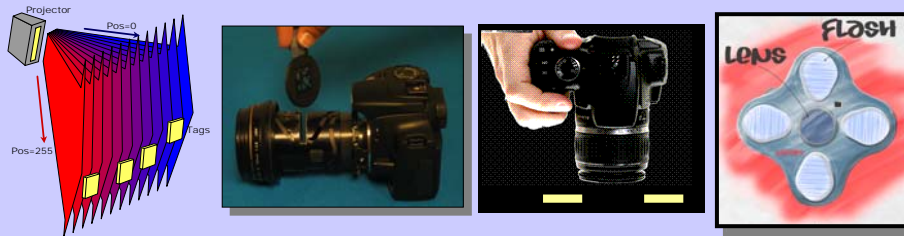


Less is More: Coded Computational Photography

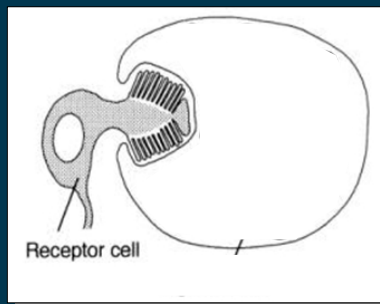


Ramesh Raskar



Mitsubishi Electric Research Labs (MERL)
Cambridge, MA

Simplest Visual Organs

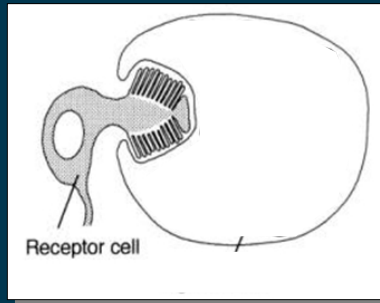


Larval Trematode Worm

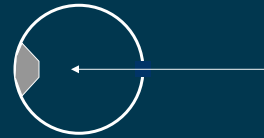


'Single Pixel' Camera

Simplest Visual Organs

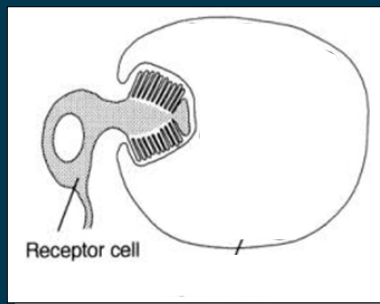


Larval Trematode Worm

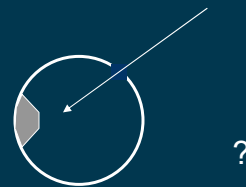


'Single Pixel' Camera

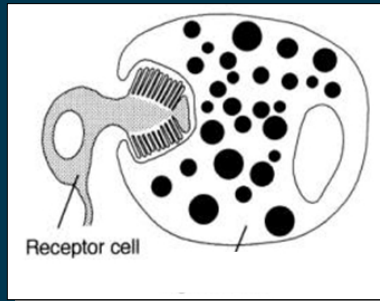
Simplest Visual Organs



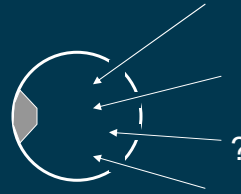
Larval Trematode Worm



Special Aperture



Larval Trematode Worm



Special Aperture

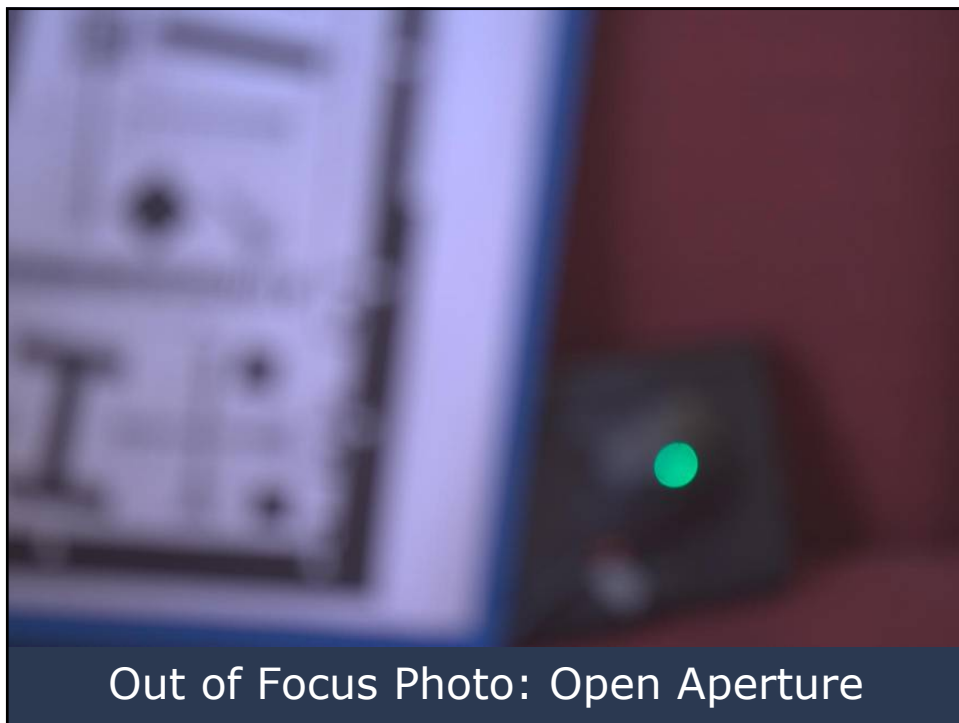
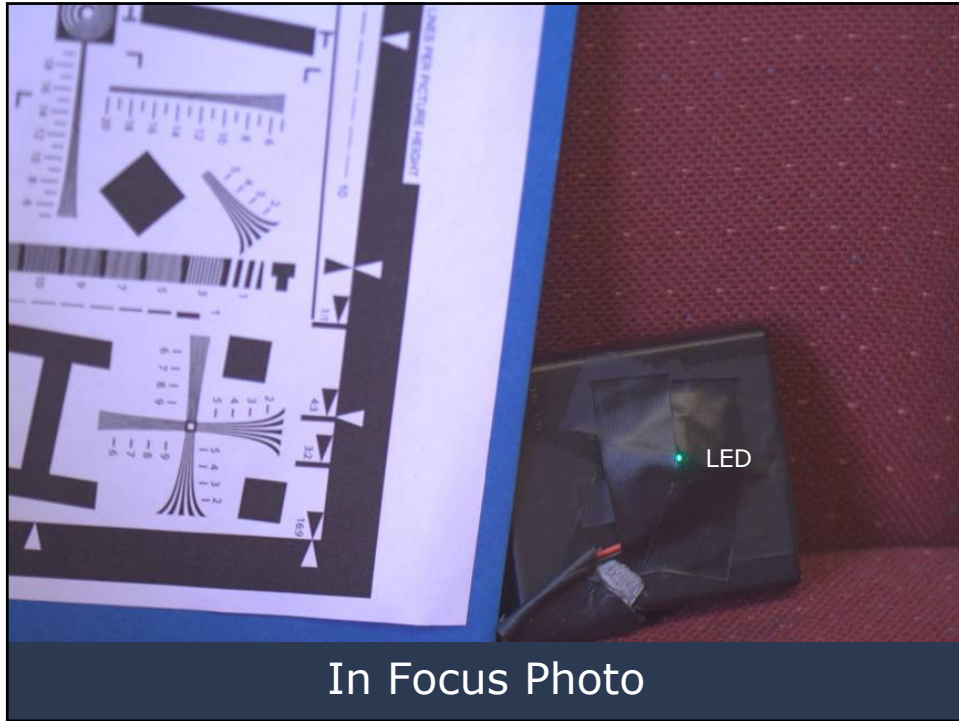


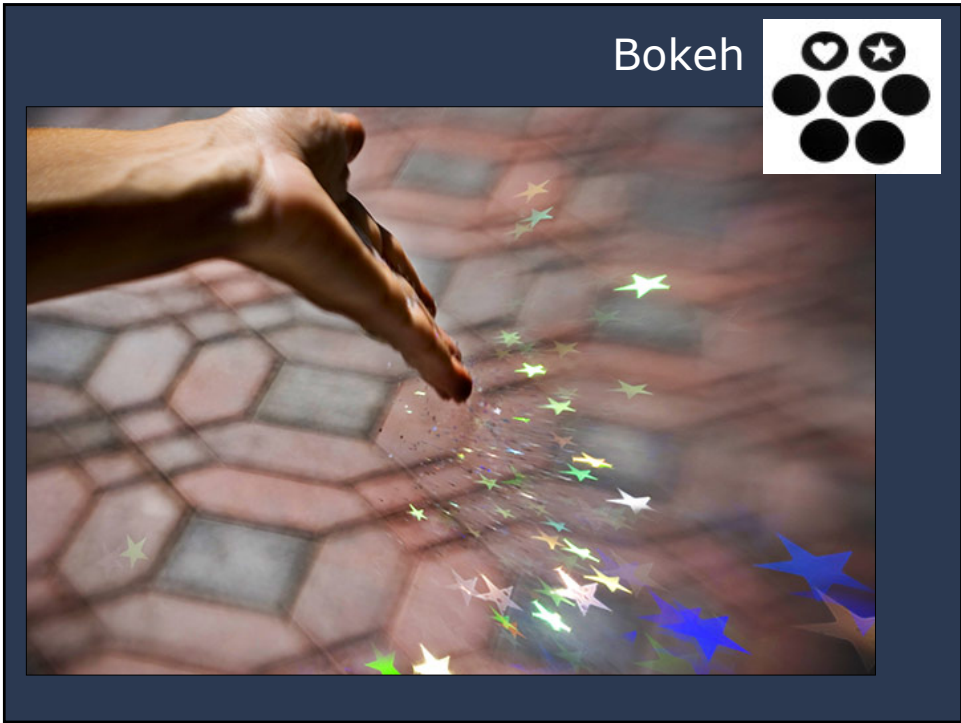
The aperture of a 100 mm lens is modified

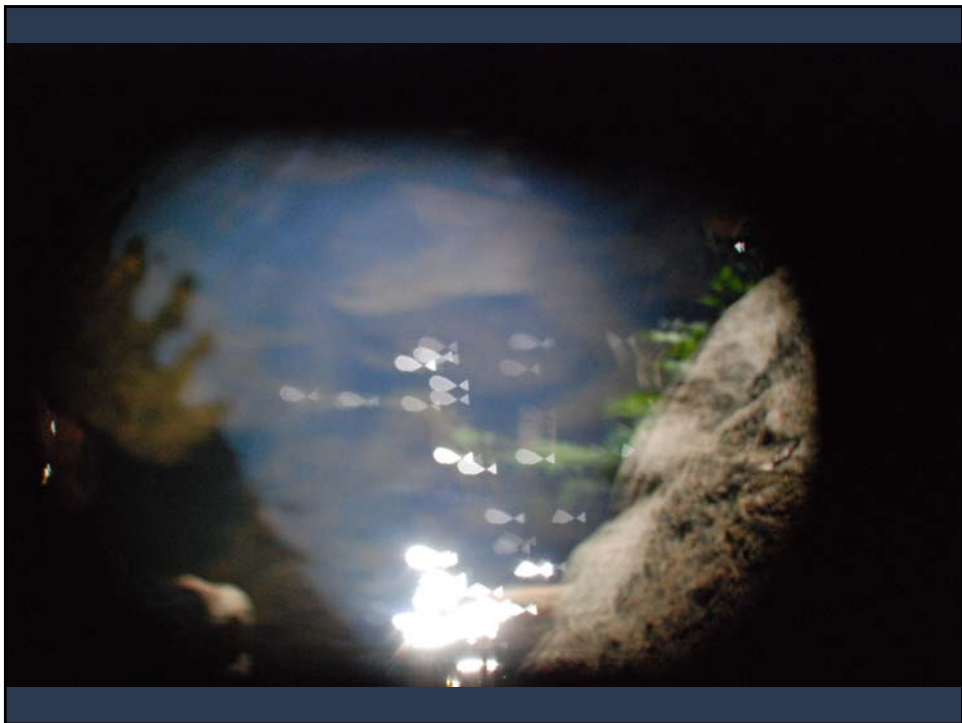
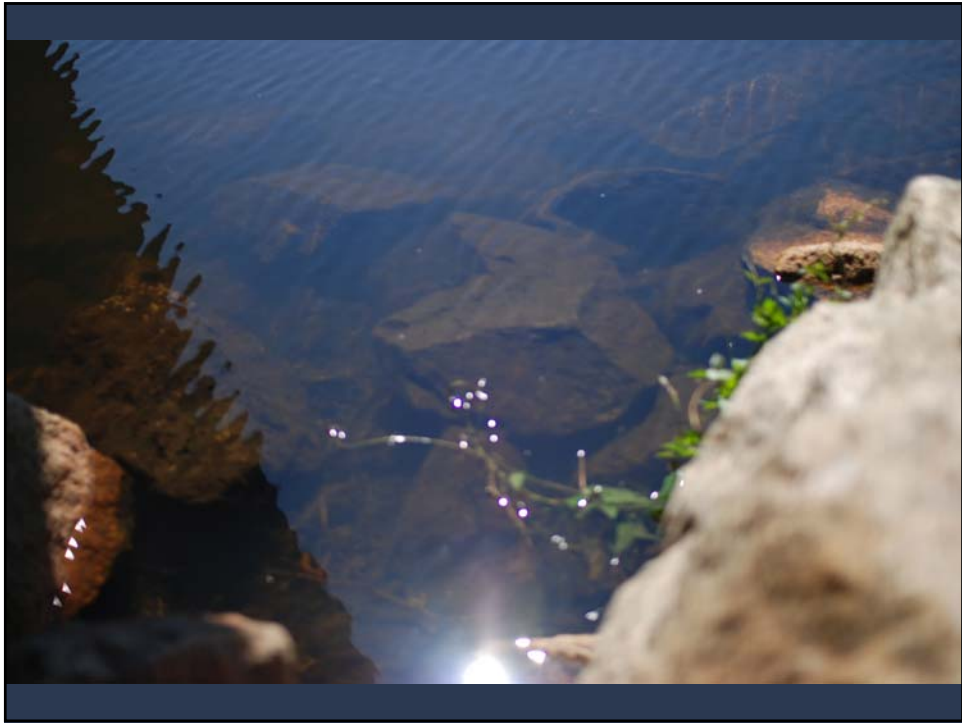


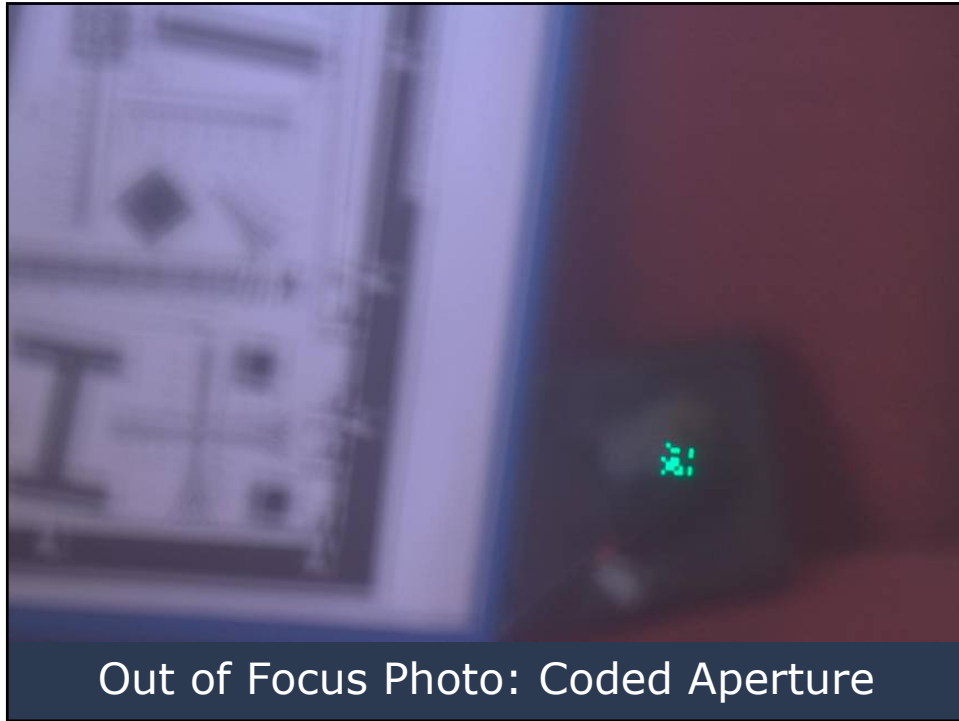
Insert a **coded mask** with chosen binary pattern

Rest of the camera is unmodified



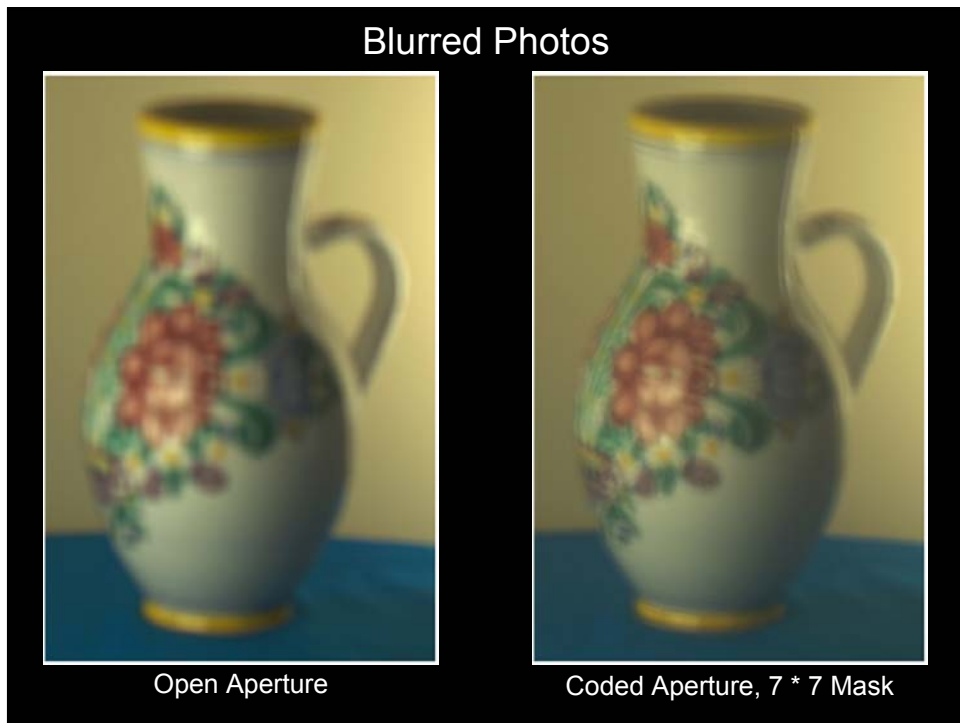
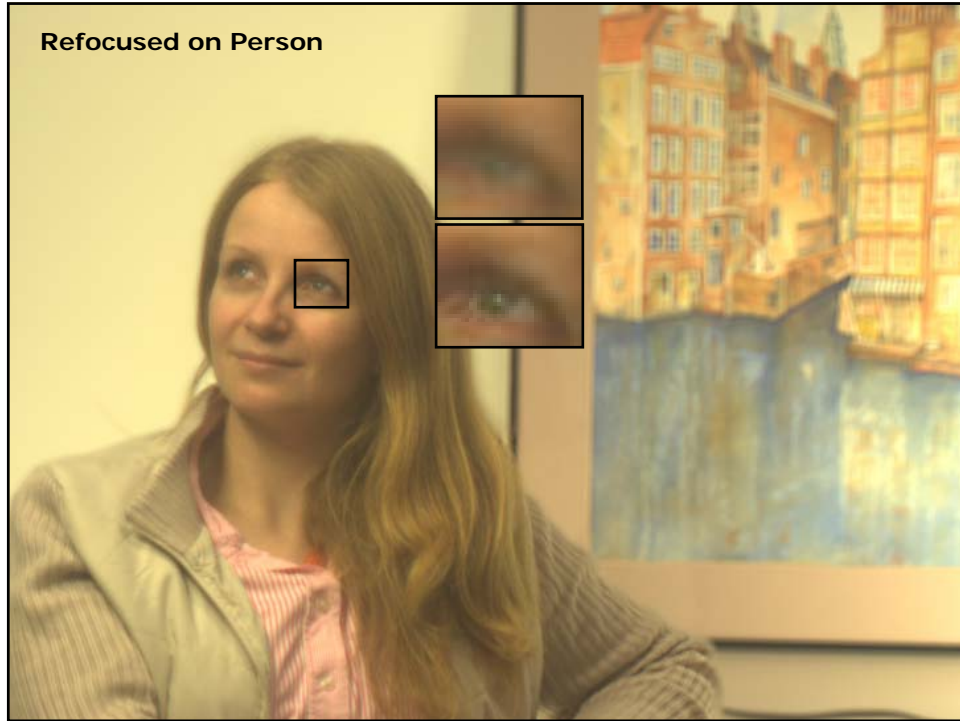






Out of Focus Photo: Coded Aperture





After Removing De-Focus Blur



Open Aperture



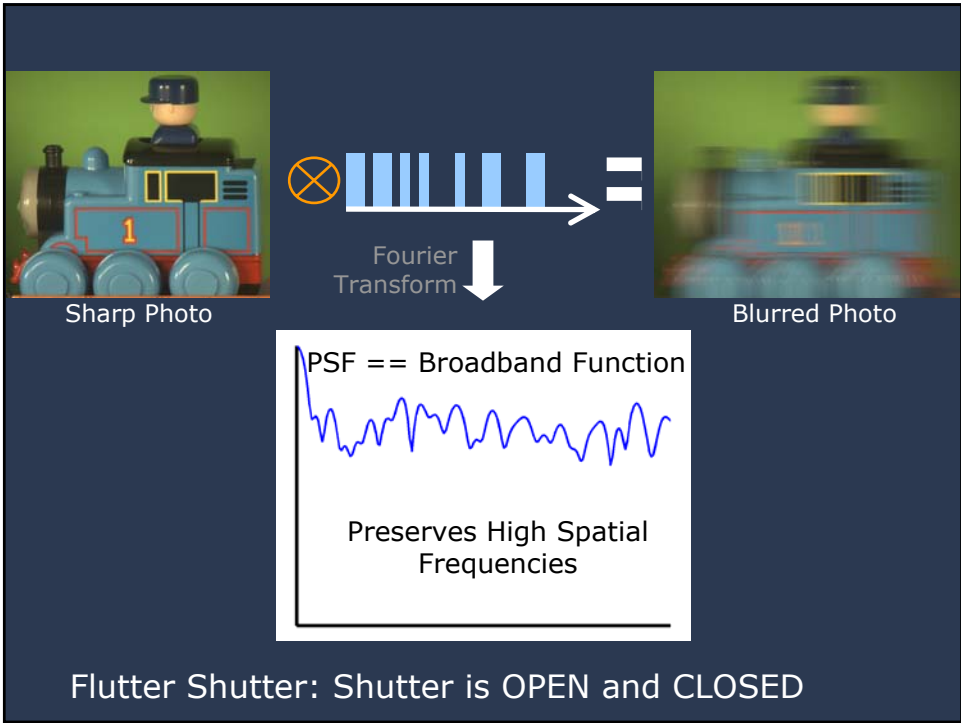
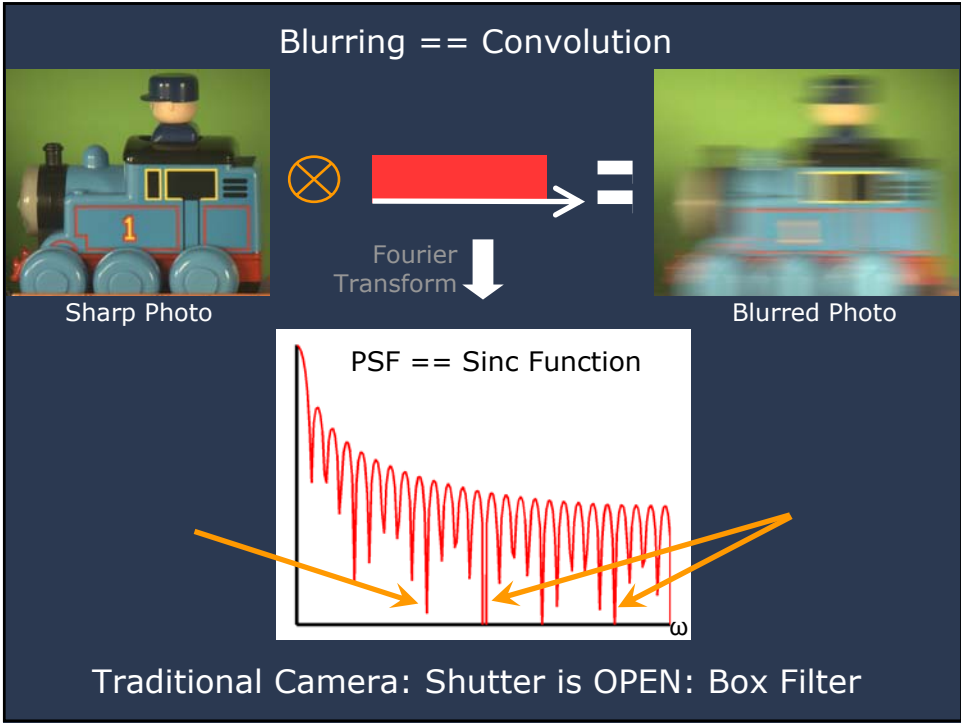
Coded Aperture, 7 * 7 Mask



Motion Blurred Photo



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

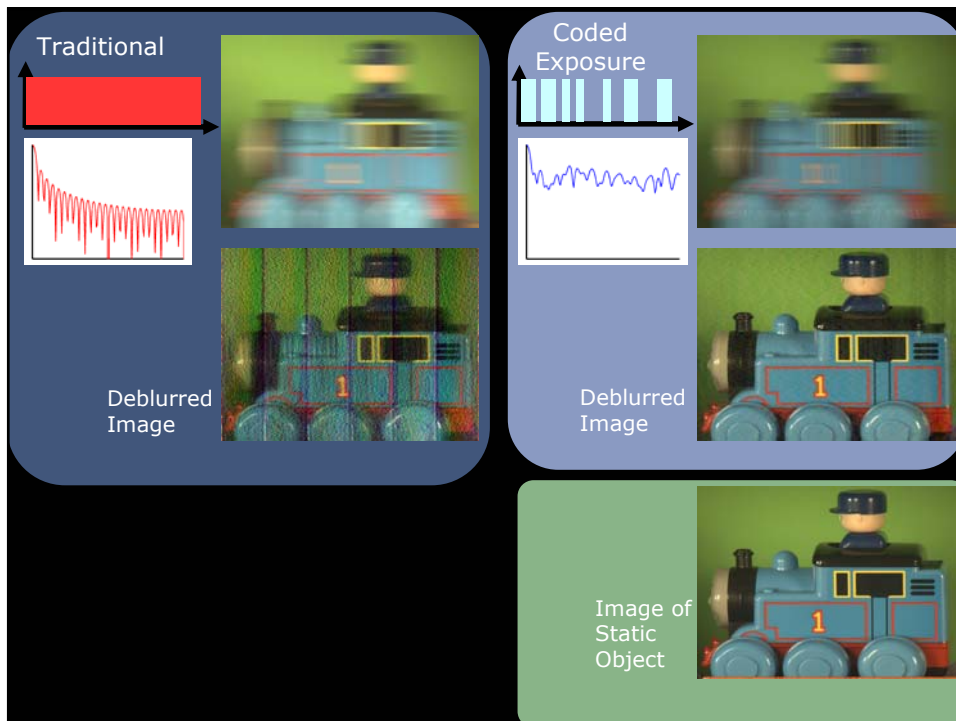


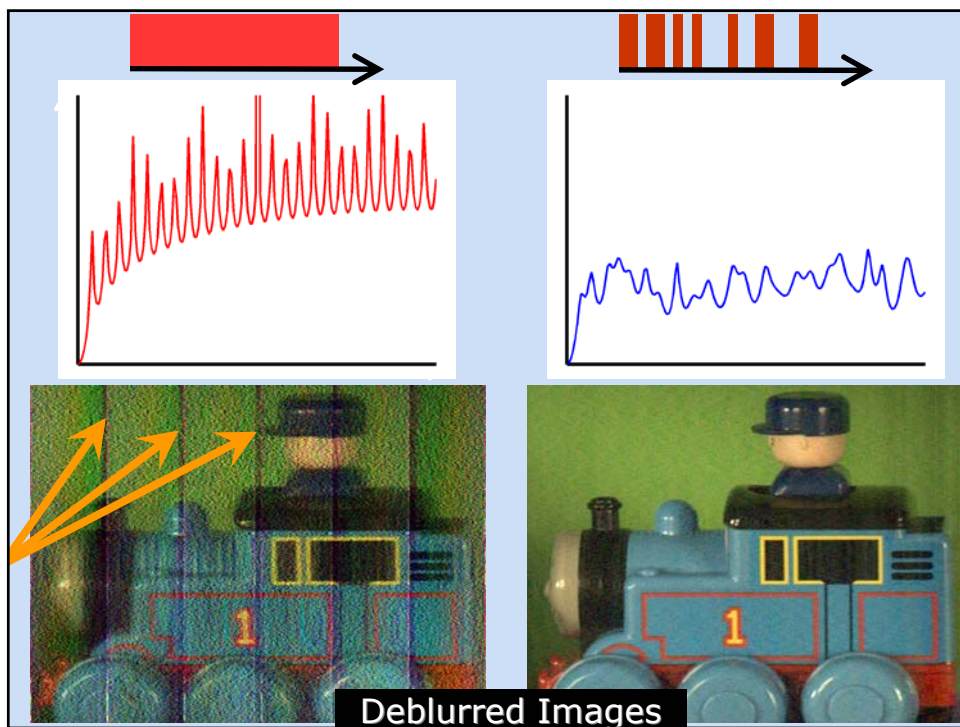
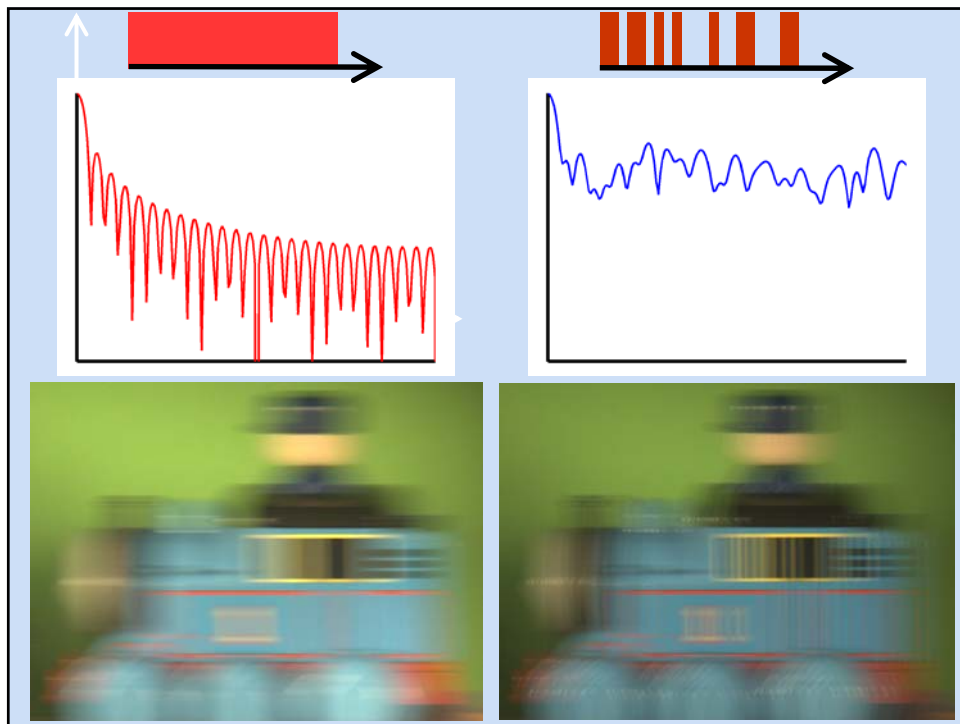
Flutter Shutter Camera

Raskar, Agrawal, Tumblin [Siggraph2006]



LCD opacity switched in coded sequence

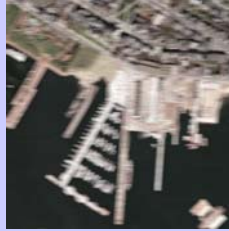
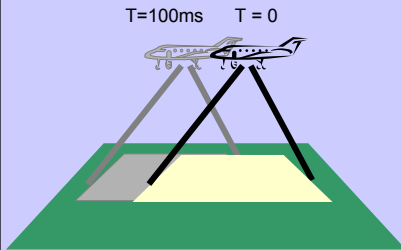




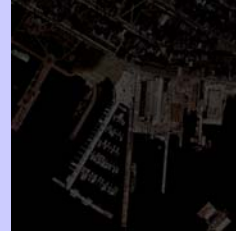


Application: Aerial Imaging

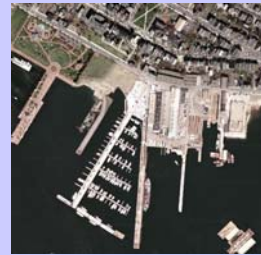
Sharpness versus Image Pixel Brightness



Long Exposure:

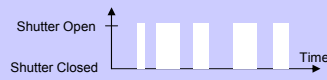


Short Exposure:



Sharp image with sufficient brightness

Flutter Shutter



Motion Blur



Defocus Blur



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



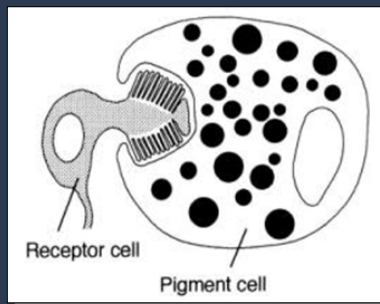
Coding in Time



Coding in Space

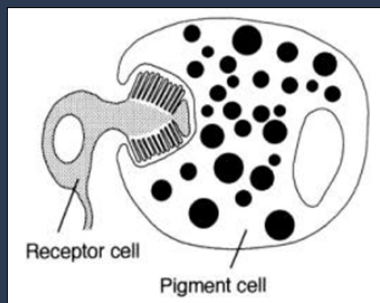
Codes at Work

- Imaging
 - Aperture Modification
 - Without Lens
 - Astronomy [Fenimore and Gotterson, '89, Skinner, '88]
 - Nuclear Medicine Imaging [Zhang et al. '99]
 - Lensless Imaging, [Zomet & Nayar, CVPR'06]
 - With Lens
 - Range Imaging, [Johnson et al. '00, Hiura and Matsuyama '98, Farid and Simoncelli '98]
 - Wavefront Coding, CDM Optics
 - Levin et al. Siggraph'07
- Illumination
 - Global Direct Separation, [Nayar, Guru, Grossberg, Raskar, Sig'06]
 - Veiling Glare Removal, [Talvala, Adams, Levoy, Sig'07]
- Audio
 - Reverberation Analysis
- Radar
 - Chirps for ranging

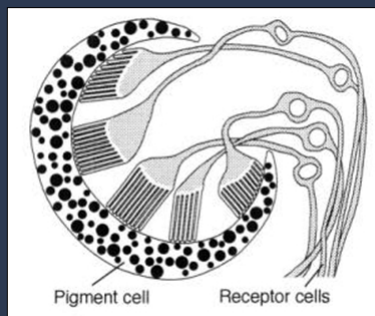


Larval Trematode Worm

Coded Aperture in Nature ?



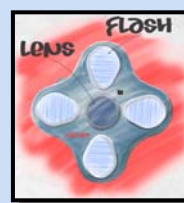
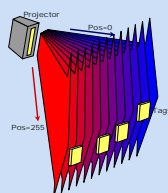
Larval Trematode Worm



Turbellarian Worm

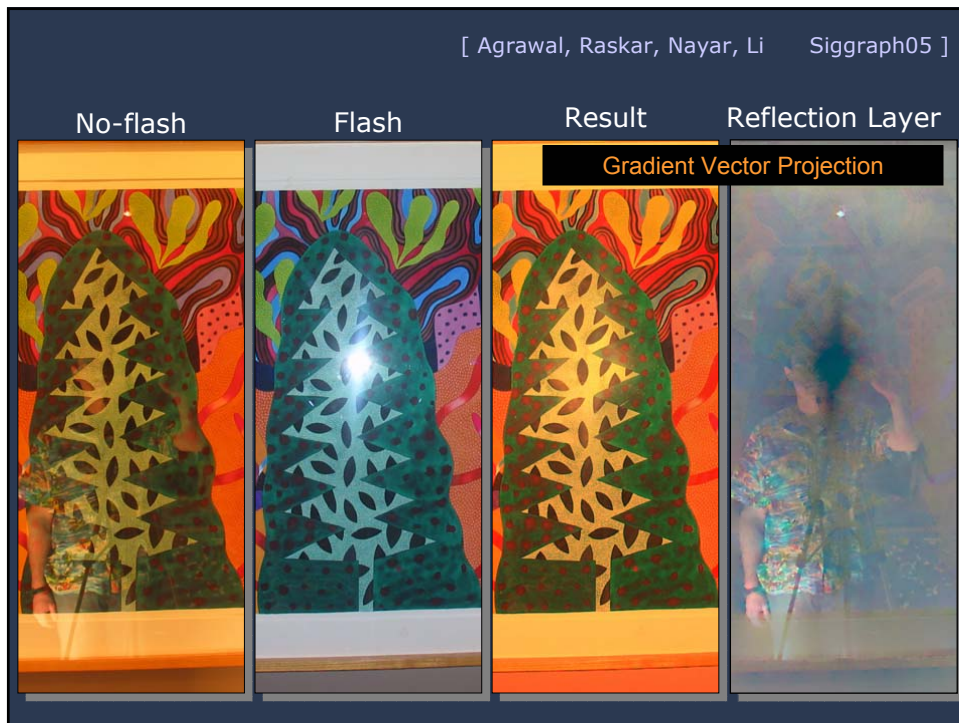
Less is More ..

- 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)

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 - Reversible encoding of data
 - Additional sensors/optics/illum
 - 'Scene analysis' : (Next software?)



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 - Not mimic human eye
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Computational Photography

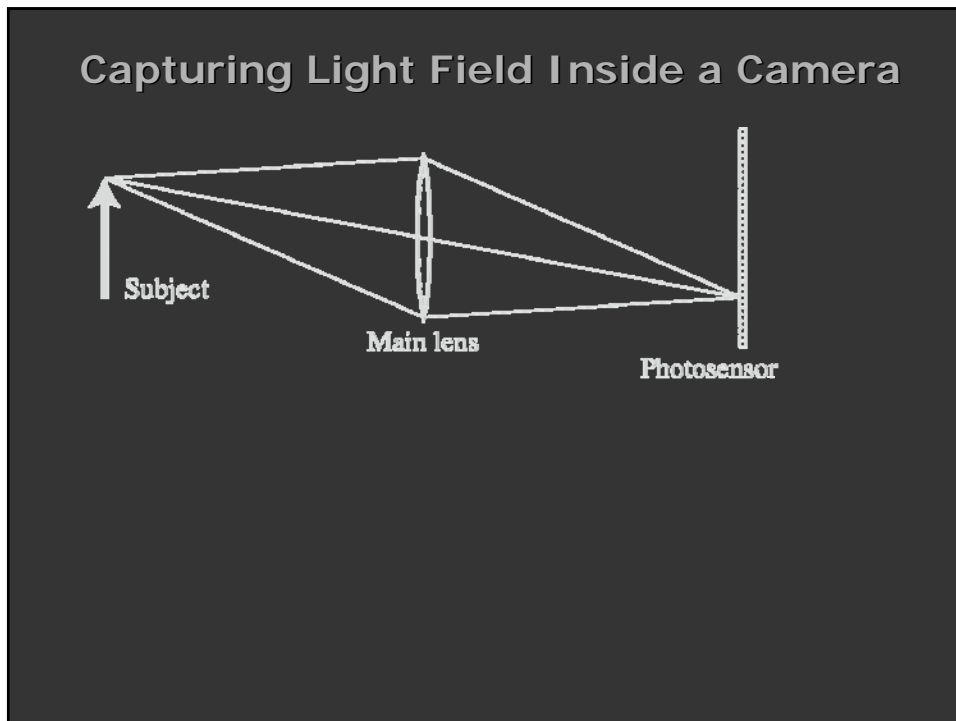
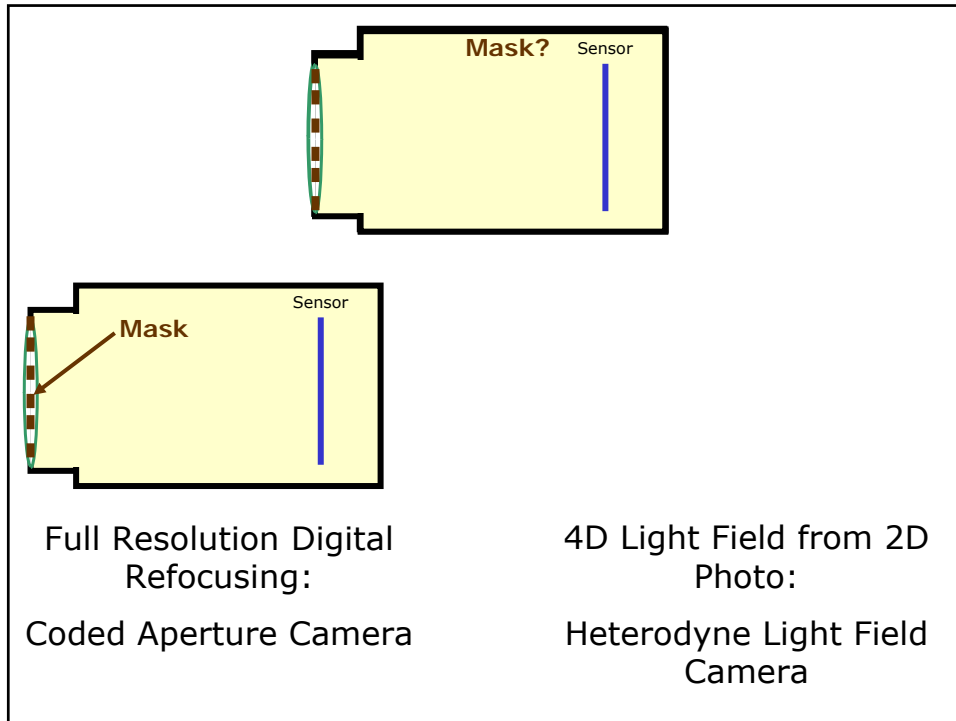
1. Epsilon Photography
 - Multiphotos by varying camera parameters
 - HDR, panorama
 - 'Ultimate camera': (Photo-editor)

2.

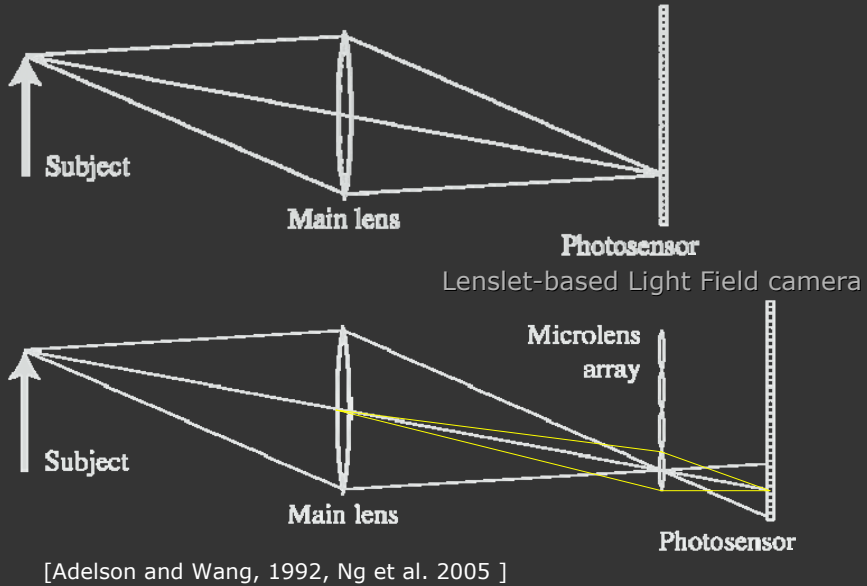
-
-
-
-

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





Capturing Light Field Inside a Camera



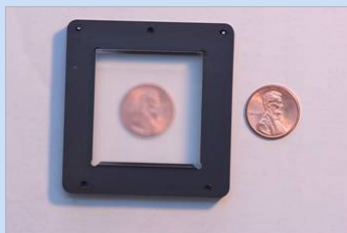
Stanford Plenoptic Camera [Ng et al 2005]



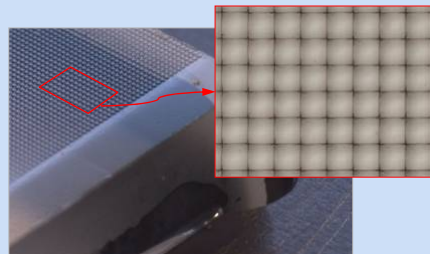
Contax medium format camera



Kodak 16-megapixel sensor



Adaptive Optics microlens array



125µ square-sided microlenses

$$4000 \times 4000 \text{ pixels} \div 292 \times 292 \text{ lenses} = 14 \times 14 \text{ pixels per lens}$$

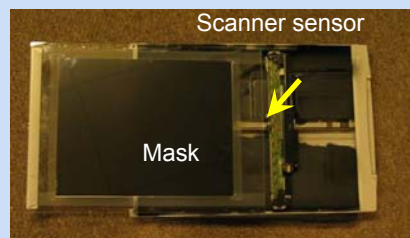
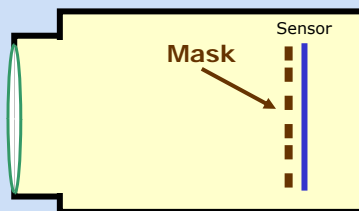
Digital Refocusing



[Ng et al 2005]

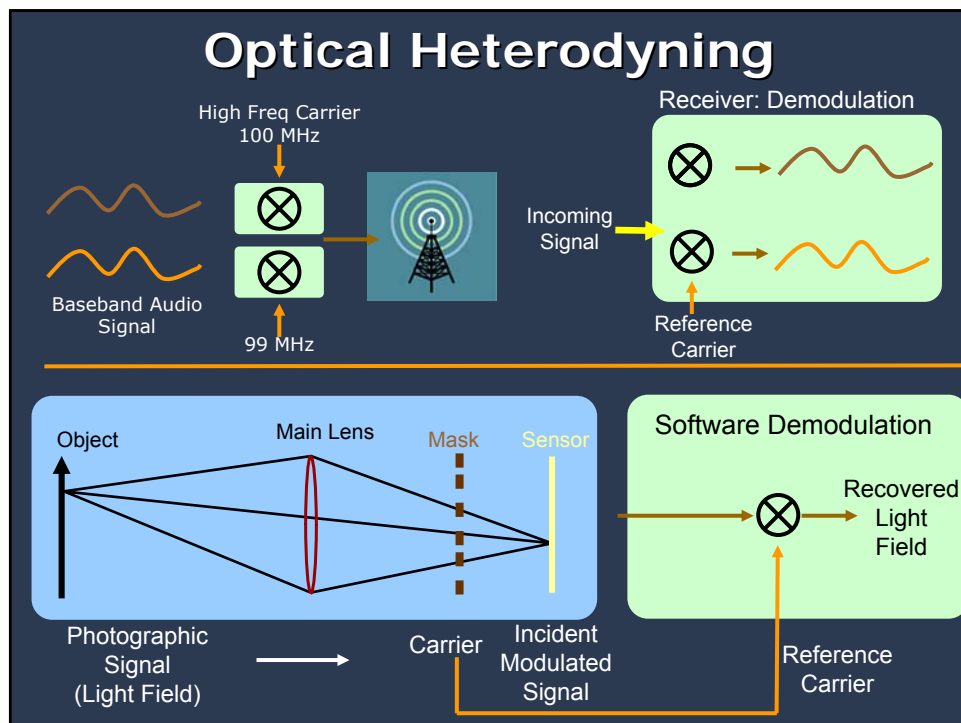
Can we achieve this with a Mask alone?

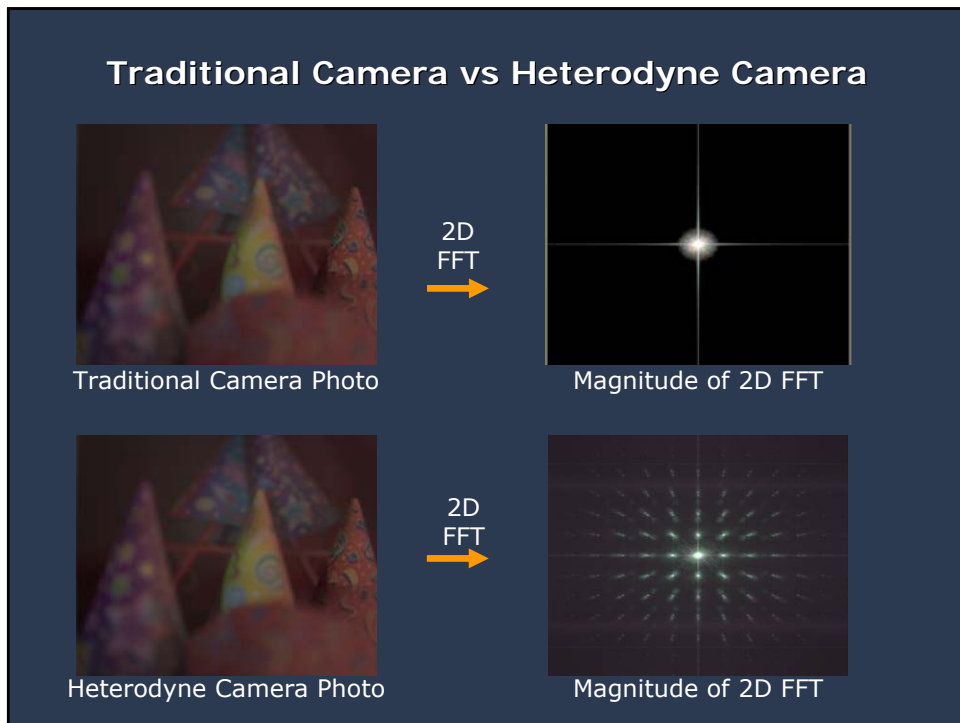
Heterodyne Light Field Camera



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

What should be the
pattern of the mask ?





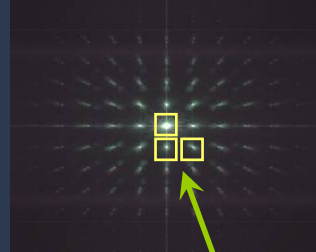
Computing 4D Light Field

2D Sensor Photo, 1800*1800



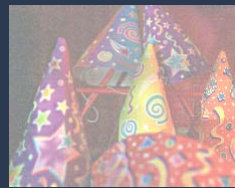
2D
FFT

2D Fourier Transform, 1800*1800



9*9=81 spectral copies

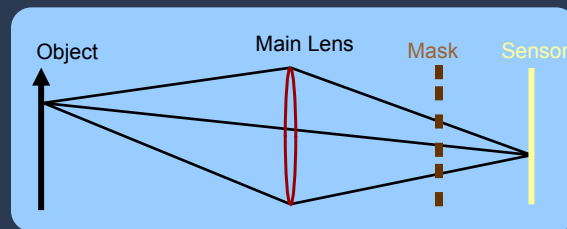
Rearrange 2D tiles into 4D planes
200*200*9*9



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

Related Work

- Light Field Capture

- Gortler et al., Levoy & Hanrahan, SIG'96, Isaksen et al.'SIG00
- Light Field Microscopy: Levoy et al. SIG'06
- Integral Photography
 - Lippman'08, Ives'30, Georgeiv et al. EGSR'06, Okano et al.'97
- Camera arrays: Wilburn et al. SIG'05
- Flatbed Scanner + Lenslet array: Yang, 2000
- Light Field Video Camera: Wilburn et al.'02
- Programmable Aperture: Liang et al. ICIP 2007

- Plenoptic Camera
 - Wang and Adelson'92
 - Ng et al.'05

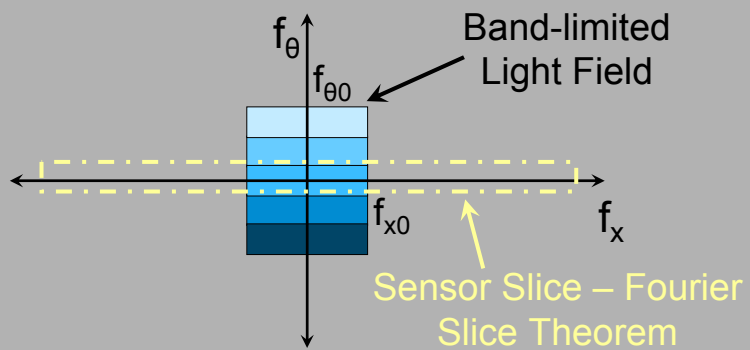
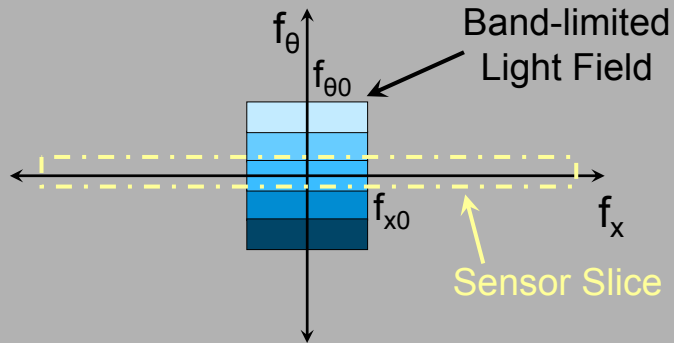


Photo = Slice of Light Field in Fourier Domain

[Ren Ng, SIGGRAPH

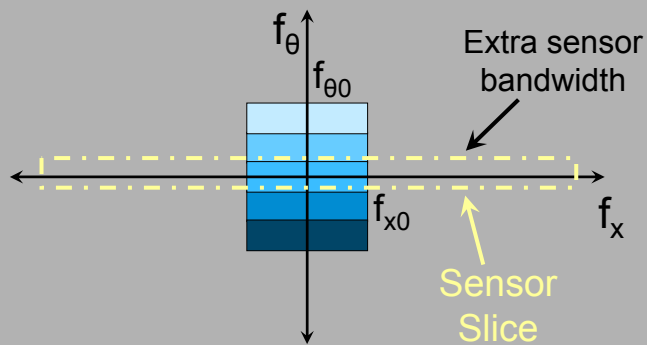
2005]

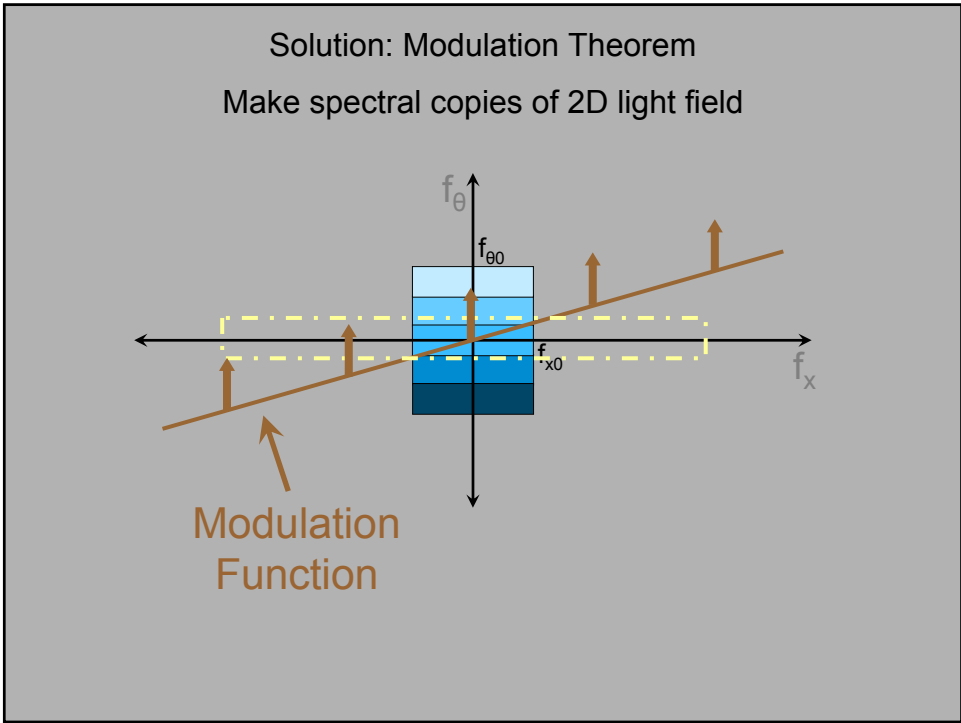
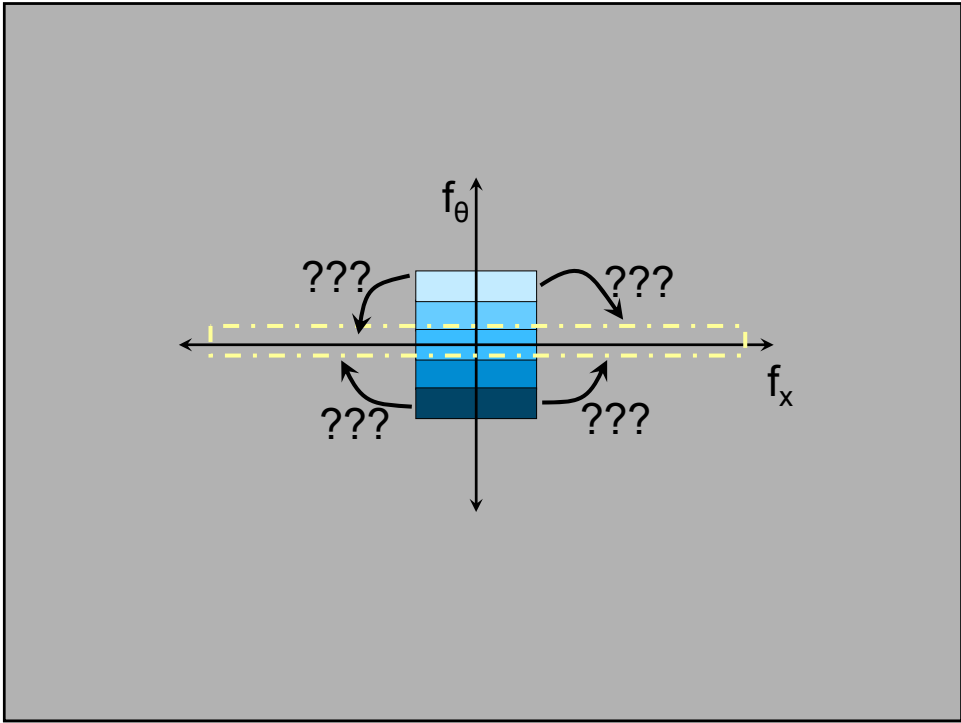
How to Capture 2D Light Field with 1D Sensor ?



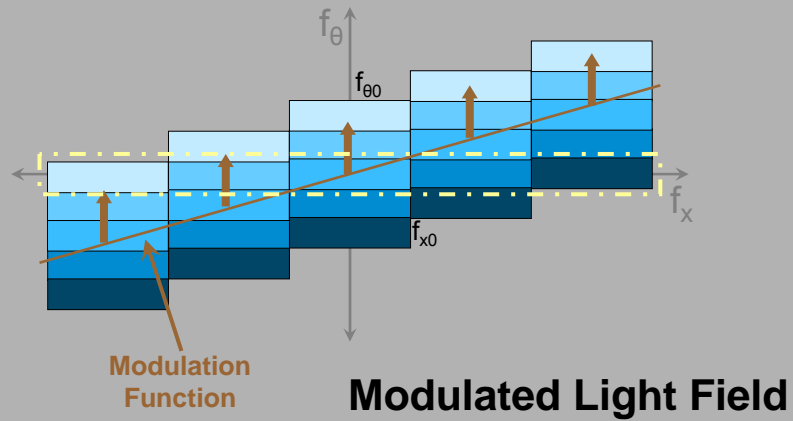
Fourier Light Field Space

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

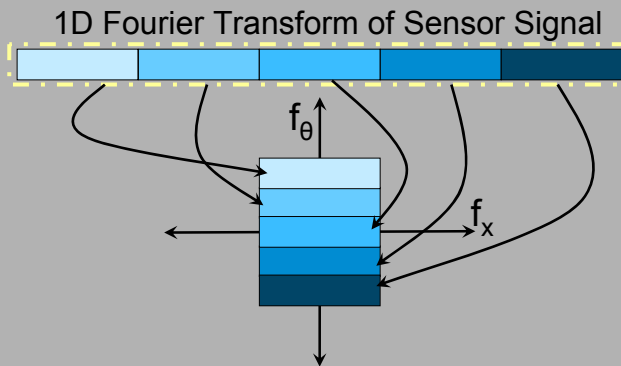




Sensor Slice captures entire Light Field

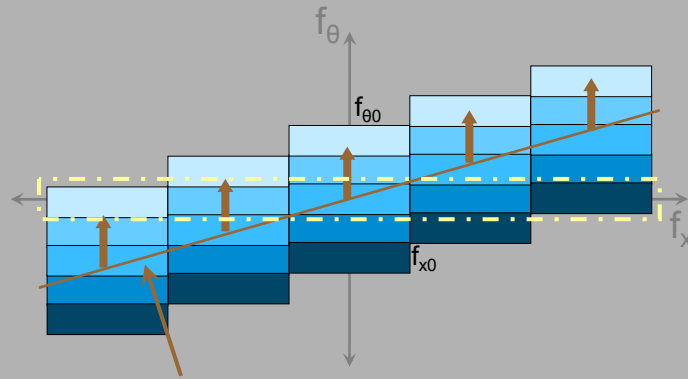


Demodulation to recover Light Field



Modulation Function == Sum of Impulses

Physical Mask = Sum of Cosines

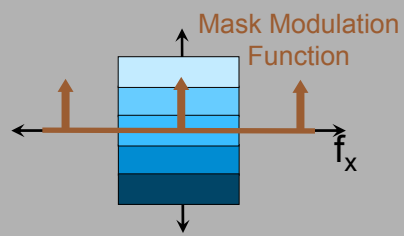
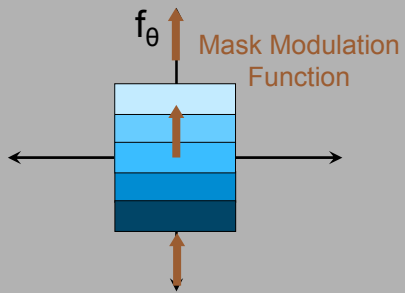
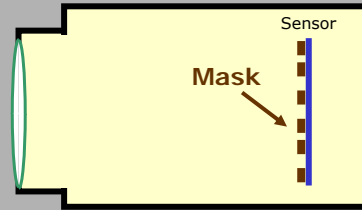
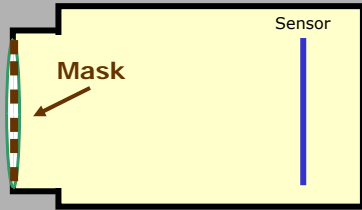


Cosine Mask Used

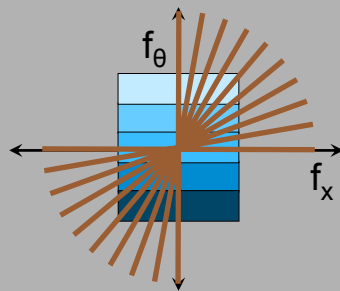
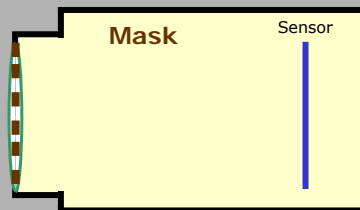
Mask Tile



Where to place the Mask?

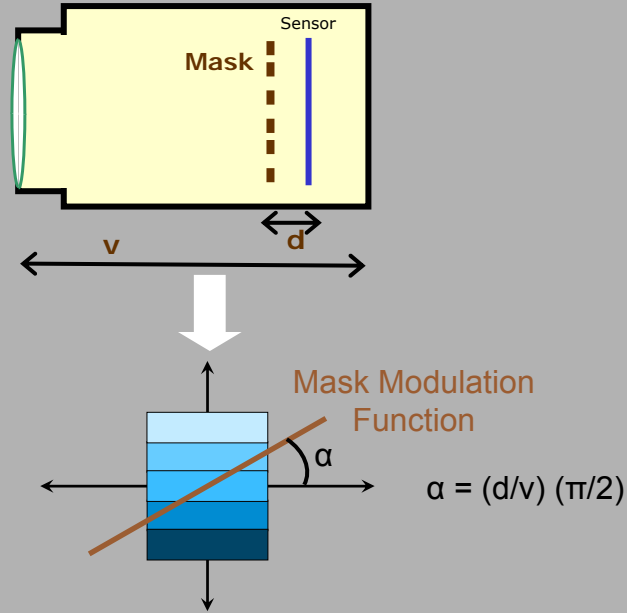


Where to place the Mask?



Mask Modulation Function

Where to place the Mask?



Captured 2D Photo

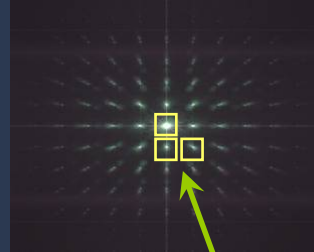


Computing 4D Light Field

2D Sensor Photo, 1800*1800



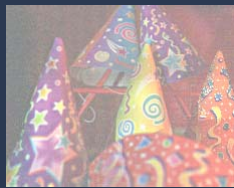
2D Fourier Transform



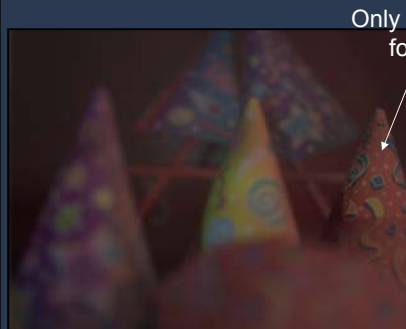
9*9=81 spectral copies



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



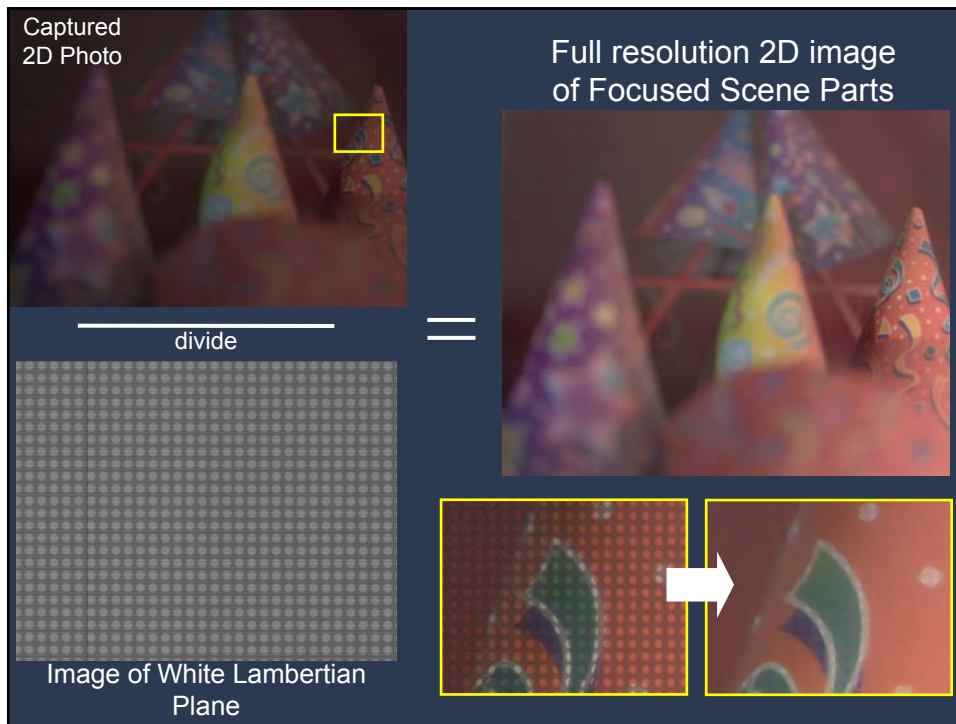
4D Light Field
200*200*9*9



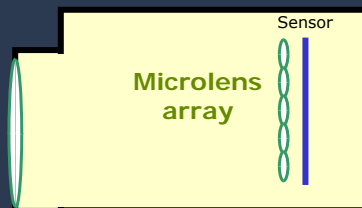
Captured Photo



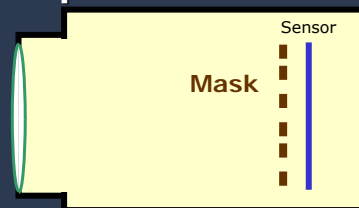
Digital Refocusing



Differences with Plenoptic Camera



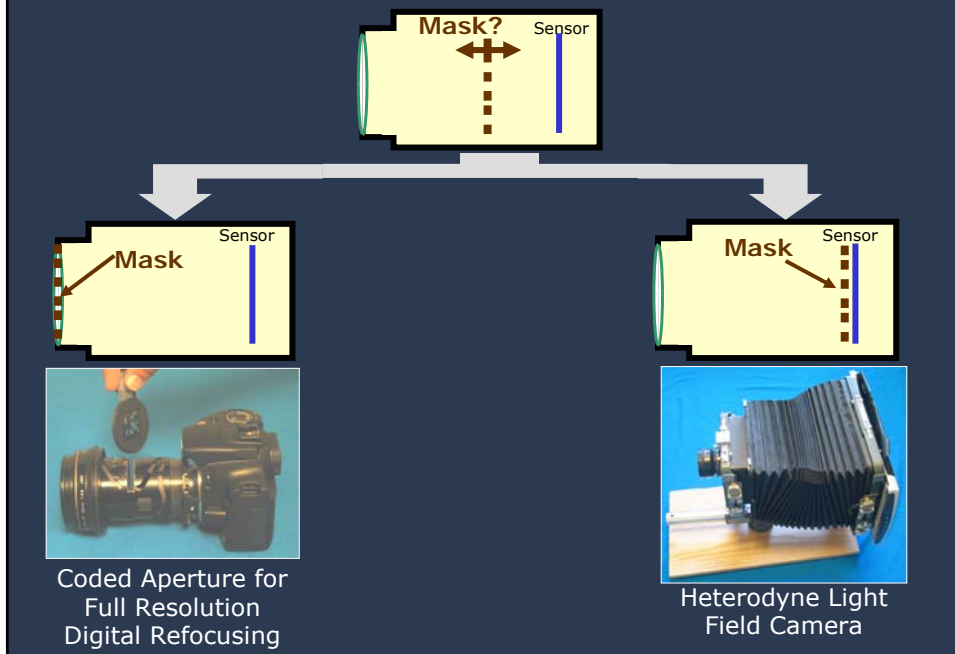
Plenoptic Camera



Heterodyne Camera

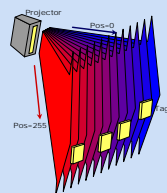
- Micro-lens array
- Samples individual rays
- Needs high alignment precision
- Wasted pixels
- Narrowband Cosine Mask
- Samples coded combination of rays
- More flexible
- No wastage

Coding and Modulation in Camera Using Masks




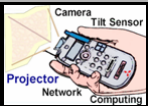







Coded Imaging

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



Projector-based Displays

	Planar	Non-planar	Curved	Objects	Pocket-Proj
Single Projector	2000 	1998 		2001 	2002 
	2000 	1999 	2002 	1999 	2003 

Vicon Optical Motion Capture



High-speed IR Camera

Medical Rehabilitation



Athlete Analysis



Body-worn markers



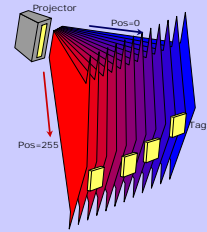
Performance Capture



Biomechanical Analysis

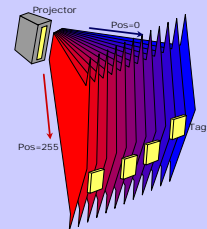
Coded Illumination

High Speed Motion Capture



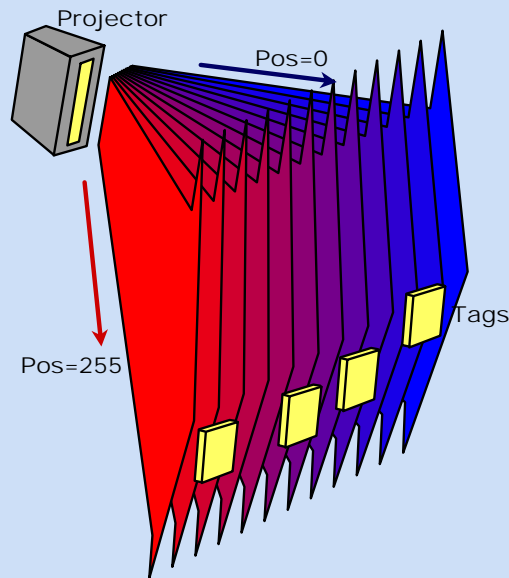
- To increase tracking speed
Code position: Non-colocated emitters
- To work in Ambient Light
Code time: 455KHz modulation
- Invisible
Code wavelength: Infrared

Light Meters



- Distributed, wireless
 - Real-time location
 - Incident light reading
- Annotate Event Photos
 - Coded Illumination
 - Capture image location of imperceptible tags
 - Works in ambient light, 500 Hz

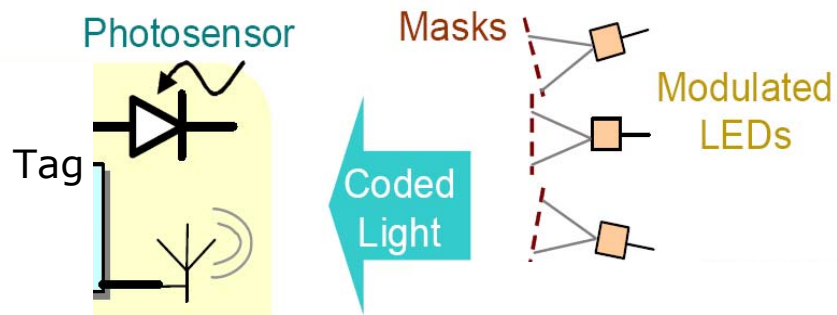
Labeling Space



Each location
receives a unique
temporal code

But 60Hz
video projector
is too slow

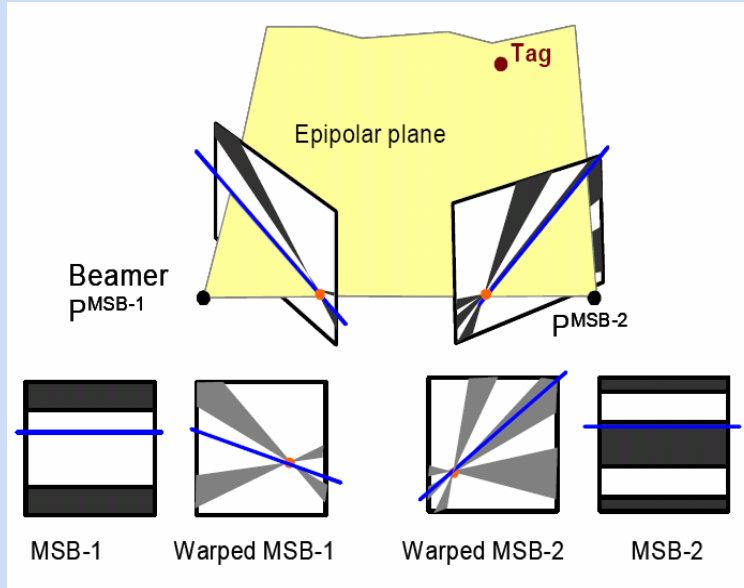
Fast Switching using Non-colocated Emitters for Structured Light



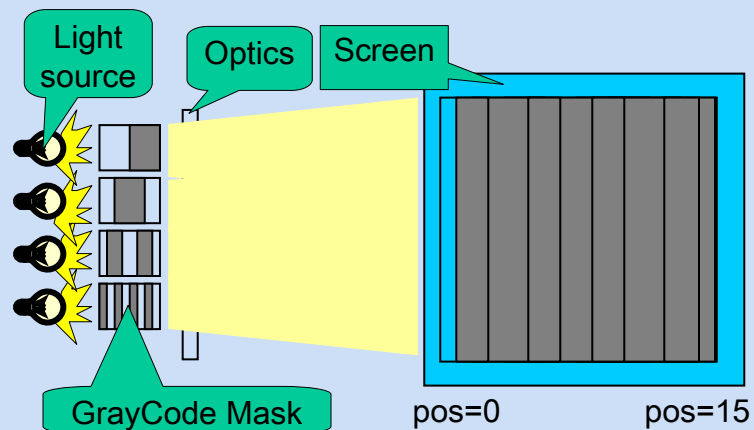
Fixed Masks
+ Blinking LEDs

Time multiplex,
Freq or CDMA ?

Fast Switching using Non-colocated Emitters for Structured Light



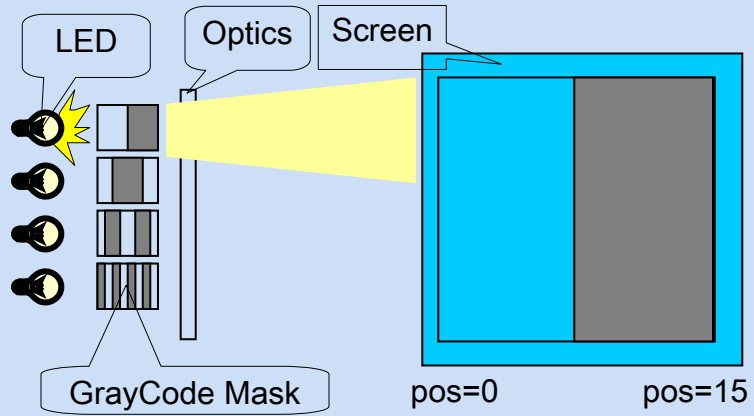
How Labeling Works



Light source blink one by one and each position on the screen has different light pattern.

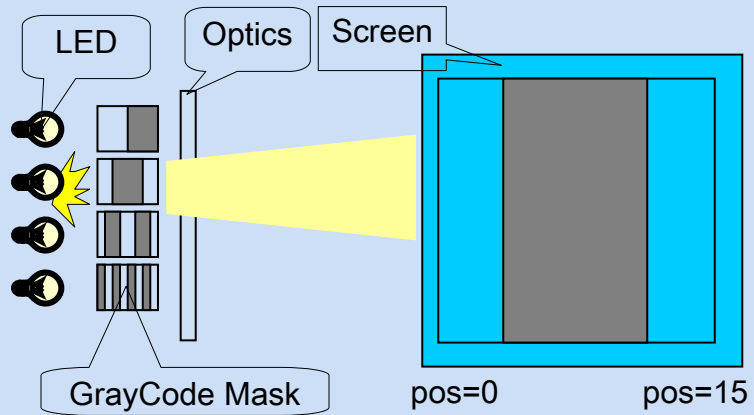
4 light make 4 bit position resolution

Labeling Space



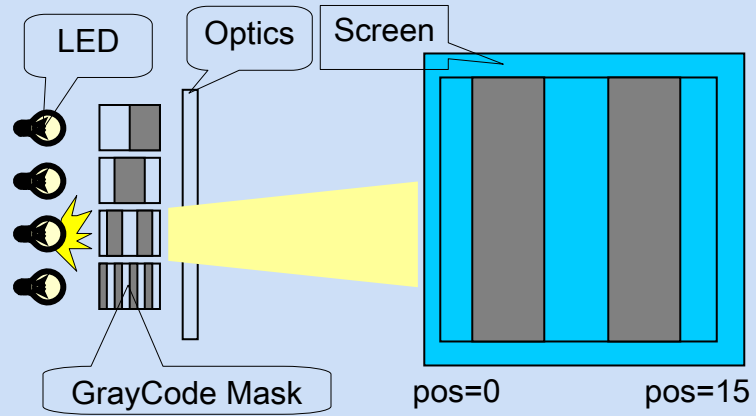
1 LED for 1 Bit pattern

Labeling Space



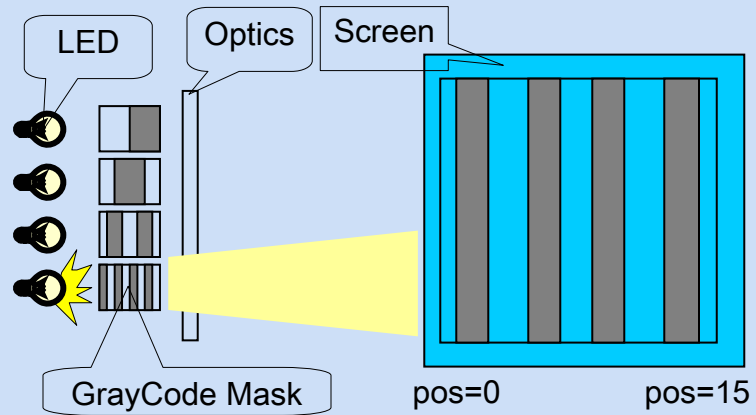
1 LED for 1 Bit pattern

Labeling Space



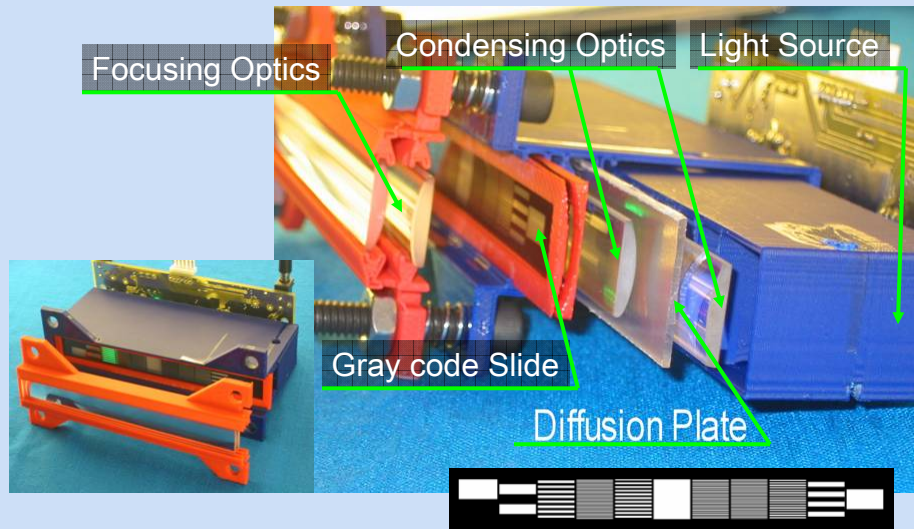
1 LED for 1 Bit pattern

Labeling Space

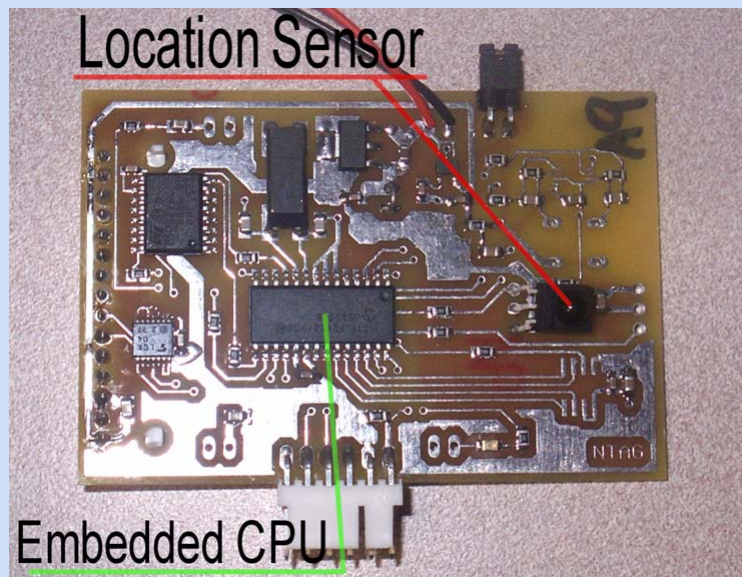


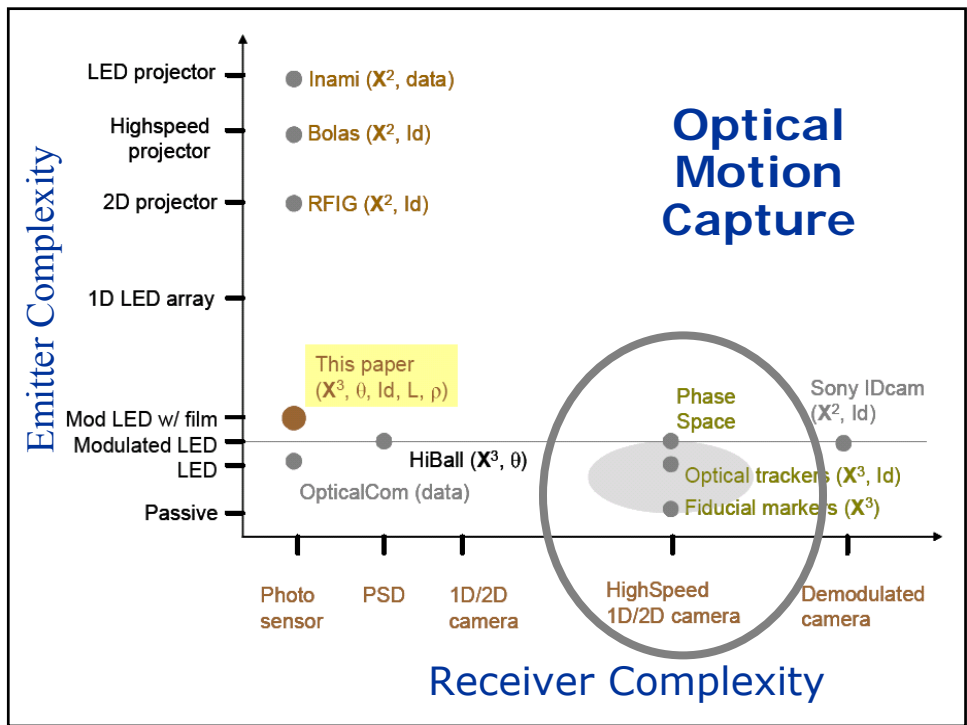
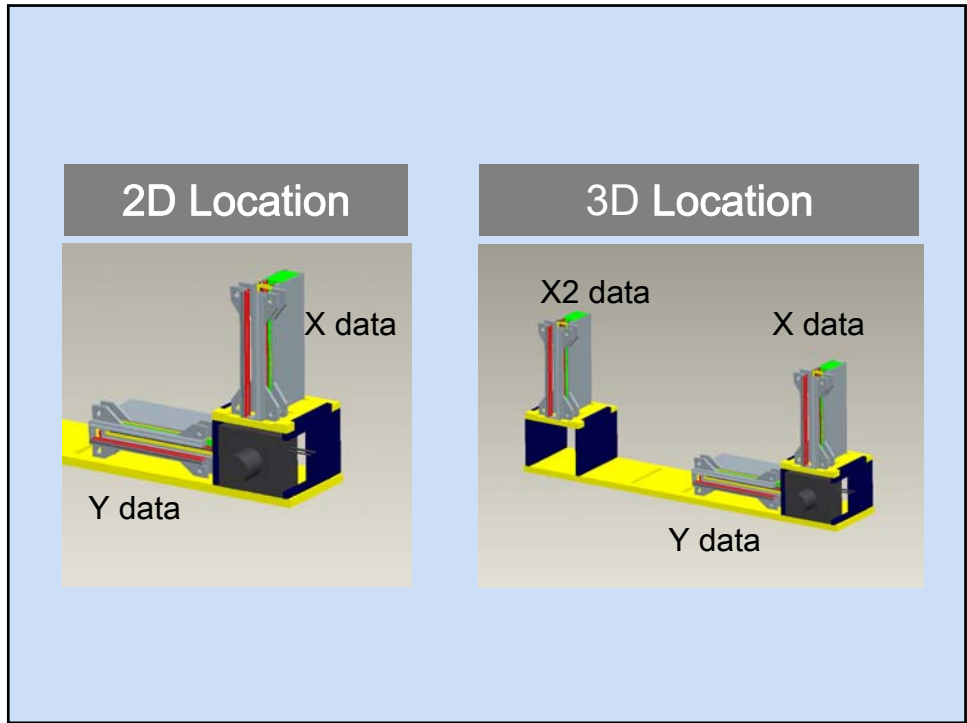
1 LED for 1 Bit pattern

Coded Illumination Projector

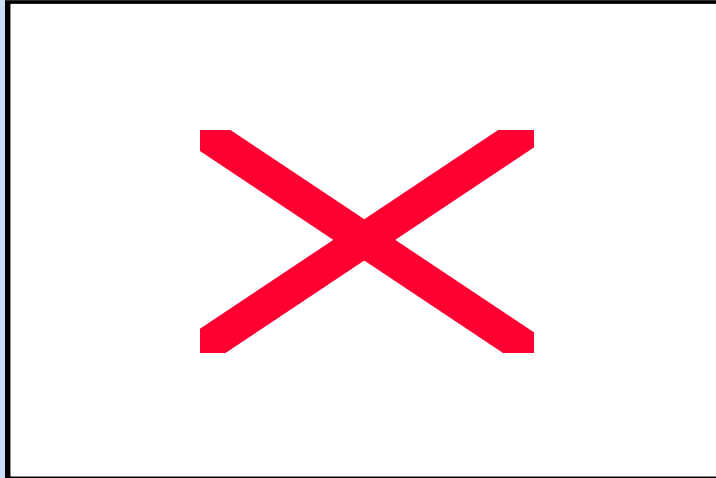


Photosensing Tag





Imperceptible tags, Ambient Lighting, Id per marker



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

High Speed Tracking



Lightmeters: Realistic Editing + Blurring



Actor with imperceptible Tags



Real-time CG with sensed illumination



Optical
Base Emitter

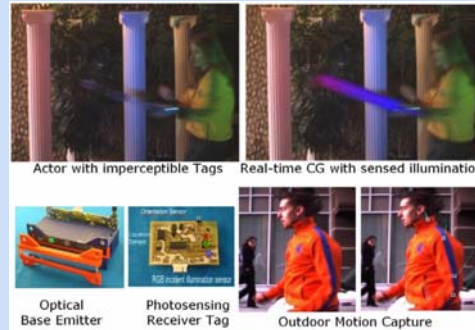


Photosensing
Receiver Tag



Outdoor Motion Capture

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

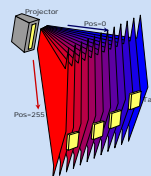
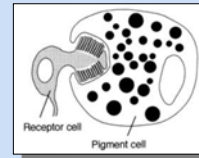
- Amit Agrawal, MERL
- Jack Tumblin, Northwestern U.
- Shree Nayar, Columbia U.
- MERL
 - Jay Thornton, Keisuke Kojima
- Mitsubishi Electric Japan
 - Kazuhiko Sumi, Haruhisa Okuda
- Coded Aperture and Light Field
 - Ashok Veerarghavan, Ankit Mohan
- Prakash, Motion Capture
 - Masahiko Inami, Hideaki 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



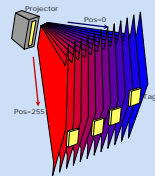
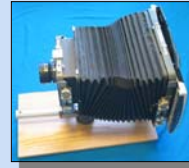
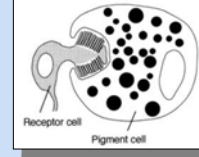


Blind Camera

Sascha Pohflepp,
U of the Art, Berlin, 2006

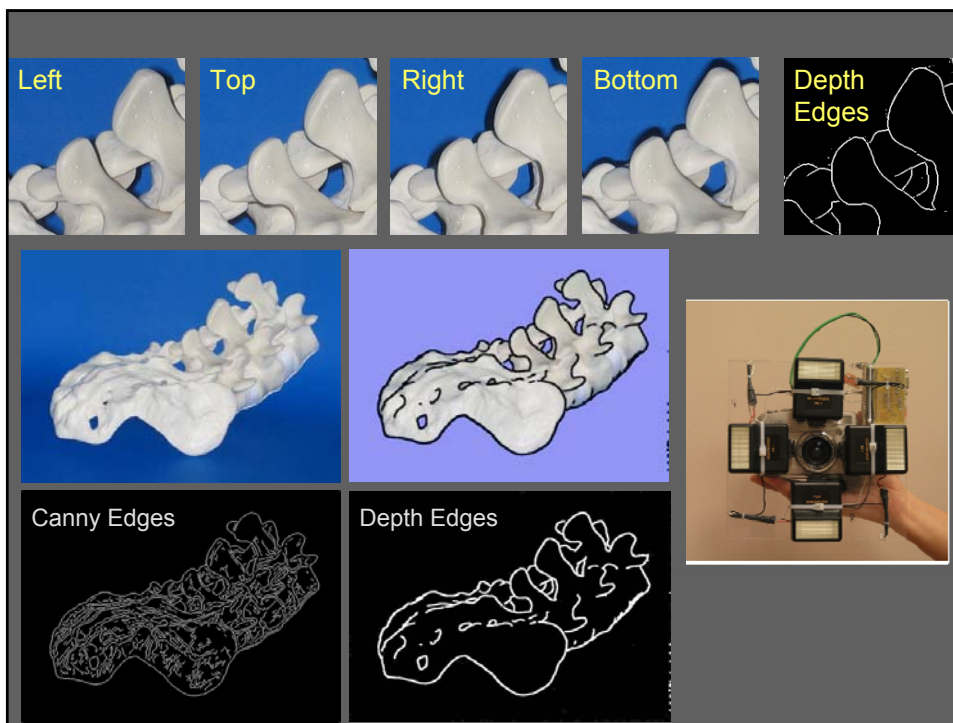
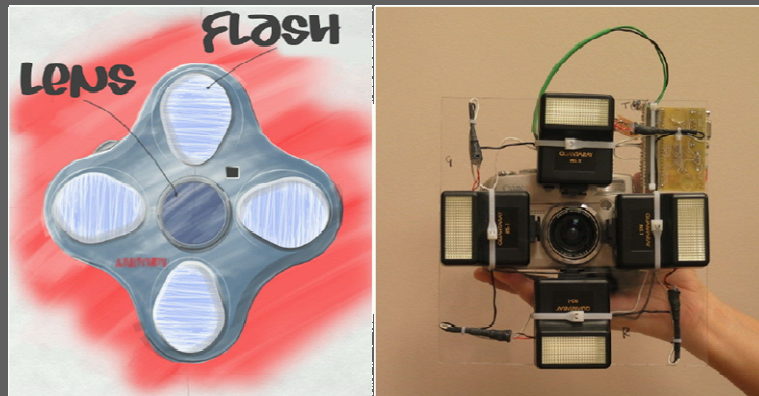
Coded Photography

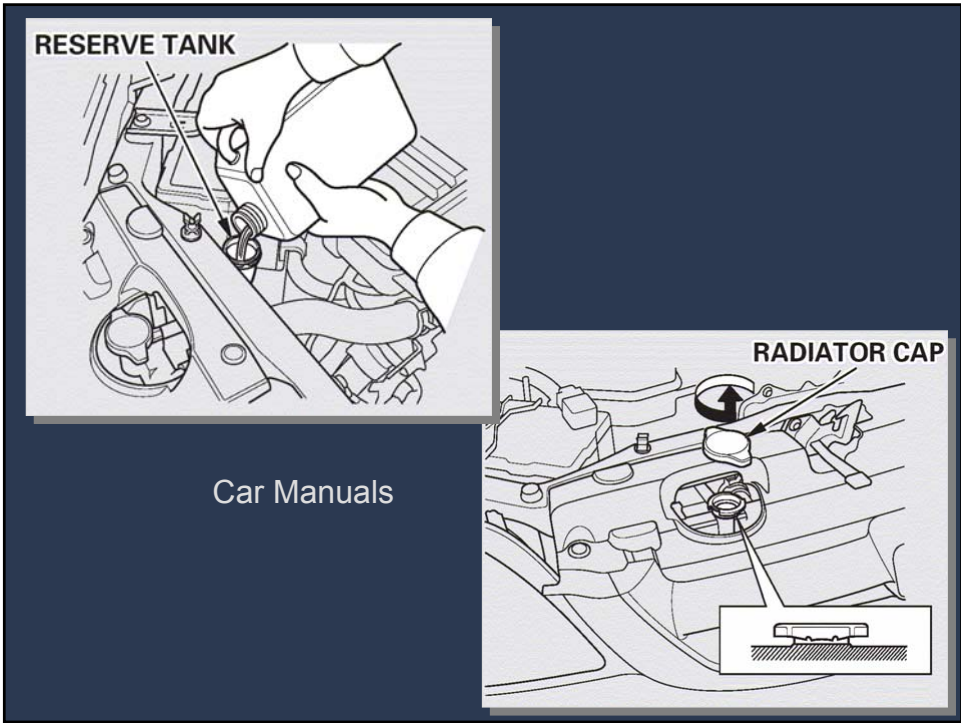
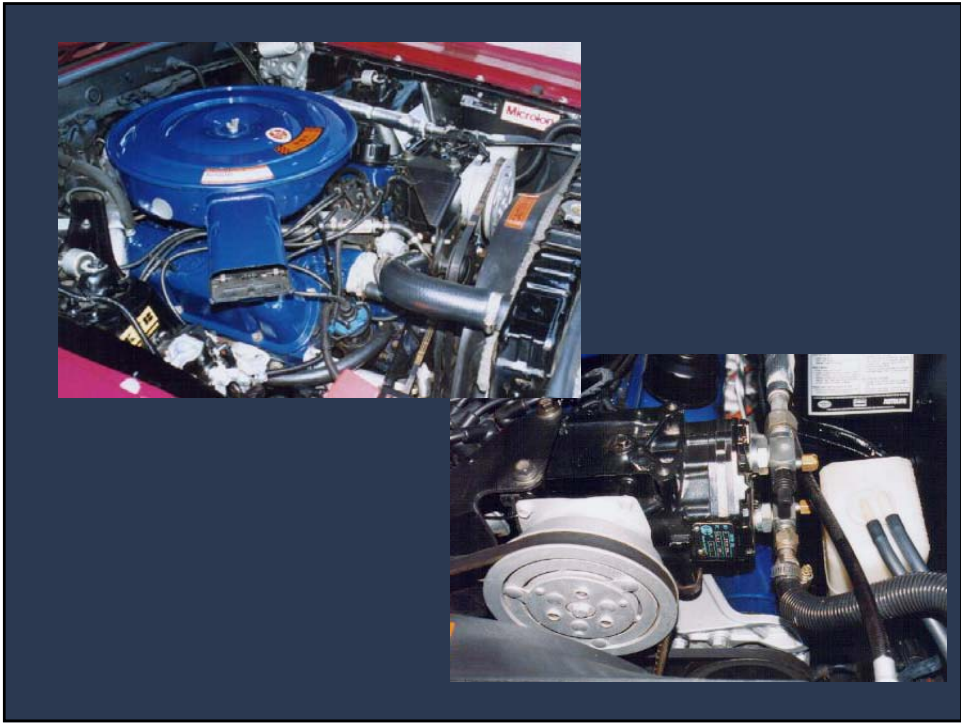
- Coded Exposure
 - Motion Deblurring
- Coded Aperture
 - Focus Deblurring
- Optical Heterodyning
 - Light Field Capture
- Coded Illumination
 - Motion Capture
 - Multi-flash: Shape Contours
- Epsilon->Coded->Impossible Photos



END

Multi-flash Camera for Detecting Depth Edges







What are the problems with 'real' photo in conveying information ?



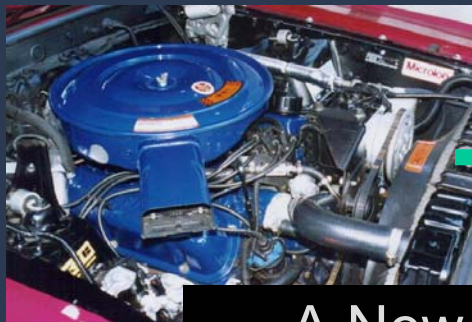
Why do we hire artists to draw what can be photographed ?



Shadows
Clutter
Many Colors



Highlight Shape Edges
Mark moving parts
Basic colors



A New Problem

Shadows

Clutter

Many Colors

Highlight Edges

Mark moving parts

Basic colors

Gestures

Input Photo



Canny Edges

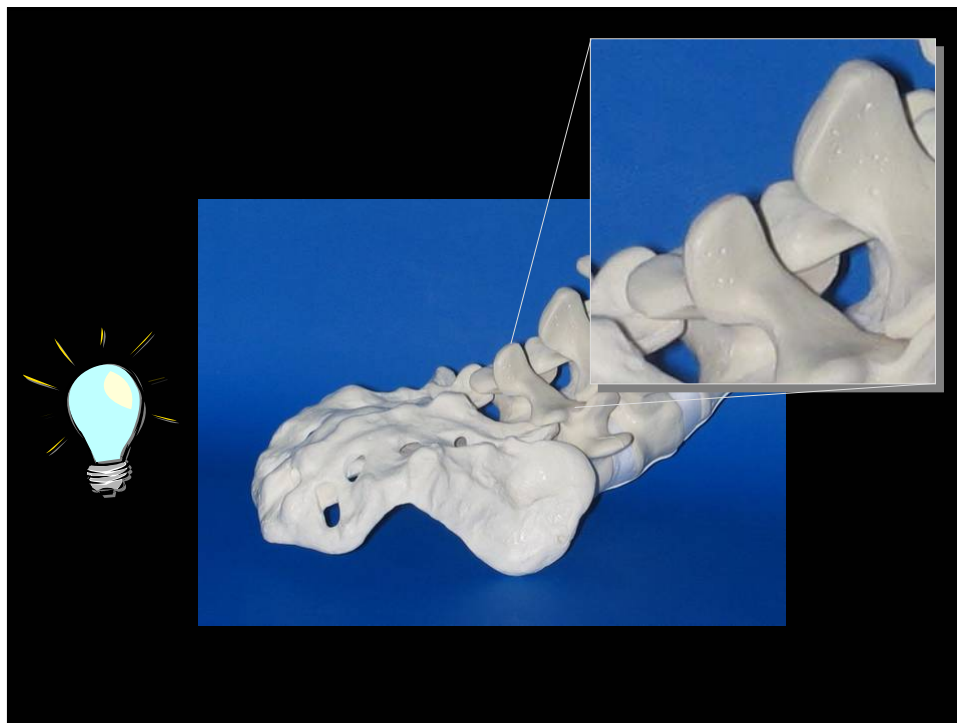
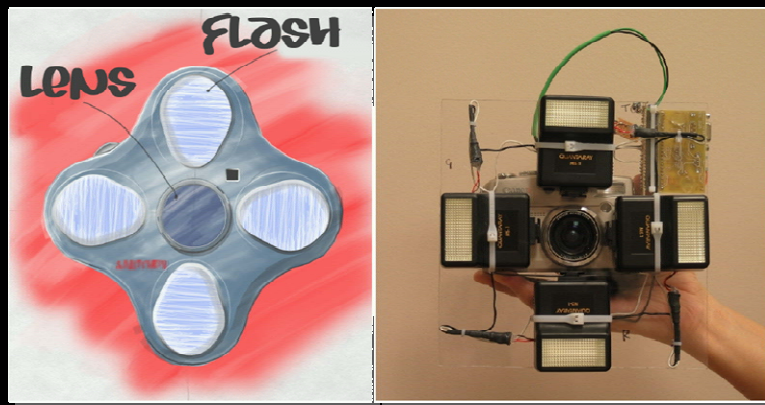


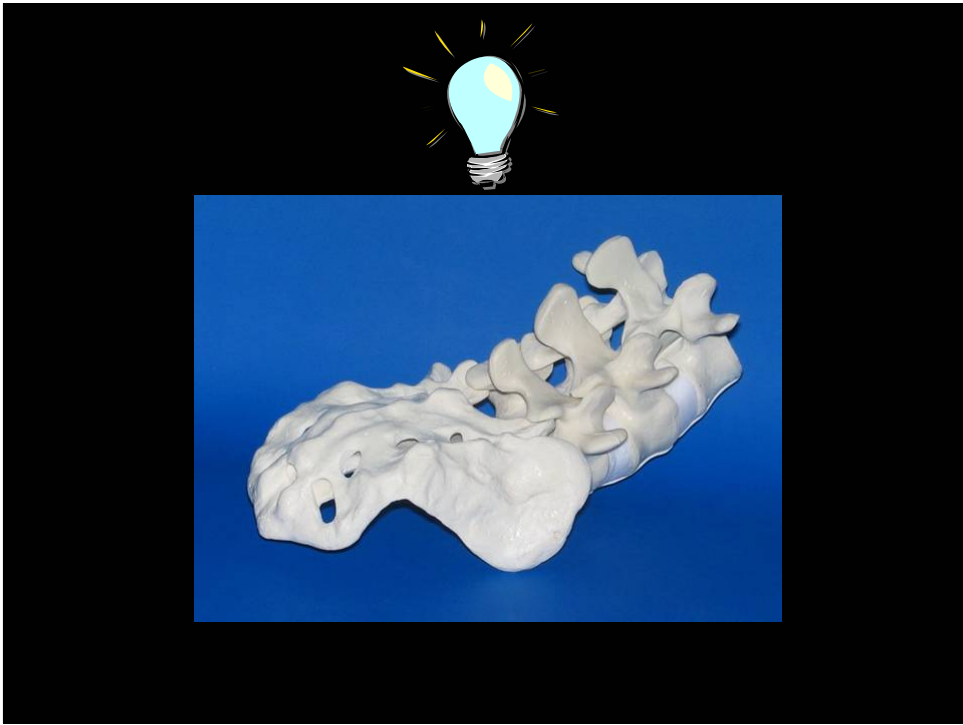
Depth Edges

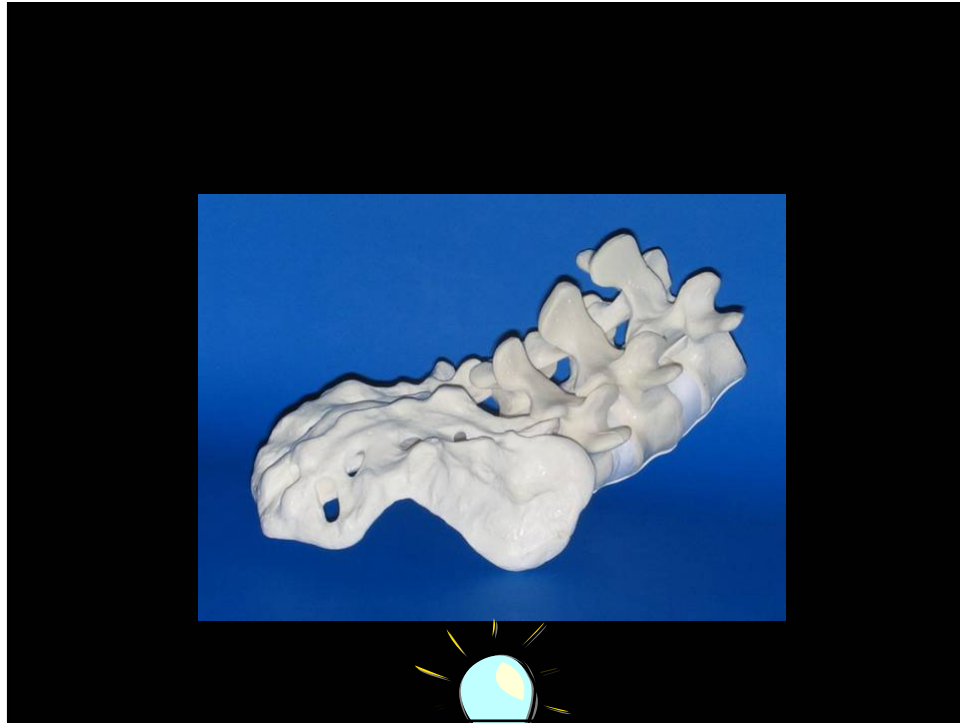


Depth Edges with MultiFlash

Raskar, Tan, Feris, Jingyi Yu, Turk – [ACM SIGGRAPH 2004](#)







Depth Discontinuities



Internal and external
Shape boundaries, Occluding contour, Silhouettes

