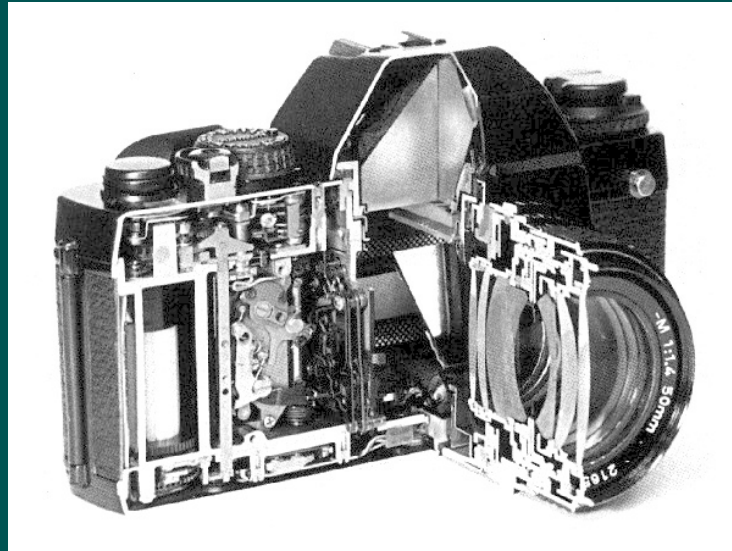


# Course 1: Computational Photography



## Organisers

Ramesh Raskar

MIT – Media Lab

Jack Tumblin

Northwestern University

# What is Photography?

## PHYSICAL

### 3D Scene

light sources,  
BRDFs,  
shapes,  
positions,  
movements,  
...

### Eyepoint

position,  
movement,  
projection,  
...

Light &  
Optics

Exposure  
Control,  
tone map

Image  
 $I(x,y,\lambda,t)$

Display  
 $RGB(x,y,t_n)$

Vision

### Scene

light sources,  
BRDFs,  
shapes,  
positions,  
movements,  
...

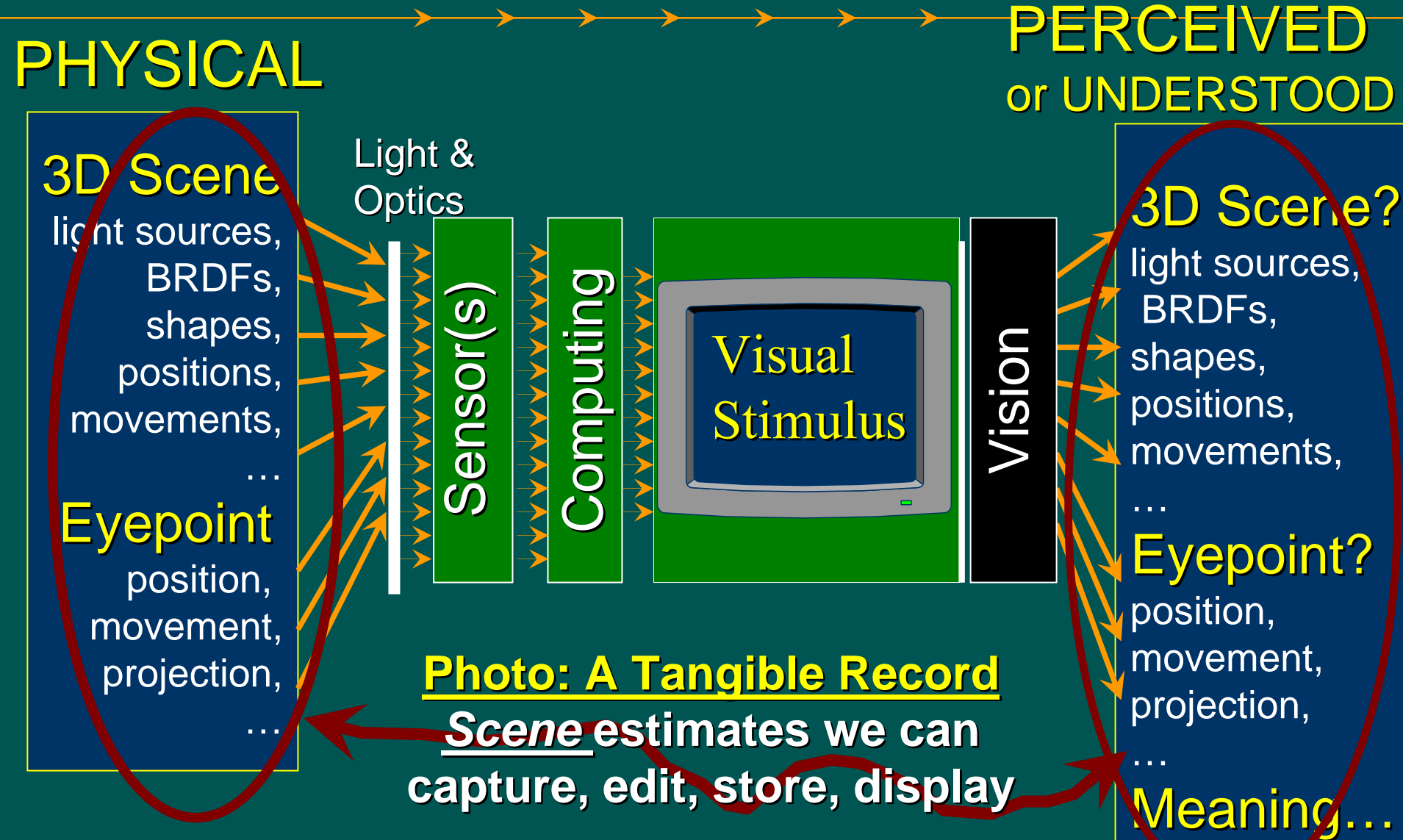
### Eyepoint

position,  
movement,  
projection,  
...

Photo: A Tangible Record

Editable, storable as  
Film or Pixels

# Ultimate Photographic Goals



# Ives' Camera



Patented 1903  
Array of pinholes  
near image plane

No. 725,567.

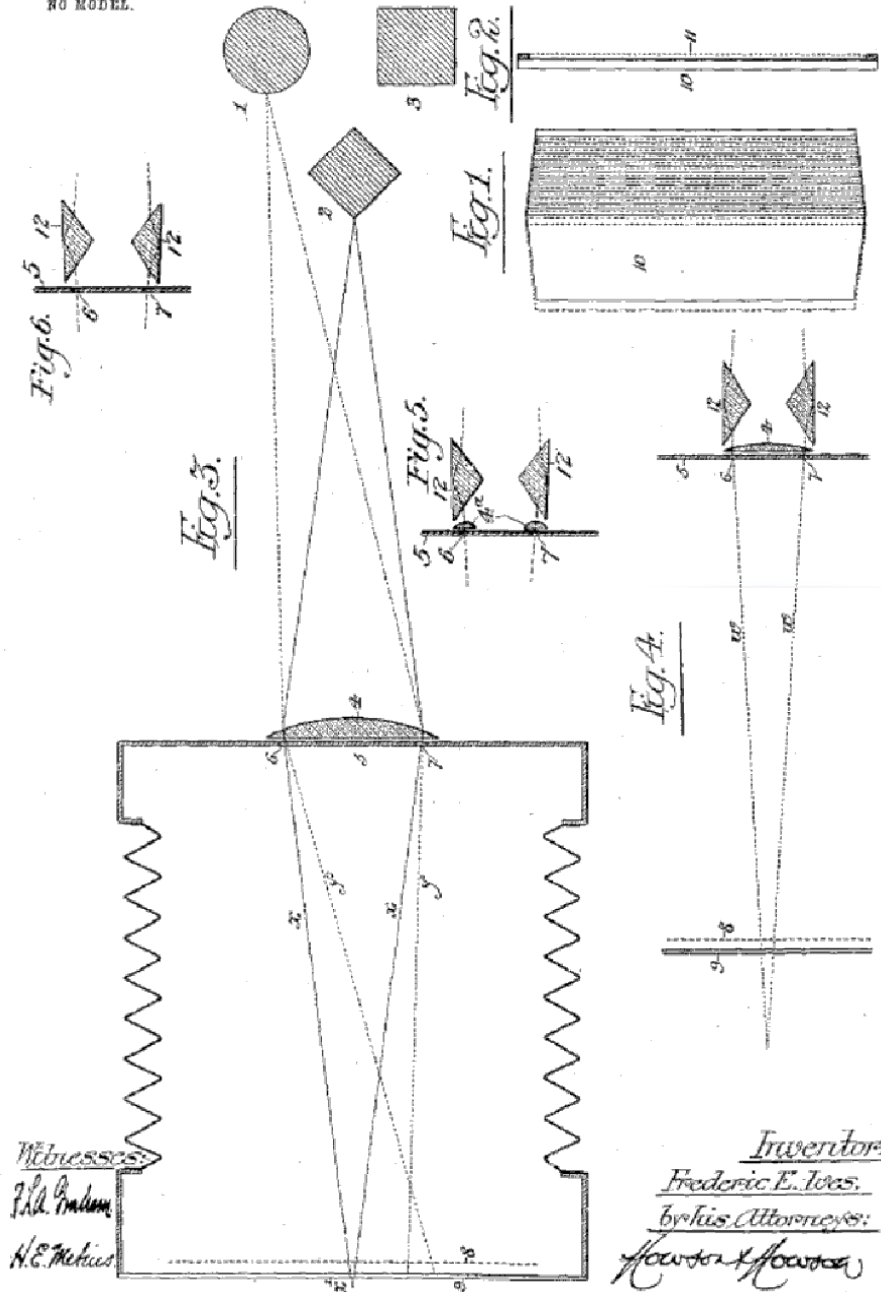
PATENTED APR. 14, 1903.

F. E. IVES.

PARALLAX STEREOGRAM AND PROCESS OF MAKING SAME.

APPLICATION FILED SEPT. 25, 1902.

NO MODEL.



Witnesses:  
P. A. Paulson  
H. E. McKies

Inventor:  
Frederic E. Ives.  
By his Attorneys:  
Howe & Howe

# Devices for recording light fields (using geometrical optics)

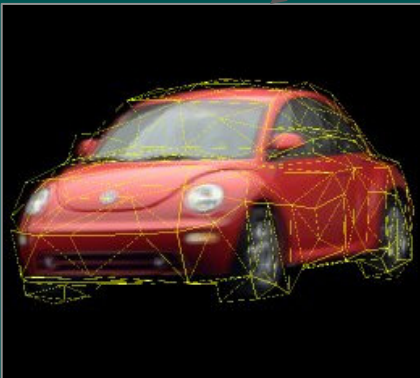
---

big  
baseline



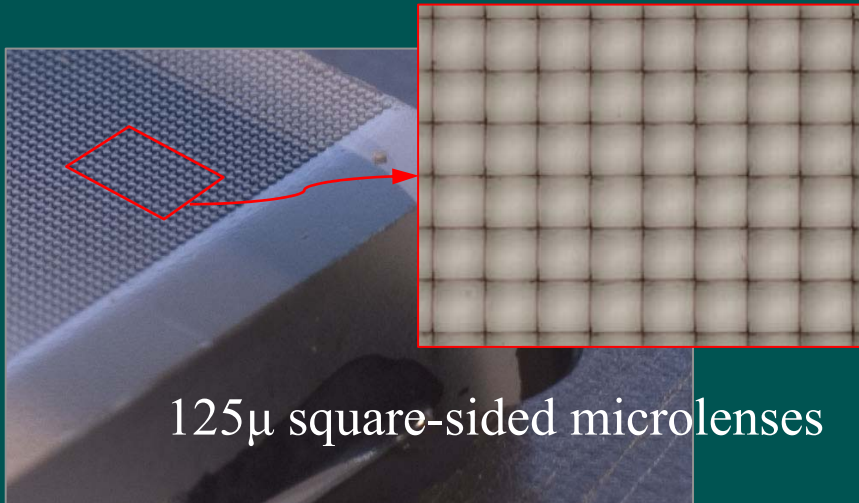
small  
baseline

- handheld camera [Buehler 2001]
- camera gantry [Stanford 2002]
- • array of cameras [Wilburn 2005]
- • plenoptic camera [Ng 2005]
- • light field microscope [Levoy 2006]



# Digital Refocusing using Light Field Camera

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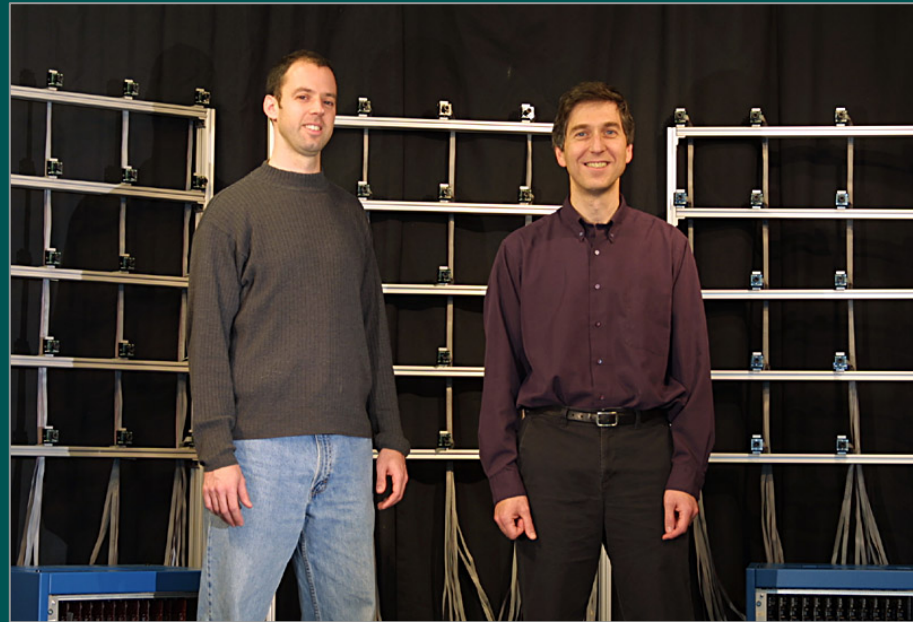


125 $\mu$  square-sided microlenses

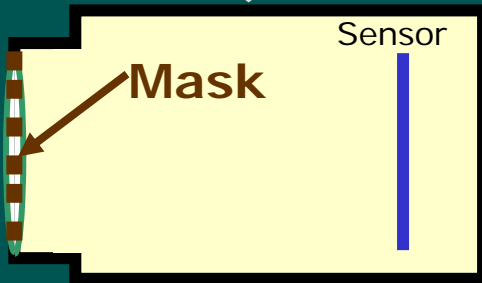
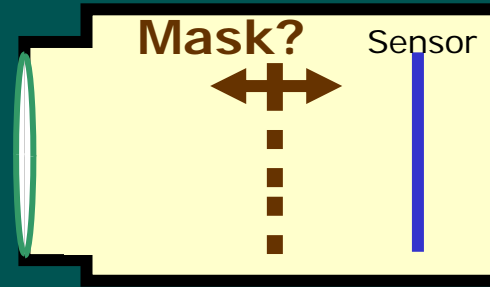
# High performance imaging using large camera arrays

*Bennett Wilburn, Neel Joshi, Vaibhav Vaish, Eino-Ville Talvala, Emilio Antunez,  
Adam Barth, Andrew Adams, Mark Horowitz, Marc Levoy*

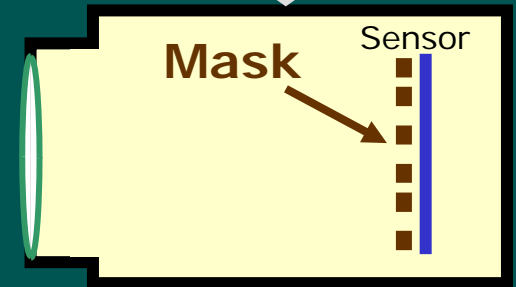
*(Proc. SIGGRAPH 2005)*



# Coding and Modulation in Camera Using Masks



Coded Aperture for Full Resolution Digital Refocusing



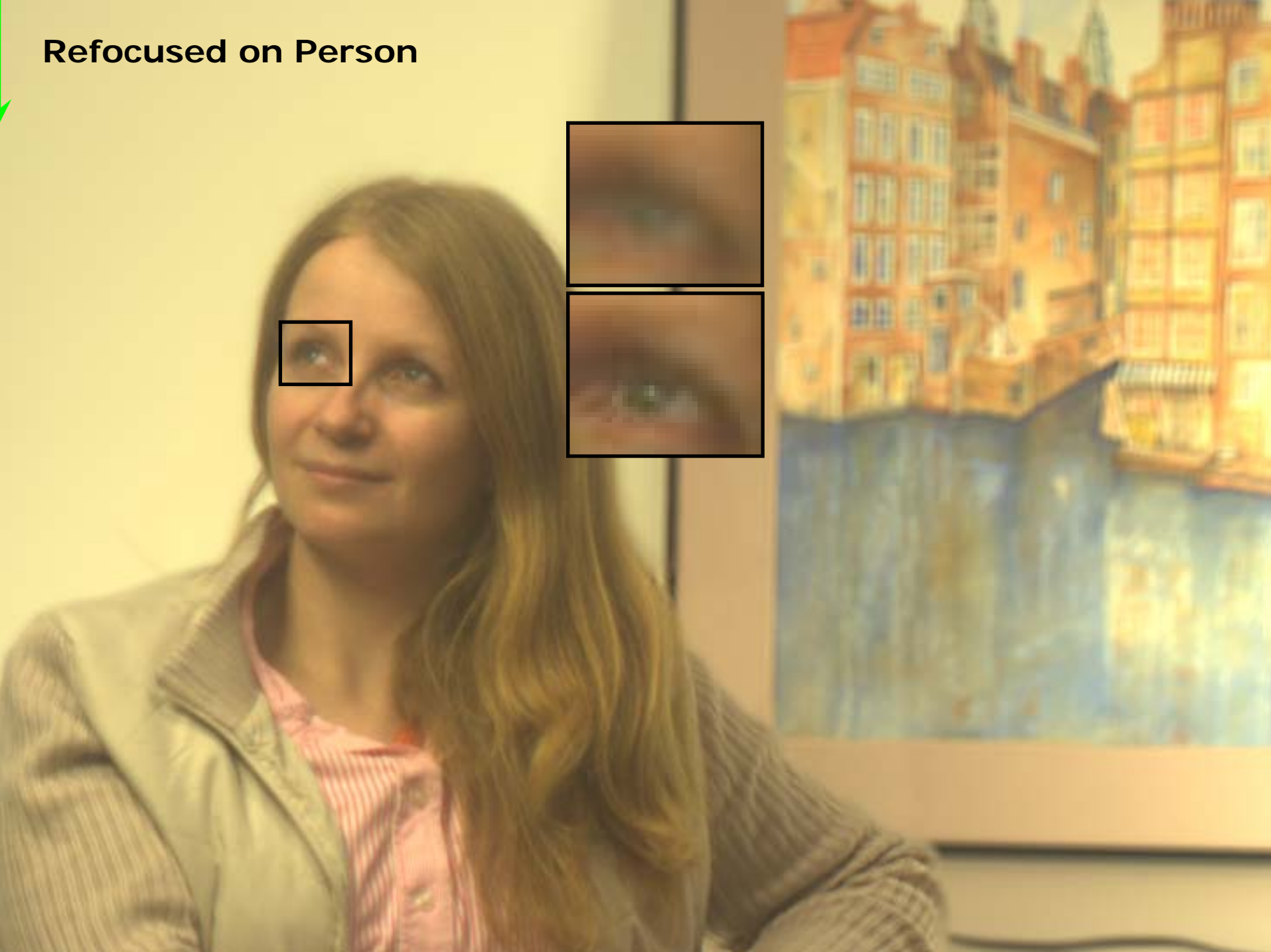
Heterodyne Light Field Camera



# Captured Blurred Photo

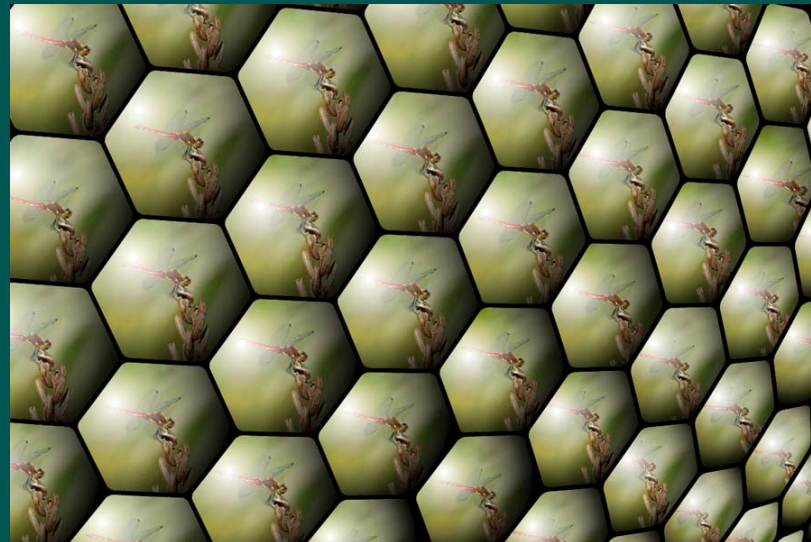
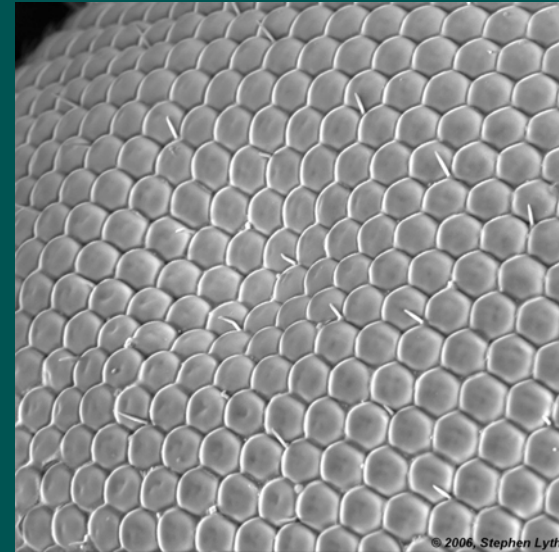


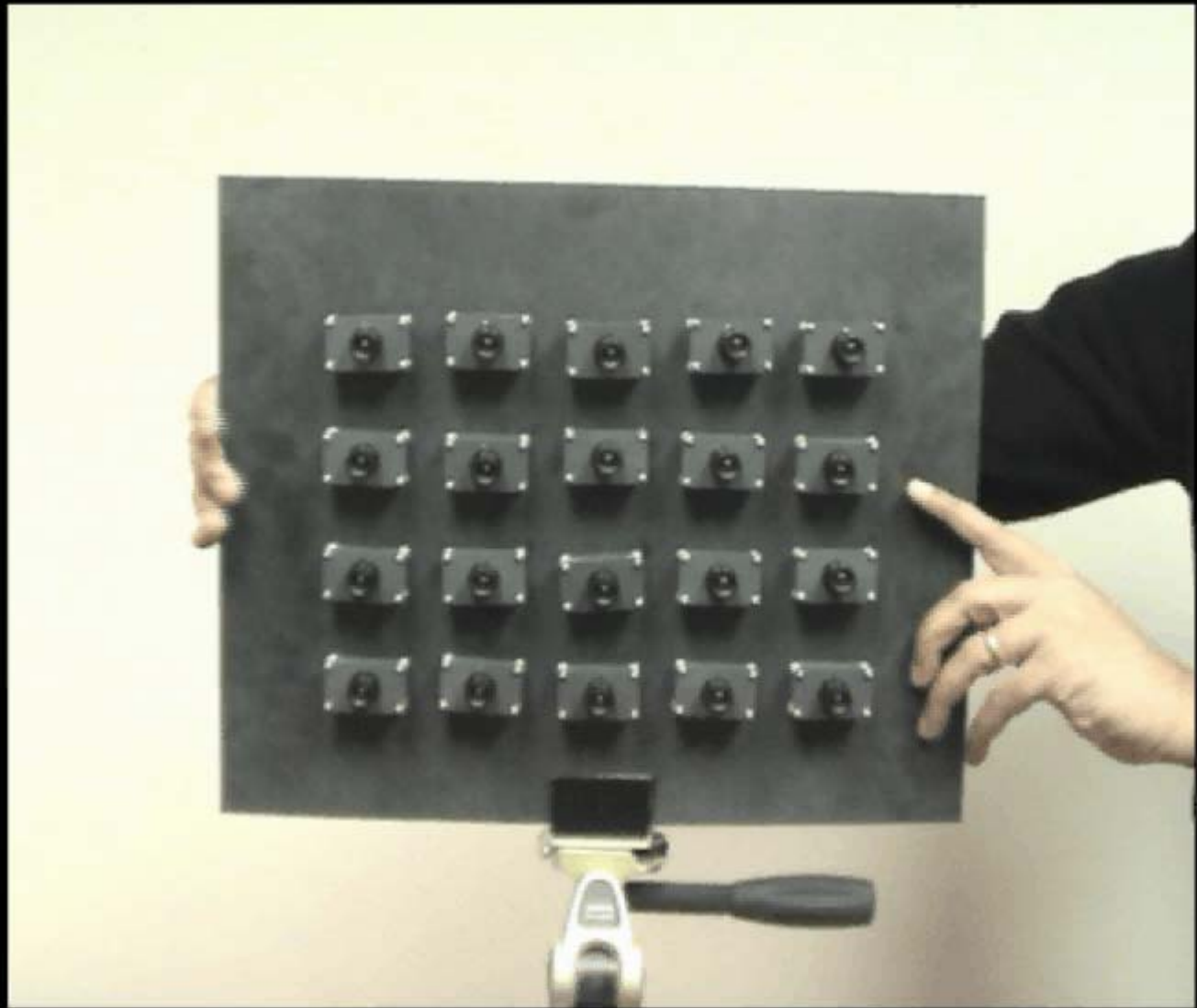
# Refocused on Person



# Compound Lens of Dragonfly

---





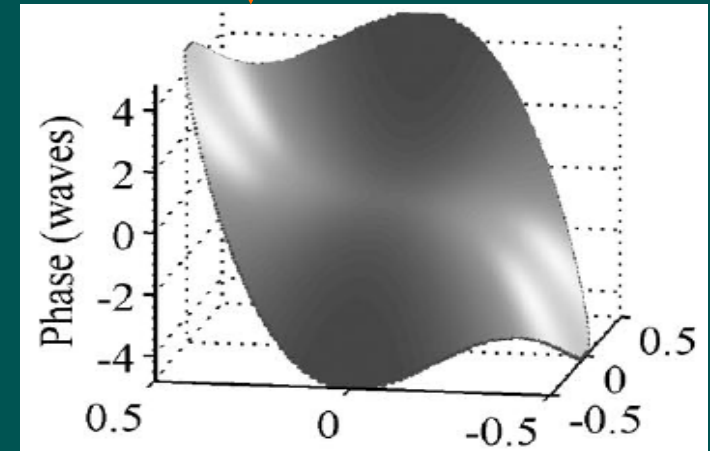
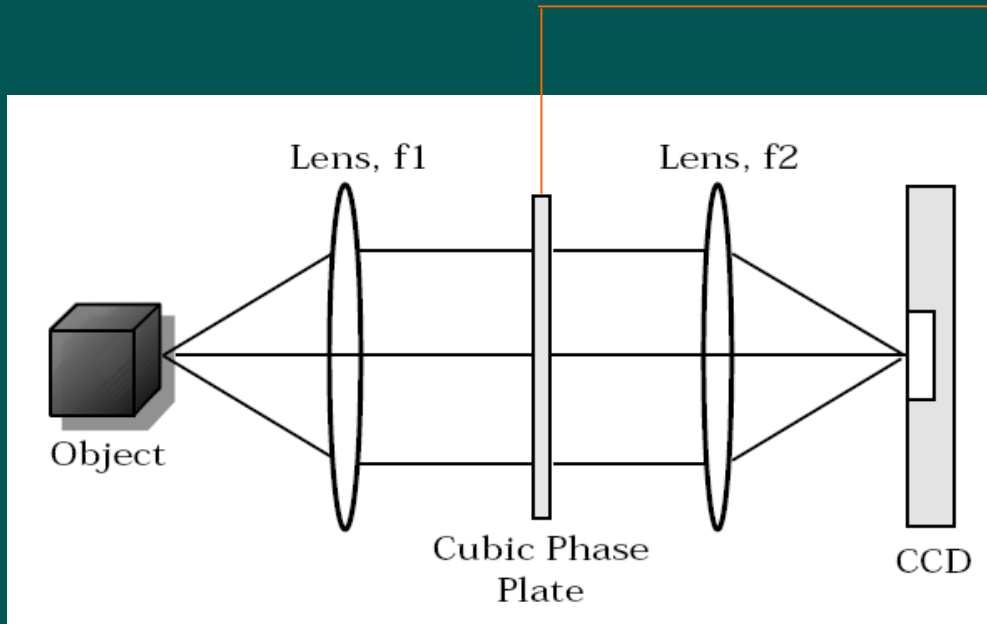






# Wavefront Coding using Cubic Phase Plate

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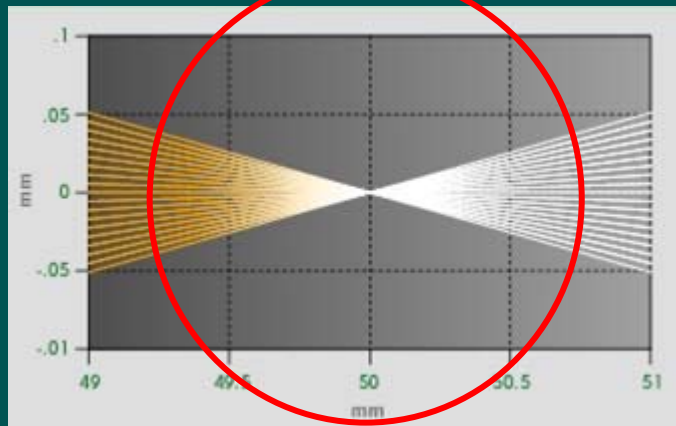
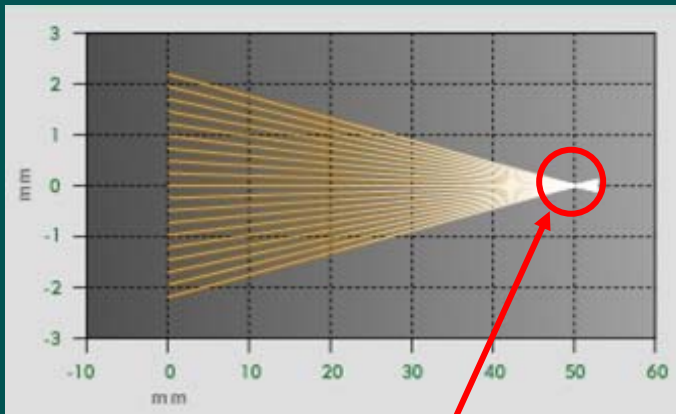


*"Wavefront Coding: jointly optimized optical and digital imaging systems",  
E. Dowski, R. H. Cormack and S. D. Sarama ,  
Aerosense Conference, April 25, 2000*

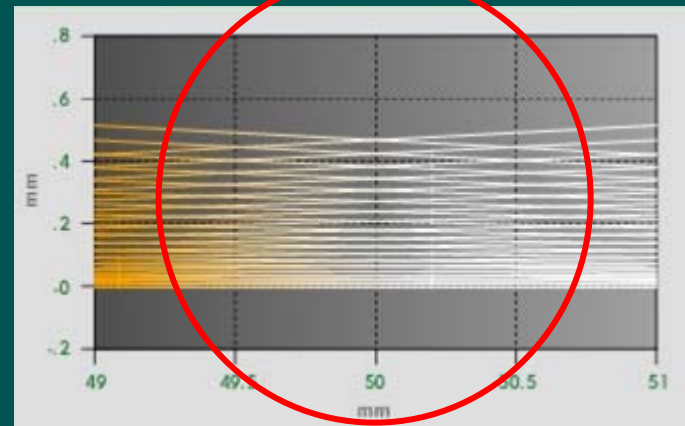
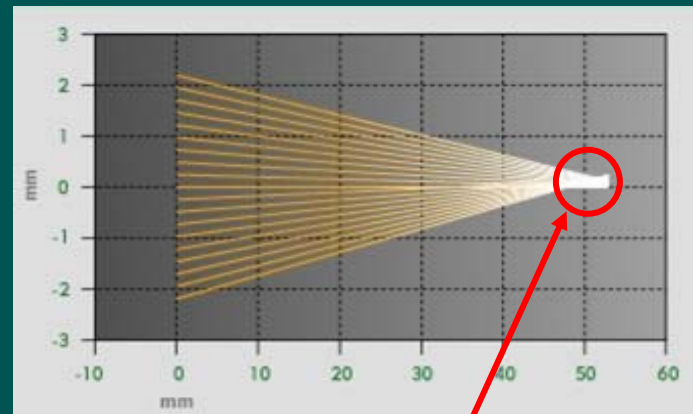


# Depth Invariant Blur

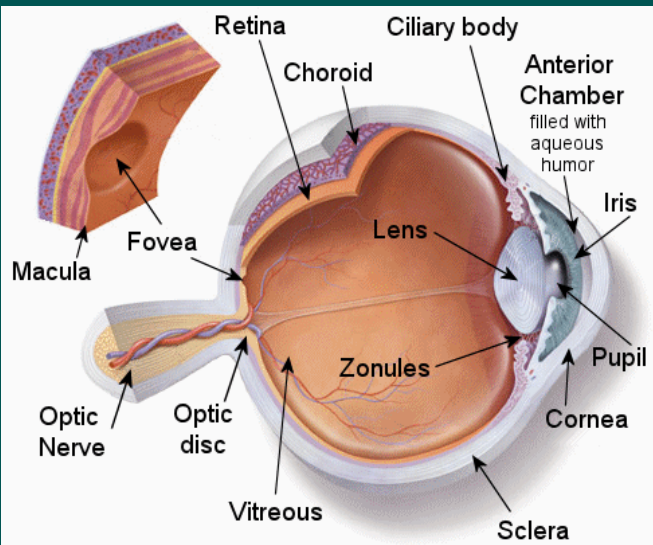
## Conventional System



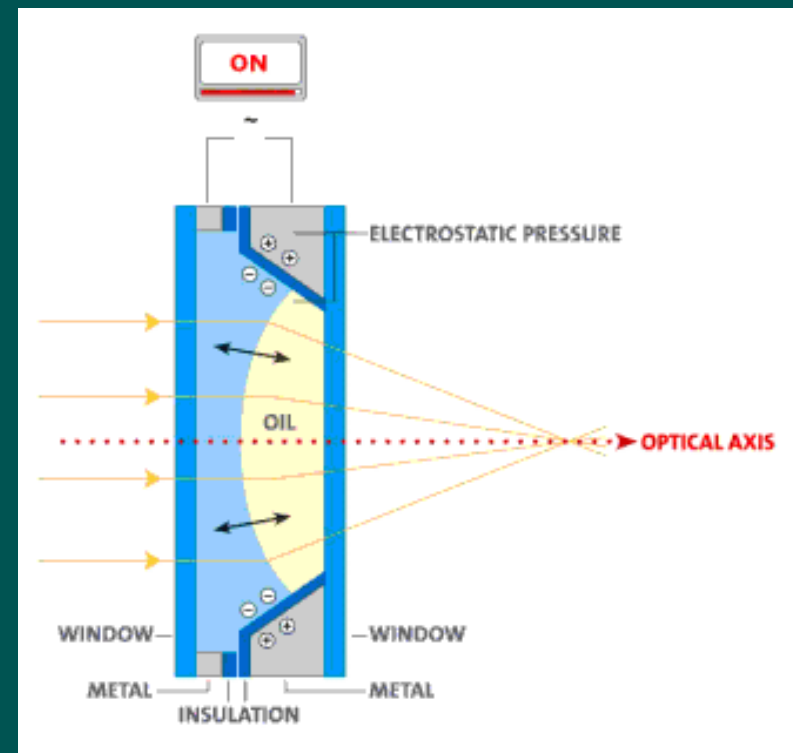
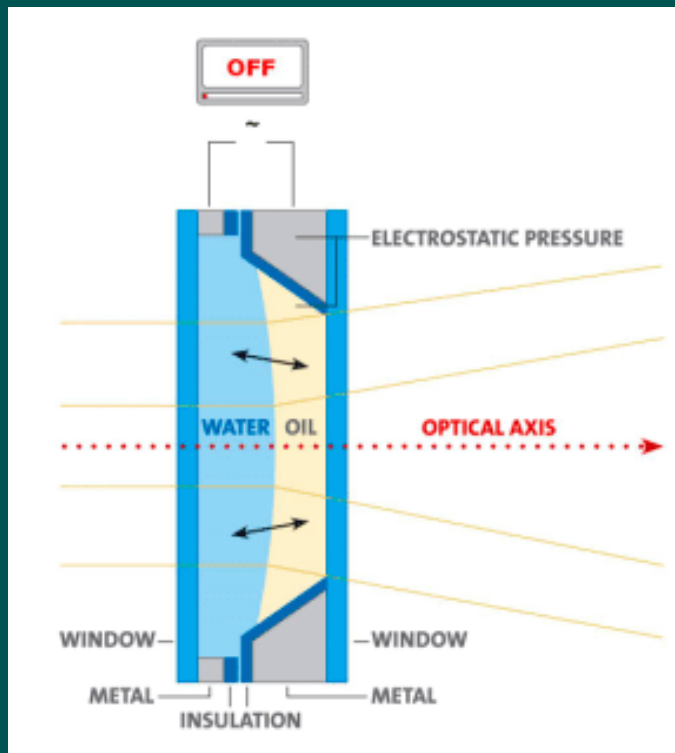
## Wavefront Coded System



# The Eye's Lens



## Varioptic Liquid Lens: Electrowetting



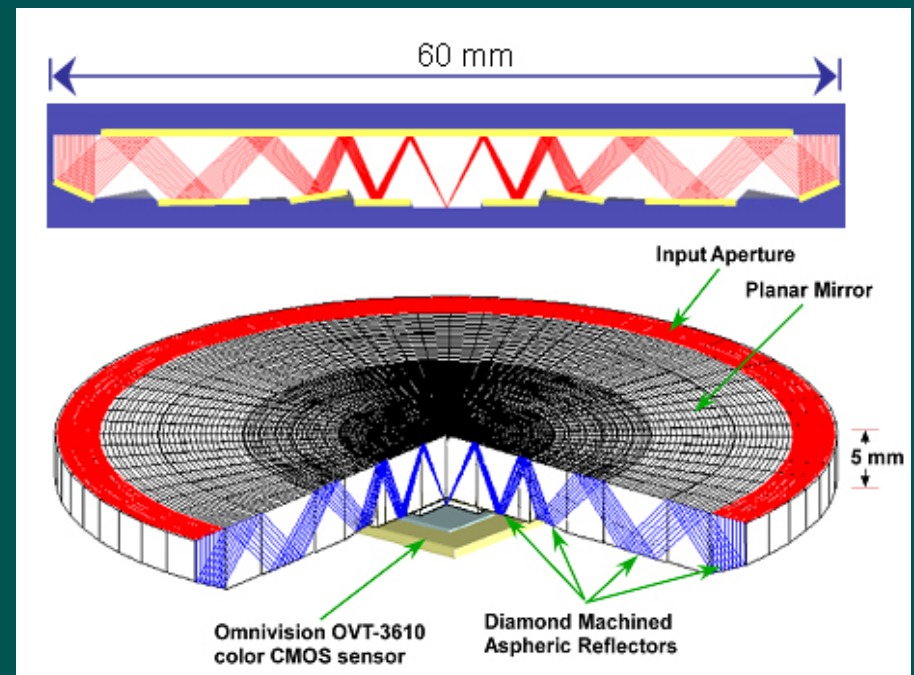
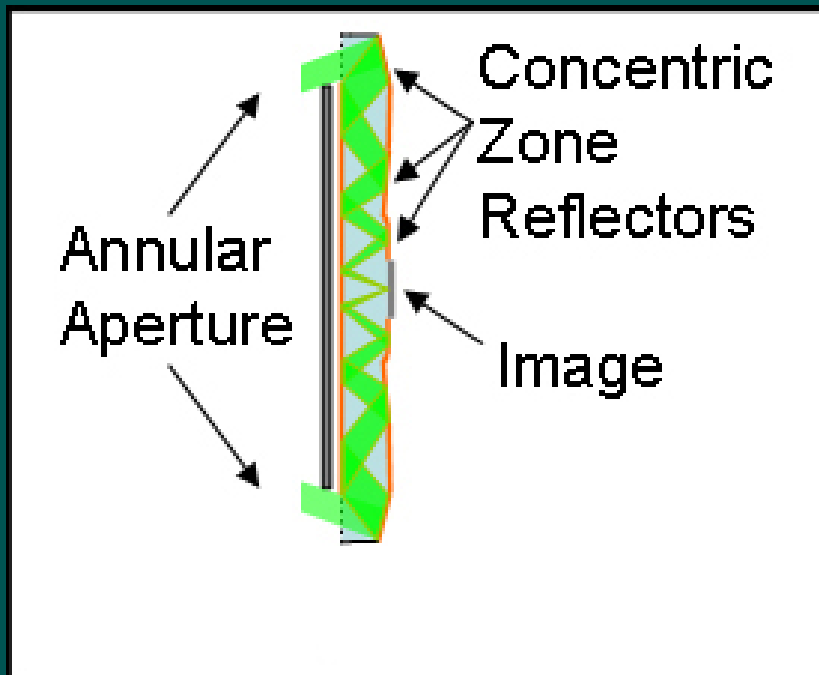
# Varioptic Liquid Lens

---



(Courtesy Varioptic Inc.)

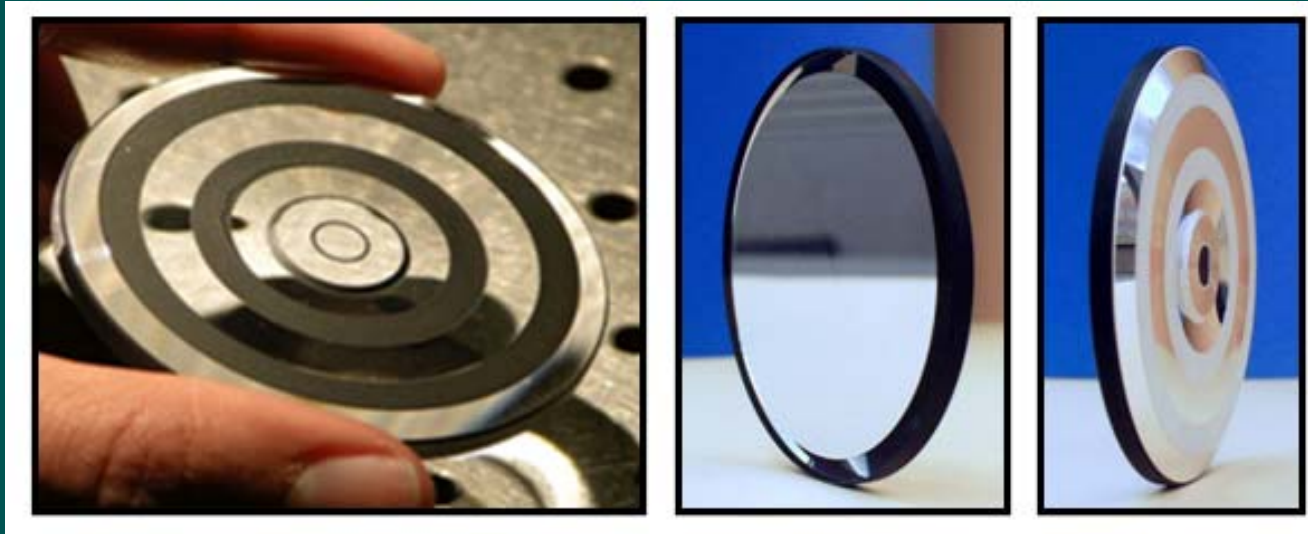
# “Origami Lens”: Thin Folded Optics (2007)



*“Ultrathin Cameras Using Annular Folded Optics,”*  
E. J. Tremblay, R. A. Stack, R. L. Morrison, J. E. Ford  
*Applied Optics*, 2007 - OSA

# Origami Lens

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Conventional  
Lens

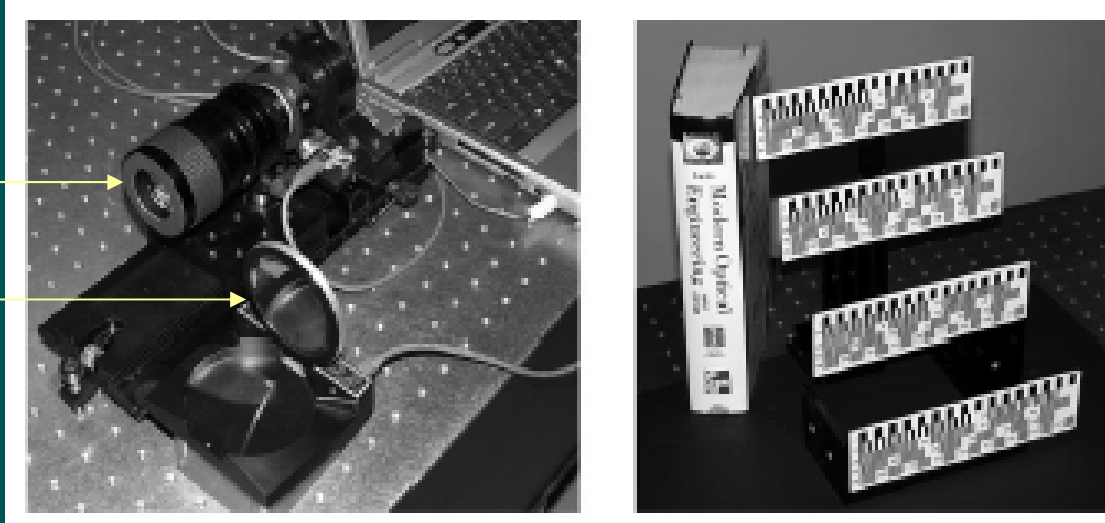


Origami  
Lens

# Optical Performance

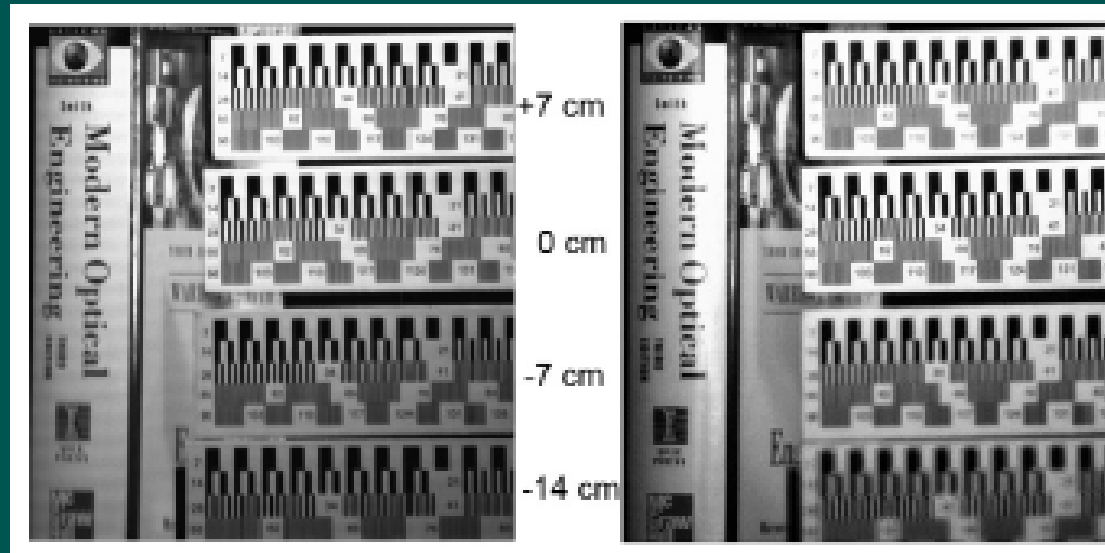
Conventional

Origami



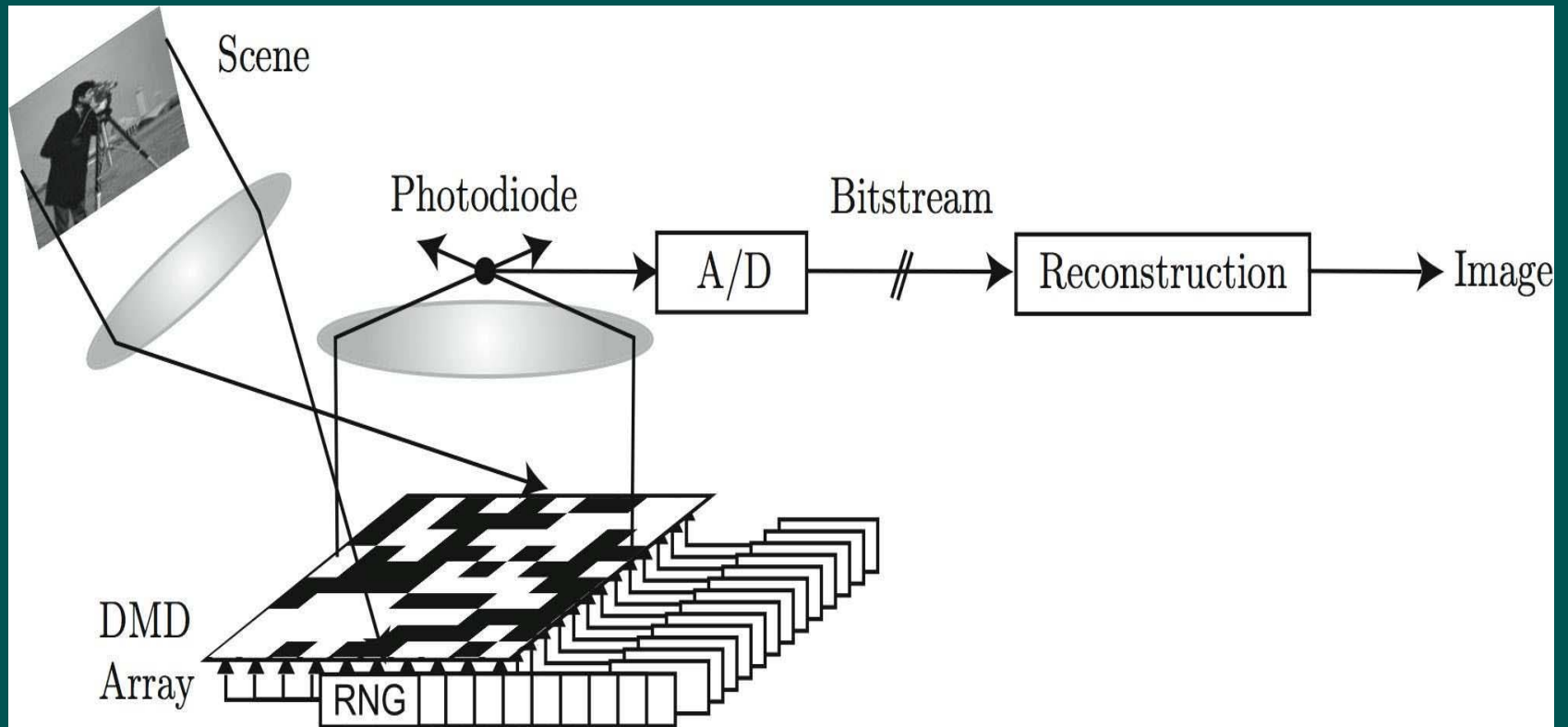
Scene

Conventional  
Lens Image

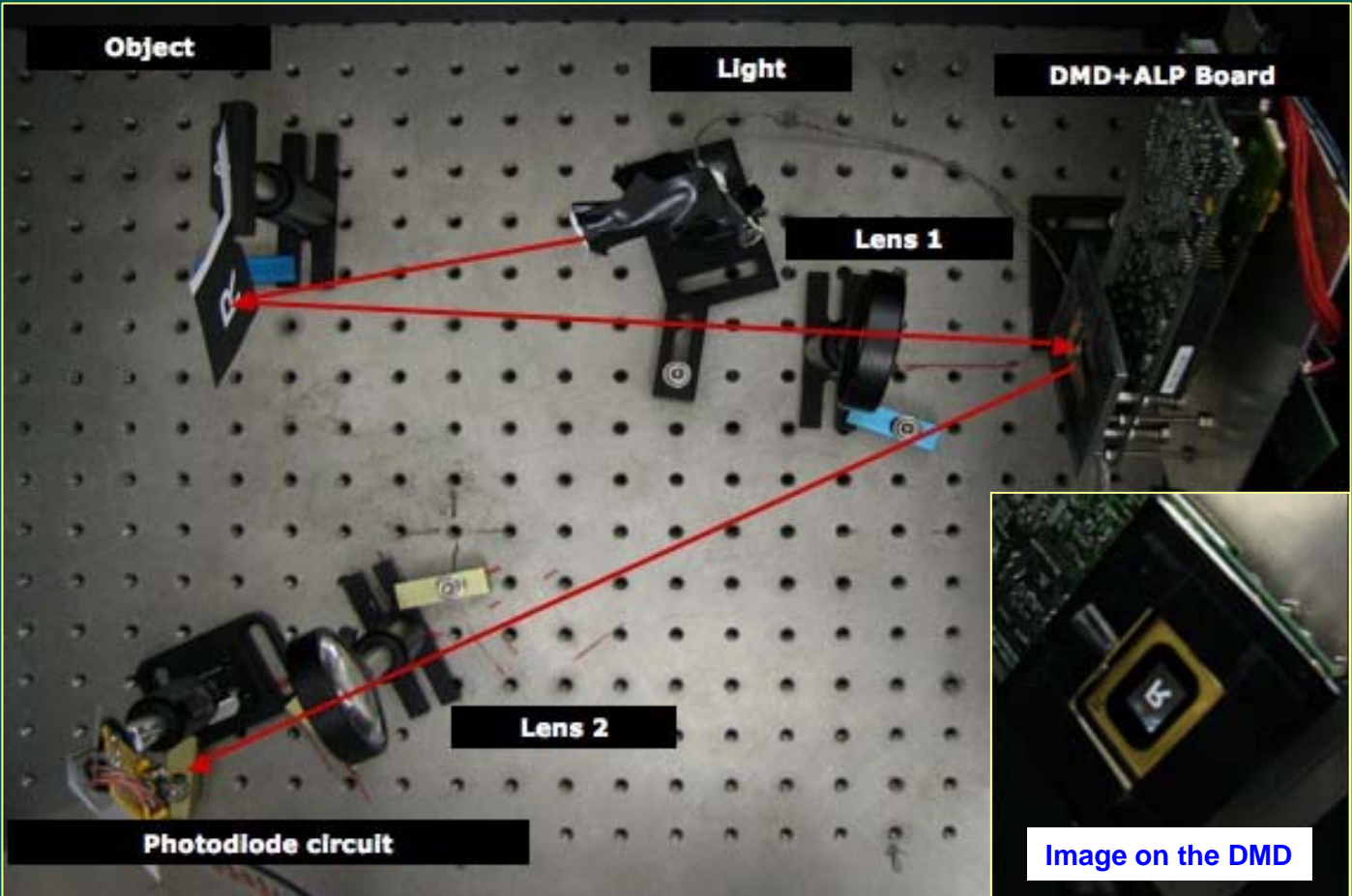


Origami  
Lens Image

# Single Pixel Camera



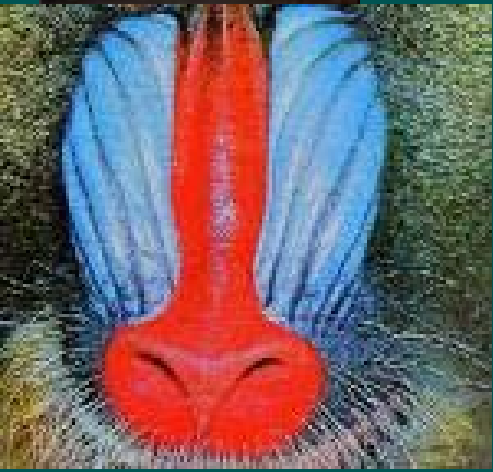
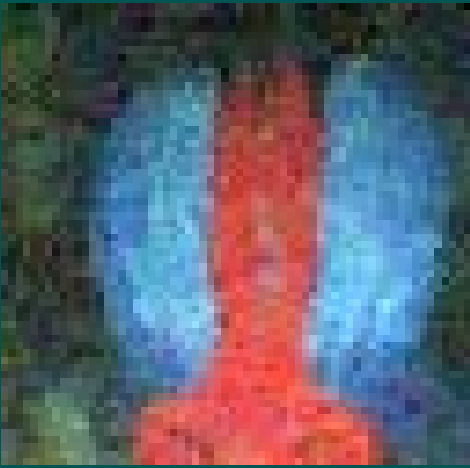

# Single Pixel Camera





# Example

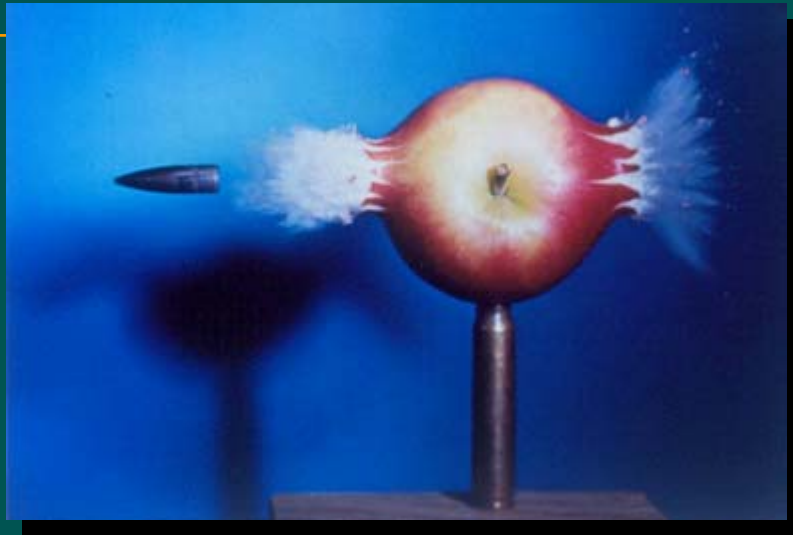
---

Original	Compressed Imaging	
		

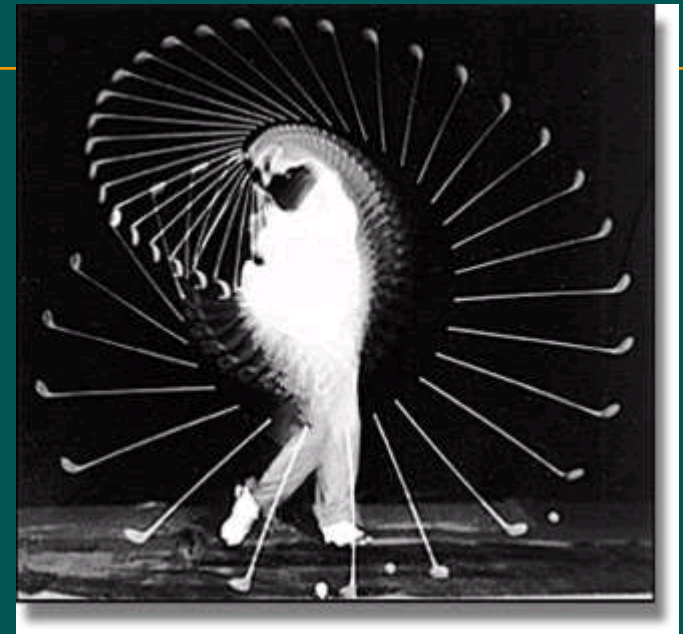
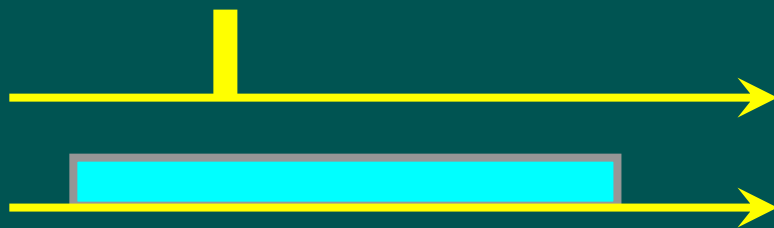
4096 Pixels  
1600 Measurements  
(40%)

65536 Pixels  
6600 Measurements  
(10%)

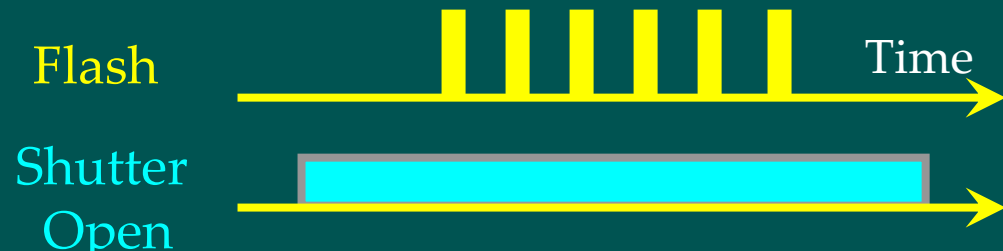
# Edgerton 1930's



Stroboscope  
(Electronic Flash)

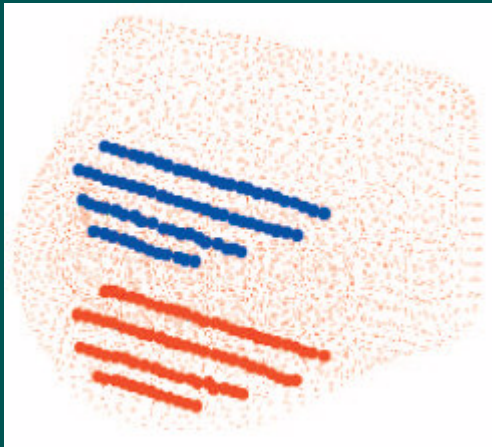


Multi-flash  
Sequential Photography

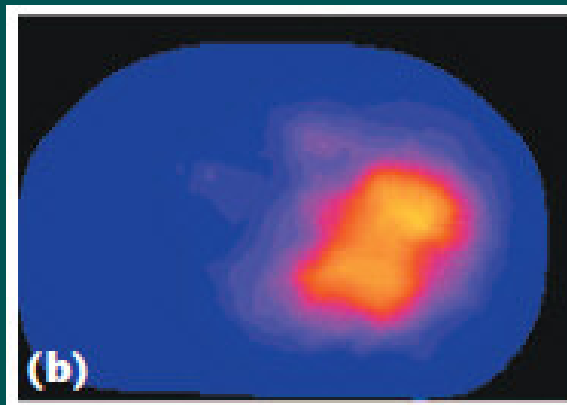


# Diffuse optical tomography

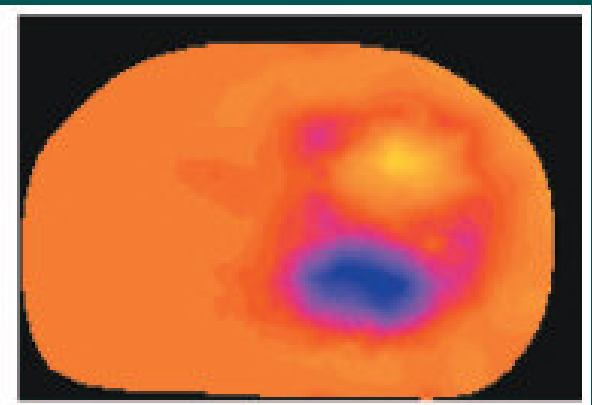
[Arridge 2003]



female breast with  
sources (red) and  
detectors (blue)



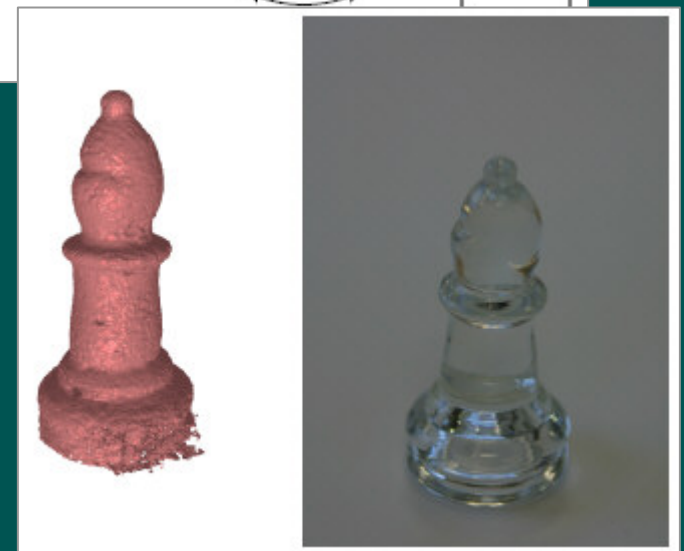
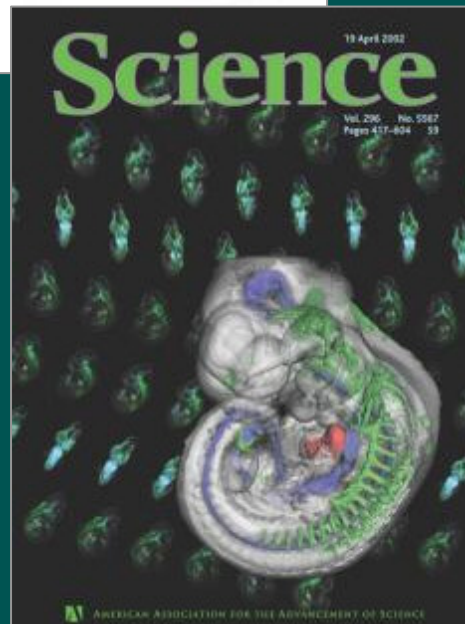
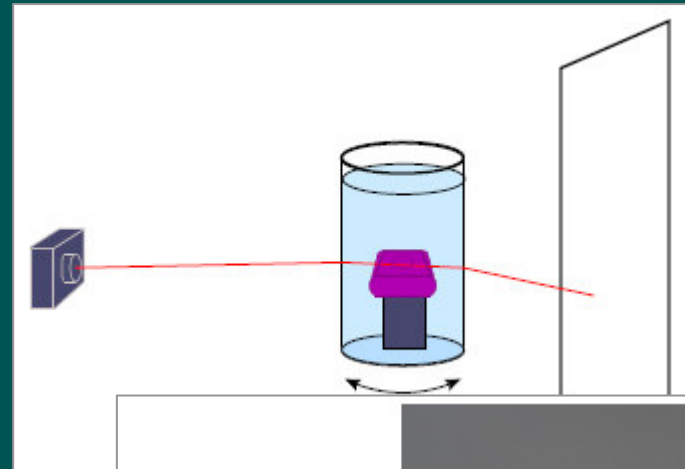
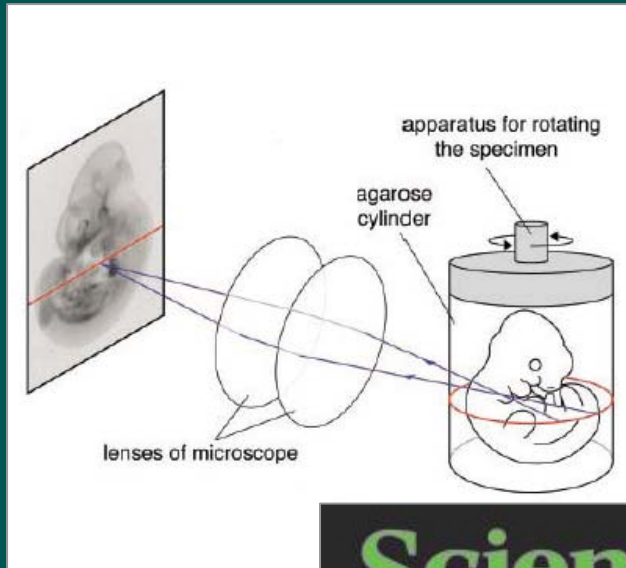
absorption  
(yellow is high)



scattering  
(yellow is high)

- assumes light propagation by multiple scattering
- model as diffusion process
- inversion is non-linear and ill-posed
- solve using optimization with regularization (smoothing)

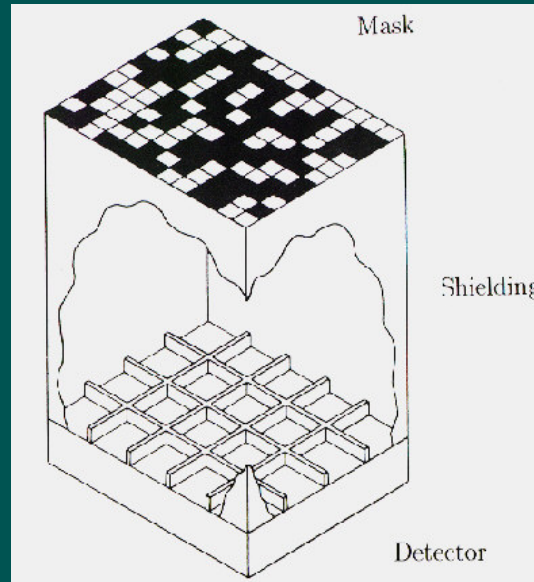
# Optical Projection Tomography (OPT)



[Sharpe 2002]

[Trifonov 2006]

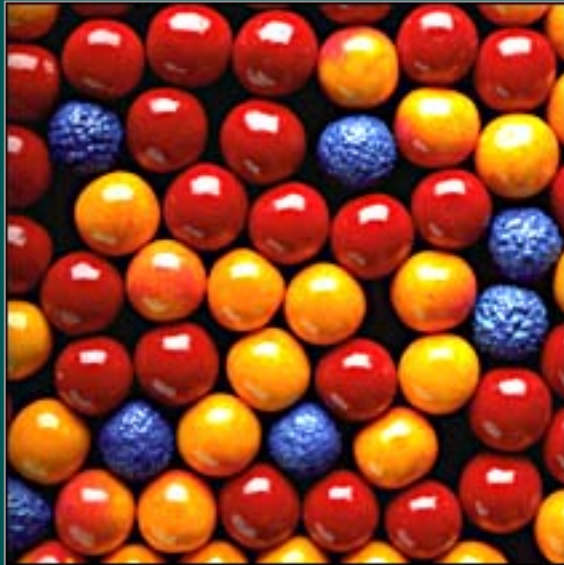
# Coded aperture imaging



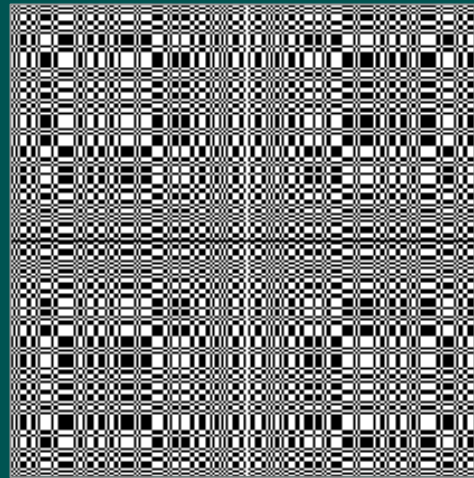
(from Zand)

- optics cannot bend X-rays, so they cannot be focused
- pinhole imaging needs no optics, but collects too little light
- use multiple pinholes and a single sensor
- produces superimposed, shifted copies of source

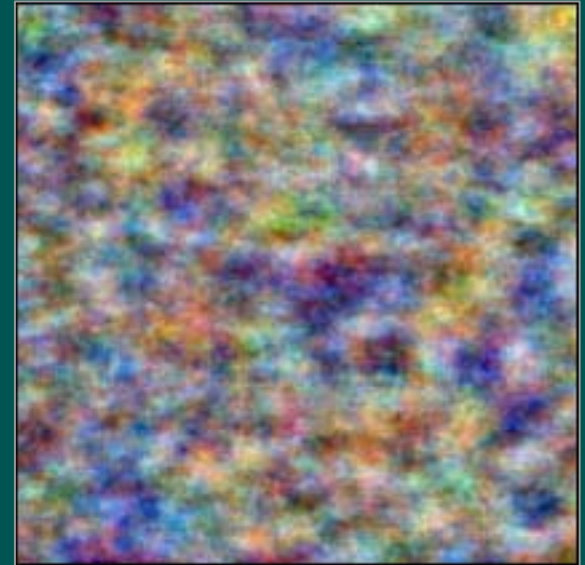
# Example using 2D images (Paul Carlisle)



\*



=





Computational  
Illumination

# 'Smarter' Lighting Equipment



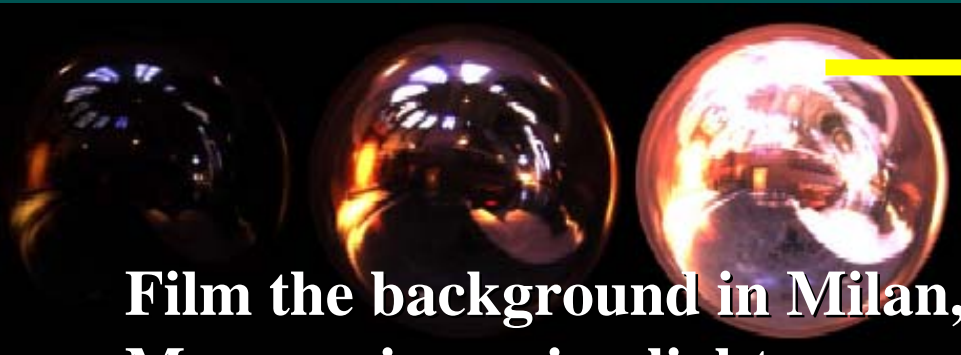
What Parameters Can We Change ?



# Image-Based Actual Re-lighting

Debevec et al., SIGG2001

Light the actress in Los Angeles



Film the background in Milan,  
Measure incoming light,

Matched LA and Milan lighting.



Matte the background



Acquired Image



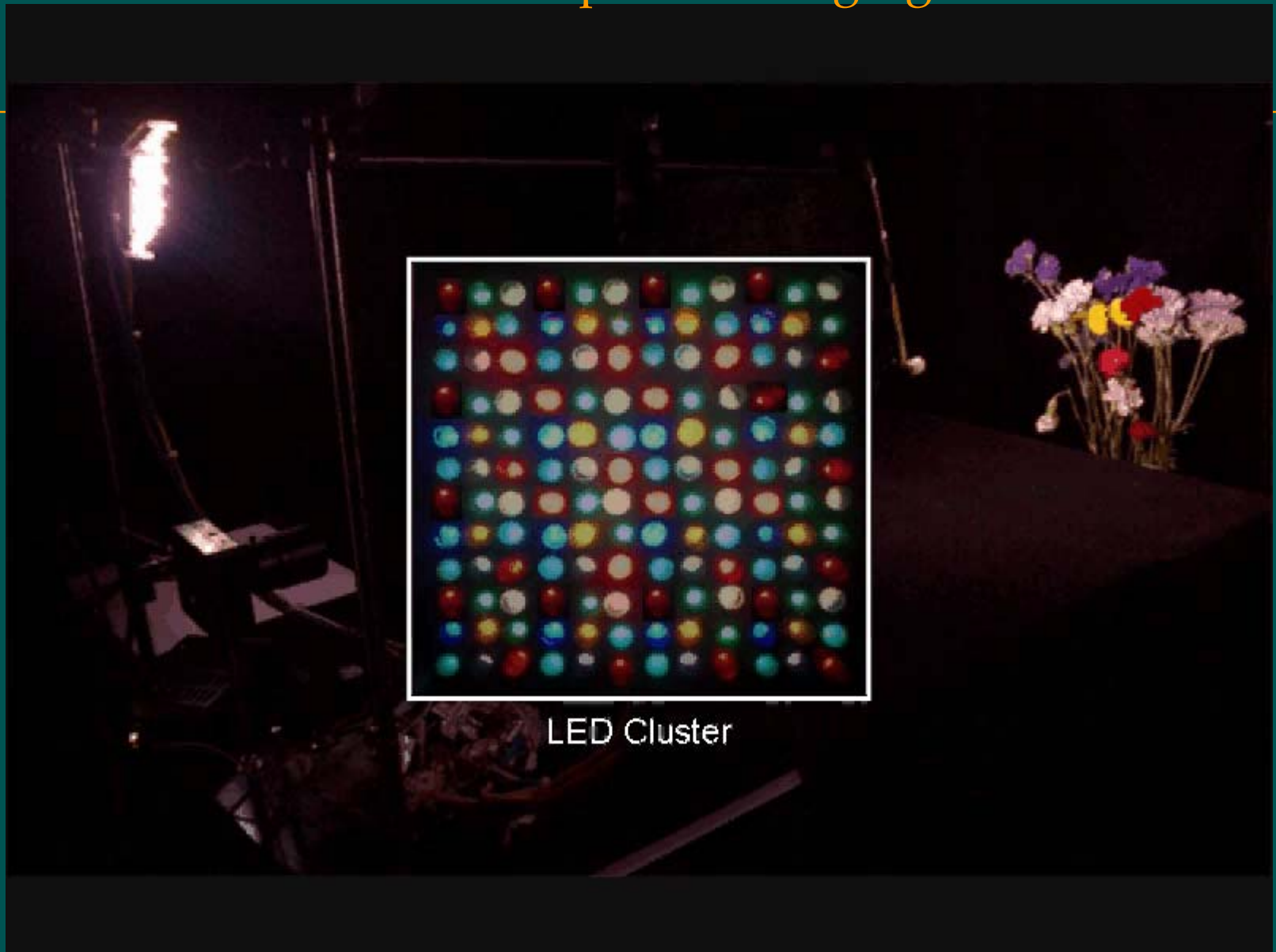
Dots  
Removed



Depth Map  
Completion

(with Francesc Moreno and Peter Belhumeur 07)

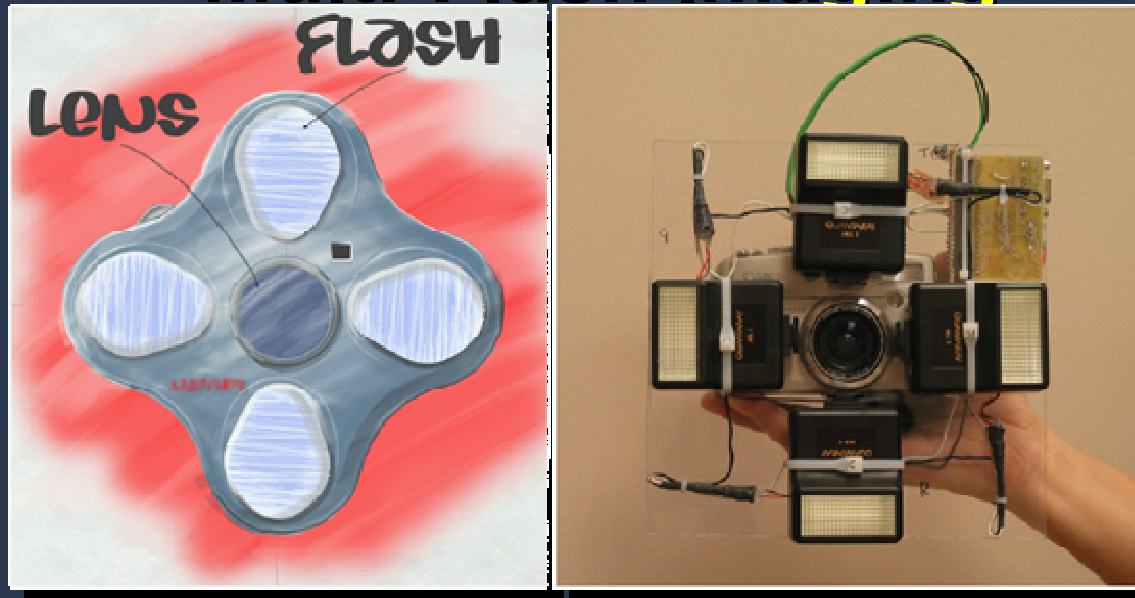
# Fast Multispectral Imaging



(with J. Park, M. Lee, M. Grossberg)

# Non-photorealistic Camera: Depth Edge Detection and Stylized Rendering

using  
**Multi-Flash Imaging**



Ramesh Raskar, Karhan Tan, Rogerio Feris,  
Jingyi Yu, Matthew Turk

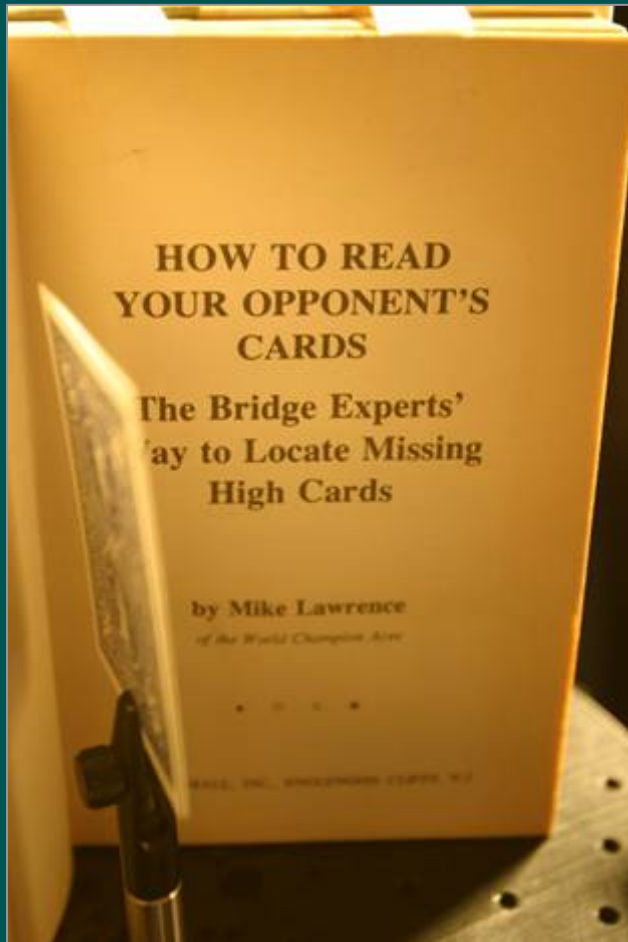
Mitsubishi Electric Research Labs (MERL), Cambridge, MA

U of California at Santa Barbara

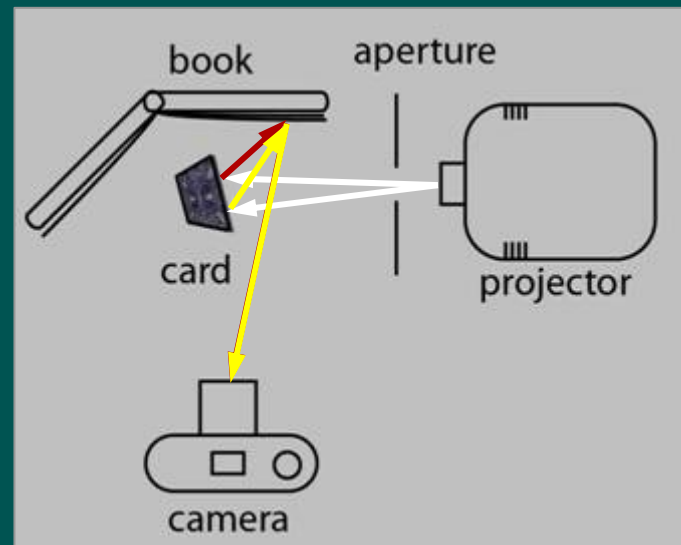
U of North Carolina at Chapel Hill



# Dual photography from diffuse reflections



the camera's view



# 'Smarter' Lighting Equipment



Programmable Parameters

# Siggraph 2006

## 16 Computational Photography Papers

### Hybrid Images

- Oliva et al (MIT)

### Drag-and-Drop Pasting

- Jia et al (MSRA)

### Two-scale Tone Management for Photographic Look

- Bae et al (MIT)

### Interactive Local Adjustment of Tonal Values

- Lischinski et al (Tel Aviv)

### Image-Based Material Editing

- Khan et al (Florida)

### Flash Matting

- Sun et al (Microsoft Research Asia)

### Natural Video Matting using Camera Arrays

- Joshi et al (UCSD / MERL)

### Removing Camera Shake From a Single Photograph

- Fergus (MIT)

### Coded Exposure Photography: Motion Deblurring

- Raskar et al (MERL)

### Photo Tourism: Exploring Photo Collections in 3D

- Snavely et al (Washington)

### AutoCollage

- Rother et al (Microsoft Research Cambridge)

### Photographing Long Scenes With Multi-Viewpoint Panoramas

- Agarwala et al (University of Washington)

### Projection Defocus Analysis for Scene Capture and Image Display

- Zhang et al (Columbia University)

### Multiview Radial Catadioptric Imaging for Scene Capture

- Kuthirummal et al (Columbia University)

### Light Field Microscopy (Project)

- Levoy et al (Stanford University)

### Fast Separation of Direct and Global Components of a Scene Using High Frequency Illumination

- Nayar et al (Columbia University)

# Siggraph 2007

## 19 Computational Photography Papers

- Image Analysis & Enhancement

- Image Deblurring with Blurred/Noisy Image Pairs
- Photo Clip Art
- Scene Completion Using Millions of Photographs

- Image Slicing & Stretching

- Soft Scissors: An Interactive Tool for Realtime High Quality Matting
- Seam Carving for Content-Aware Image Resizing
- Image Vectorization Using Optimized Gradient Meshes
- Detail-Preserving Shape Deformation in Image Editing

- Light Field & High-Dynamic-Range Imaging

- Veiling Glare in High-Dynamic-Range Imaging
- Ldr2Hdr: On-the-Fly Reverse Tone Mapping of Legacy Video and Photographs

- Appearance Capture & Editing

- Multiscale Shape and Detail Enhancement from Multi-light Image Collections

- Computational Cameras

- Active Refocusing of Images and Videos
- Multi-Aperture Photography
- Dappled Photography: Mask-Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing
- Image and Depth from a Conventional Camera with a Coded Aperture

- Big Images

- Capturing and Viewing Gigapixel Images
- Efficient Gradient-Domain Compositing Using Quadrees

- Video Processing

- Factored Time-Lapse Video
- Computational Time-Lapse Video (project page)
- Real-Time Edge-Aware Image Processing With the Bilateral Grid



# More ..

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- IEEE Computer,
  - August 2006 Special Issue
  - Bimber, Nayar, Levoy, Debevec, Cohen/Szeliski
- IEEE CG&A,
  - March 2007 Special issue
  - Durand and Szeliski
- Science News cover story
  - April 2007
  - Featuring 3 course speakers: Levoy, Nayar, Georgiev
- Siggraph 2007
  - 19 papers
  - Bilateral Filter course, 8:30am, Room 4
- (Expected Symposium on Comp Photo, Summer 2008)