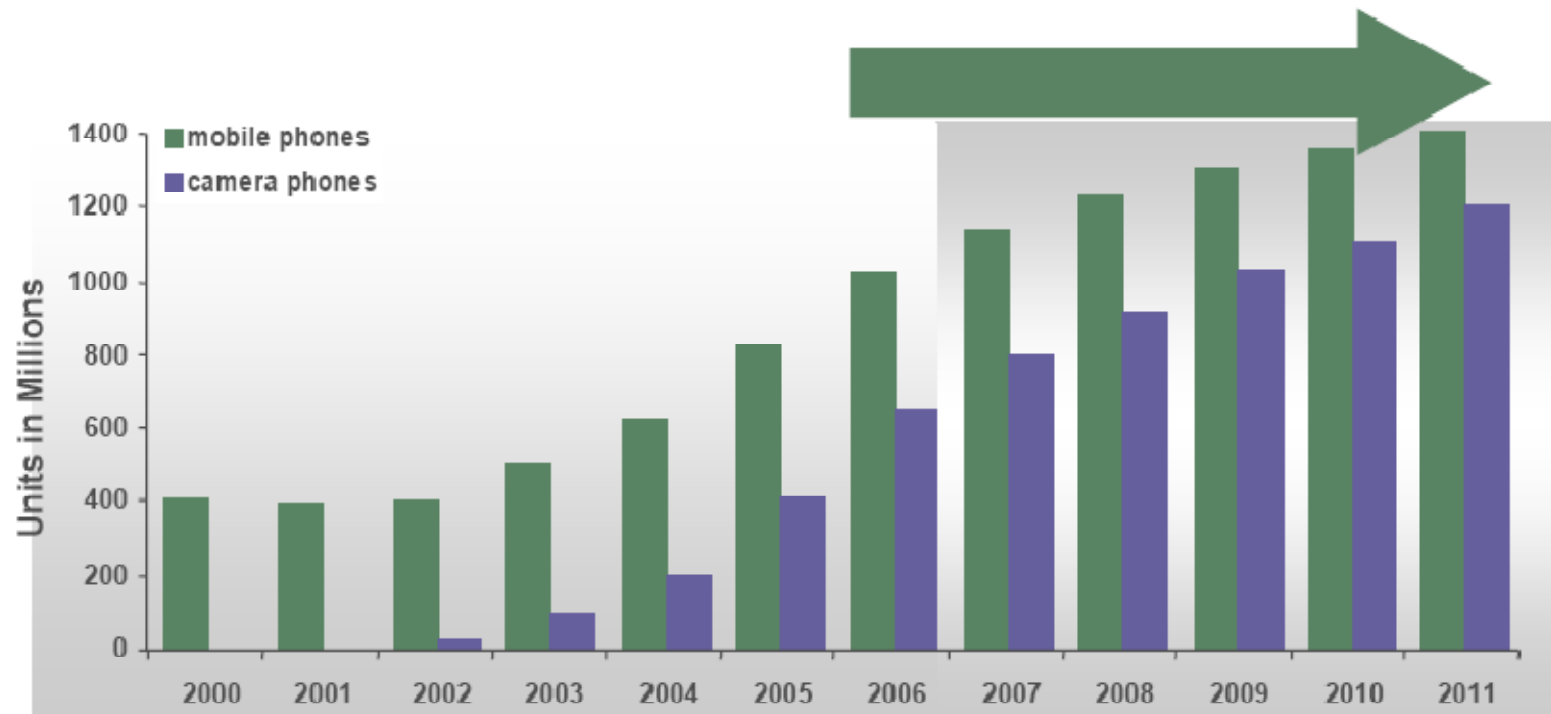


Ramesh Raskar

Camera Culture

Associate Professor, MIT Media Lab

Integration of Cameras in Mobile Phones

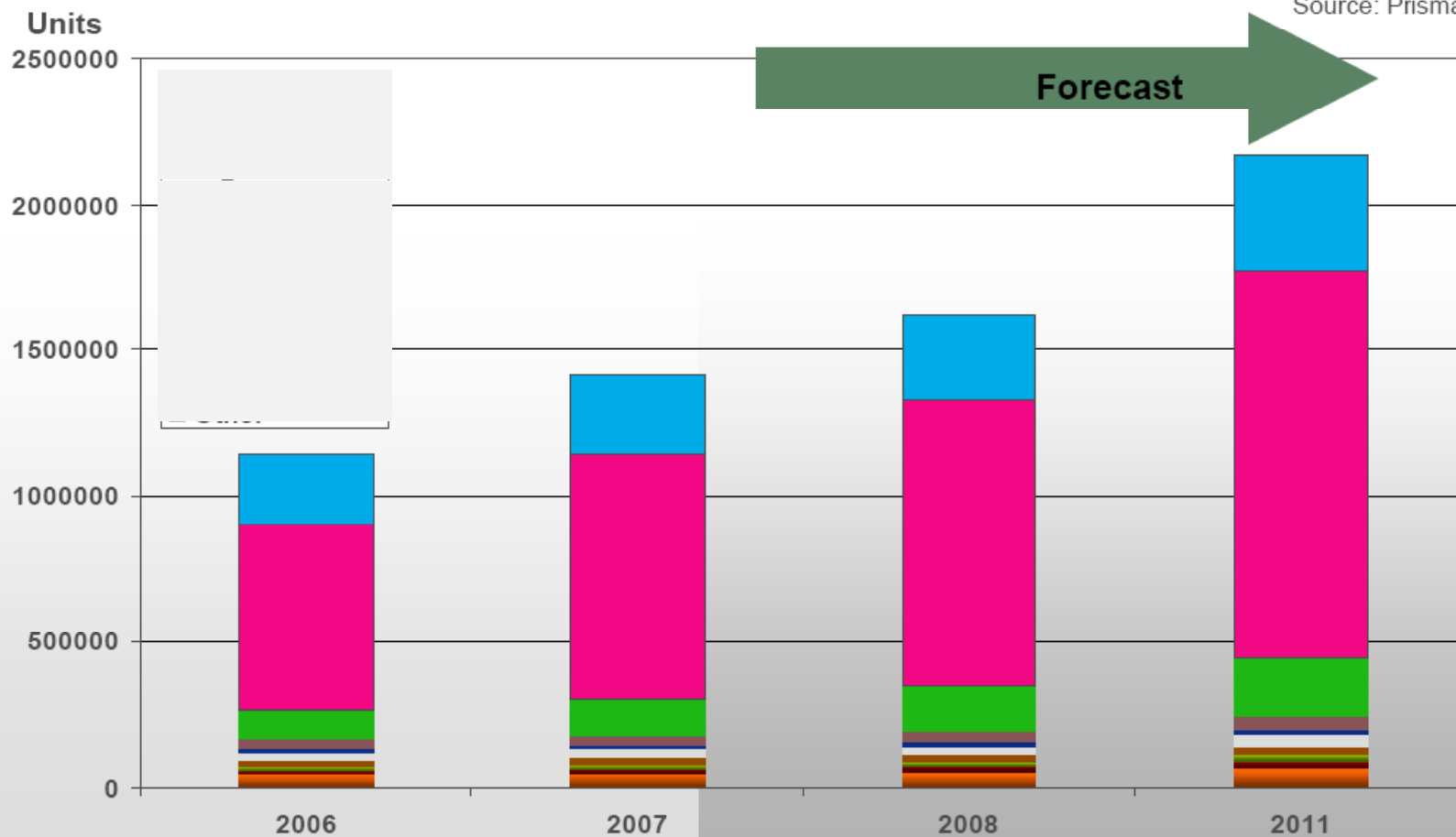


Where are the 'camera's?

Image Sensors Markets



Source: Prismark, March 2008



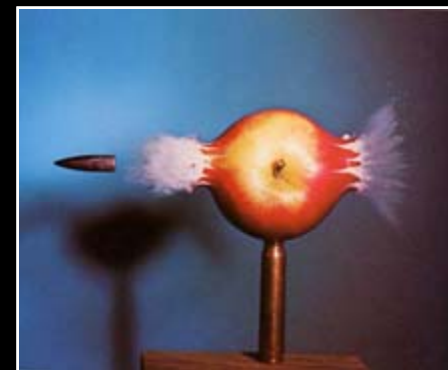
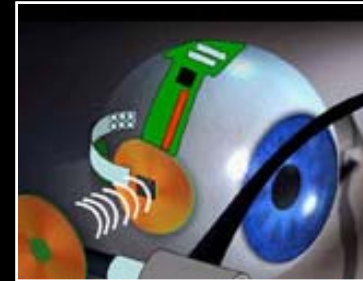


We focus on creating tools to better capture and share visual information

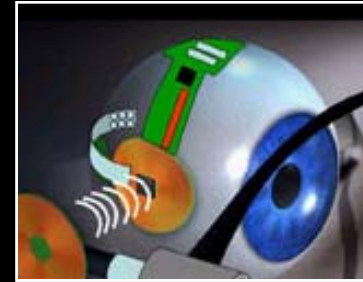
The goal is to create an entirely **new class of imaging platforms** that have an understanding of the world that far exceeds human ability and produce meaningful abstractions that are well within human comprehensibility

Questions

- What will a camera look like in 10,20 years?



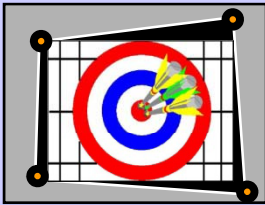
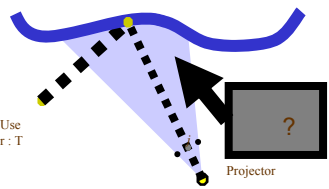

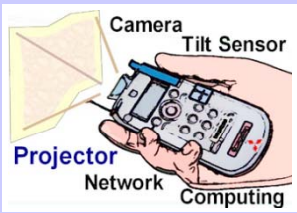
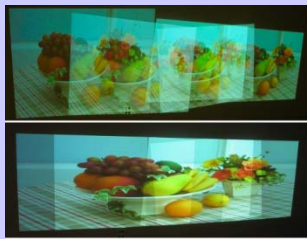


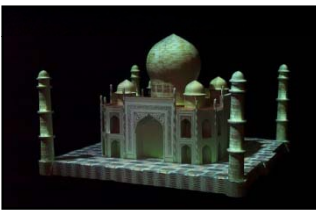

Cameras of Tomorrow





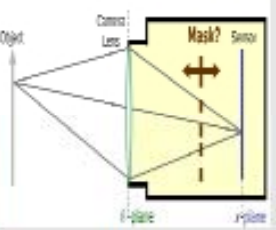

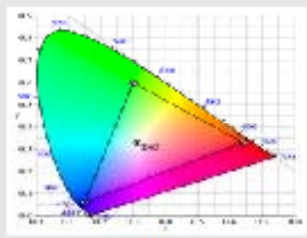
Approach

- Not just USE but CHANGE camera
 - Optics, illumination, sensor, movement
 - Exploit wavelength, speed, depth, polarization etc
 - Probes, actuators
- We have exhausted bits in pixels
 - Scene understanding is challenging
 - Build feature-revealing cameras
 - Process photons
- Technology, Applications, Society
 - We study impact of Imaging on all fronts

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



Motion Blurred Photo



Flutter Shutter Camera

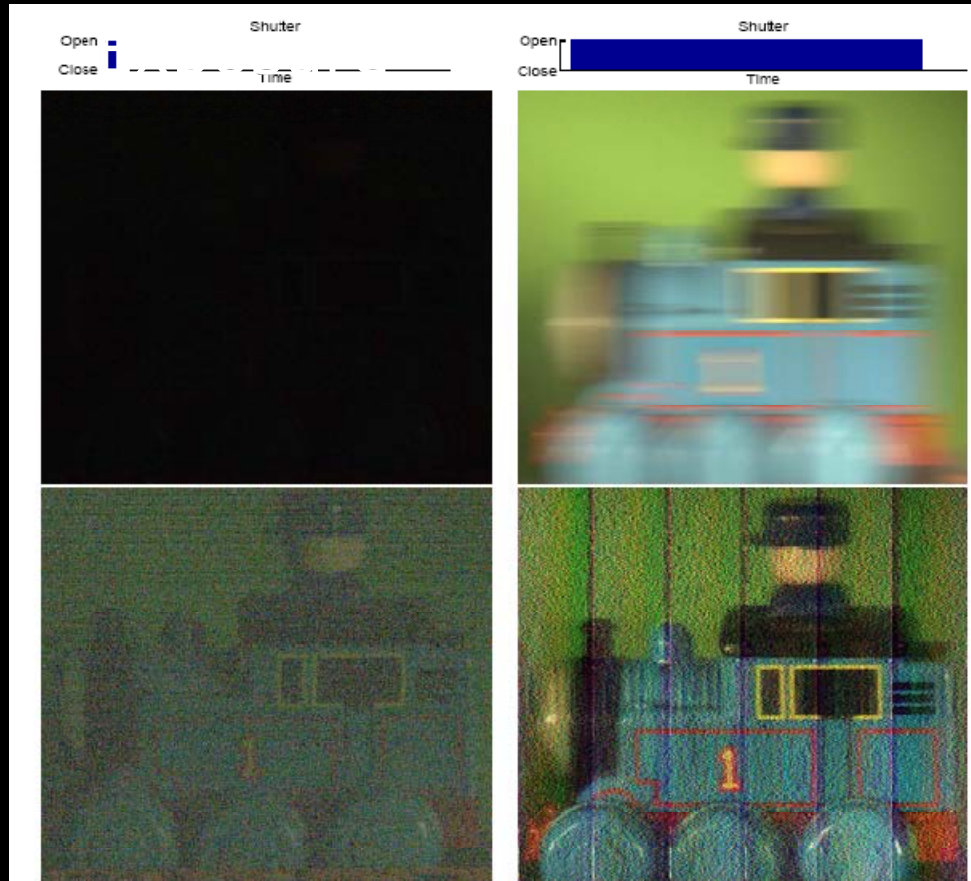
Raskar, Agrawal, Tumblin [Siggraph2006]



LCD opacity switched
in coded sequence

Short

Traditional



← Shutter

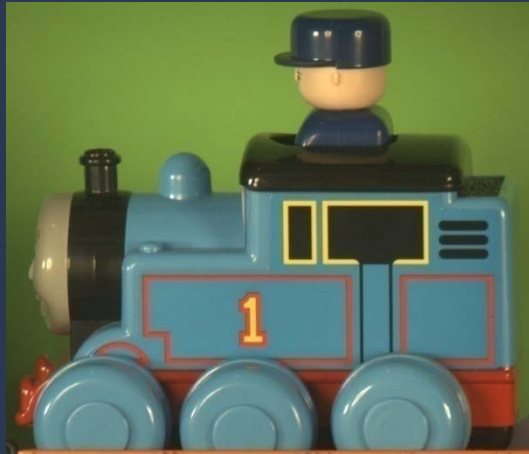
← Captured
Single
Photo

← Deblurred
Result

Dark
and noisy

Banding Artifacts and
some spatial frequencies
are lost

Blurring == Convolution

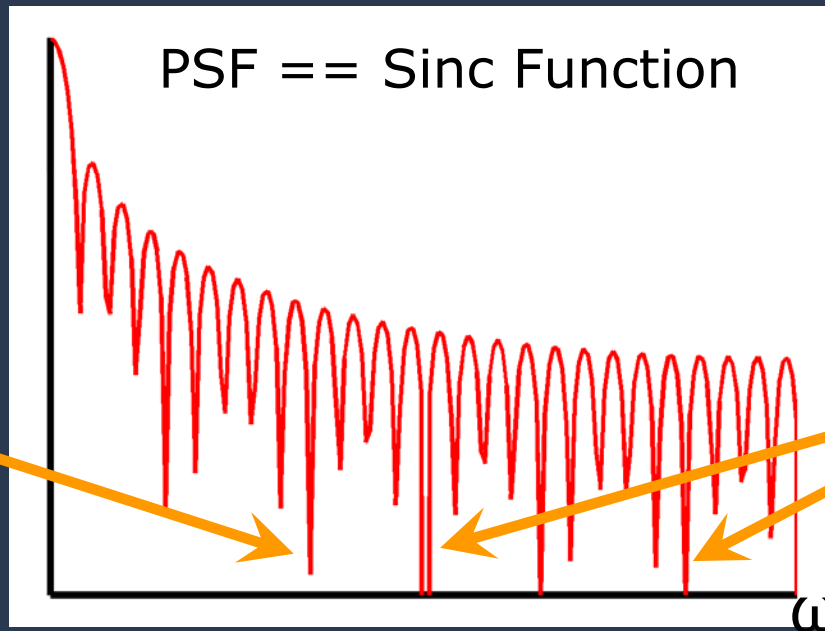


Sharp Photo

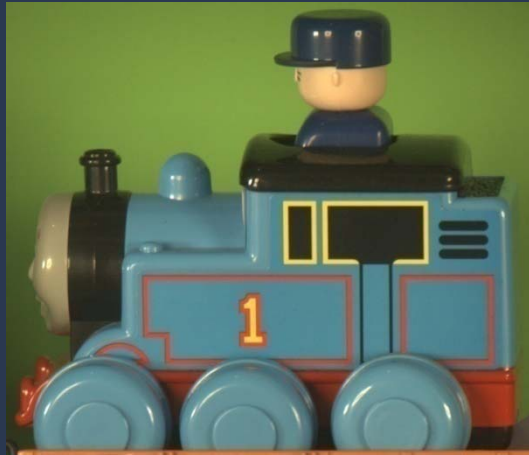


Blurred Photo

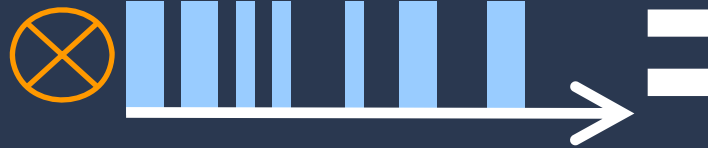
Fourier Transform



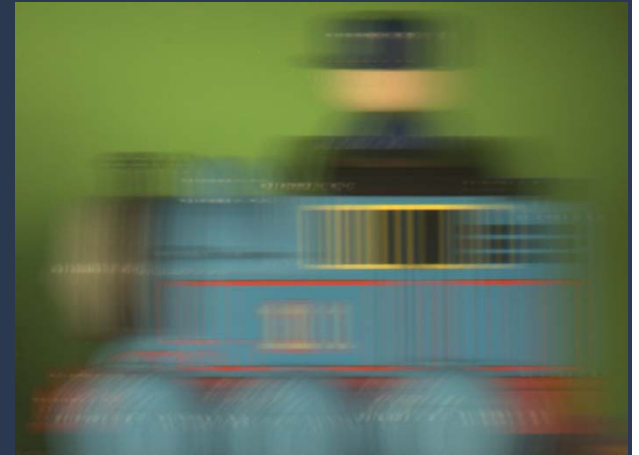
Traditional Camera: Shutter is OPEN: Box Filter



Sharp Photo

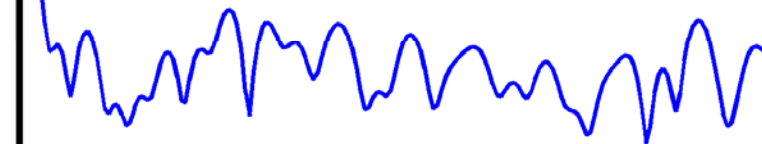


Fourier Transform



Blurred Photo

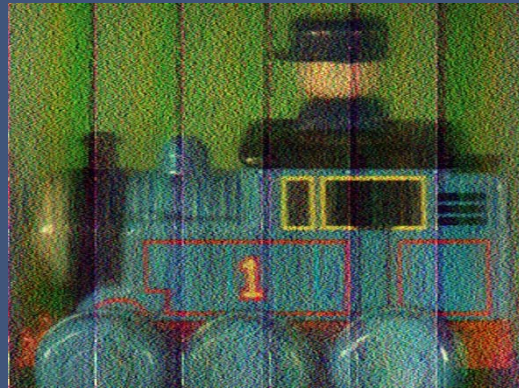
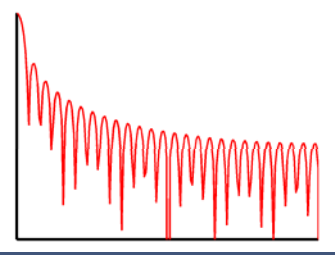
PSF == Broadband Function



Preserves High Spatial Frequencies

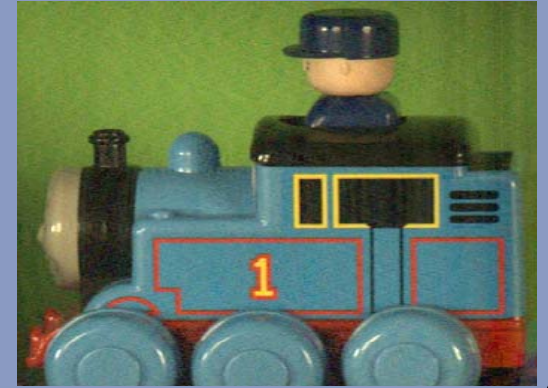
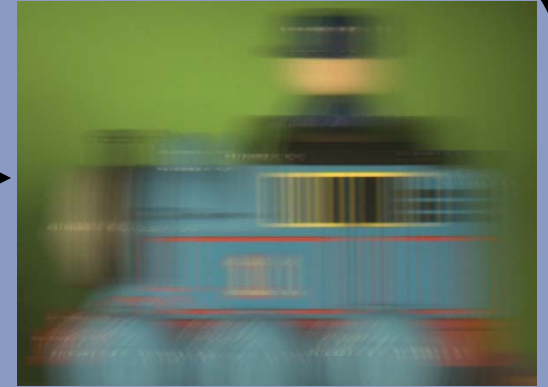
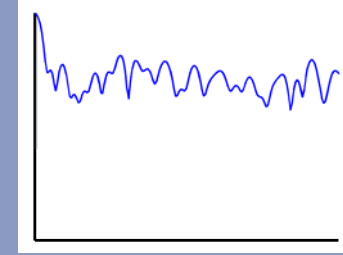
Flutter Shutter: Shutter is OPEN and CLOSED

Traditional



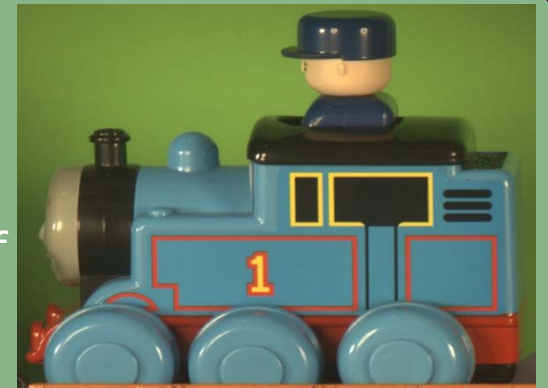
Deblurred Image

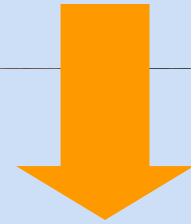
Coded Exposure



Deblurred Image

Image of Static Object





Coded Exposure



Temporal 1-D broadband code:
Motion Deblurring

Coded Aperture



Spatial 2-D broadband mask:
Focus Deblurring

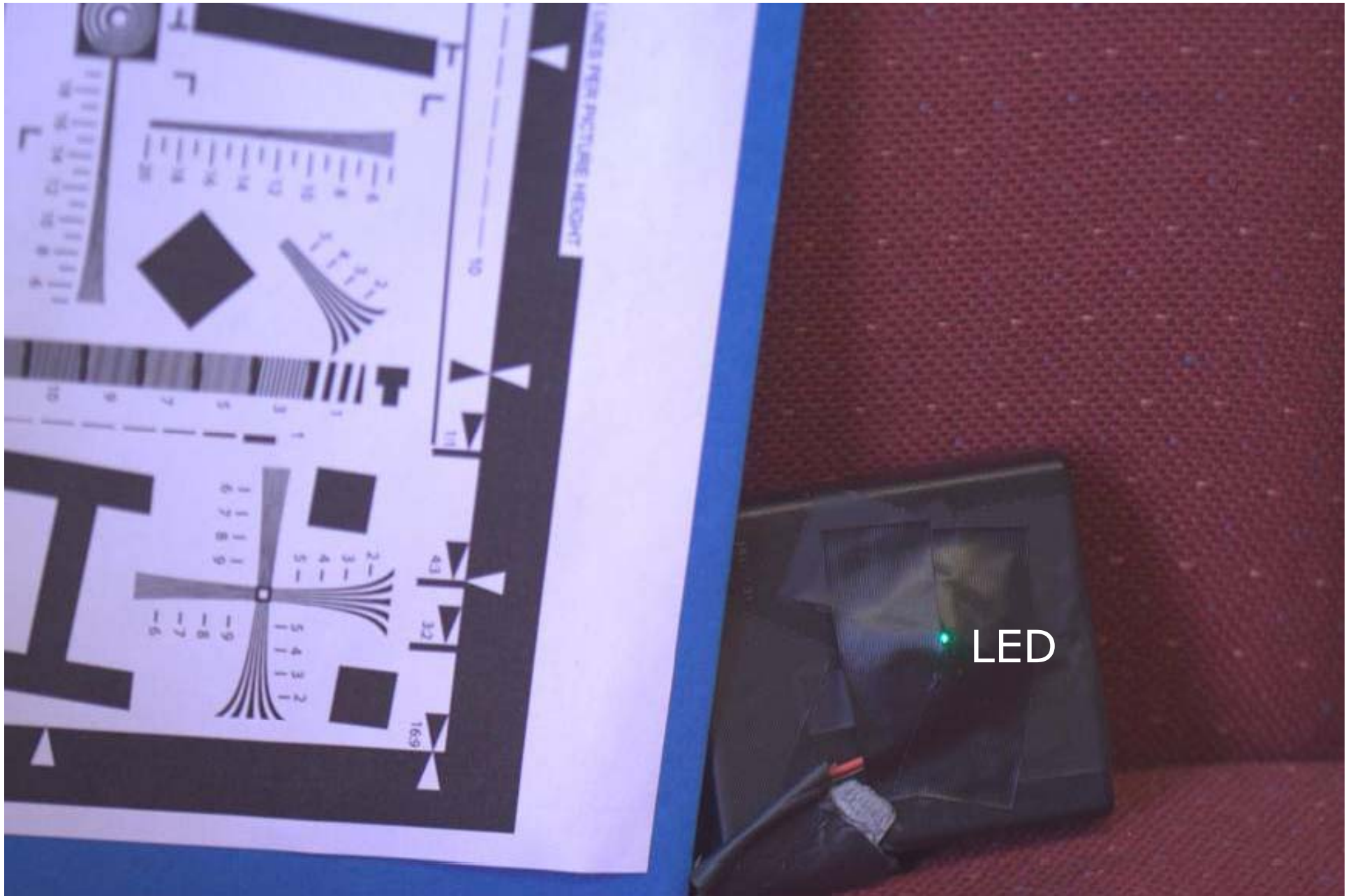
Coded Aperture Camera



The aperture of a 100 mm lens is modified

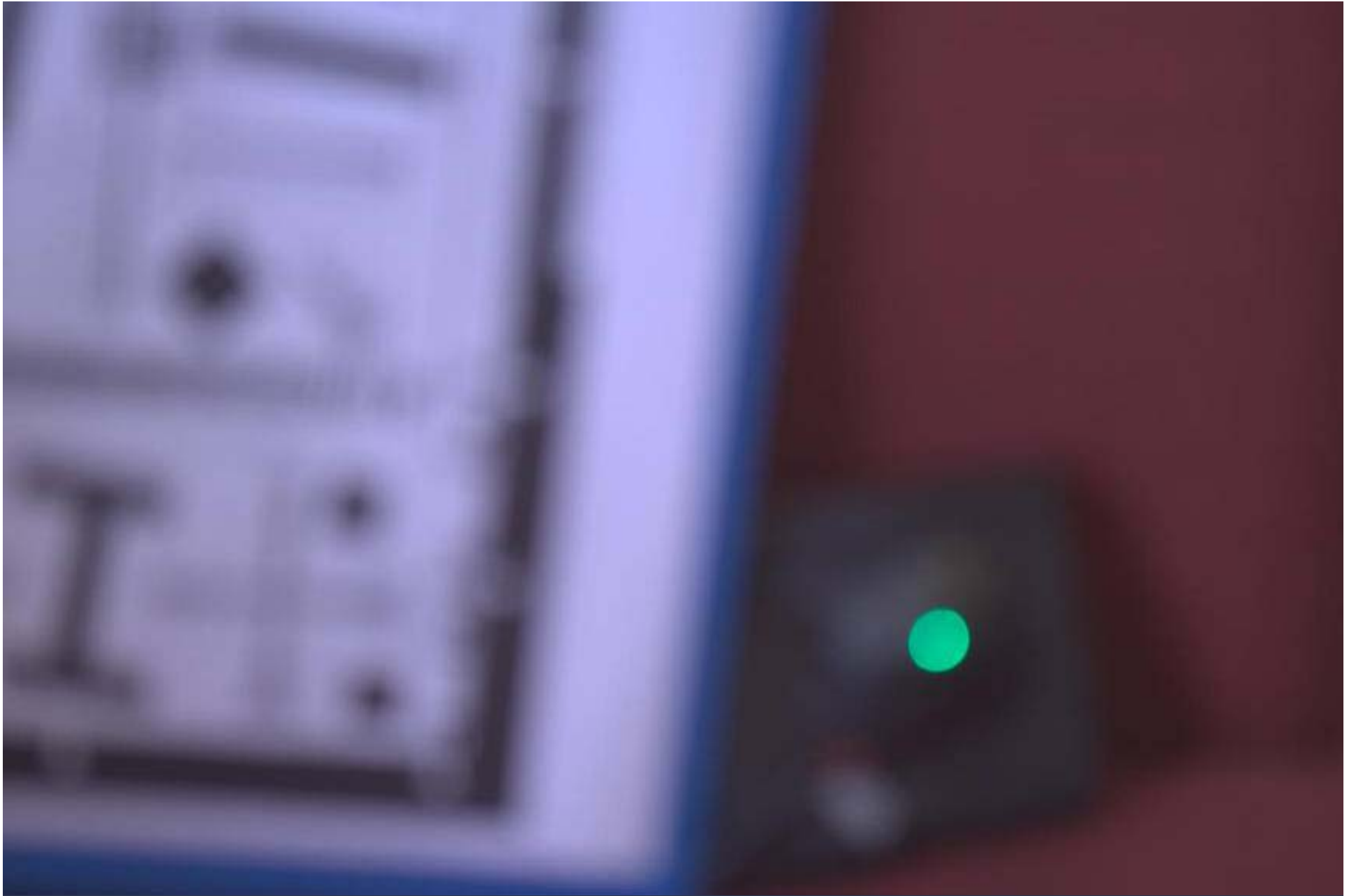
Insert a **coded mask** with chosen binary pattern

Rest of the camera is unmodified



LED

In Focus Photo



Out of Focus Photo: Open Aperture

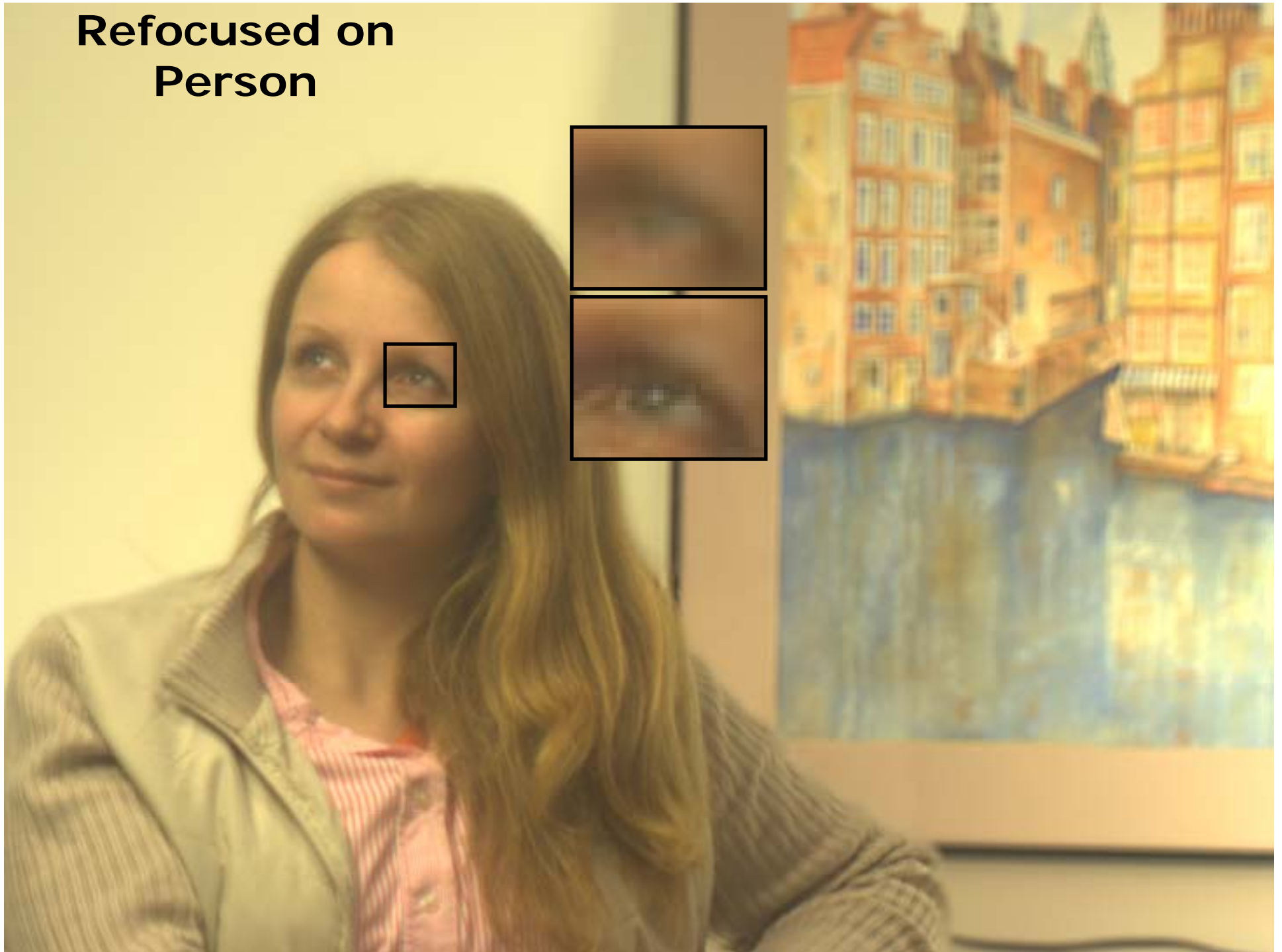


Out of Focus Photo: Coded Aperture

**Captured Blurred
Photo**



**Refocused on
Person**

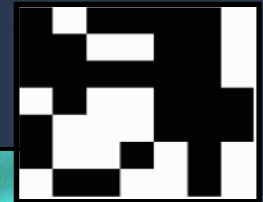


Less is More

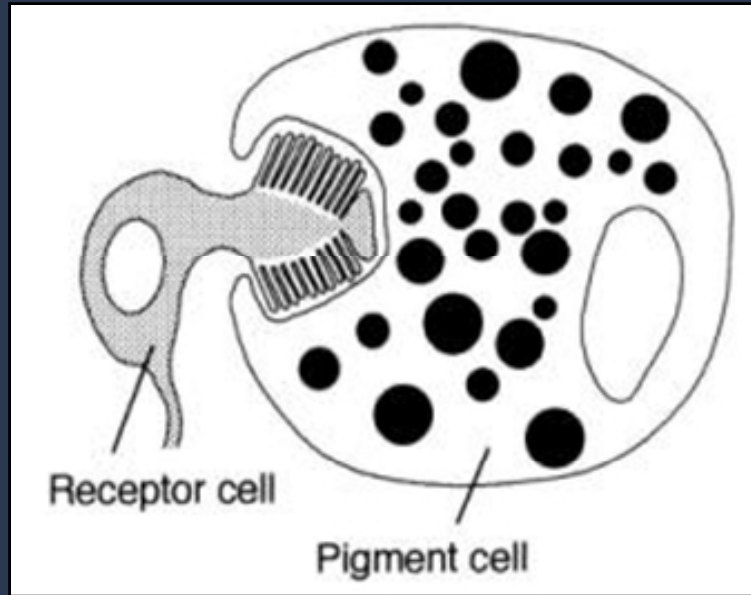
Blocking Light == More Information



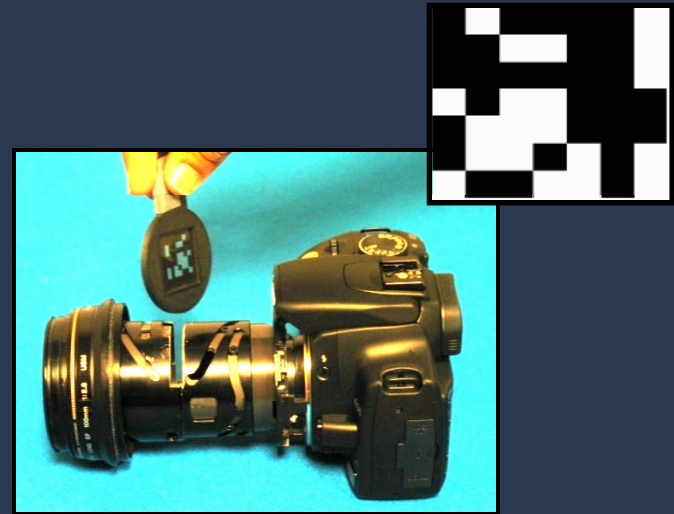
Coding in Time



Coding in Space

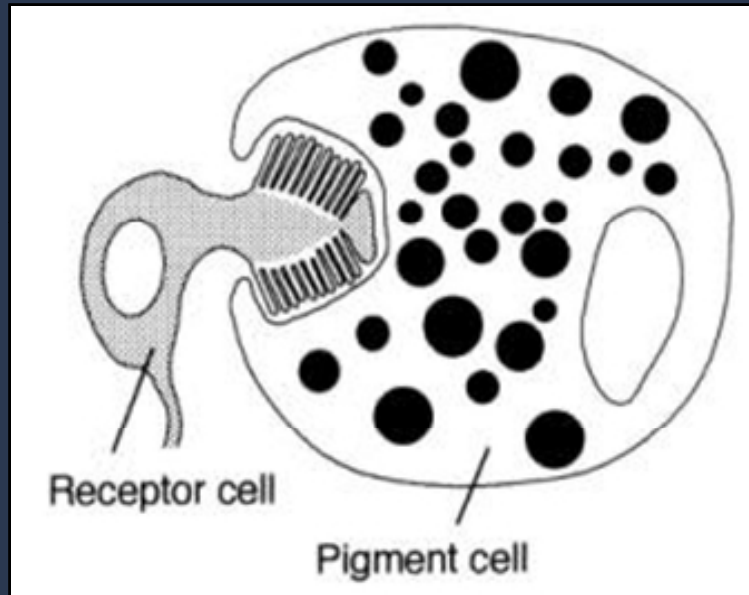


Larval Trematode Worm

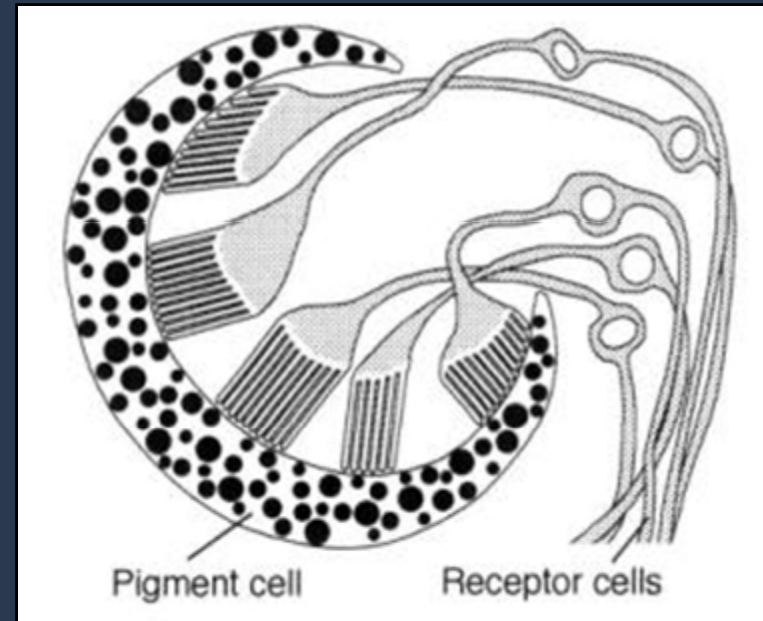


Coded Aperture Camera

Shielding Light ...



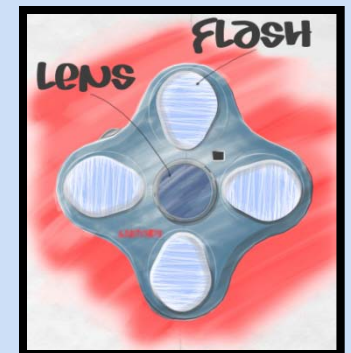
Larval Trematode Worm



Turbellarian Worm

Coded Computational Photography

- Coded Exposure
 - Motion Deblurring [2006]
- Coded Aperture
 - Focus Deblurring [2007]
 - Glare reduction [2008]
- Optical Heterodyning
 - Light Field Capture [2007]
- Coded Illumination
 - Motion Capture [2007]
 - Multi-flash: Shape Contours [2004]
- Coded Spectrum
 - Agile Wavelength Profile [2008]
- Epsilon->Coded->Essence Photography



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’



Epsilon Photography

- Dynamic range
 - Exposure bracketing [Mann-Picard, Debevec]
- Wider FoV
 - Stitching a panorama
- Depth of field
 - Fusion of photos with limited DoF [Agrawala04]
- Noise
 - Flash/no-flash image pairs [Petschnigg04, Eisemann04]
- Frame rate
 - Triggering multiple cameras [Wilburn05, Shechtman02]

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’



- 3D
 - Stereo of multiple cameras
- Higher dimensional LF
 - Light Field Capture
 - lenslet array [Adelson92, Ng05], '3D lens' [Georgiev05], heterodyne masks [Veeraraghavan07]
- Boundaries and Regions
 - Multi-flash camera with shadows [Raskar08]
 - Fg/bg matting [Chuang01, Sun06]
- Deblurring
 - Engineered PSF
 - Motion: Flutter shutter [Raskar06], Camera Motion [Levin08]
 - Defocus: Coded aperture, Wavefront coding [Cathey95]
- Global vs direct illumination
 - High frequency illumination [Nayar06]
 - Glare decomposition [Talvala07, Raskar08]
- Coded Sensor
 - Gradient camera [Tumblin05]

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’



Capturing the Essence of Visual Experience

– Exploiting online collections

- Photo-tourism [Snavely2006]
- Scene Completion [Hays2007]

– Multi-perspective Images

- Multi-linear Perspective [Jingyi Yu, McMillan 2004]
- Unwrap Mosaics [Rav-Acha et al 2008]
- Video texture panoramas [Agrawal et al 2005]

– Non-photorealistic synthesis

- Motion magnification [Liu05]

– Image Priors

- Learned features and natural statistics
- Face Swapping: [Bitouk et al 2008]
- Data-driven enhancement of facial attractiveness [Leyvand et al 2008]
- Deblurring [Fergus et al 2006, Jia et al 2008]

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’

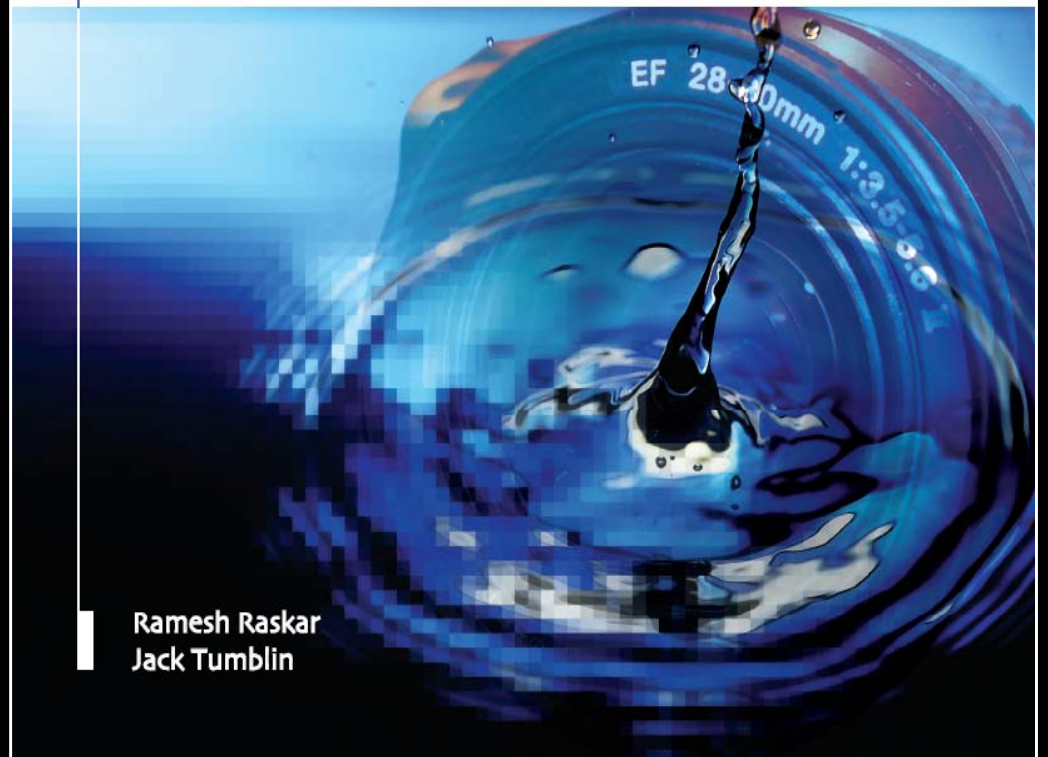


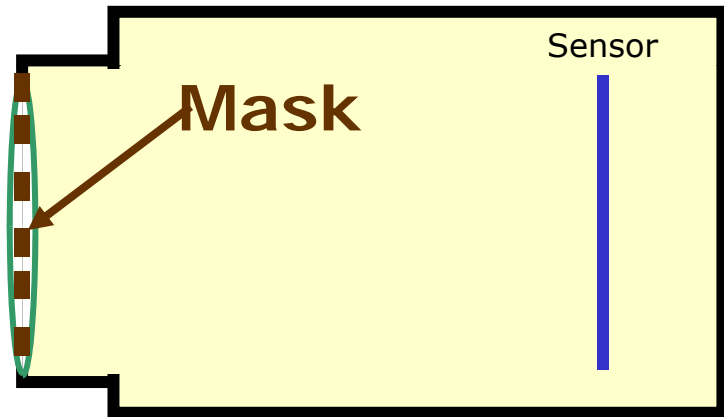
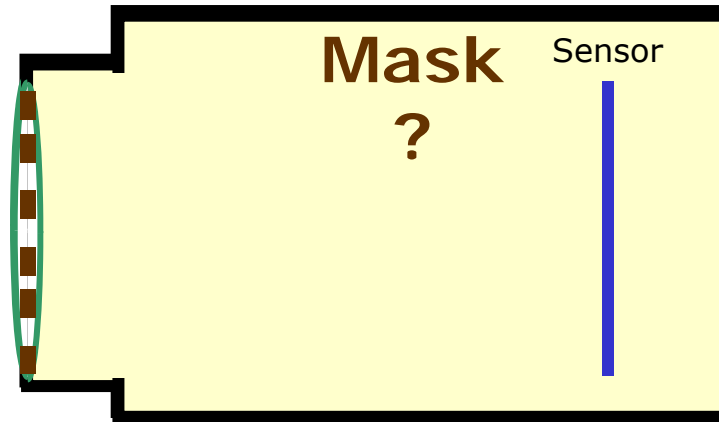
- Ramesh Raskar and Jack Tumblin
- Book Publishers: A K Peters

Computational Photography

Mastering New Techniques
for Lenses, Lighting, and Sensors

Ramesh Raskar
Jack Tumblin





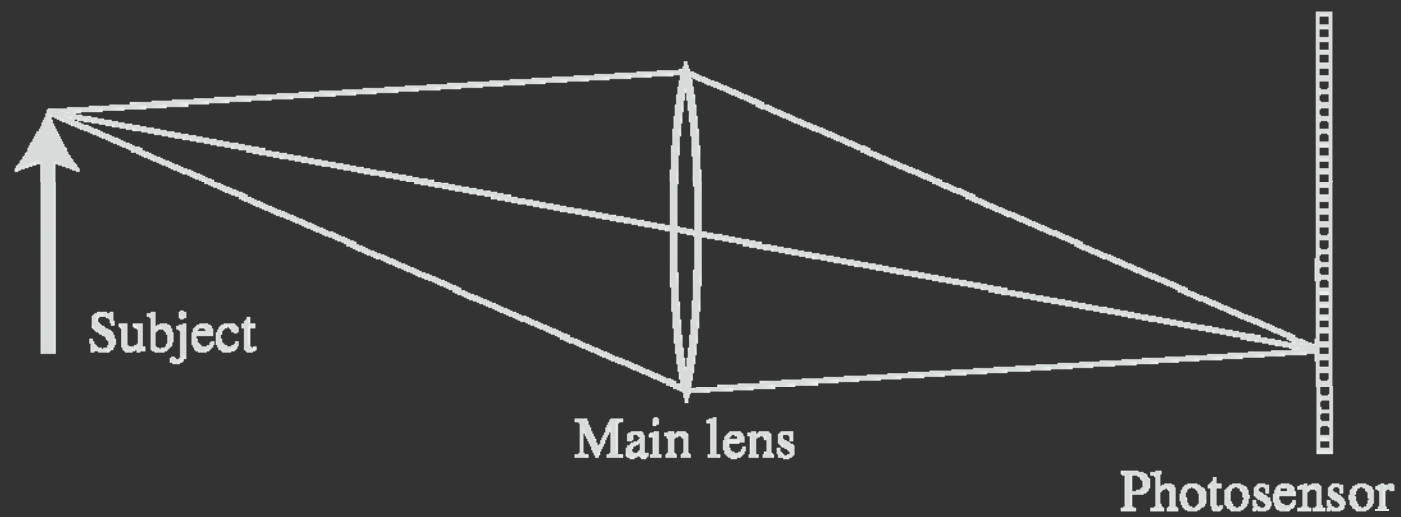
Full Resolution Digital
Refocusing:

Coded Aperture Camera

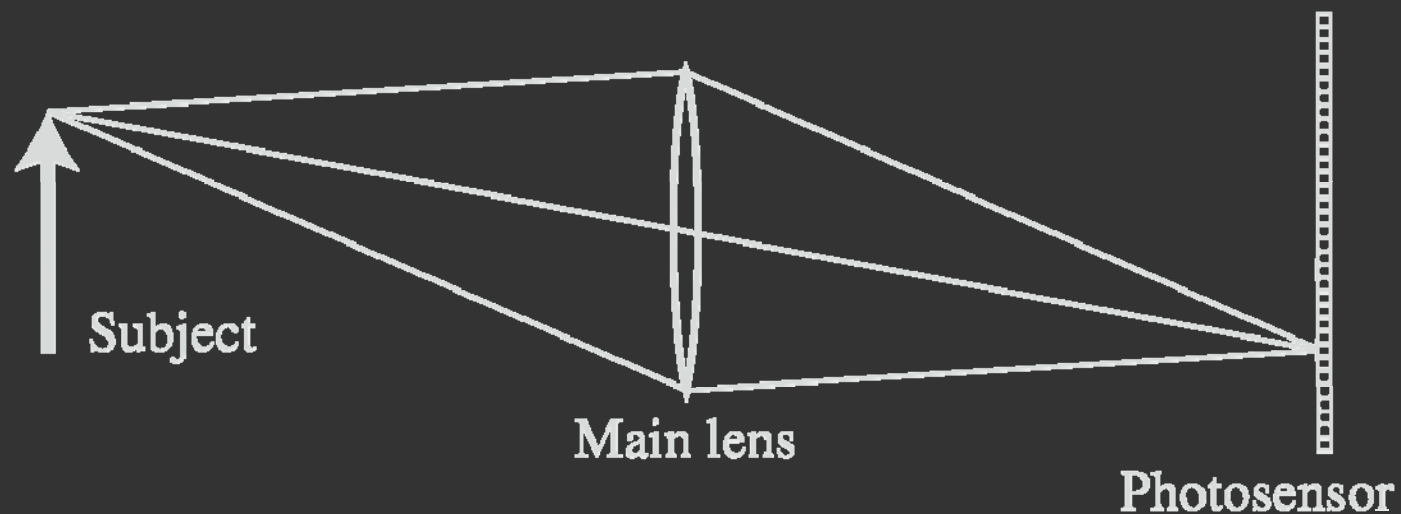
4D Light Field from
2D Photo:

Heterodyne Light Field
Camera

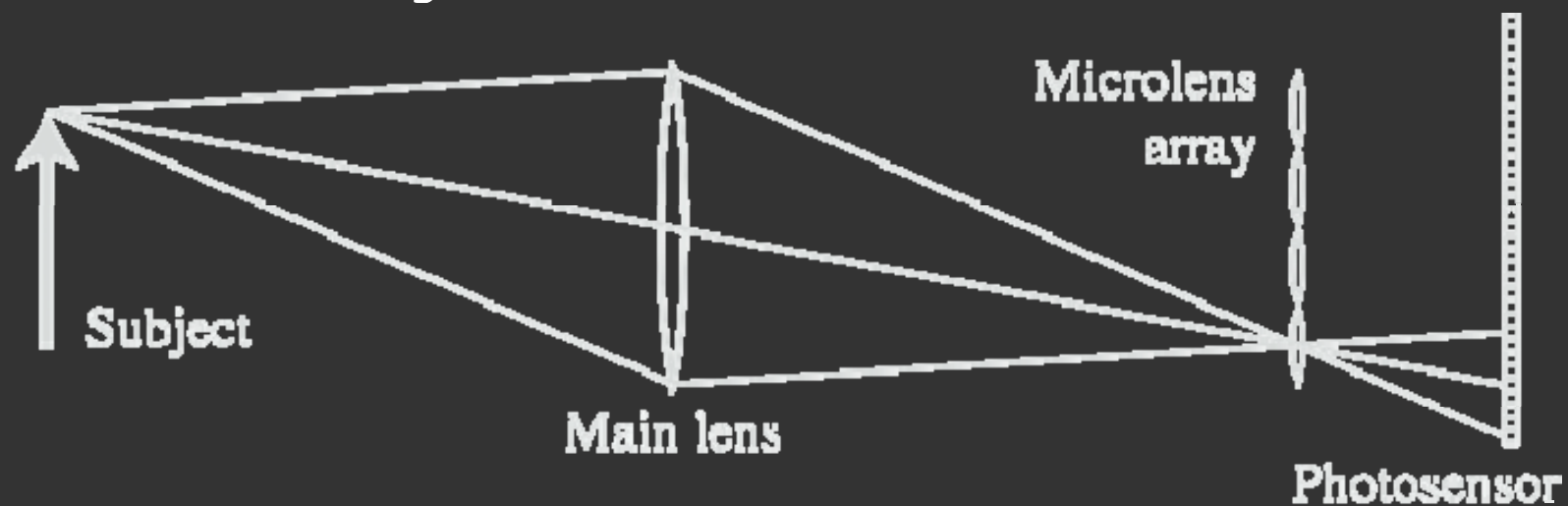
Light Field Inside a Camera



Light Field Inside a Camera



Lenslet-based Light Field camera



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

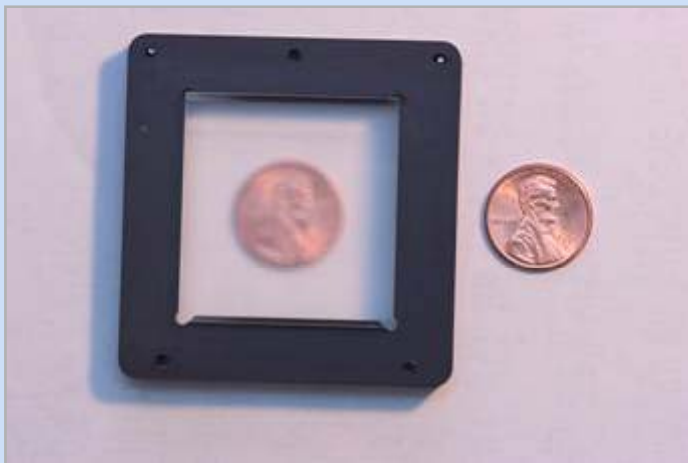
Stanford Plenoptic Camera [Ng et al 2005]



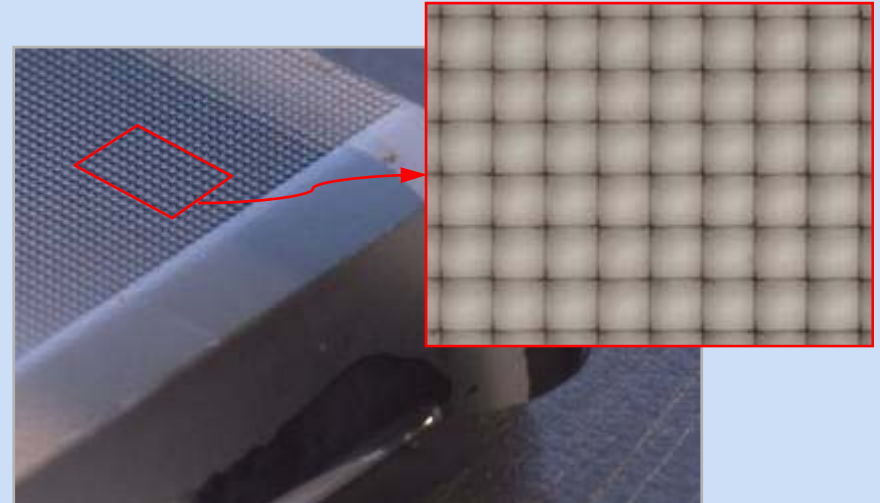
Contax medium format camera



Kodak 16-megapixel sensor



Adaptive Optics microlens array



125μ square-sided microlenses

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

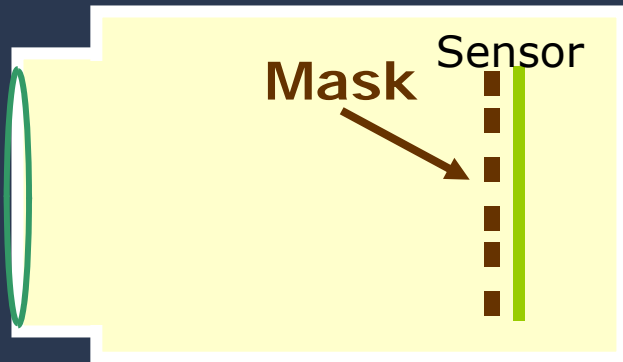
Digital Refocusing



[Ng et al 2005]

Can we achieve this with a Mask alone?

Mask based Light Field Camera

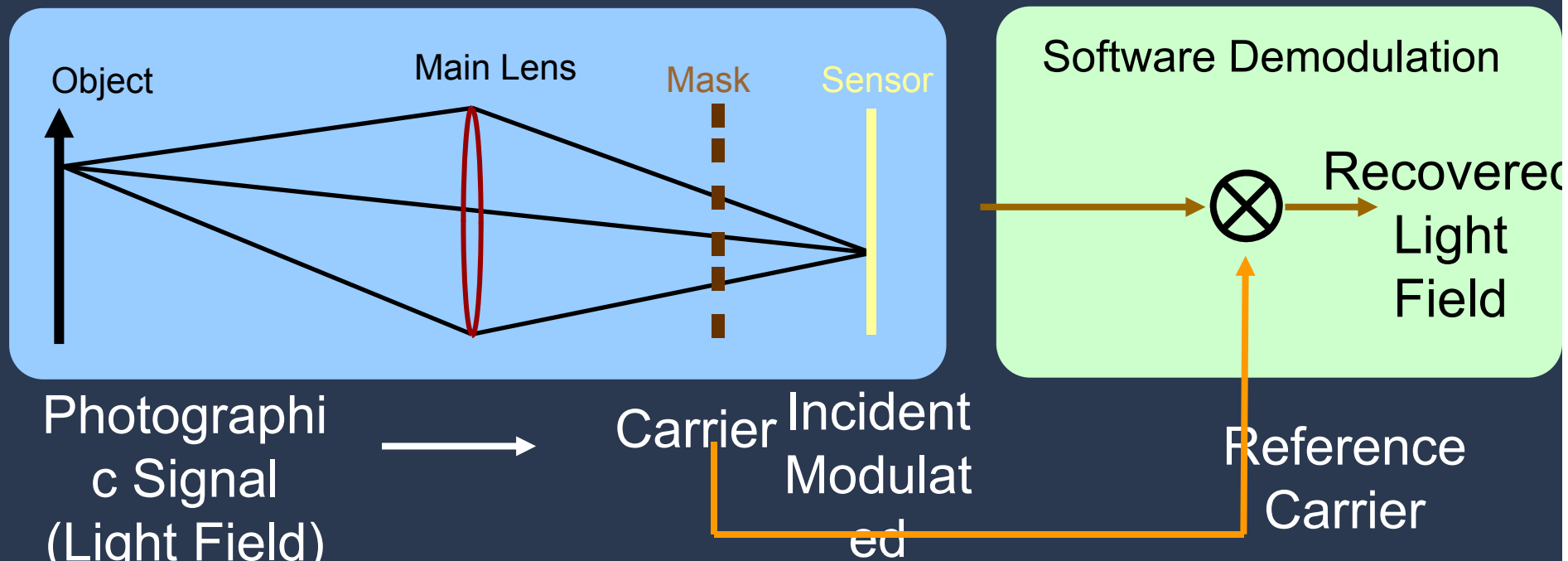
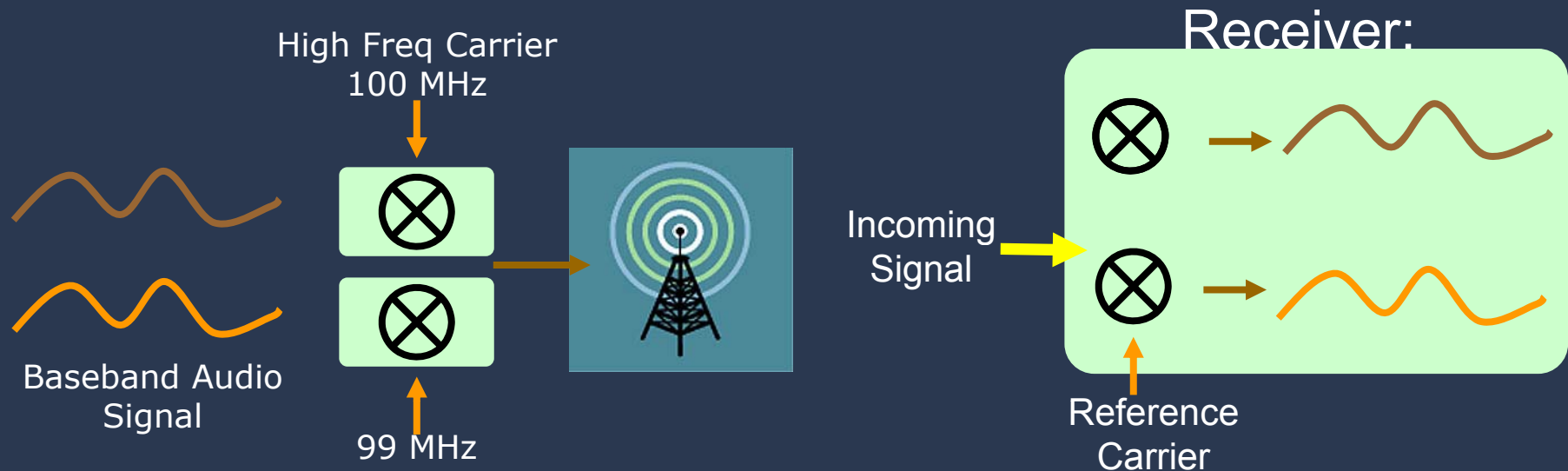


[Veeraraghavan, Raskar, Agrawal, Tumblin, Mohan, Siggraph 2007]

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

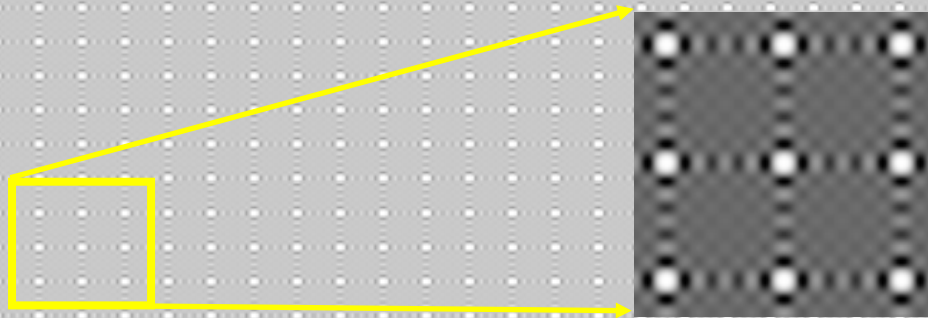
What should be the
pattern of the mask ?

Optical Heterodyning



Cosine Mask Used

Mask Tile



$$\frac{1}{f_0}$$

Captured 2D Photo



Encoding due to
Mask

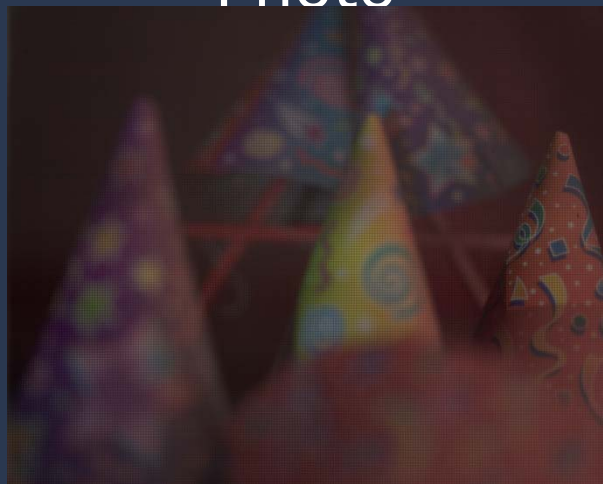


Traditional Camera
Photo

2D
FFT
→

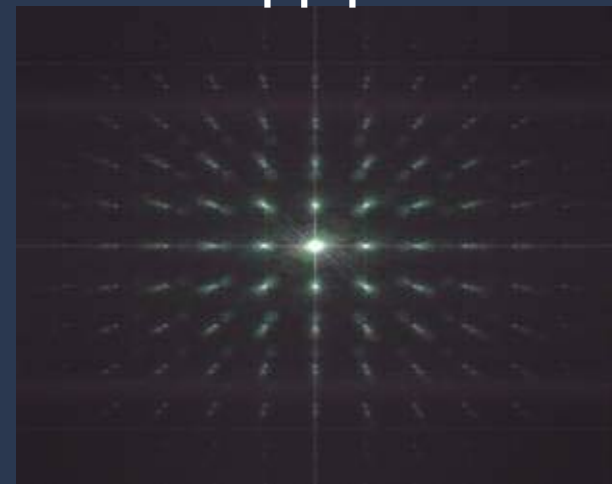


Magnitude of 2D
FFT



Heterodyne Camera
Photo

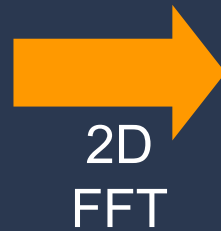
2D
FFT
→



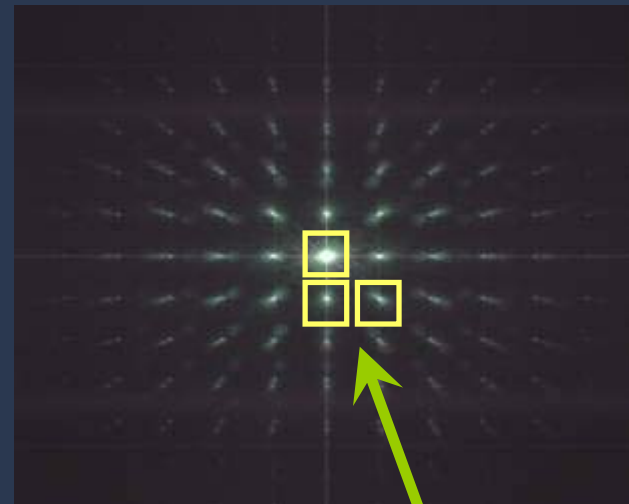
Magnitude of 2D
FFT

Computing 4D Light Field

2D Sensor Photo, 1800*1800



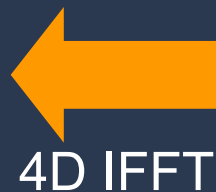
2D Fourier Transform, 1800*1800



9*9=81 spectral copies

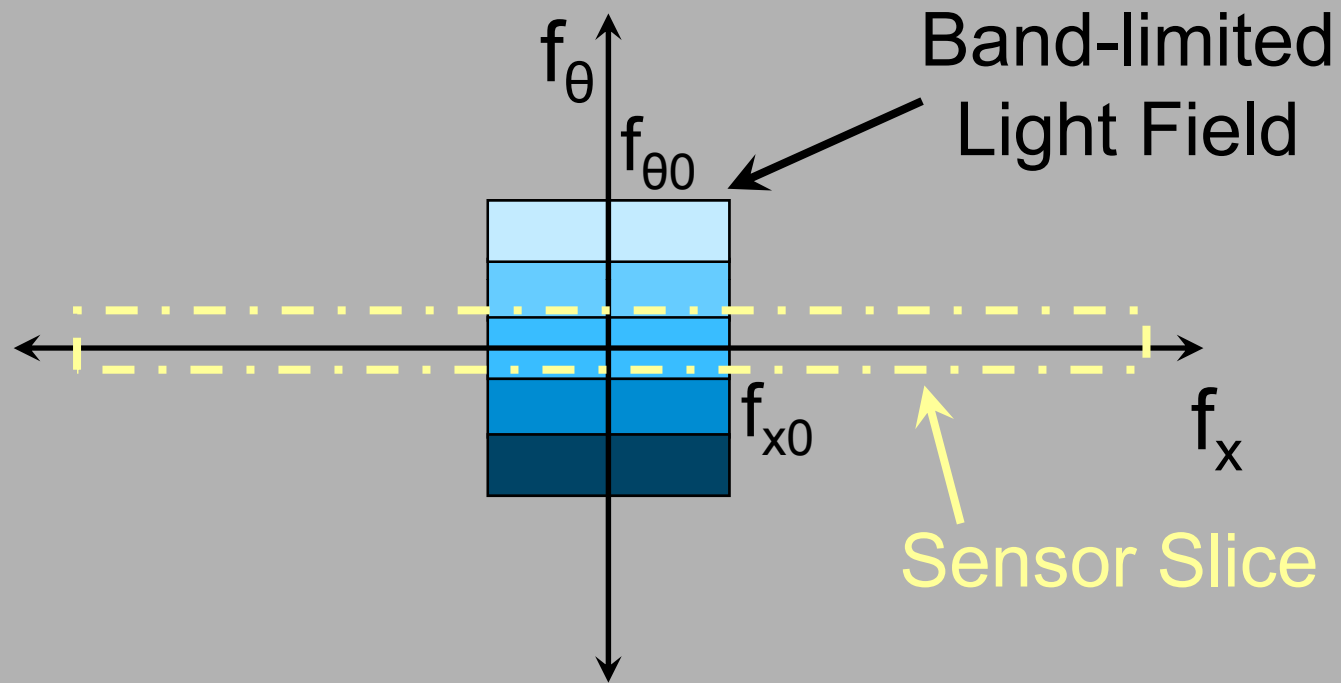


Rearrange 2D tiles into 4D
 $200*200*9*9$
planes



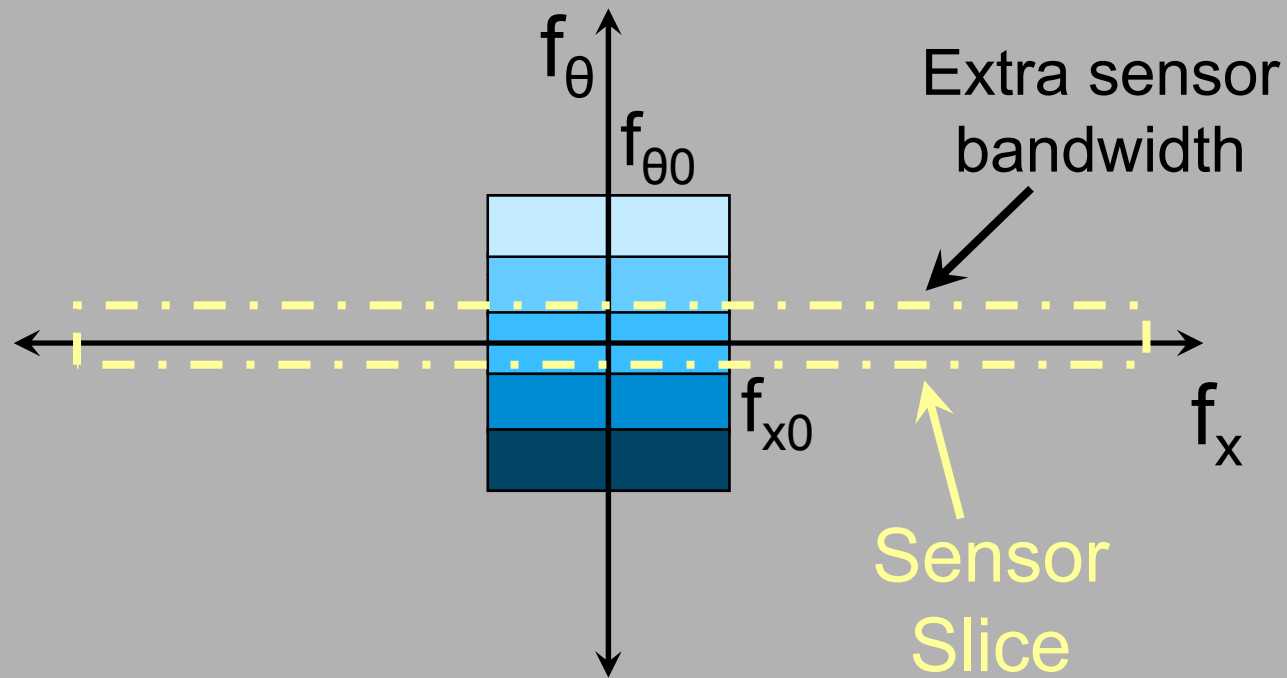
4D Light Field
 $200*200*9*9$

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



Fourier Light Field Space

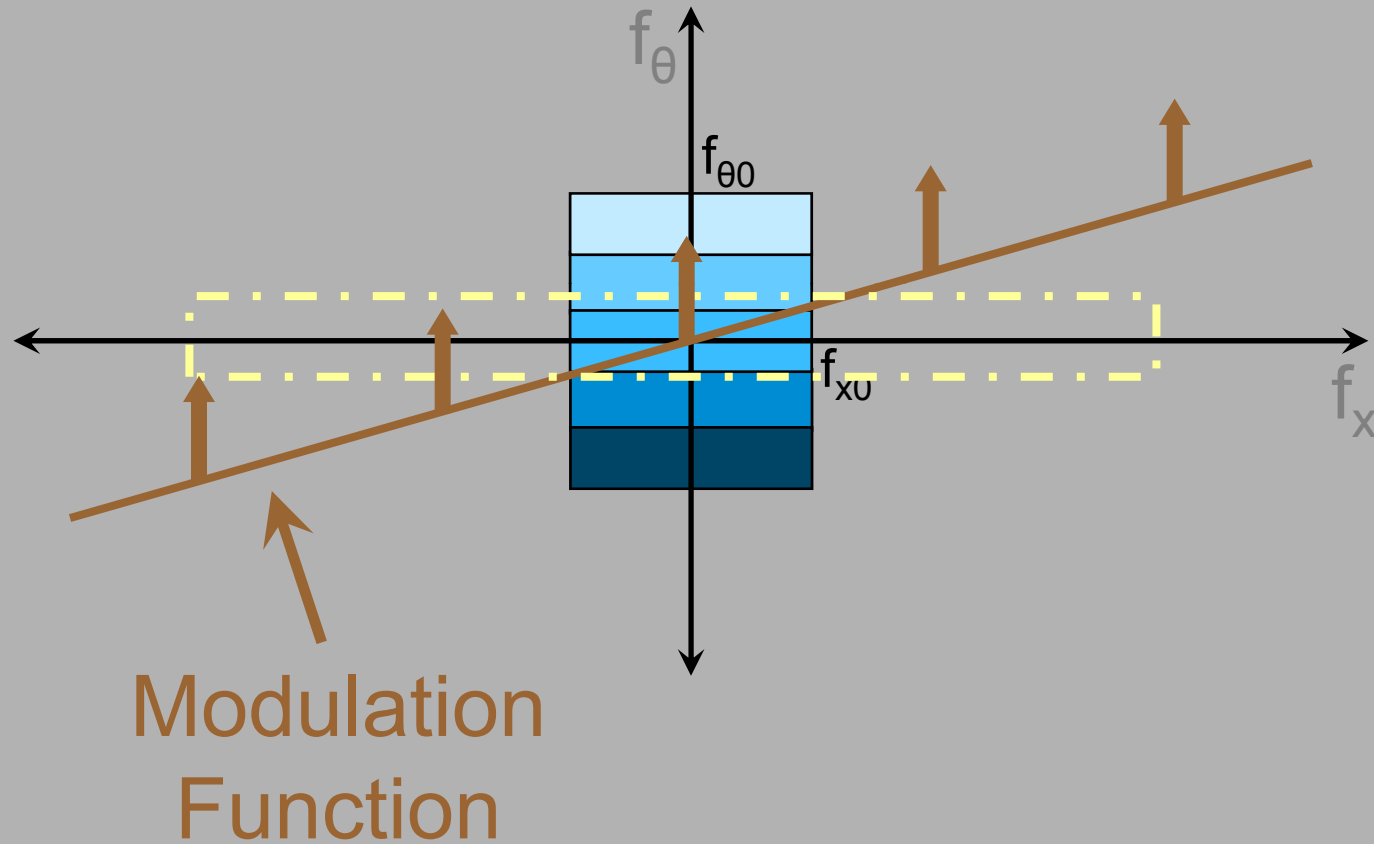
Extra sensor bandwidth cannot capture extra *dimension* of the light field



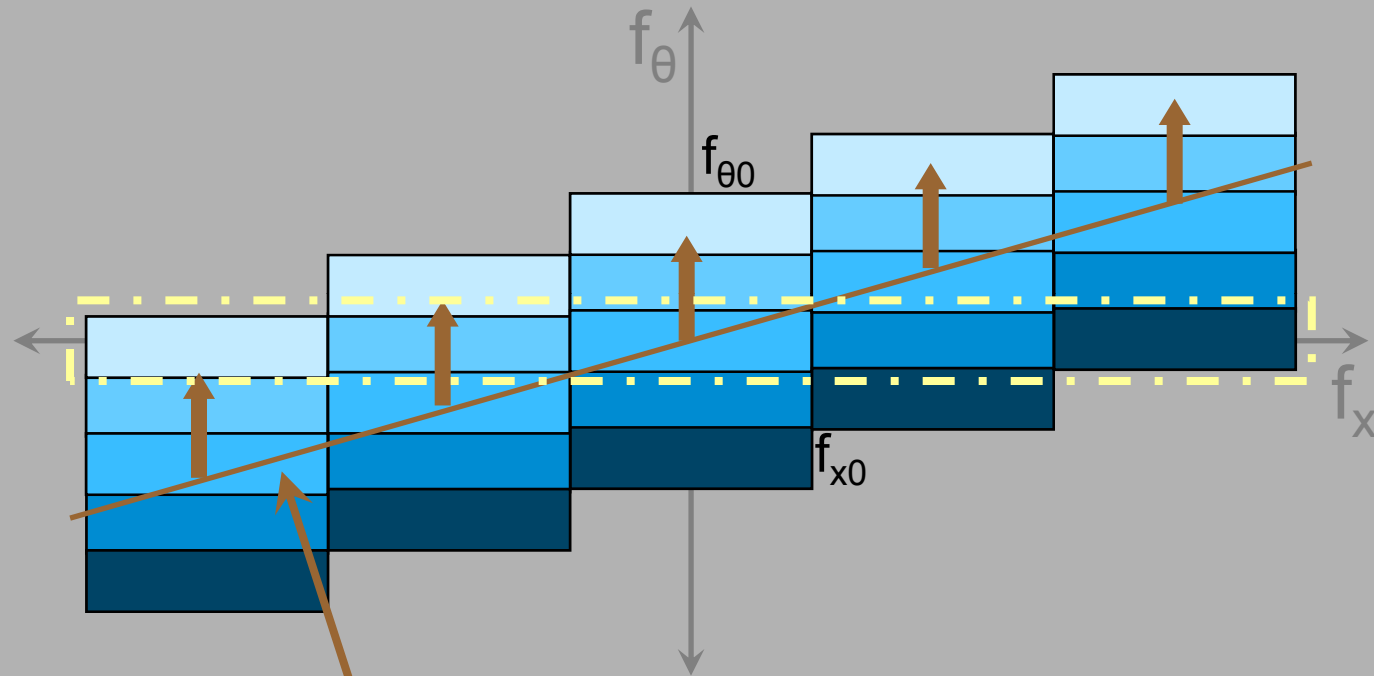
Fourier Light Field Space

Solution: Modulation Theorem

Make spectral copies of 2D light field



Sensor Slice captures entire Light Field

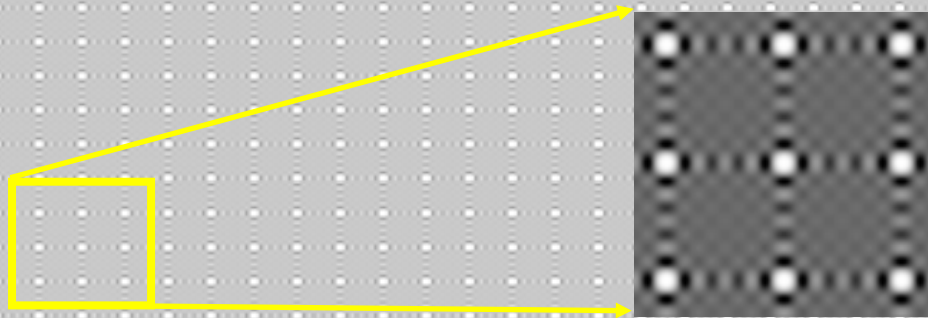


Modulation
Function

Modulated Light Field

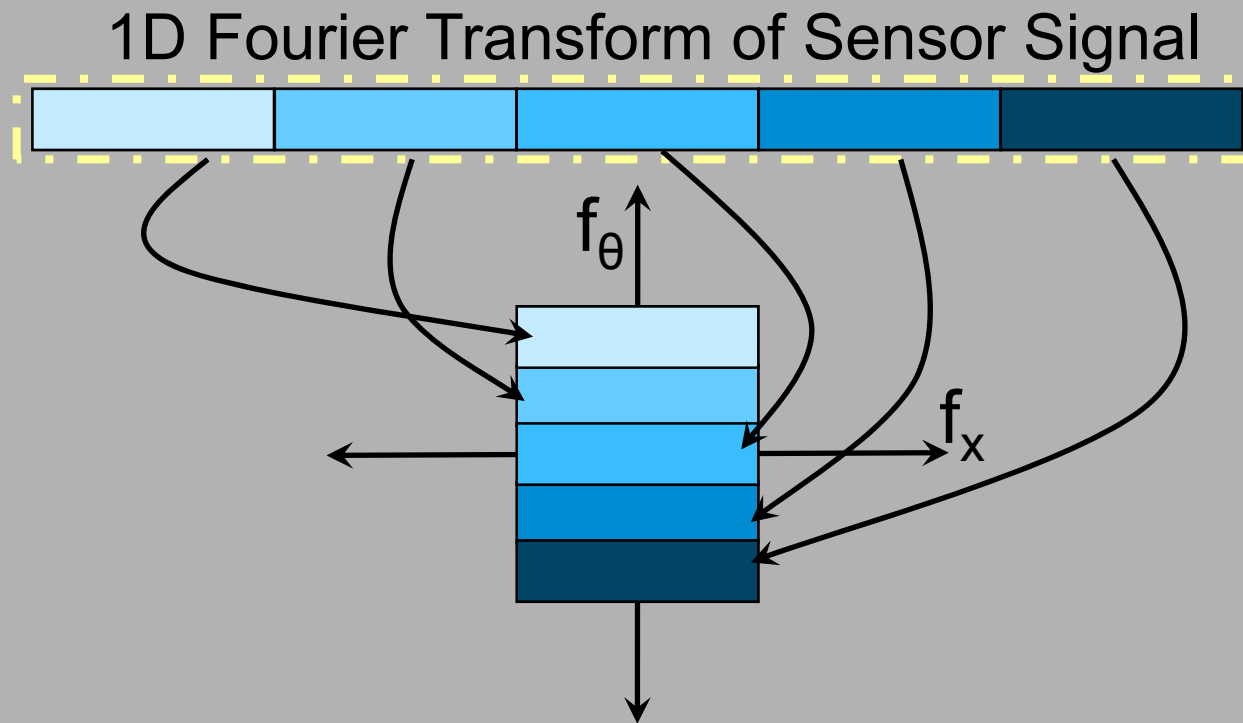
Cosine Mask Used

Mask Tile



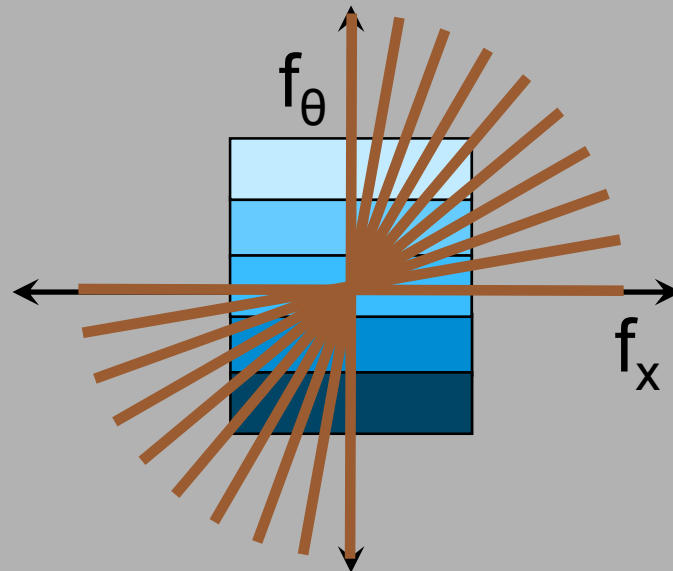
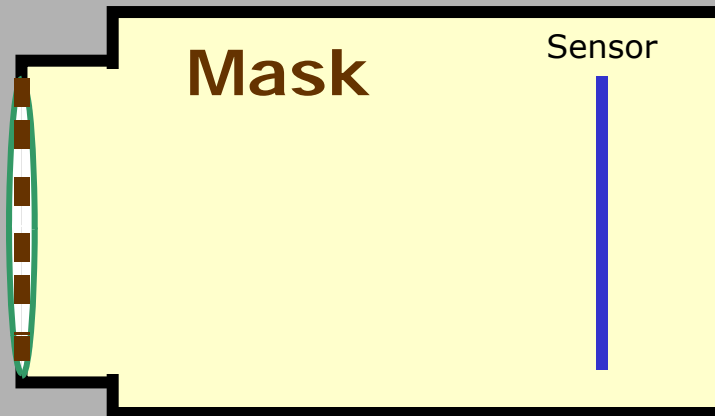
$$1/f_0$$

Demodulation to recover Light Field



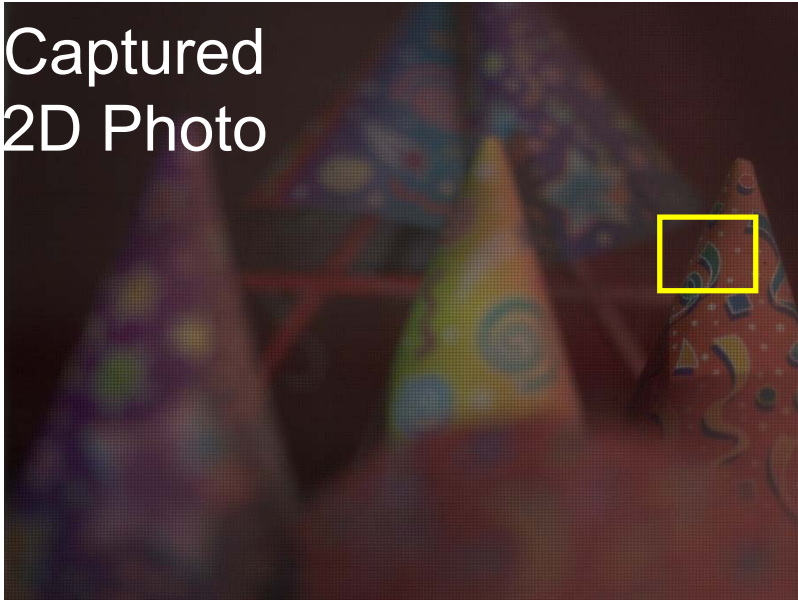
Reshape 1D Fourier Transform into 2D

Where to place the Mask?



Mask
Modulation
Function

Captured
2D Photo



divide

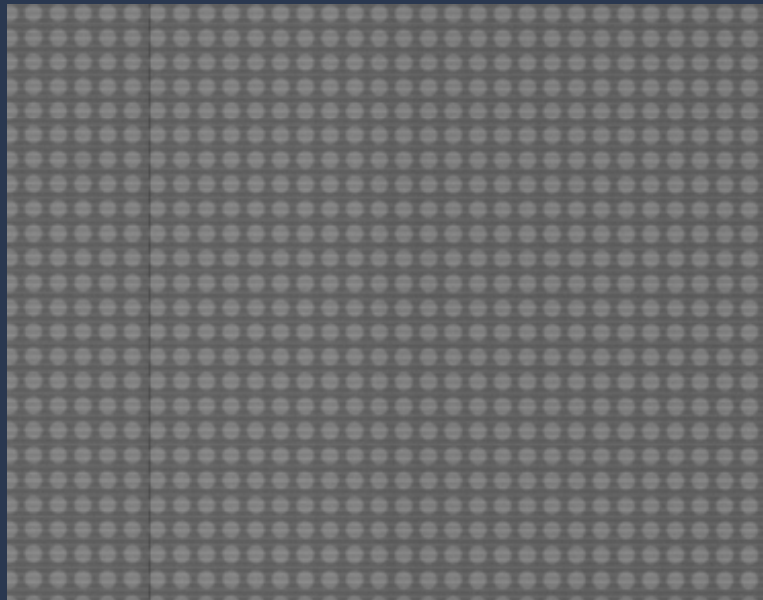


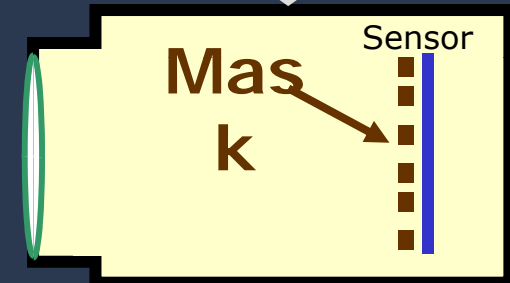
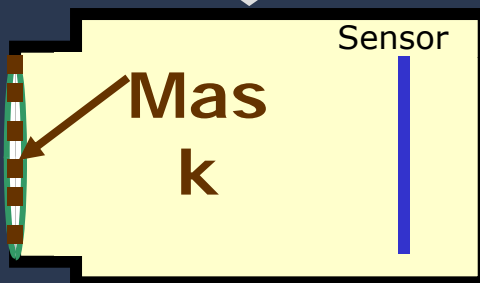
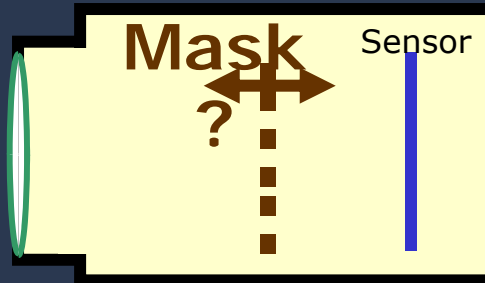
Image of White Lambertian
Plane

=

Full resolution 2D image
of Focused Scene Parts



Coding and Modulation in Camera Using Masks

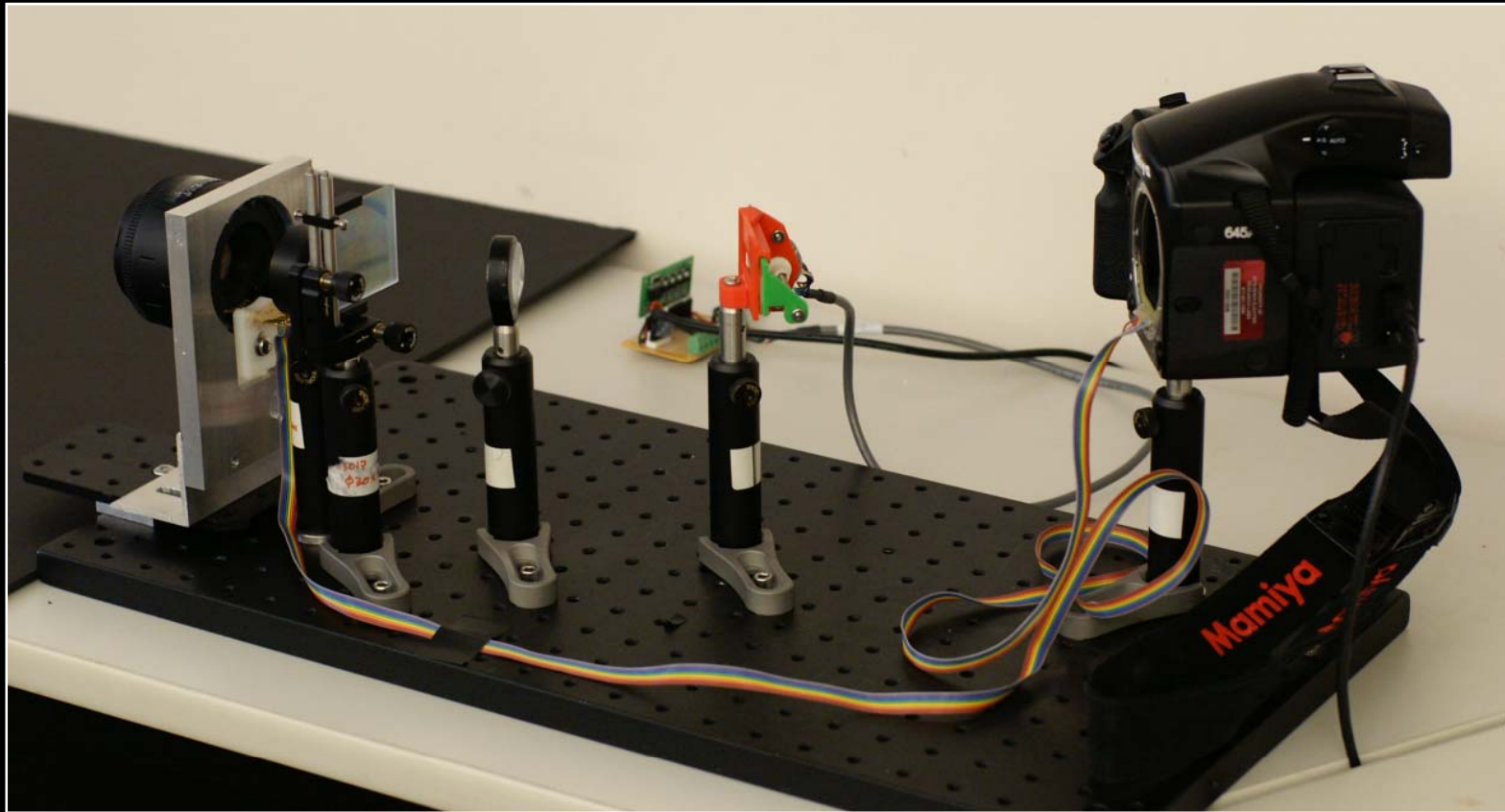


Coded Aperture for Full Resolution



Heterodyne Light Field

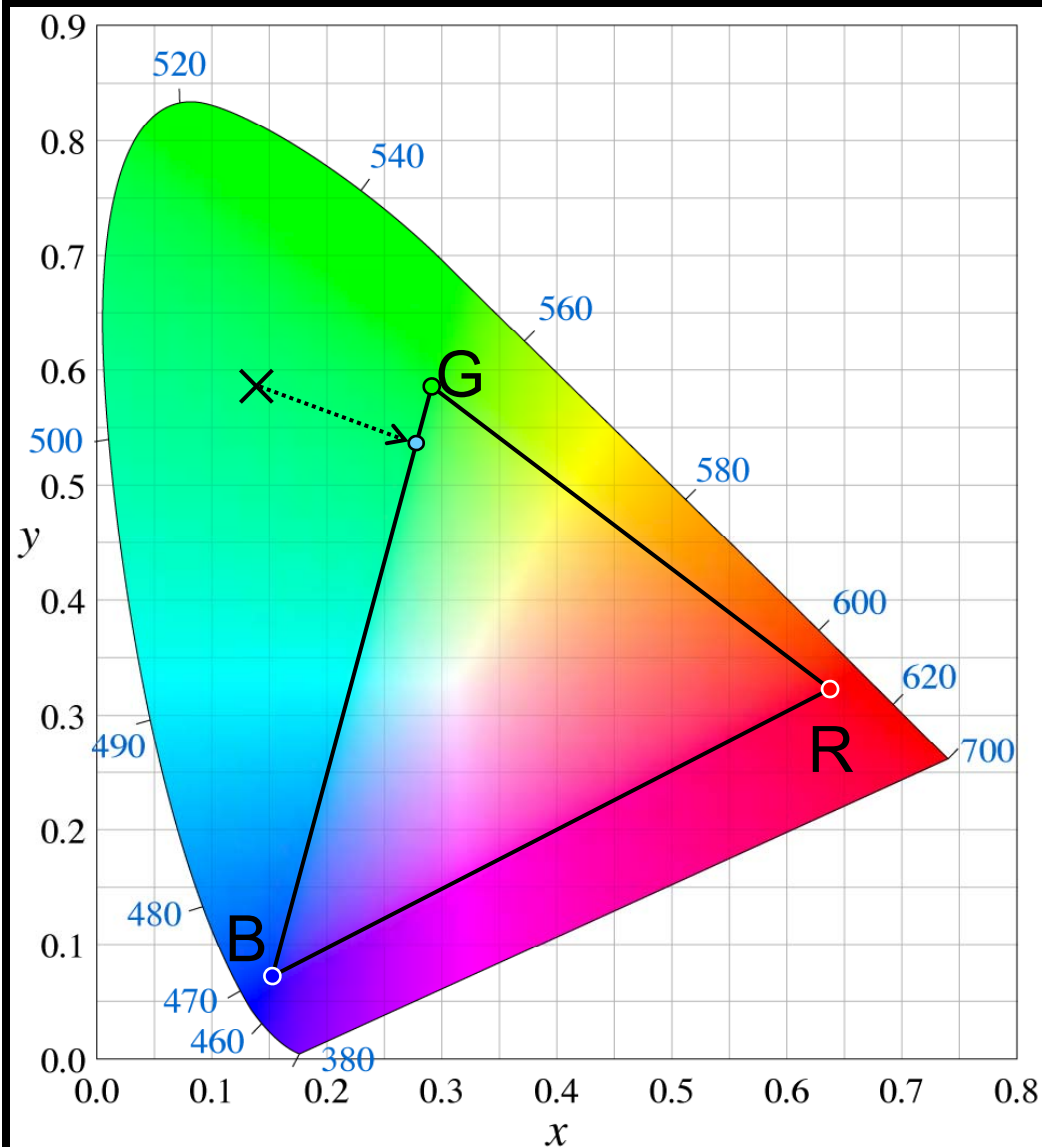
Agile Spectrum Imaging



Programmable Color Gamut for Sensor

With Ankit Mohan, Jack Tumblin [Eurographics 2008]

Traditional Fixed Color Gamut

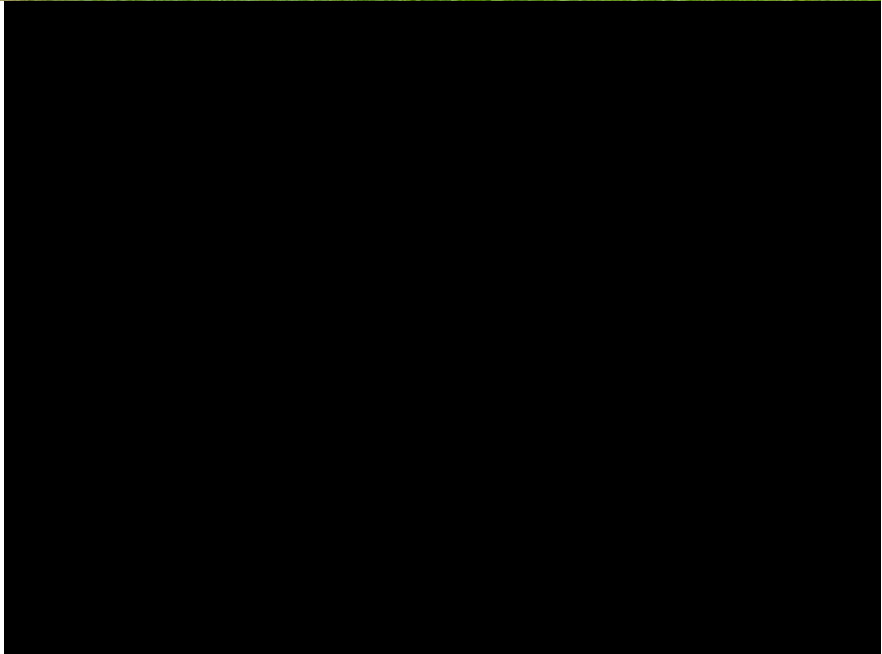
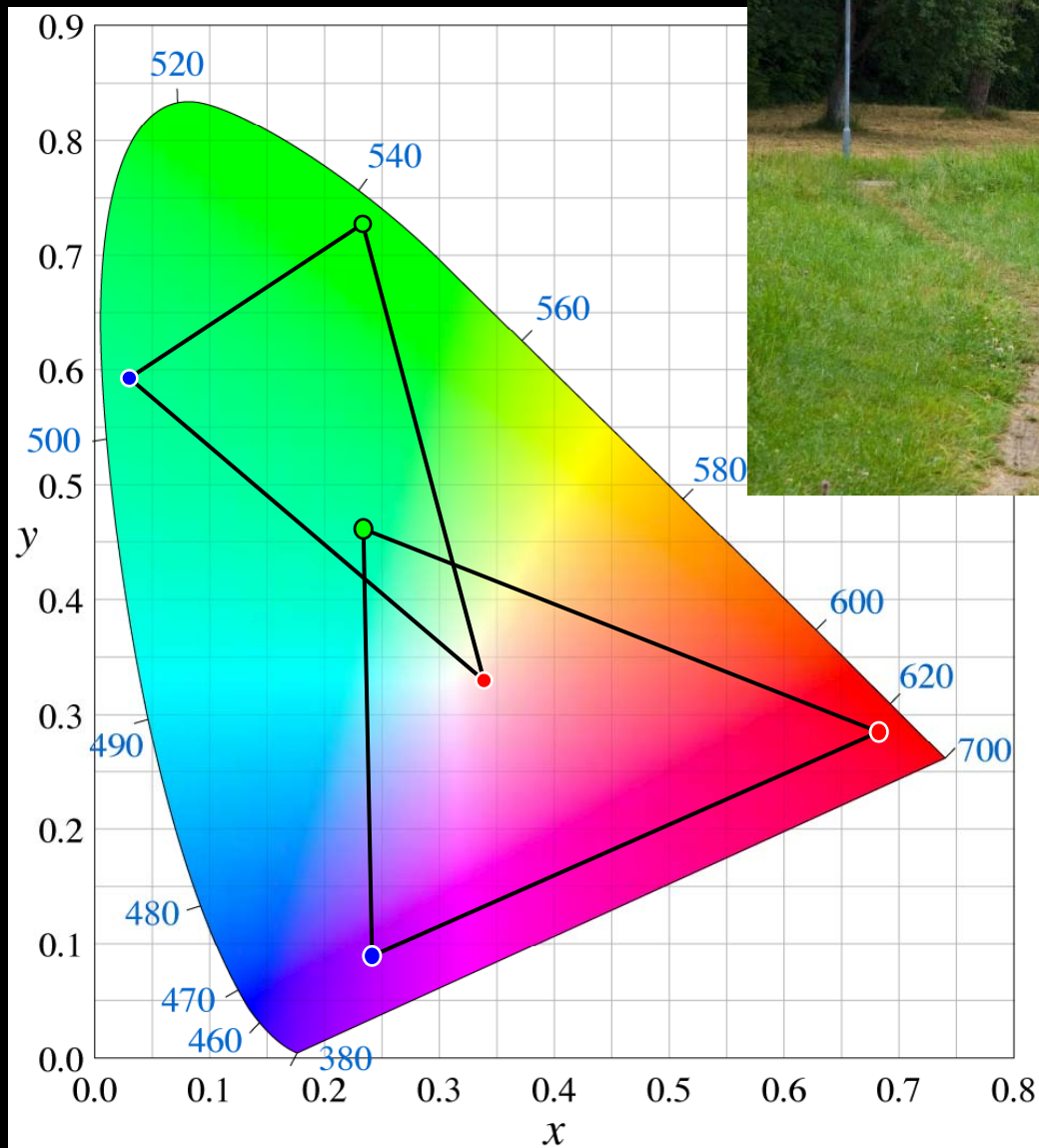


$R \approx 0.0$

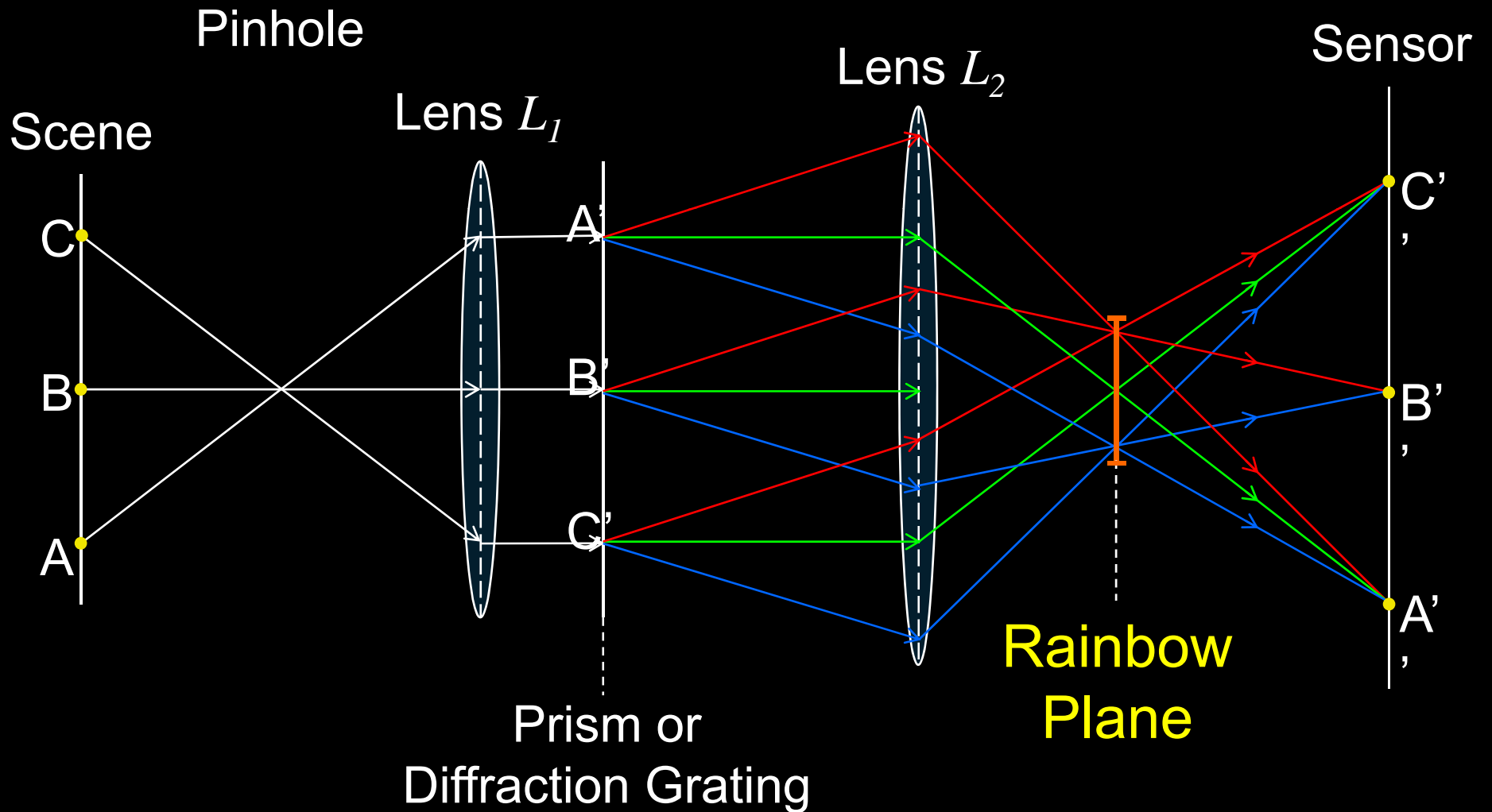
$G \approx 0.2$

$B \approx 0.8$

Adaptive Color Primaries



Rainbow Plane inside Camera



Lens Flare Reduction/Enhancement using 4D Ray Sampling



Glare
Enhanced



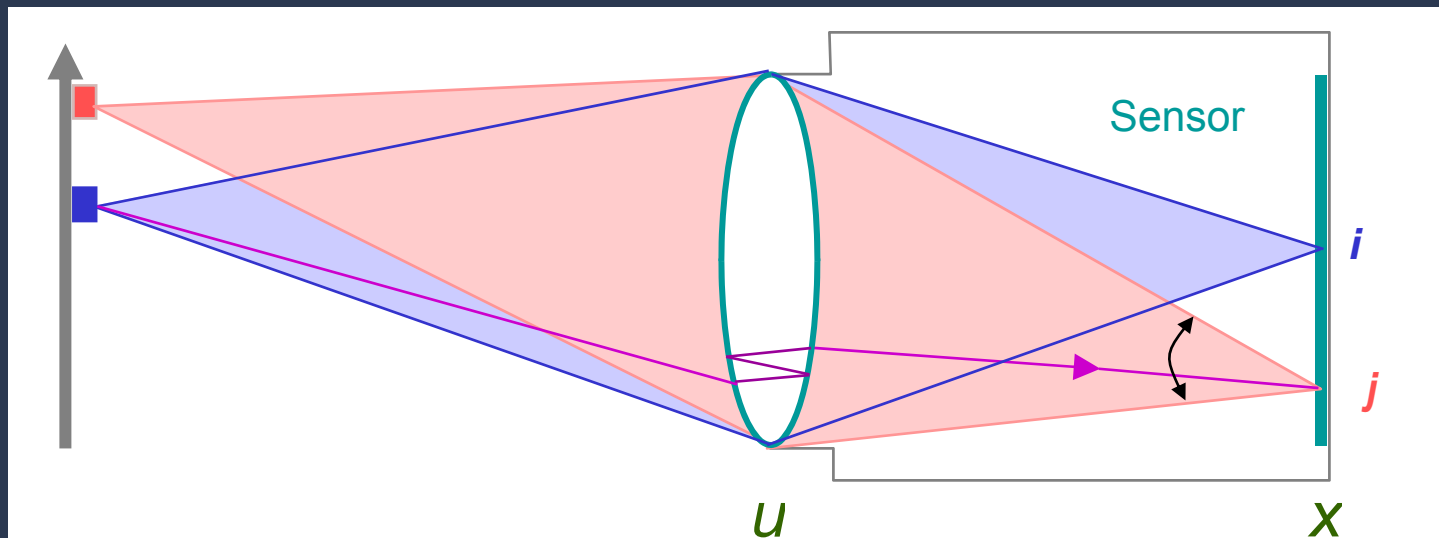
Captured



Glare
Reduced

Glare = low frequency noise in 2D



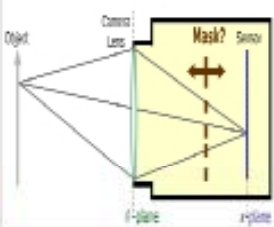

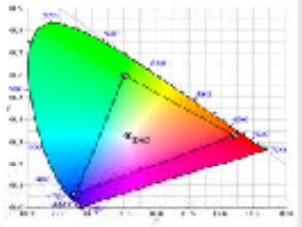
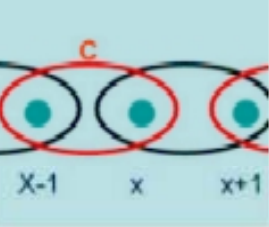
- But is high frequency noise in 4D
- Remove via simple outlier rejection



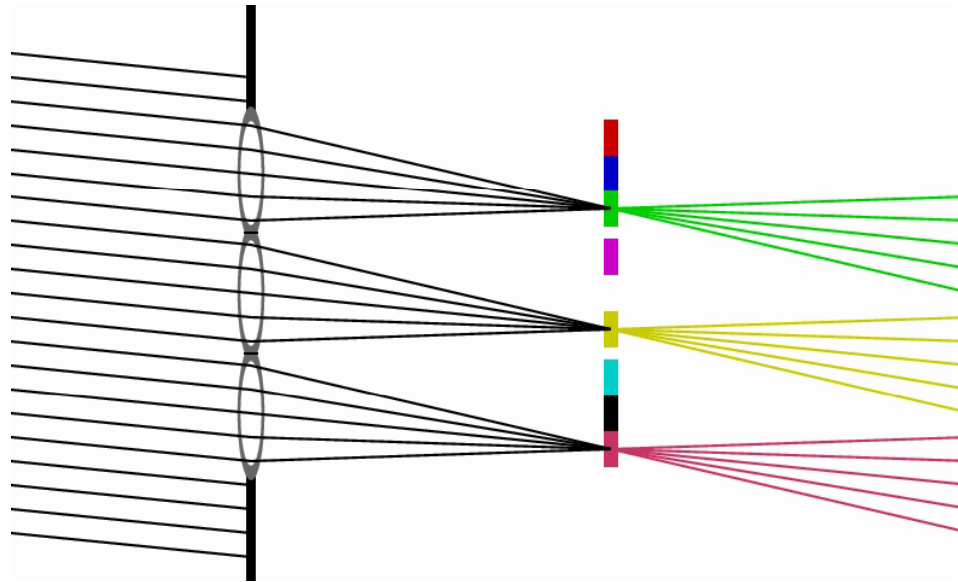
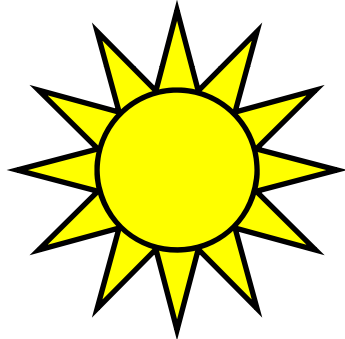
Camera Culture
MIT Media Lab



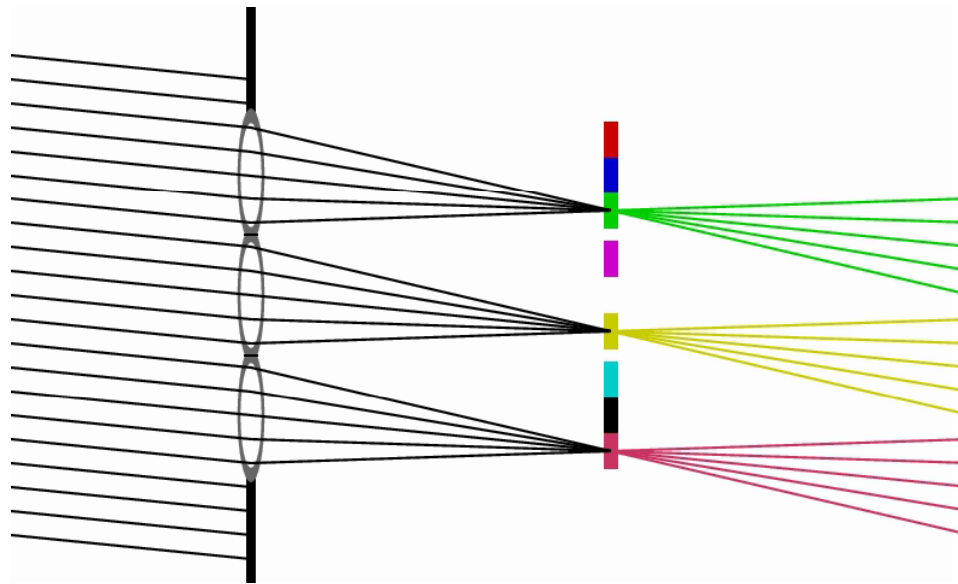
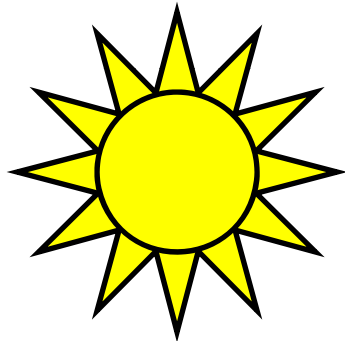
Computational Camera and Photography

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

Dependence on incident angle



Dependence on incident angle



Towards a 6D Display

Passive Reflectance Field Display

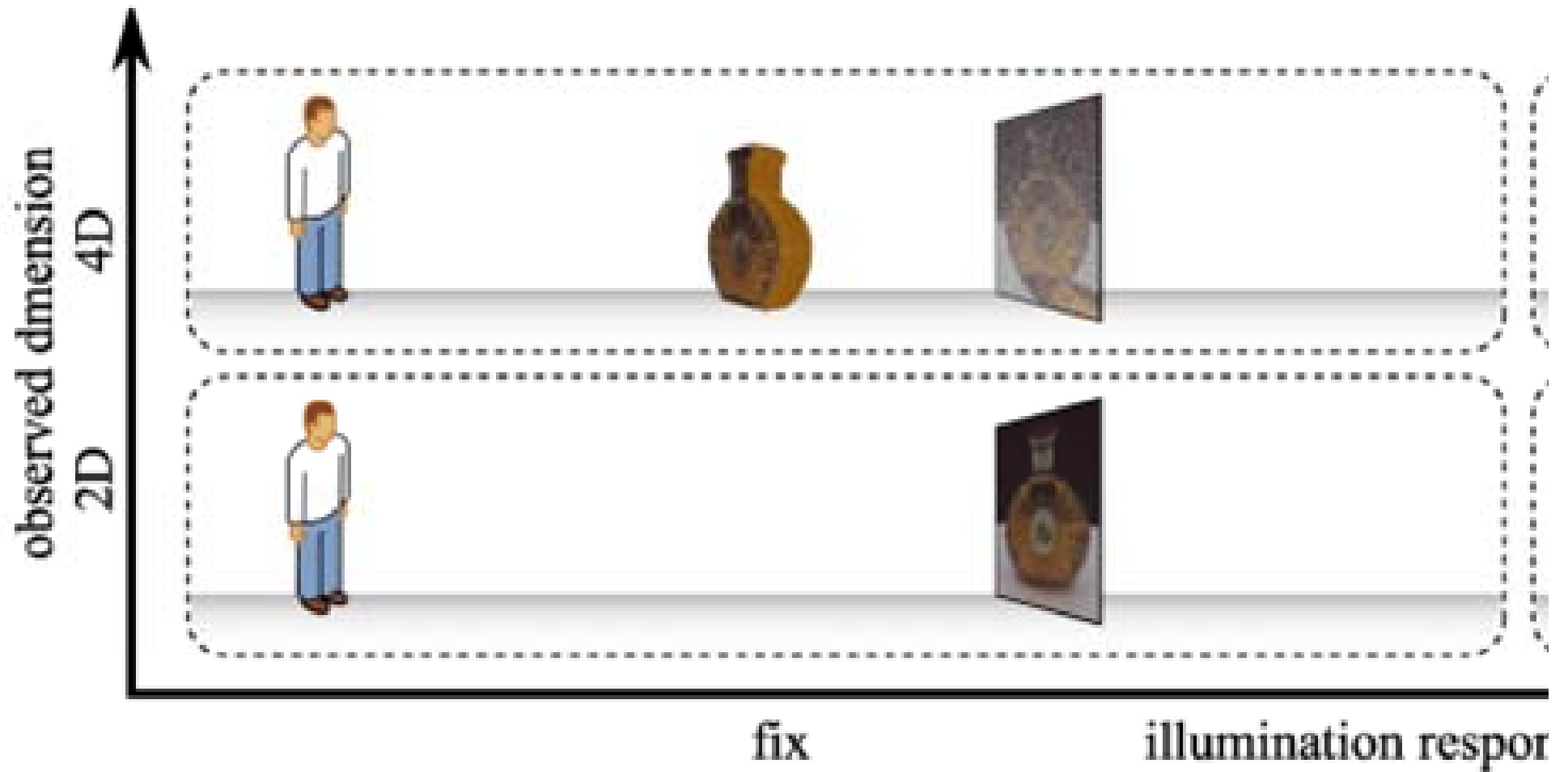


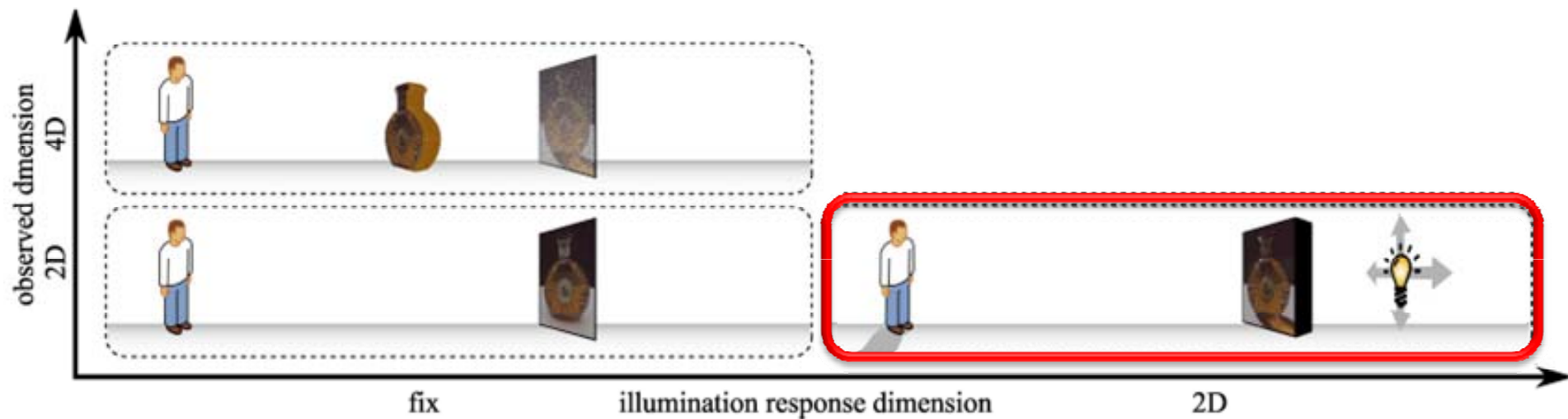
Martin Fuchs, Ramesh Raskar,
Hans-Peter Seidel, Hendrik P. A. Lensch

Siggraph 2008

¹ MPI Informatik, Germany ² MIT

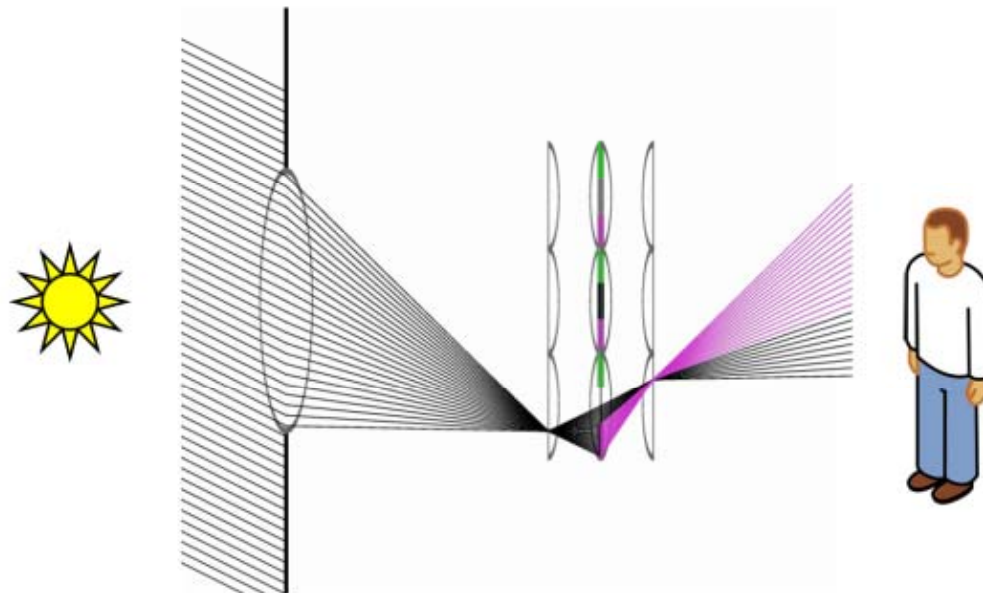
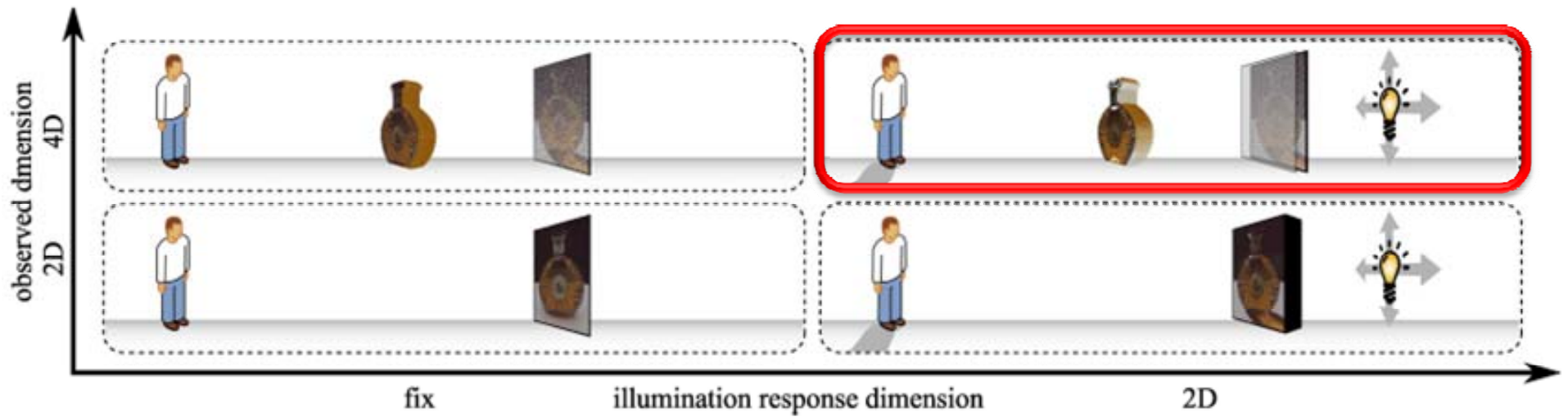
View dependent 4D Display

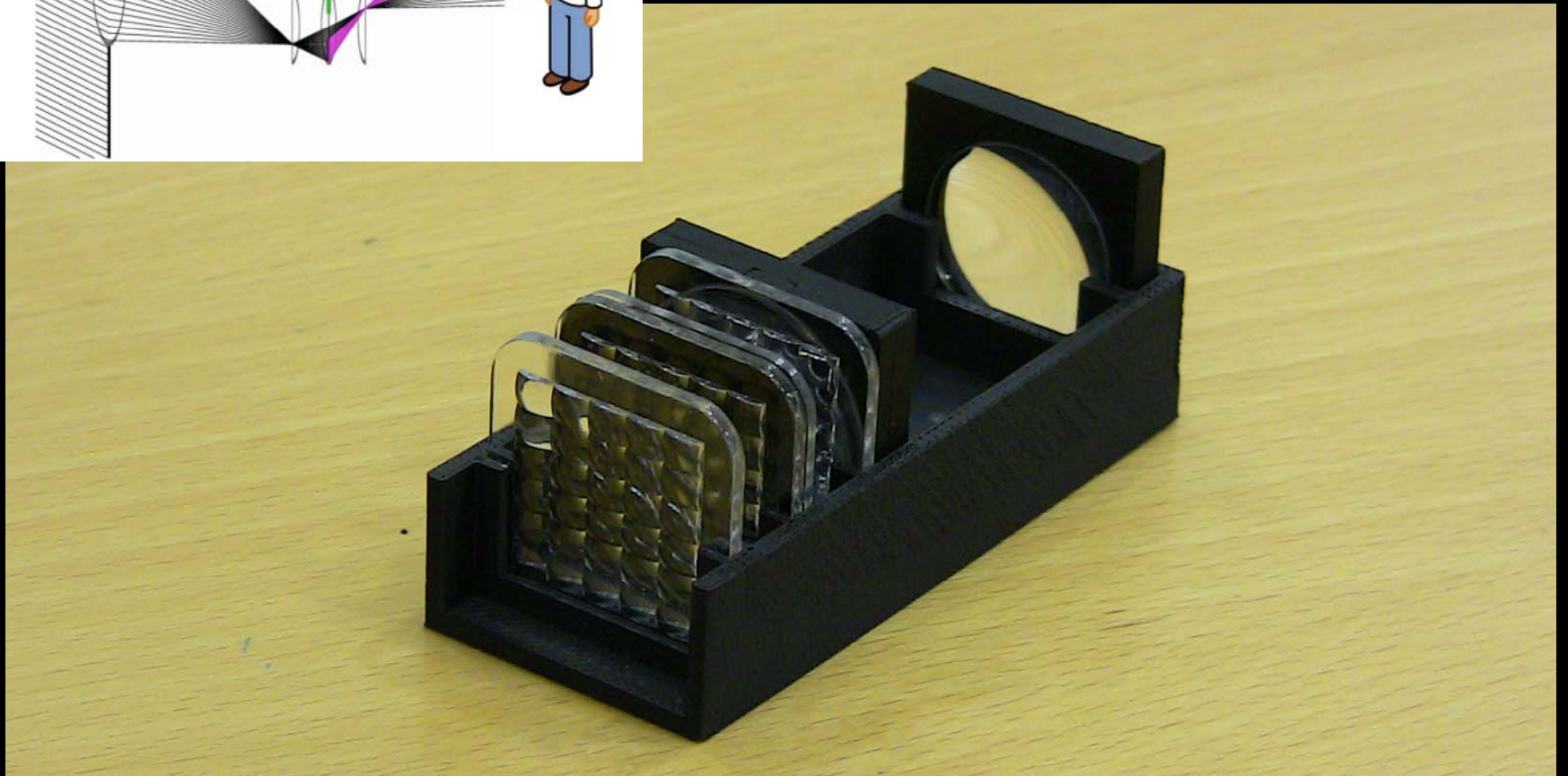
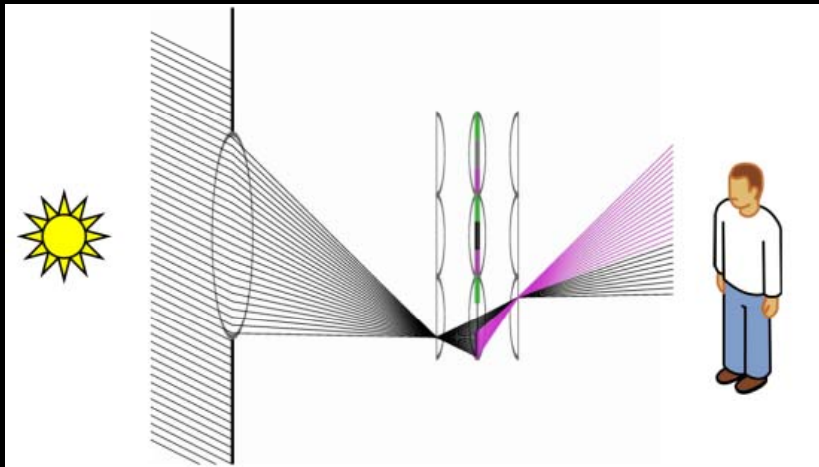






6D = light sensitive 4D display





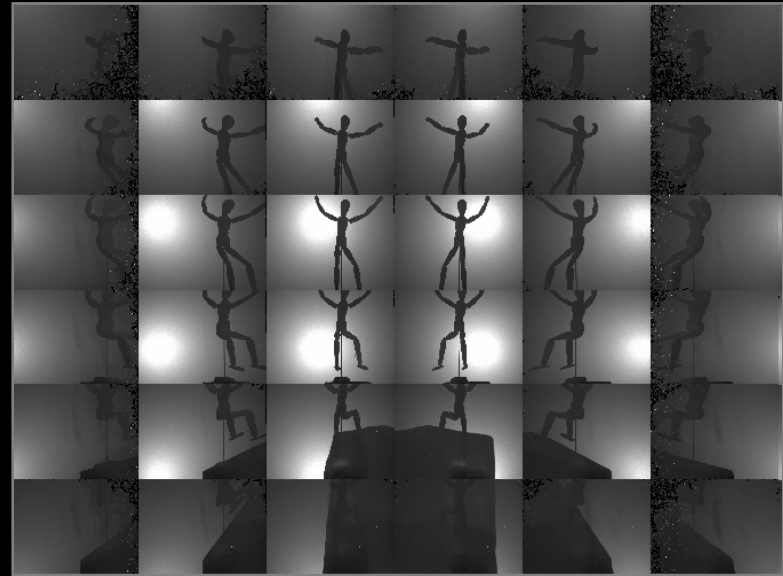
One Pixel of a 6D Display = 4D Display

Single shot visual hull



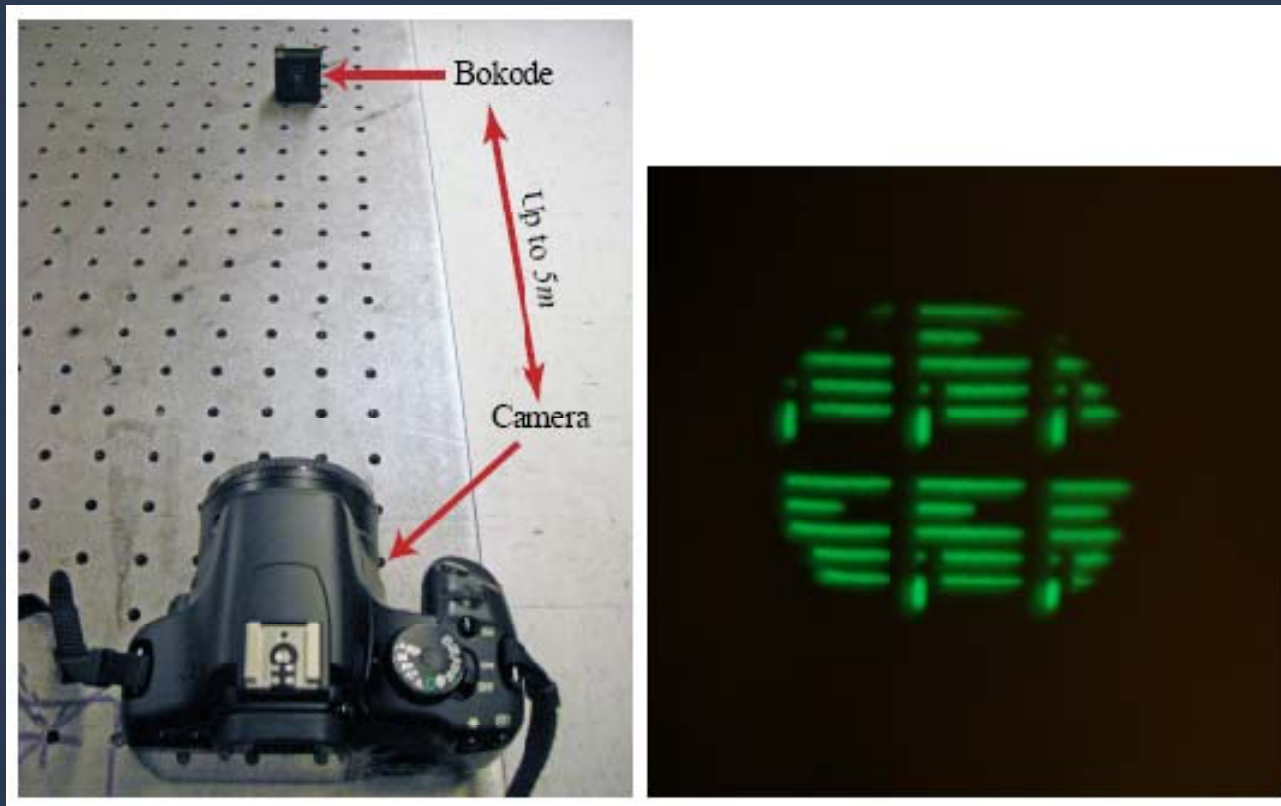
Lanman, Raskar, Agrawal, Taubin [Siggraph Asia 2008]

Single shot 3D reconstruction: Simultaneous Projections using Masks



Long Distance Bar-codes

- Barcode size : 3mm x 3mm
- Distance from camera : 5 meter



Projects

- Lightweight Medical Imaging
 - High speed Tomography
 - Muscle, blood flow activity with wearable devices for patients
- Femto-second Analysis of Light Transport
 - Building and modeling future ultra-high speed cameras
 - Avoid car-crashes, analyze complex scenes
- Programmable Wavelength in Thermal Range
 - Facial expressions, Healthcare
 - Human-emotion aware computing, Fast diagnosis
- Second skin
 - Wearable fabric for bio-I/O via high speed optical motion capture
 - Record and mimic any human motion, Care for elderly, Teach a robot



Vicon Motion Capture

Medical Rehabilitation



Athlete Analysis



High-speed
IR Camera

Body-worn markers

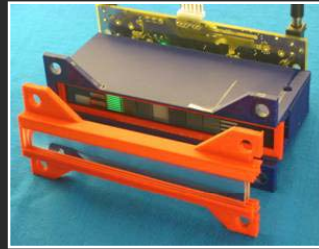


Performance Capture



Biomechanical Analysis

Inverse Optical Mo-Cap



Traditional



Device	High Speed Projector + Photosensing Markers	High Speed Camera + Reflecting/Emitting Markers
Params	Location, Orientation, Illum	Location
Settings	Natural Settings Ambient Light Outdoors, Stage lighting Imperceptible tags Hidden under wardrobe	Controlled Lighting Visible, High contrast Markers
#of Tags	Unlimited Space Labeling Unique Id	Limited No Unique Id Marker swapping
Speed	Virtually unlimited Optical comm comps	Limited Special high fps camera
Cost	Low Open-loop projectors Current: Projector/Tag=\$100	High High bandwidth camera Current Camera: \$10K

Inside of Projector

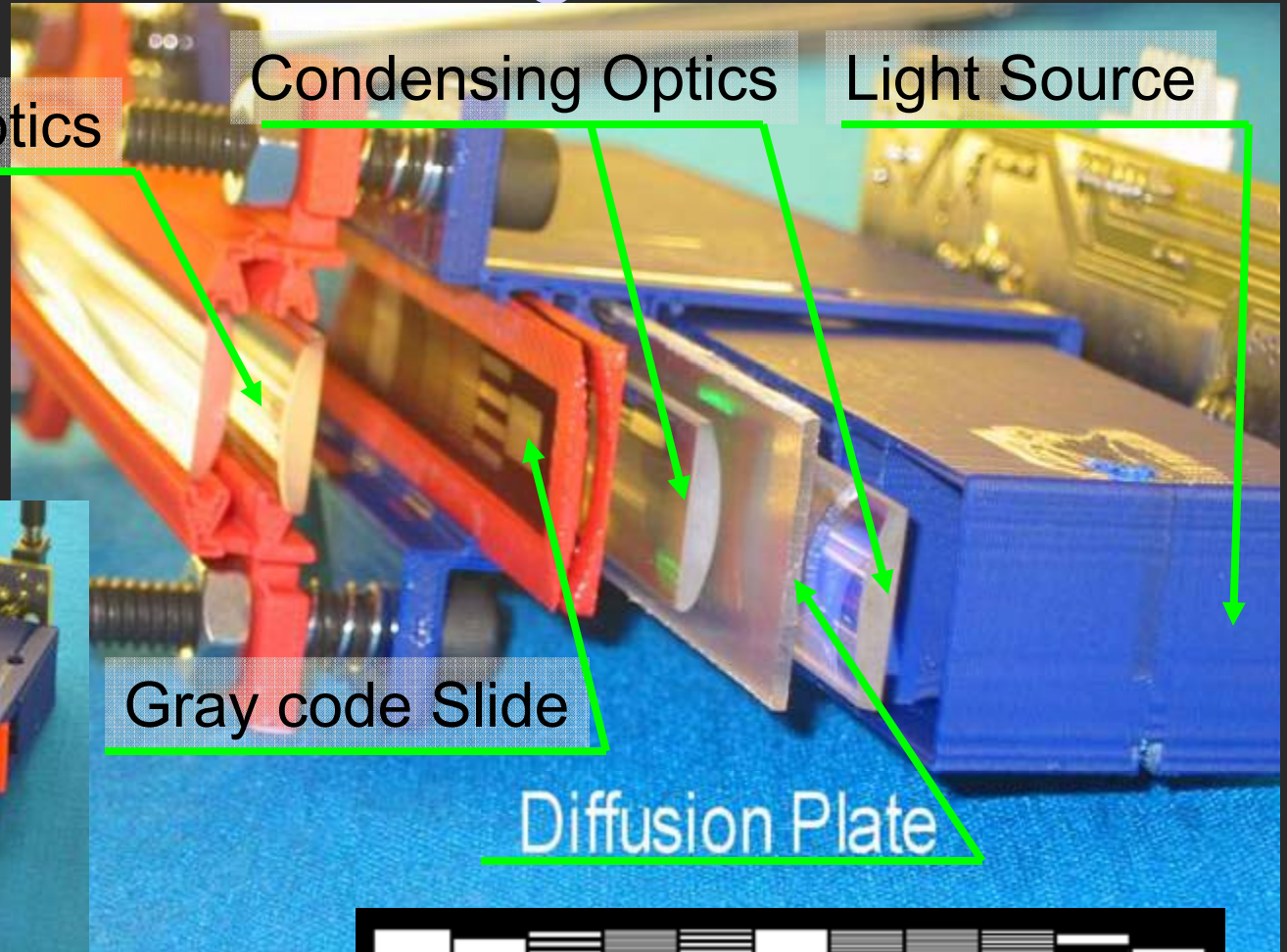
Focusing Optics

Condensing Optics

Light Source

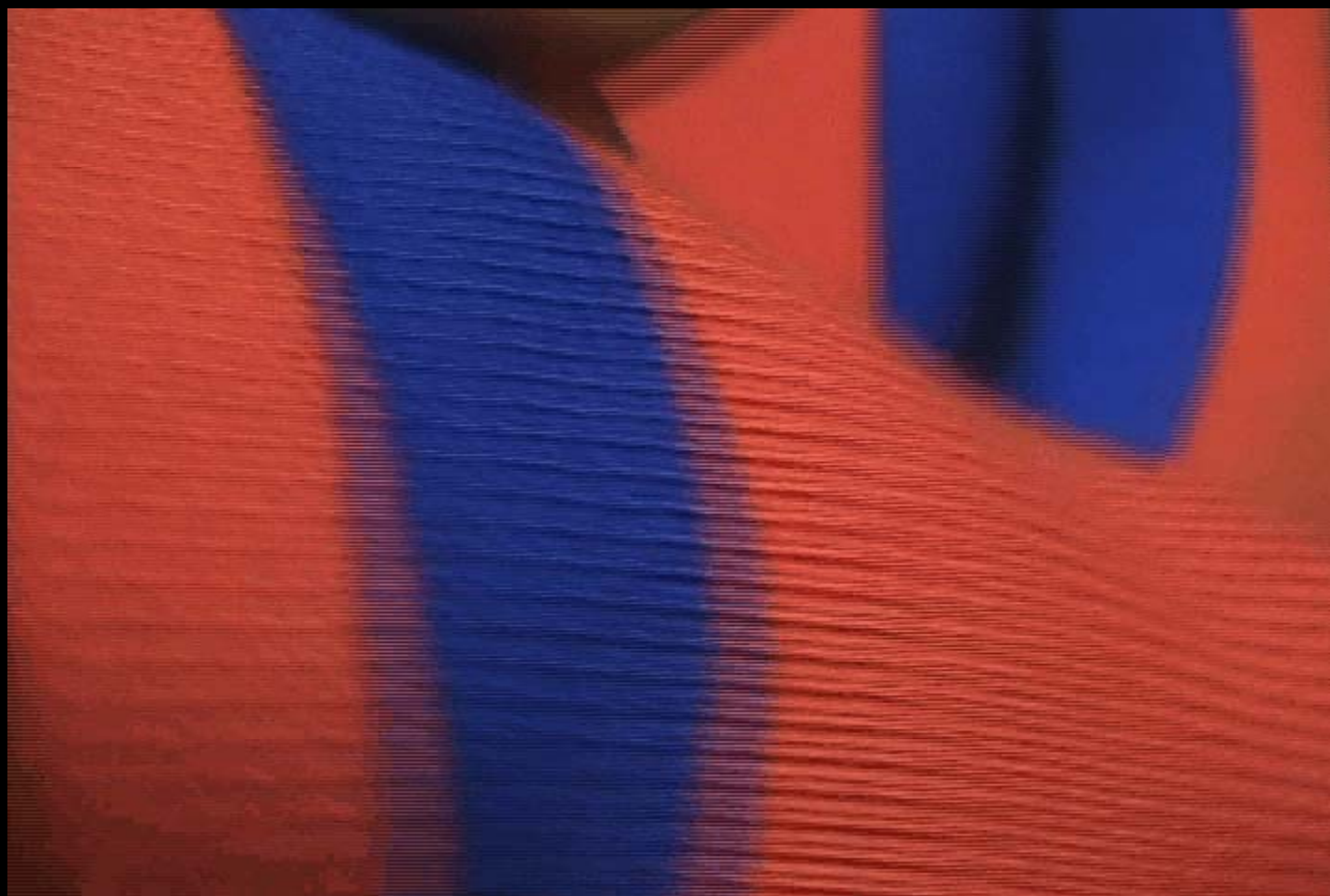
Gray code Slide

Diffusion Plate



The Gray code pattern

Imperceptible Tags under clothing, tracked under ambient light



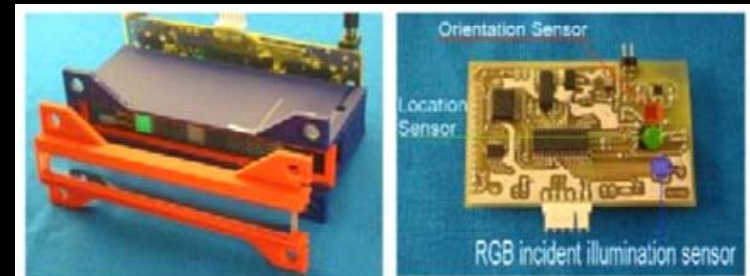
Towards Second Skin

Coded Illumination

Motion Capture Clothing

- 500 Hz with 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
 - Light sensitive fabric for dense sampling
- Non-imaging, complete privacy
- Base station and tags only a few 10's \$

- Full body scan + actions
 - Elderly, patients, athletes, performers
 - Breathing, small twists, multiple segments or people
 - Animation Analysis



Optical
Base Emitter

Photosensing
Receiver Tag

Coded Imaging

Coding in Time

Coded Exposure for Motion Deblurring

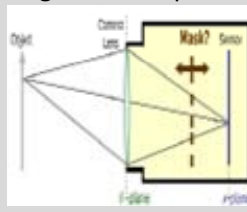


Coding in Space (Optical Path)

Coded Aperture for Extended Depth of Field



Mask-based Optical Heterodyning for Light Field Capture



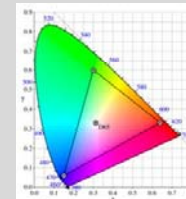
Coded Illumination

Multi-flash Imaging for Depth Edge Detection



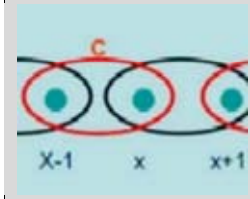
Coded Wavelength

Agile Spectrum Imaging

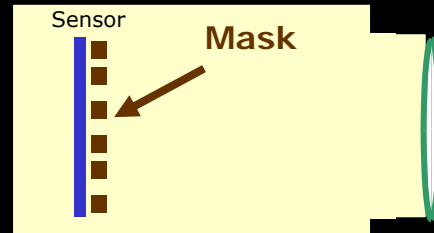
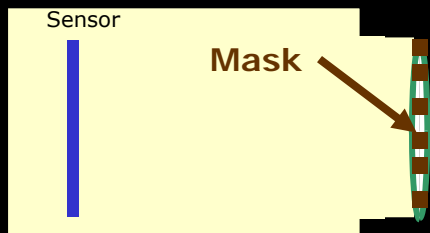
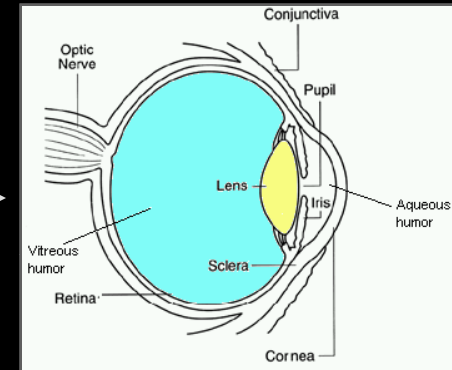
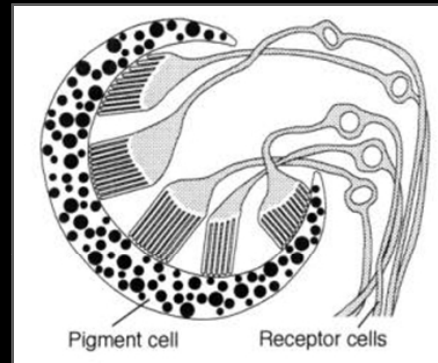
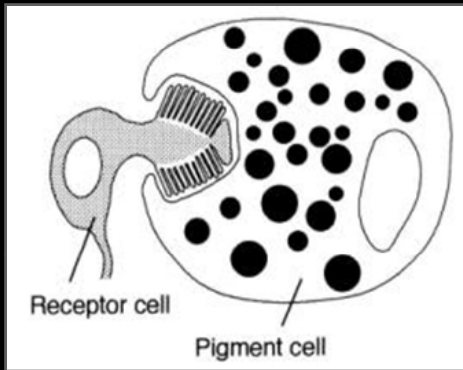


Coded Sensing

Gradient Encoding Sensor for HDR



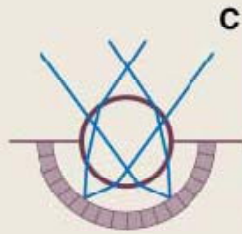
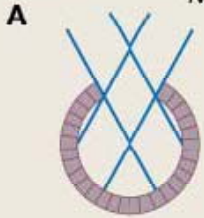
Forerunners ..



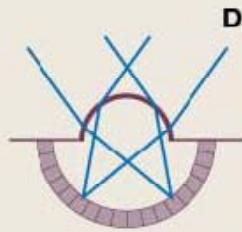
Chambered eyes



Nautilus



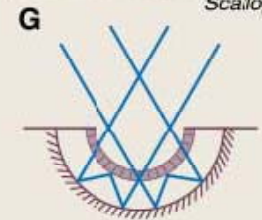
Octopus



Red-tailed hawk



Scallop



Shadow

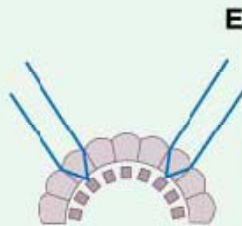
Refractive

Reflective

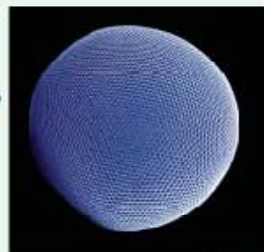
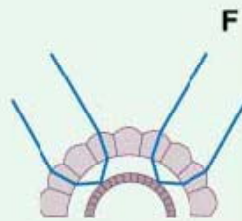
Compound eyes



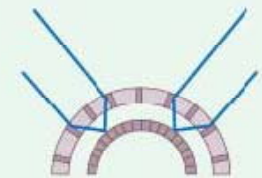
Sea fan



Dragonfly



Krill eye

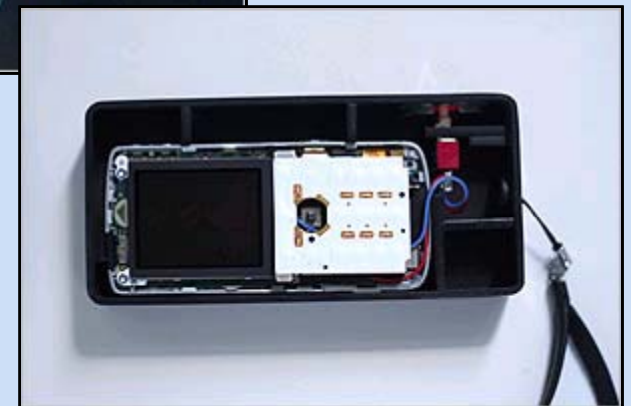


Lobster

Tools
for
Visual
Computing

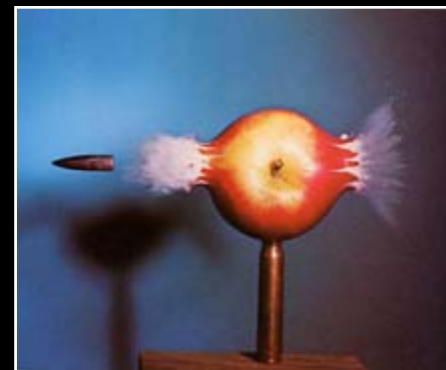
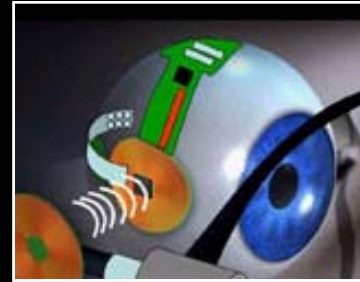


Blind Camera



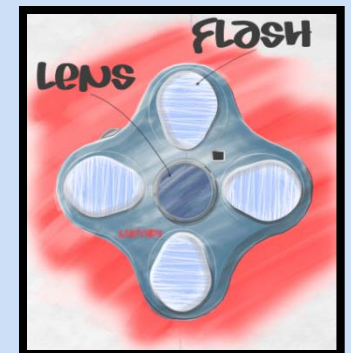
Sascha Pohflepp,
U of the Art, Berlin, 2006

Cameras of Tomorrow



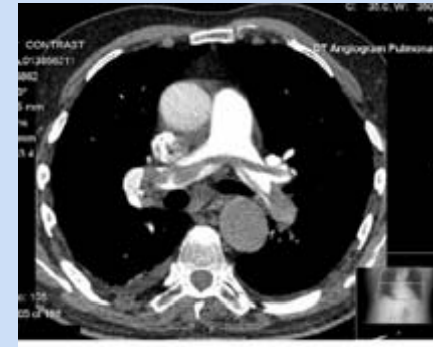
Cameras of Tomorrow

- Coded Exposure
 - Motion Deblurring [2006]
- Coded Aperture
 - Focus Deblurring [2007]
 - Glare reduction [2008]
- Optical Heterodyning
 - Light Field Capture [2007]
- Coded Illumination
 - Motion Capture [2007]
 - Multi-flash: Shape Contours [2004]
- Coded Spectrum
 - Agile Wavelength Profile [2008]
- Epsilon->Coded->Essence Photography



- Capture

- Cameras Everywhere
- Deep pervasive sensing

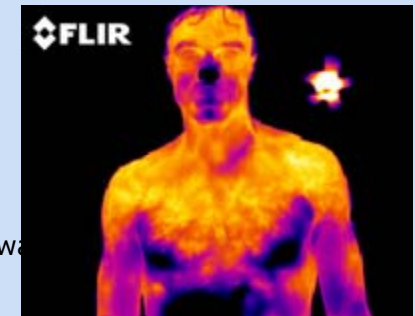


- Analysis

- Computer Vision
 - Personalized services, tracking in real world
 - Animation
- Mo-cap
- Simulation of bio/chemical/physical processes at all scales

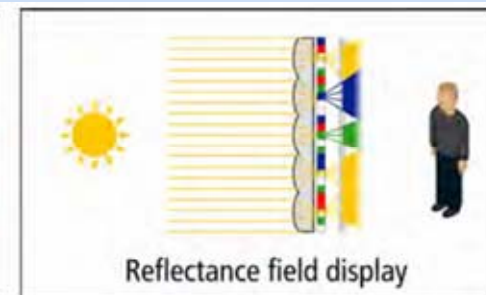
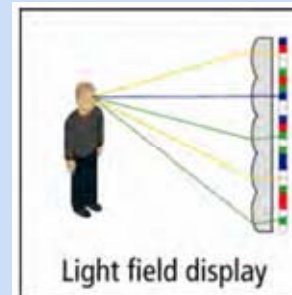
- Synthesis

- Virtual Human, Digital Actors, Tele-avatars
- Exa and Zeta-scale computing:
 - simulate every neural activity, predict weather for weeks, simulate impact of global w



- Display

- Real world AR
- Realistic Displays: 6D or 8D





We focus on creating tools to better capture and share visual information

The goal is to 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