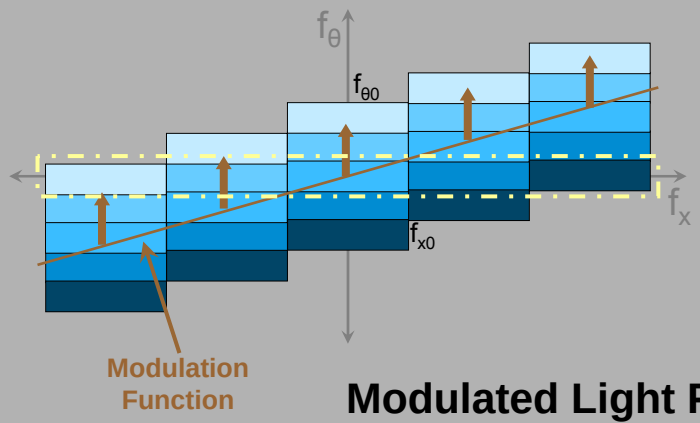


Solution: Modulation Theorem

Make spectral copies of 2D light field

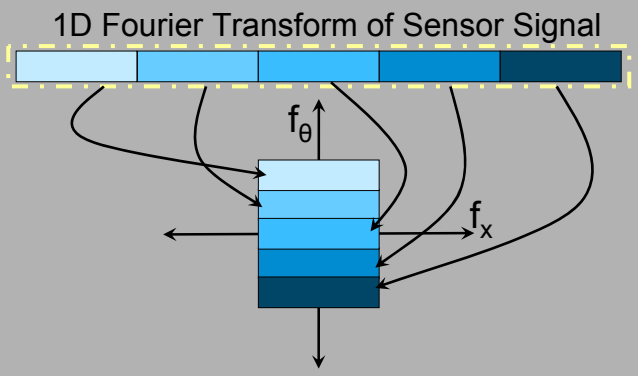


Sensor Slice captures entire Light Field



Modulated Light Field

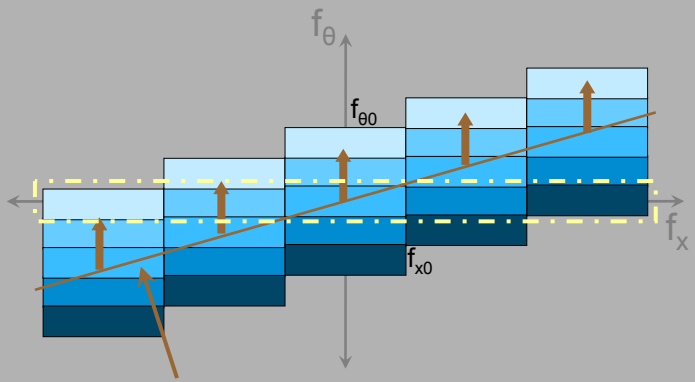
Demodulation to recover Light Field

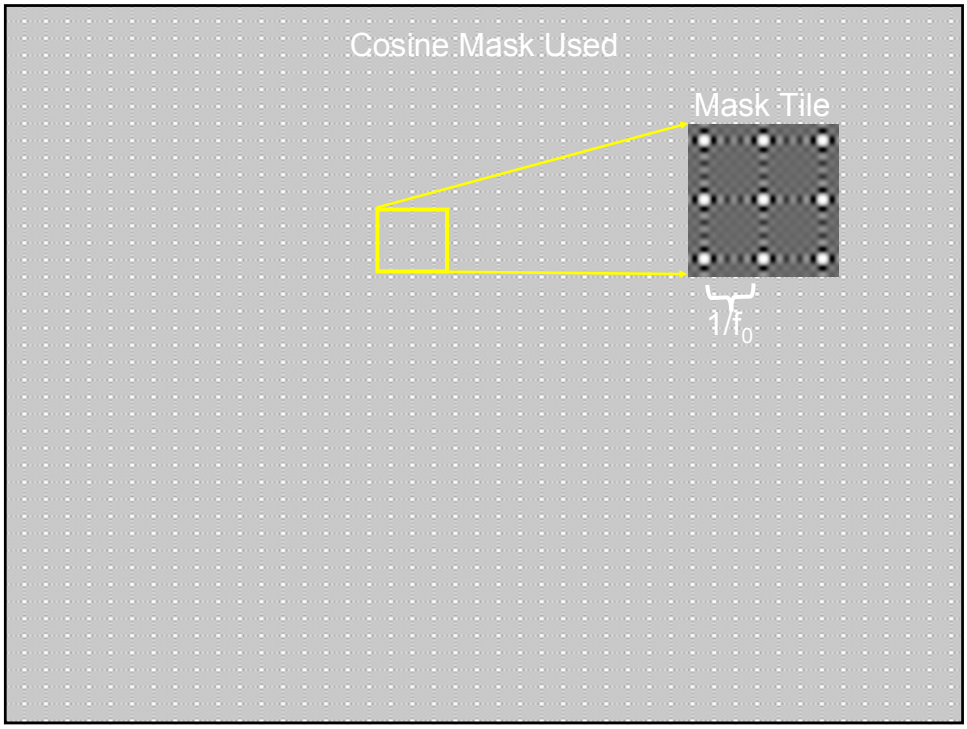


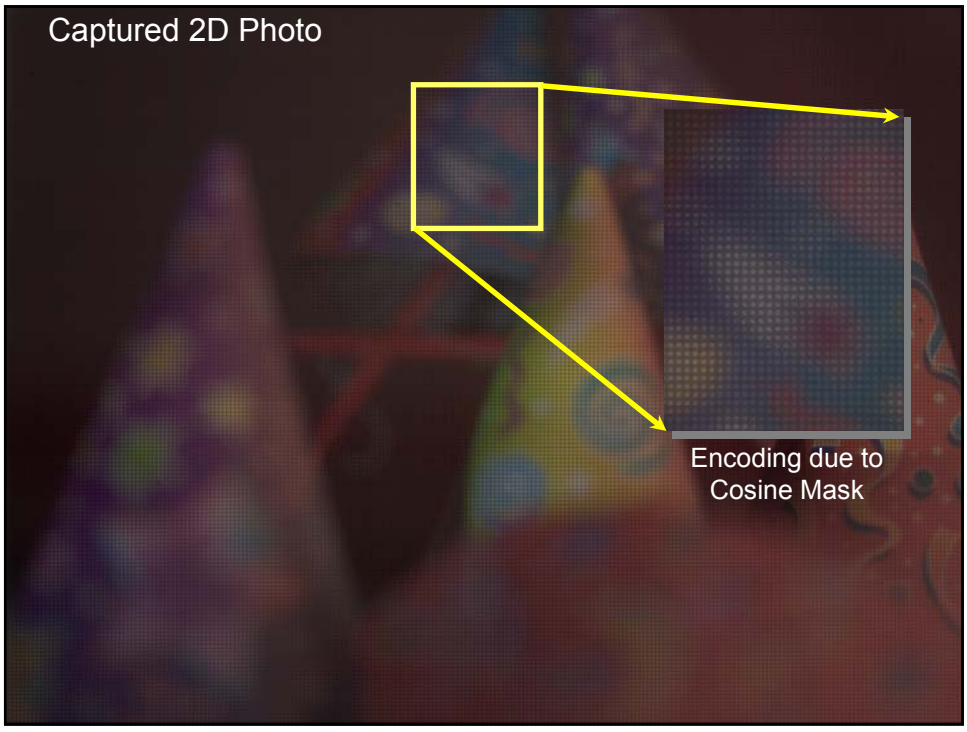
Reshape 1D Fourier Transform into 2D

Modulation Function == Sum of Impulses

Physical Mask = Sum of Cosines




Cosine Mask Used
Mask Tile
$1/f_0$

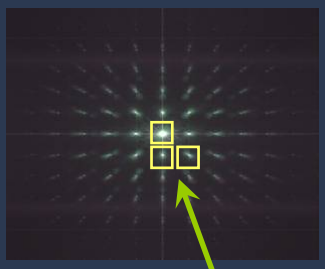

Captured 2D Photo
Encoding due to
Cosine Mask

Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D
FFT

2D Fourier Transform

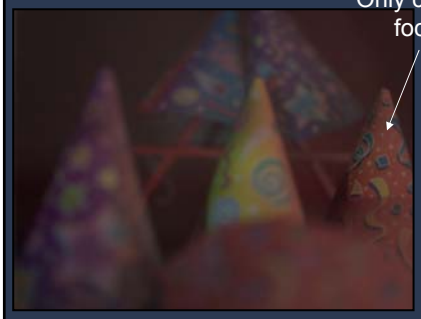


9*9=81 spectral copies

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

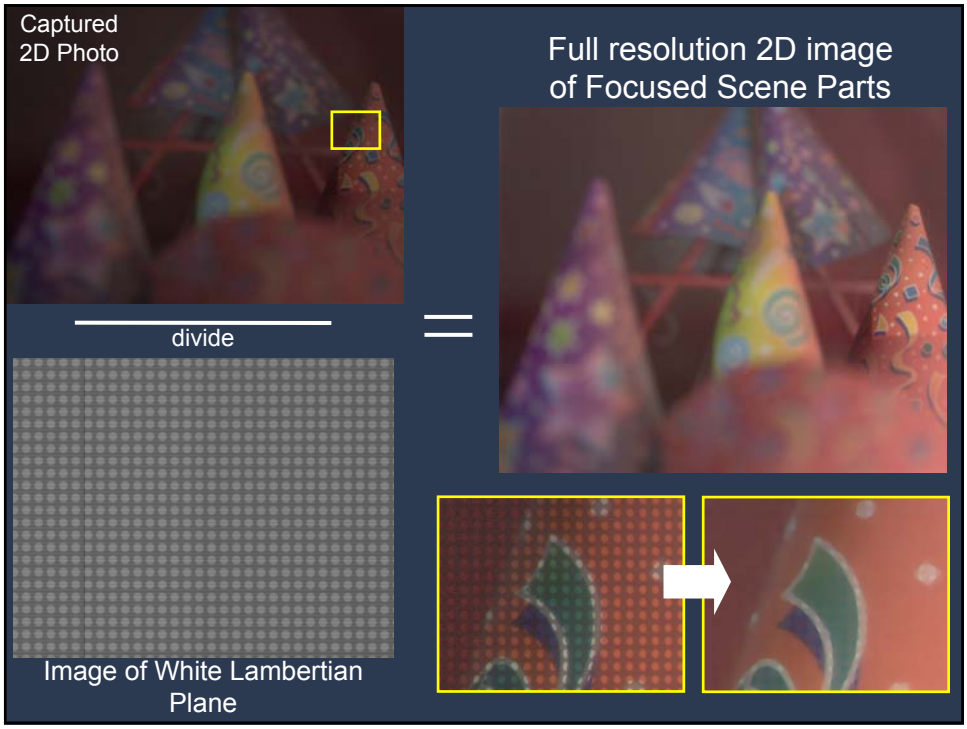
4D IFFT

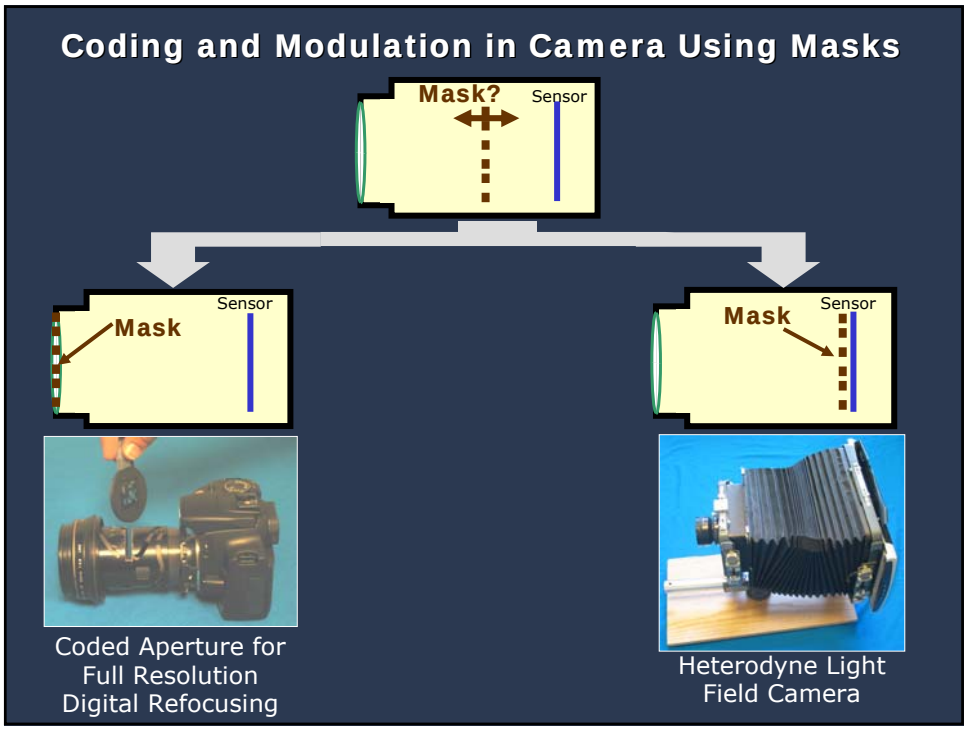
4D Light Field
200*200*9*9



Captured Photo

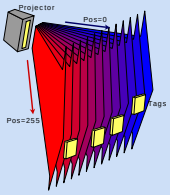
Digital Refocusing


Captured
2D Photo
divide
Image of White Lambertian
Plane
Full resolution 2D image
of Focused Scene Parts


Coding and Modulation in Camera Using Masks
Mask?
Sensor
Mask
Sensor
Mask
Sensor
Coded Aperture for
Full Resolution
Digital Refocusing
Heterodyne Light
Field Camera

Coded Imaging

- Coded Exposure
  - Motion Deblurring
- Coded Aperture
  - Focus Deblurring
- Optical Heterodyning
  - Light Field Capture
- Coded Illumination
  - Motion Capture
  - Multi-flash: Cartoons



Vicon Optical Motion Capture

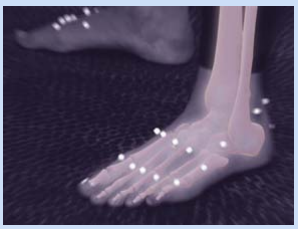
High-speed IR Camera

Medical Rehabilitation

Athlete Analysis

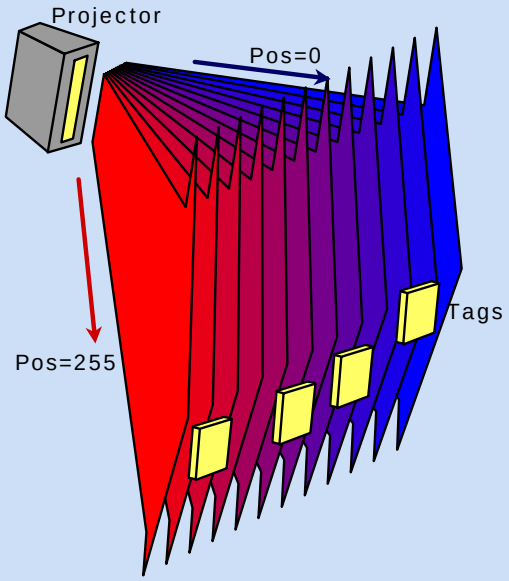
Body-worn markers

Performance Capture



Biomechanical Analysis

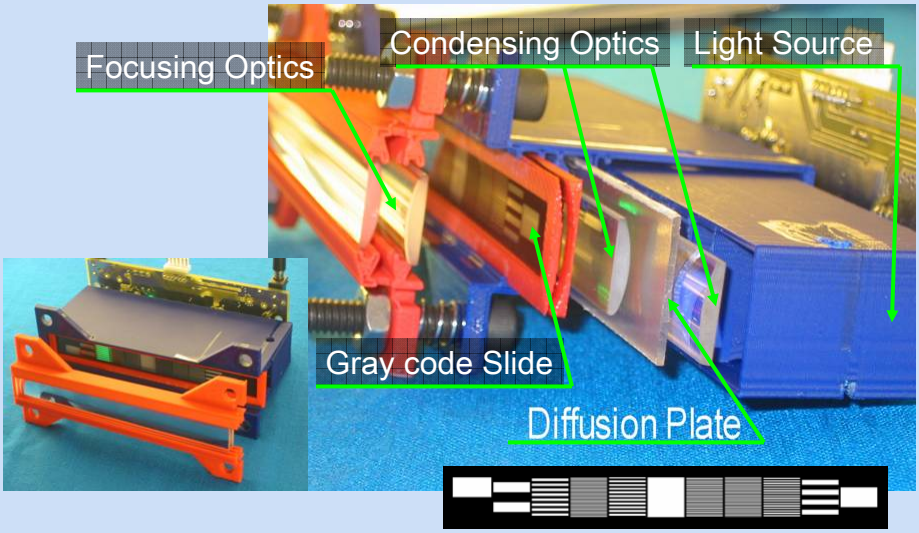
Labeling Space



Each location receives a unique temporal code

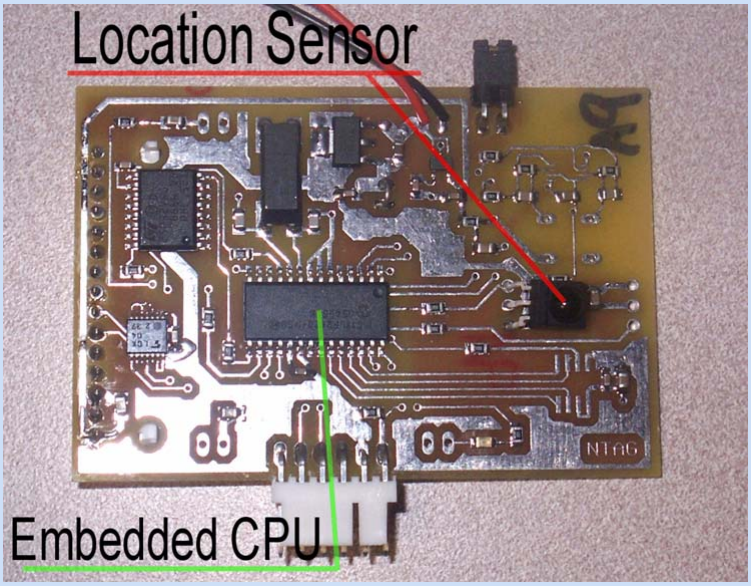
But 60Hz video projector is too slow

Coded Illumination Projector

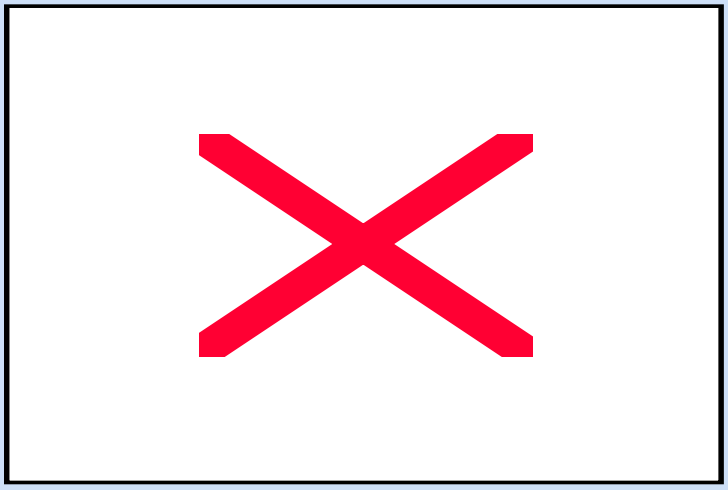


The Gray code pattern

Photosensing Tag

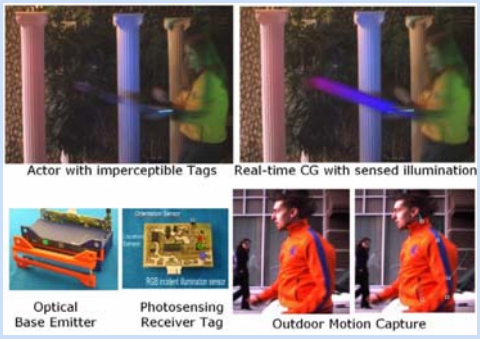


Imperceptible tags, Ambient Lighting, Id per marker



Prakash [Raskar, Nii, Summet et al Siggraph 2007]

Coded Illumination for Motion Capture



- 500 Hz Tracking
- Id for each Marker Tag
- Capture in Natural Environment
  - Visually imperceptible tags
  - Photosensing Tag can be hidden under clothes
  - Ambient lighting is ok
- Unlimited Number of Tags Allowed
- Base station and tags only a few 10's $

Acknowledgements

- Amit Agrawal, MERL
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- Shree Nayar, Columbia U.

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- Mitsubishi Electric Japan
  - Kazuhiko Sumi, Haruhisa Okuda

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  - Ashok Veerarghavan, Ankit Mohan
- Prakash, Motion Capture
  - Masahiko Inami, Hideaki Nii, Yuki Hashimoto, Jay Summet, Erich Bruns, Paul Dietz, Bert de Decker, Philippe Bekaert

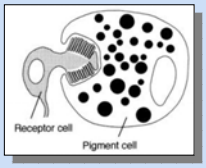
- Prof Yagi, Prof Ikeuchi and ACCV Organizers

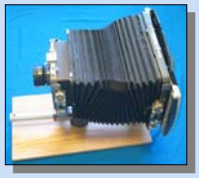
Future of Coding Light

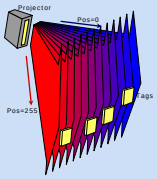
- How to block light in other ways?
  - Time, Space, Illumination .. Wavelength? On Sensor?
- What other blockers?
  - Dynamic masks (LCDs), non-planar or colored masks?
- Applications
  - Estimate params in presence of low pass convolution
  - Light Field Applications: lens aberration, microscopy

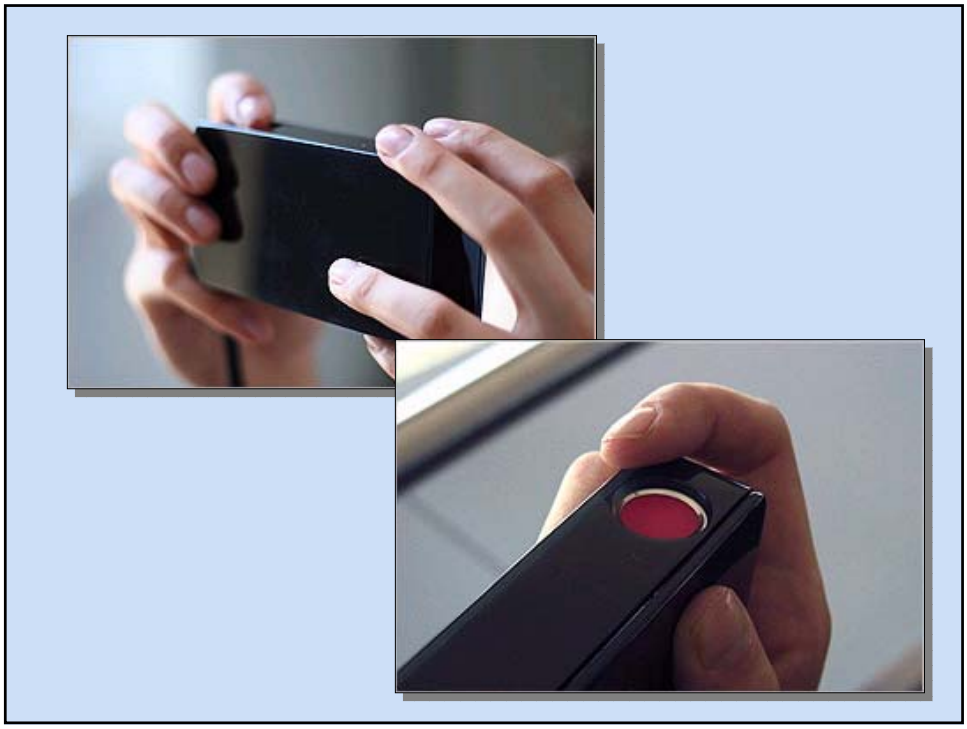
Coded Photography

- Coded Exposure
  - Motion Deblurring
- Coded Aperture
  - Focus Deblurring
- Optical Heterodyning
  - Light Field Capture
- Coded Illumination
  - Motion Capture
  - Multi-flash: Shape Contours
- Epsilon->Coded->Impossible Photos









Blind Camera

Sascha Pohflepp,
U of the Art, Berlin, 2006

Coded Photography

- Coded Exposure
  - Motion Deblurring
- Coded Aperture
  - Focus Deblurring
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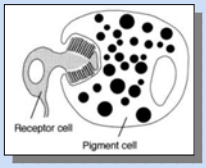
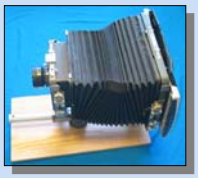
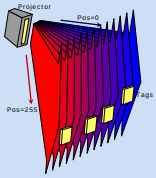
- Coded Illumination
  - Motion Capture
  - Multi-flash: Shape Contours
- Epsilon->Coded->Impossible Photos







END