MAS 131/ 531 Computational Camera & Photography:

Ramesh Raskar
MIT Media Lab
http://cameraculture.media.mit.edu/

Image removed due to copyright restrictions.
Photo of airplane propeller, taken with iPhone and showing aliasing effect:
http://scalarmotion.wordpress.com/2009/03/15/propeller-image-aliasing/

Shower Curtain: Diffuser

Courtesy of Shree Nayar. Used with permission.
Source: http://www1.cs.columbia.edu/CAVE/projects/separation/occluders_gallery.php

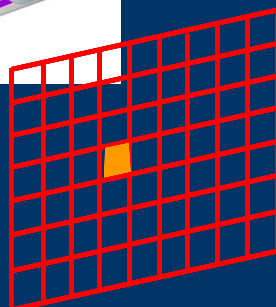
Direct

Global

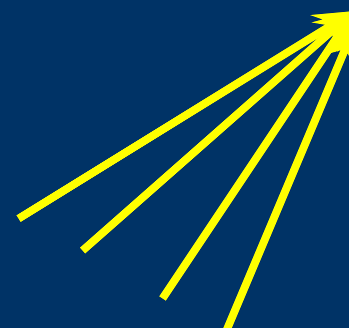
A Teaser: Dual Photography

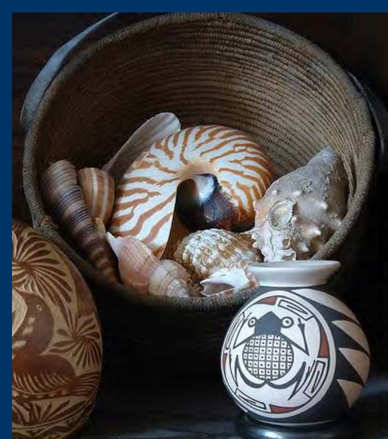
Projector

Figure by MIT OpenCourseWare.



Photocell





Scene

Images: Projector by MIT OpenCourseWare.
Photocell courtesy of afternoon_sunlight on Flickr.
Scene courtesy of sbpoet on Flickr.

A Teaser: Dual Photography

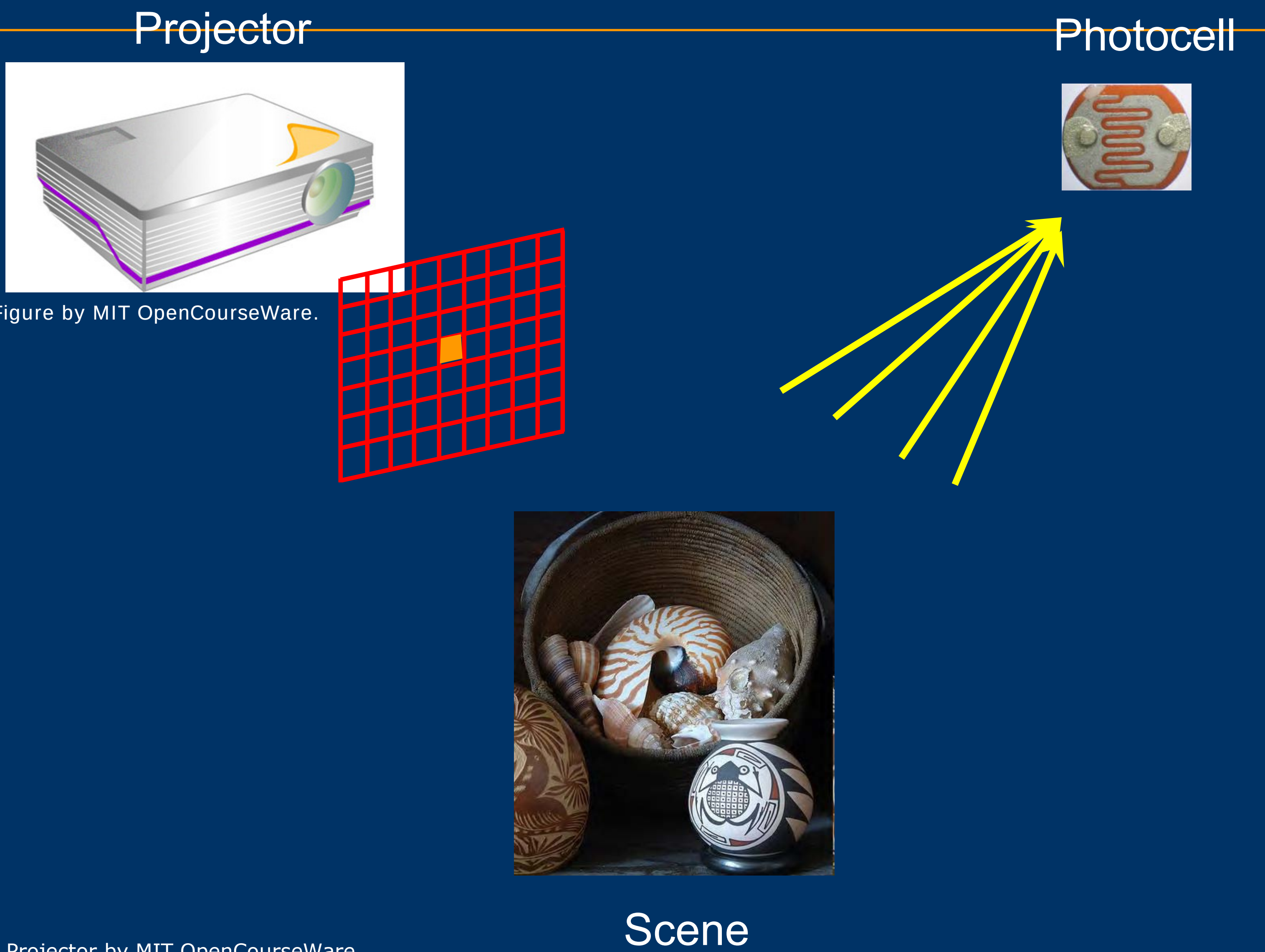
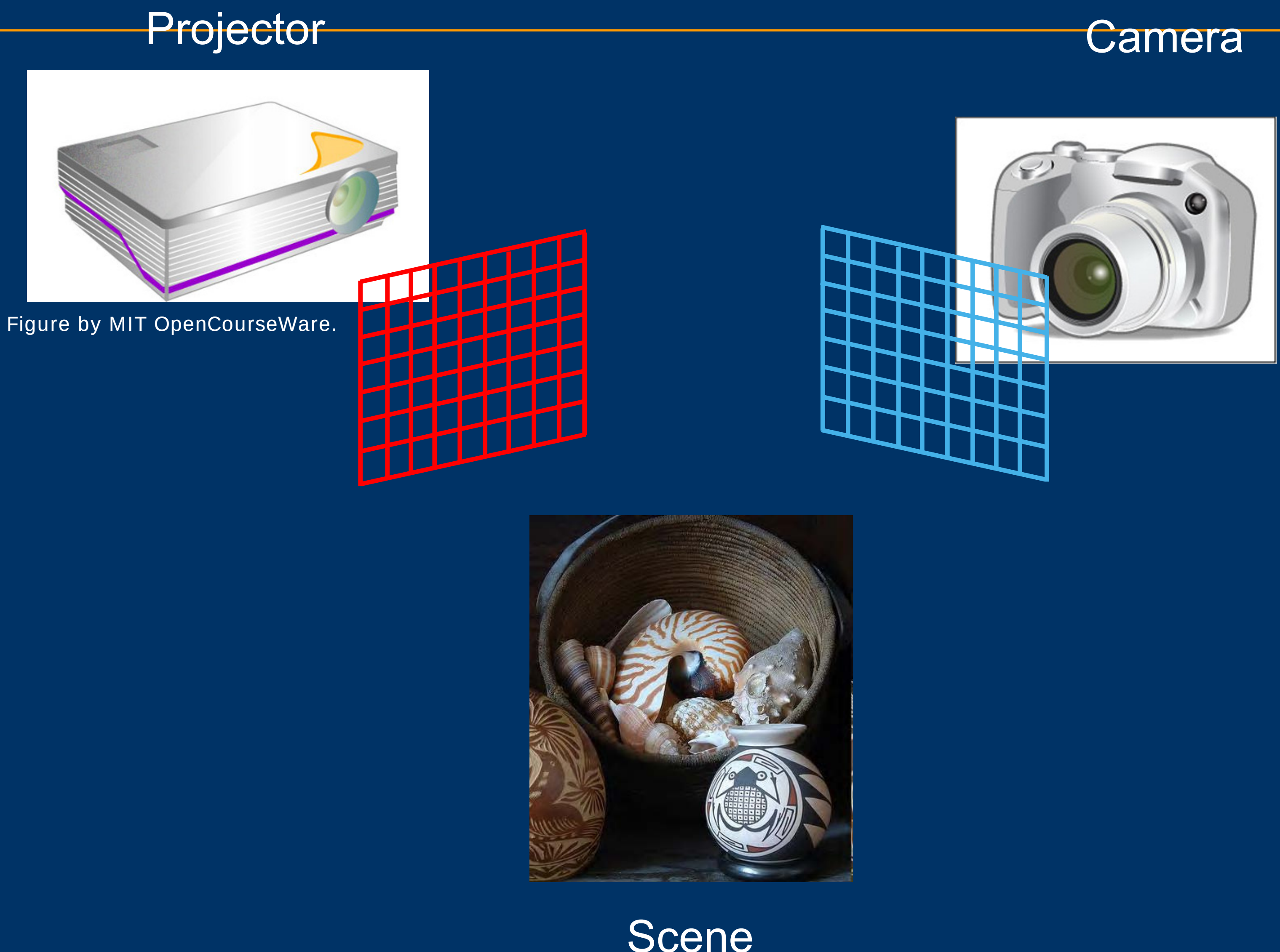


Figure by MIT OpenCourseWare.

A Teaser: Dual Photography



Images: Projector and camera by MIT OpenCourseWare.
Scene courtesy of sbpoet on Flickr.

The 4D transport matrix:

Contribution of each projector pixel to each camera pixel

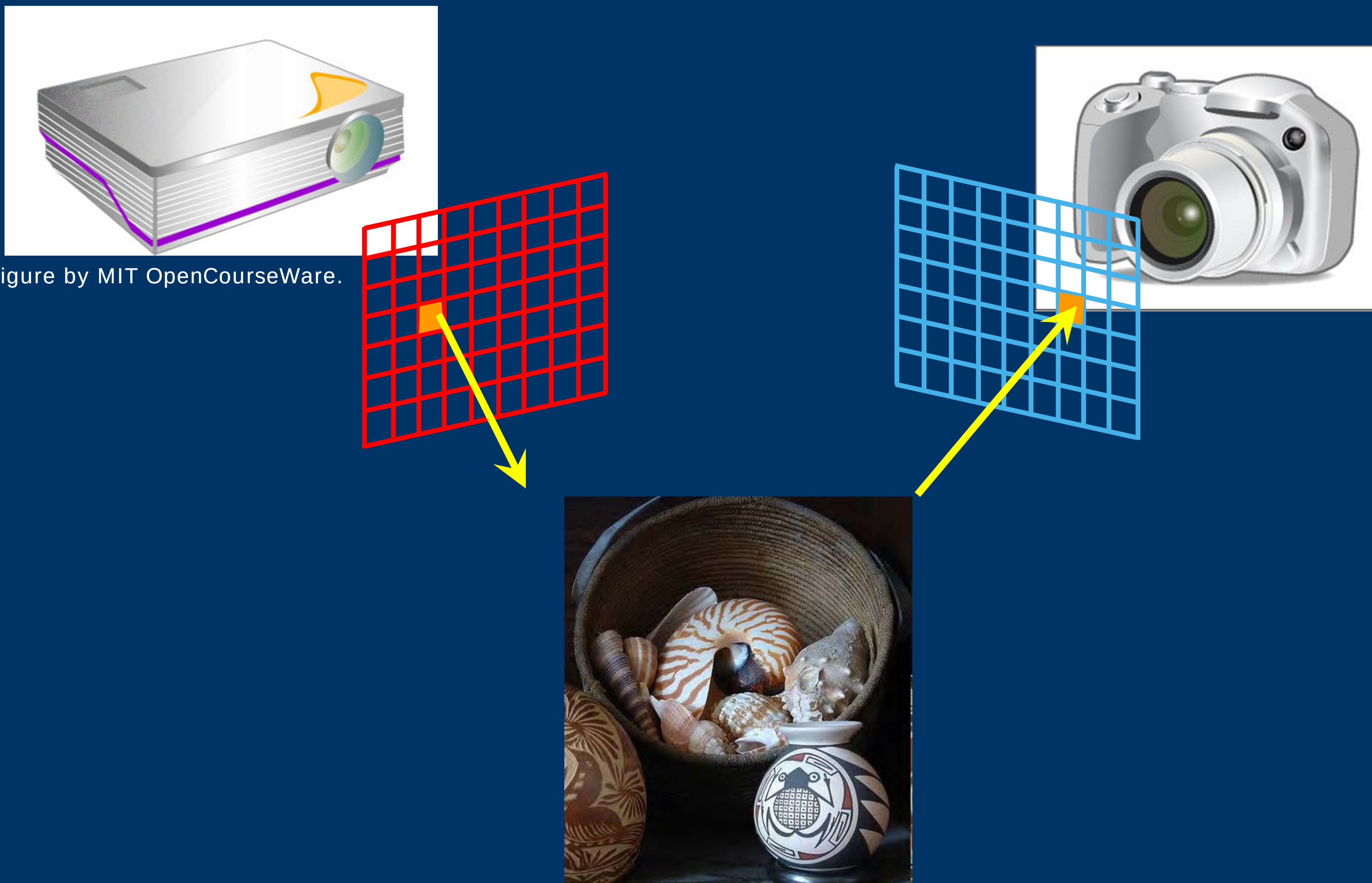


Figure by MIT OpenCourseWare.

Photo courtesy of sbpoet on Flickr.

The 4D transport matrix:

Contribution of each projector pixel to each camera pixel

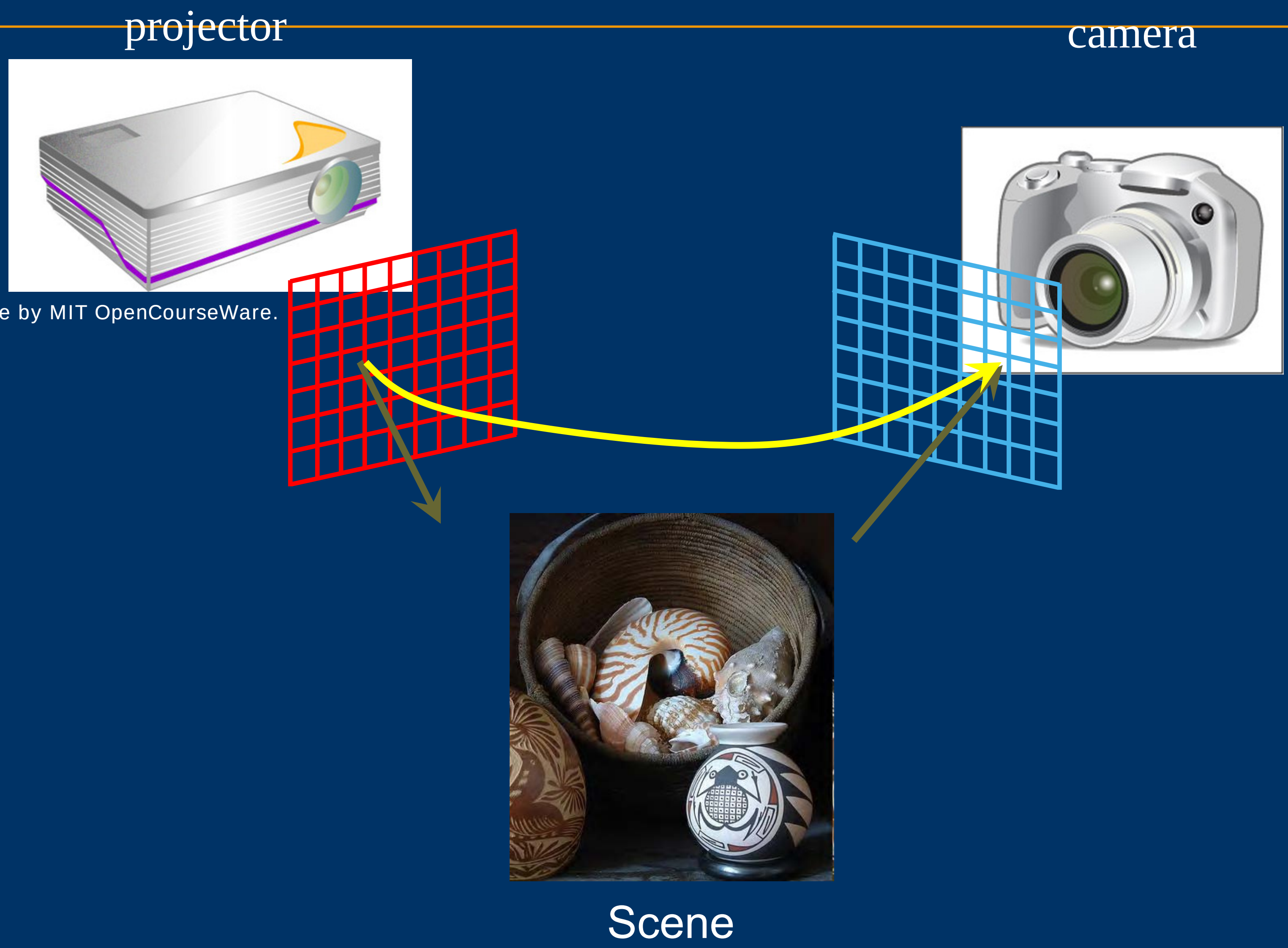


Figure by MIT OpenCourseWare.

Sen et al, Siggraph 2005

Images: Projector and camera by MIT OpenCourseWare.
Scene courtesy of sbpoet on Flickr.

The 4D transport matrix:
Which projector pixel contributes to each camera pixel

projector

camera

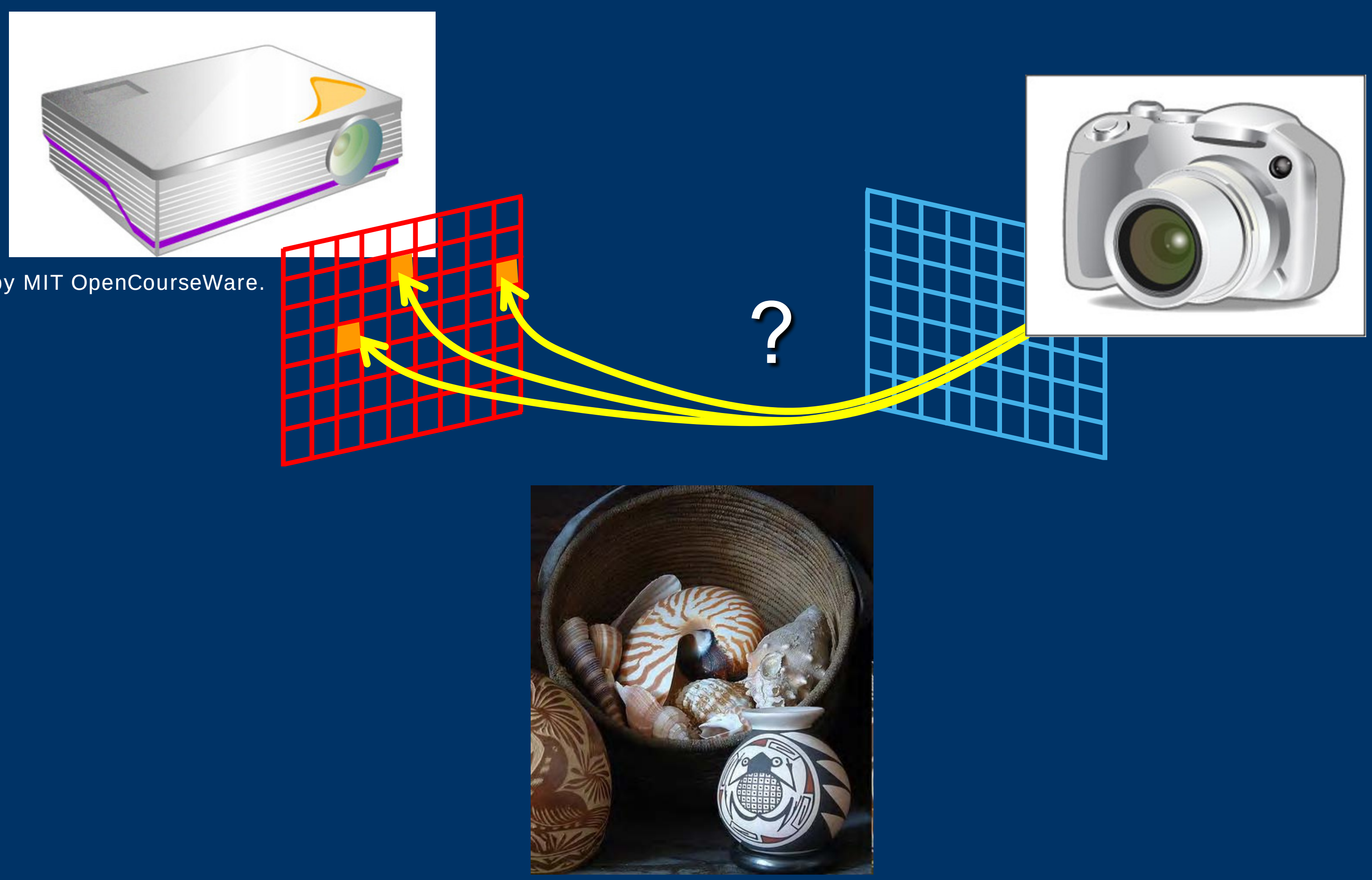


Figure by MIT OpenCourseWare.

Scene

Sen et al, Siggraph 2005

Dual photography from diffuse reflections: Homework Assignment 2

Images removed due to copyright restrictions.
See Sen et al, "Dual Photography," SIGGRAPH 2005;
specifically Figure 16 in the paper.

the camera's view

Sen et al, Siggraph 2005

Digital cameras are boring: Film-like Photography

- Roughly the same features and controls as film cameras
  - zoom and focus
  - aperture and exposure
  - shutter release and advance
  - one shutter press = one snapshot

Figure by MIT OpenCourseWare.

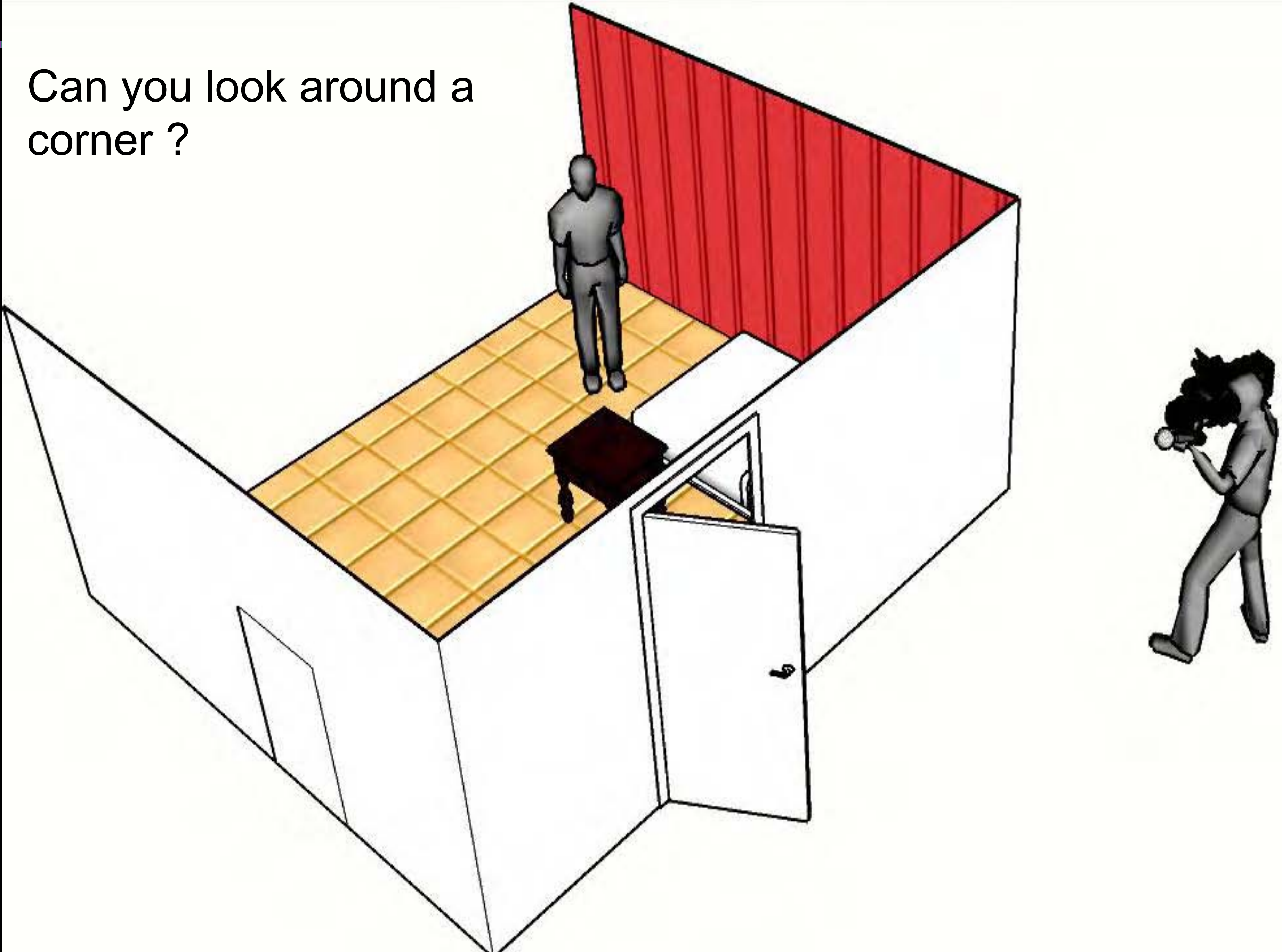
Improving FILM-LIKE Camera Performance

What would make it 'perfect' ?

- Dynamic Range
- Vary Focus Point-by-Point
- Field of view vs. Resolution
- Exposure time and Frame rate

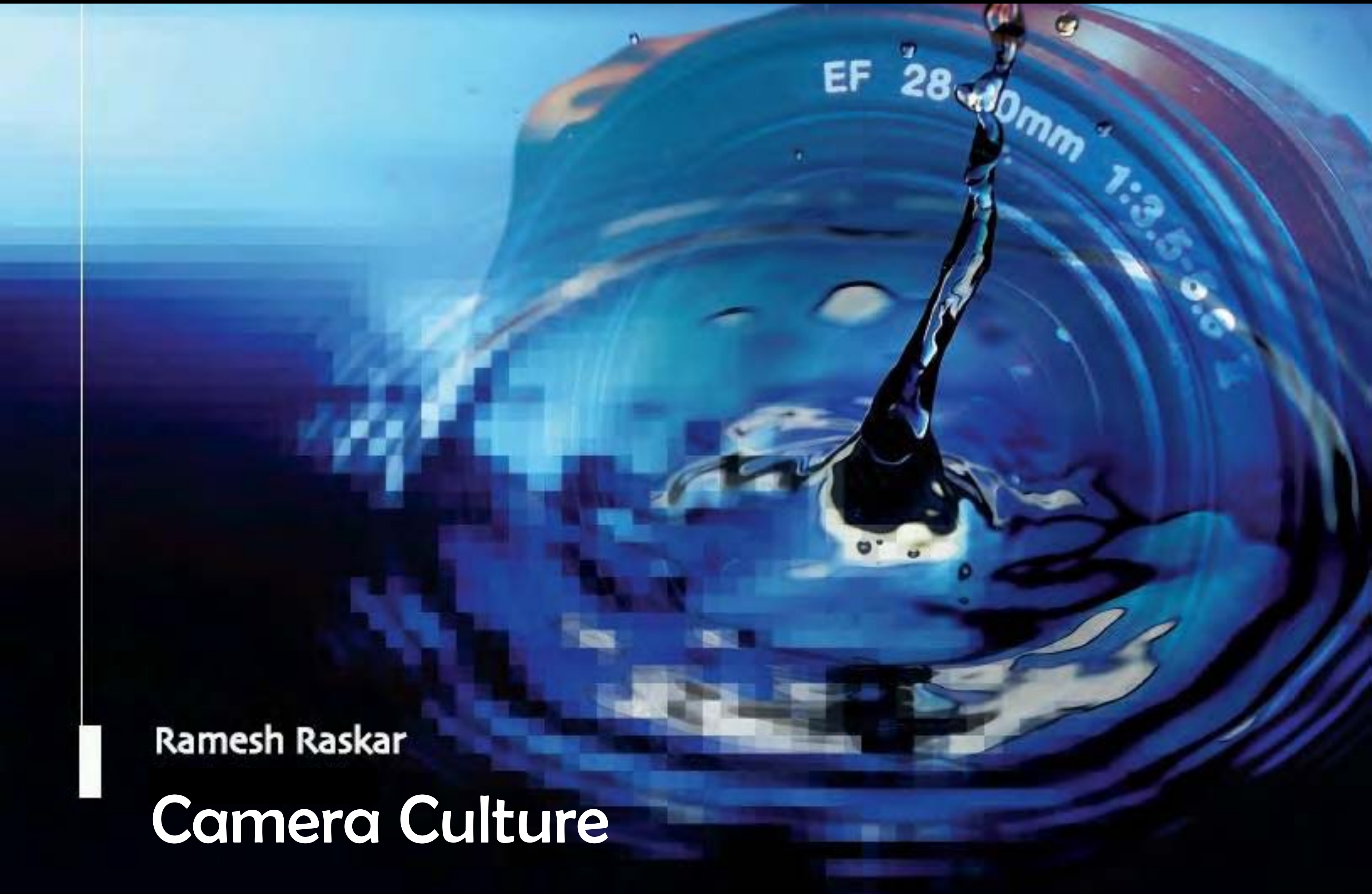
- What type of ‘Cameras’ will we study?
- Not just film-mimicking 2D sensors
  - 0D sensors
    - Motion detector
    - Bar code scanner
    - Time-of-flight range detector
  - 1D sensors
    - Line scan camera (photofinish)
    - Flatbed scanner
    - Fax machine
  - 2D sensors
  - 2-1/2D sensors
  - ‘3D’ sensors
  - 4D and 6D tomography machines and displays

Can you look around a corner ?



Convert LCD into a big flat camera? Beyond Multi-touch

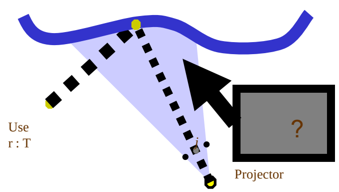
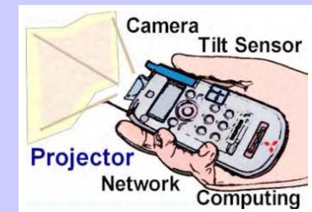
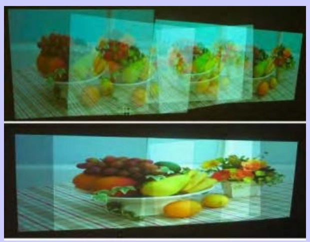
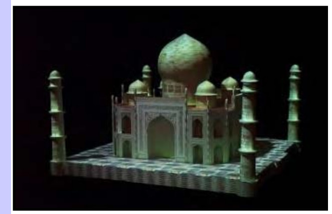
Images removed due to copyright restrictions.



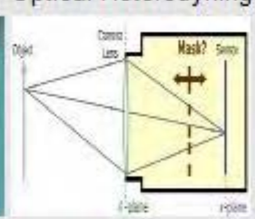
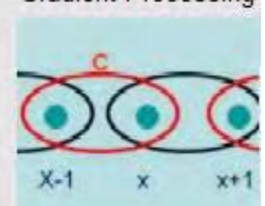
Ramesh Raskar

Camera Culture

Computational Illumination

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

Computational Photography

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

Questions

- What will a camera look like in 10,20 years?
- How will the next billion cameras change the social culture?
- How can we augment the camera to support best ‘image search’?
- What are the opportunities in pervasive recording?
  - e.g. GoogleEarth Live
- How will ultra-high-speed/resolution imaging change us?
- How should we change cameras for movie-making, news reporting?

Approach

- Not just USE but CHANGE camera
  - Optics, illumination, sensor, movement
  - Exploit wavelength, speed, depth, polarization etc
  - Probes, actuators, Network
- We have exhausted bits in pixels
  - Scene understanding is challenging
  - Build feature-revealing cameras
  - Process photons

Plan

- What is Computational Camera?
- Introductions
- Class format
- Fast Forward Preview
  - Sample topics
- First warmup assignment

Tools

for

Visual

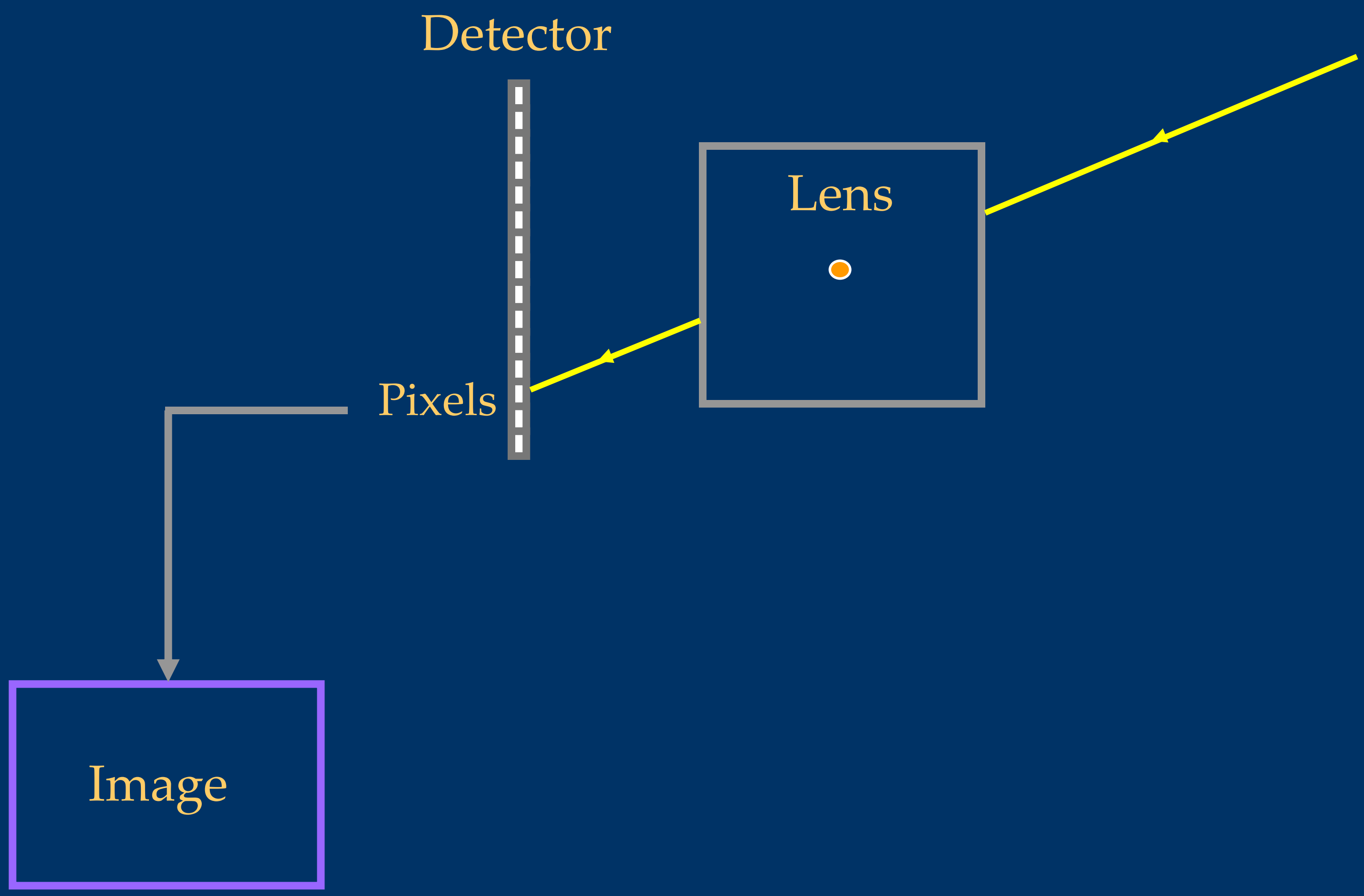
Computing

Shadow	Refractive	Reflective

Image removed due to copyright restrictions.
See Fig. 1, "Eight major types of optics in animal eyes."
In Fernald, R. D. "Casting a Genetic Light on the Evolution of Eyes."
Science 313, no. 5795 (29 September 2006): 1914-1918.
http://dx.doi.org/10.1126/science.1127889

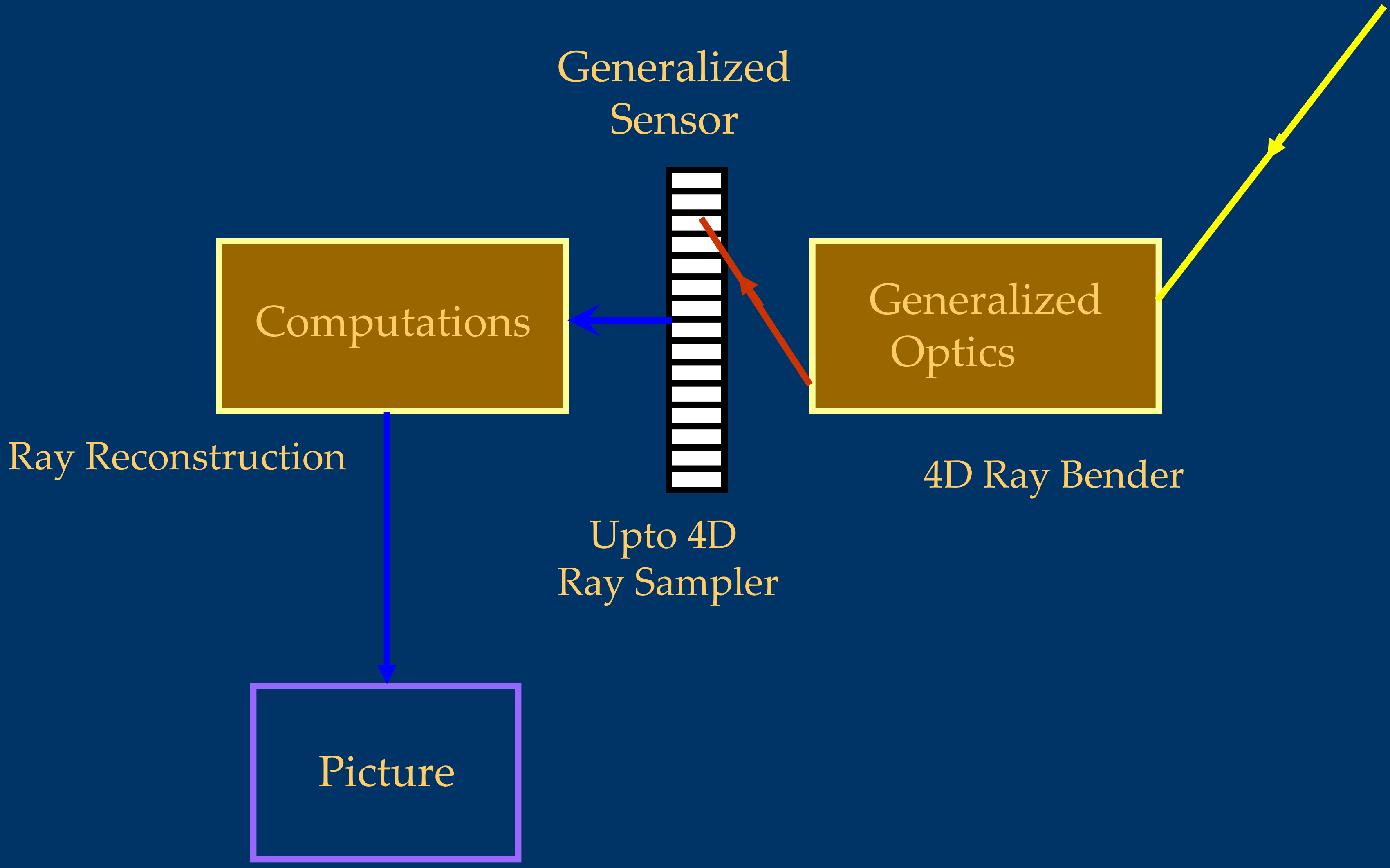
Fernald, Science [Sept 2006]

Traditional 'film-like' Photography



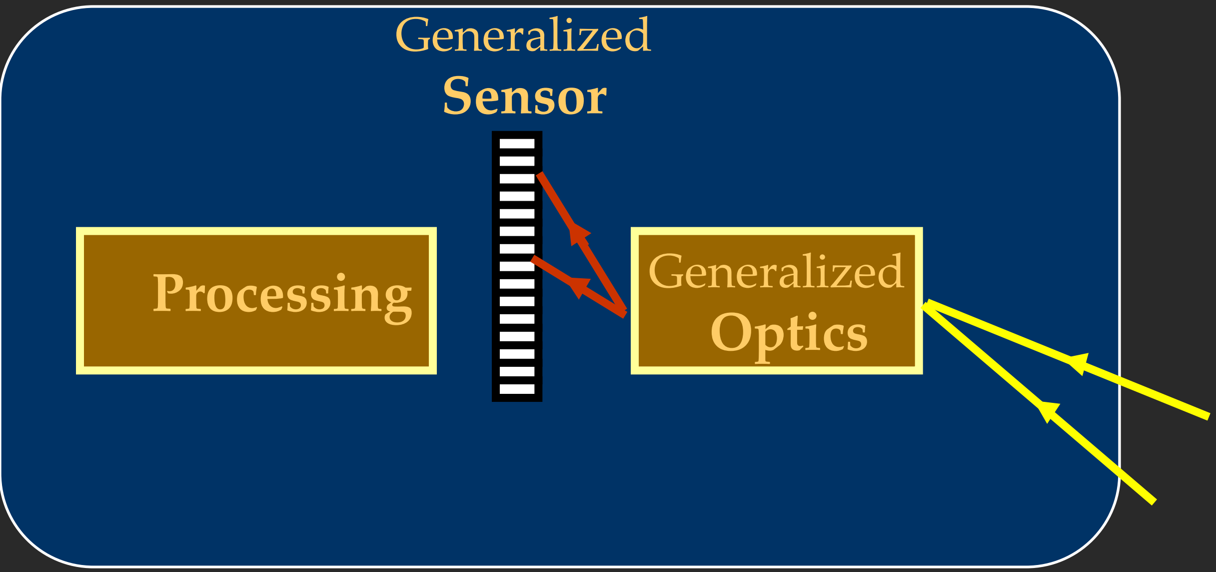
Slide by Shree Nayar

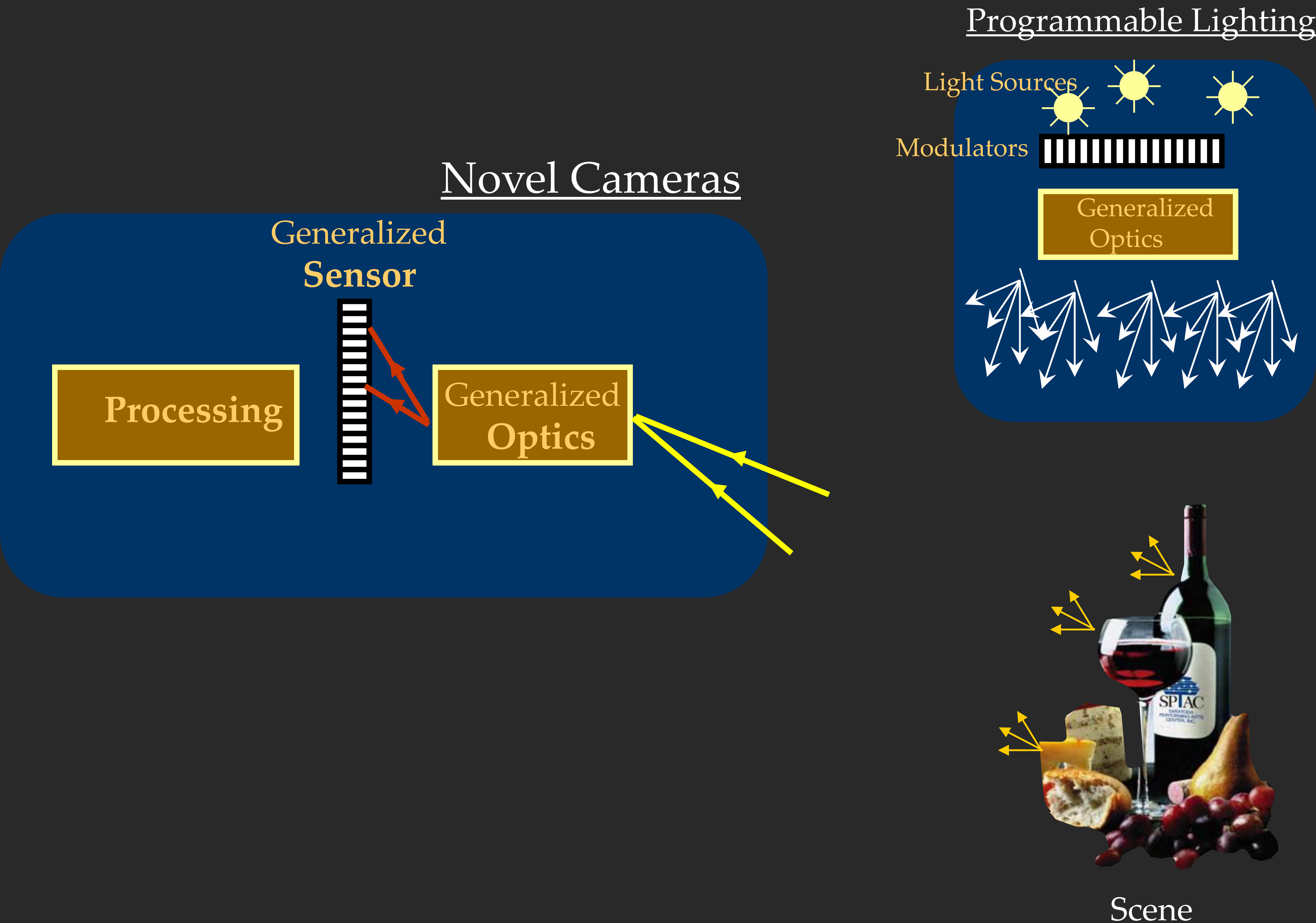
Computational Camera:
Optics, Sensors and Computations



Raskar and Tumblin

Novel Cameras




Programmable Lighting
Light Sources
Modulators
Generalized
Optics
Novel Cameras
Generalized
Sensor
Processing
Generalized
Optics
Scene

Cameras Everywhere

Image removed due to copyright restrictions.
Tessera: Growth of the mobile phone and camera phone markets

Where are the ‘cameras’?

Graph removed due to copyright restrictions.
Tessera: Growth of image sensor markets 2006-2011.
Market segments = optical mouse, mobile phone, digital camera, PC camera, camcorder, scanner, toys, security, industrial, other;
Mobile phone dominates the market, optical mouse is #2…

Simply getting depth is challenging !

Images removed due to copyright restrictions.

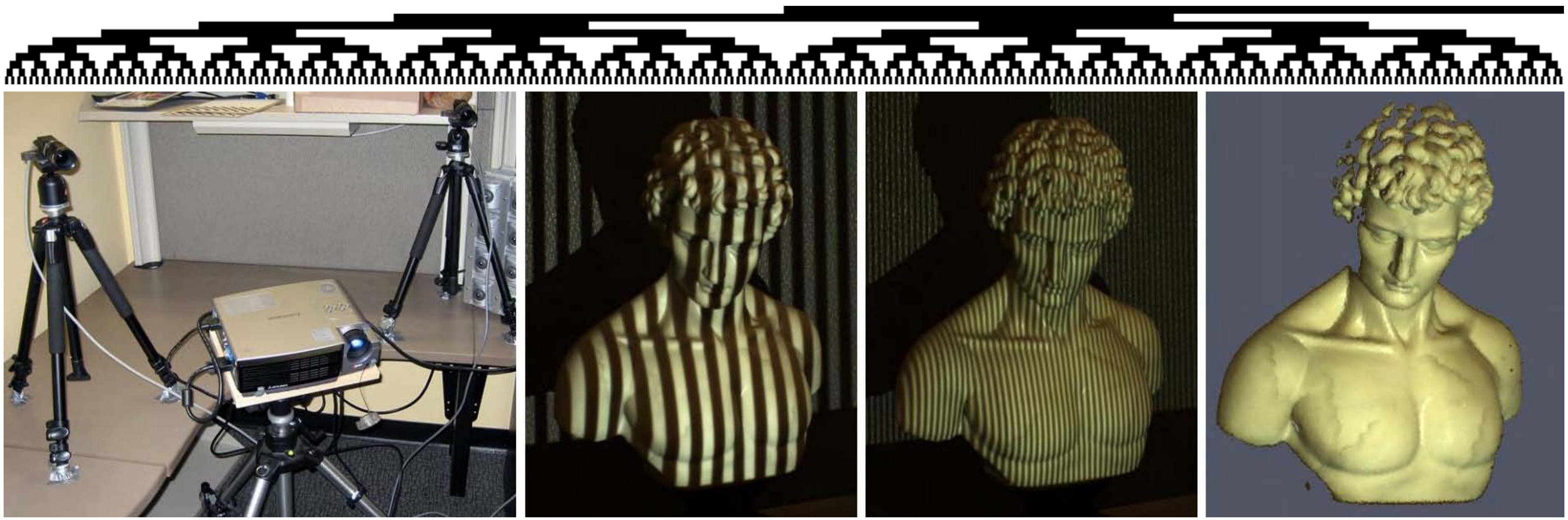
- Must be simultaneously *illuminated* and *imaged* (occlusion problems)
- Non-Lambertian BRDFs (transparency, reflections, subsurface scattering)
- Acquisition time (dynamic scenes), large (or small) features, etc.

M. Levoy. Why is 3D scanning hard? 3DPVT, 2002

Godin et al. An Assessment of Laser Range Measurement on Marble Surfaces. Intl. Conf. Optical 3D Measurement Techniques, 2001

Lanman and Taubin'09

Taxonomy of 3D Scanning:



- **Contact** — Direct Measurements
  (rulers, calipers, pantographs, coordinate measuring machines (CMM), AFM)
- **Non-Contact**
  - **Passive** — Shape-from-X
    (stereo/multi-view, silhouettes, focus/defocus, motion, texture, etc.)
  - **Active**
    - **Transmissive**
      - Computed Tomography (CT)
      - Transmissive Ultrasound
    - **Reflective**
      - Non-optical Methods
        (reflective ultrasound, radar, sonar, MRI)
      - Active Variants of Passive Methods
        (stereo/focus/defocus using projected patterns)
      - Time-of-Flight
      - Triangulation
        (laser striping and structured lighting)

Lanman and Taubin'09

DARPA Grand Challenge

Photo: DARPA

Do-It-Yourself (DIY) 3D Scanners

Images removed due to copyright restrictions.

See:

- http://blog.makezine.com/archive/2006/10/how_to_build_your_own_3d.html
- http://www.make-digital.com/make/vol14/?pg=195
- http://www.shapeways.com/blog/uploads/david-starter-kit.jpg
- http://www.shapeways.com/blog/archives/248-DAVID-3D-Scanner-Starter-Kit-Review.html#extended
- http://www.david-laserscanner.com/
- http://www.youtube.com/watch?v=XSrW-wAWZe4
- http://www.chromecow.com/MadScience/3DScanner/3DScan_02.htm

What is ‘interesting’ here?
Social voting in the real world = ‘popular’

Photos removed due to copyright restrictions.

See the University of Washington / Microsoft Photo Tourism site:
http://phototour.cs.washington.edu/

Computational Photography

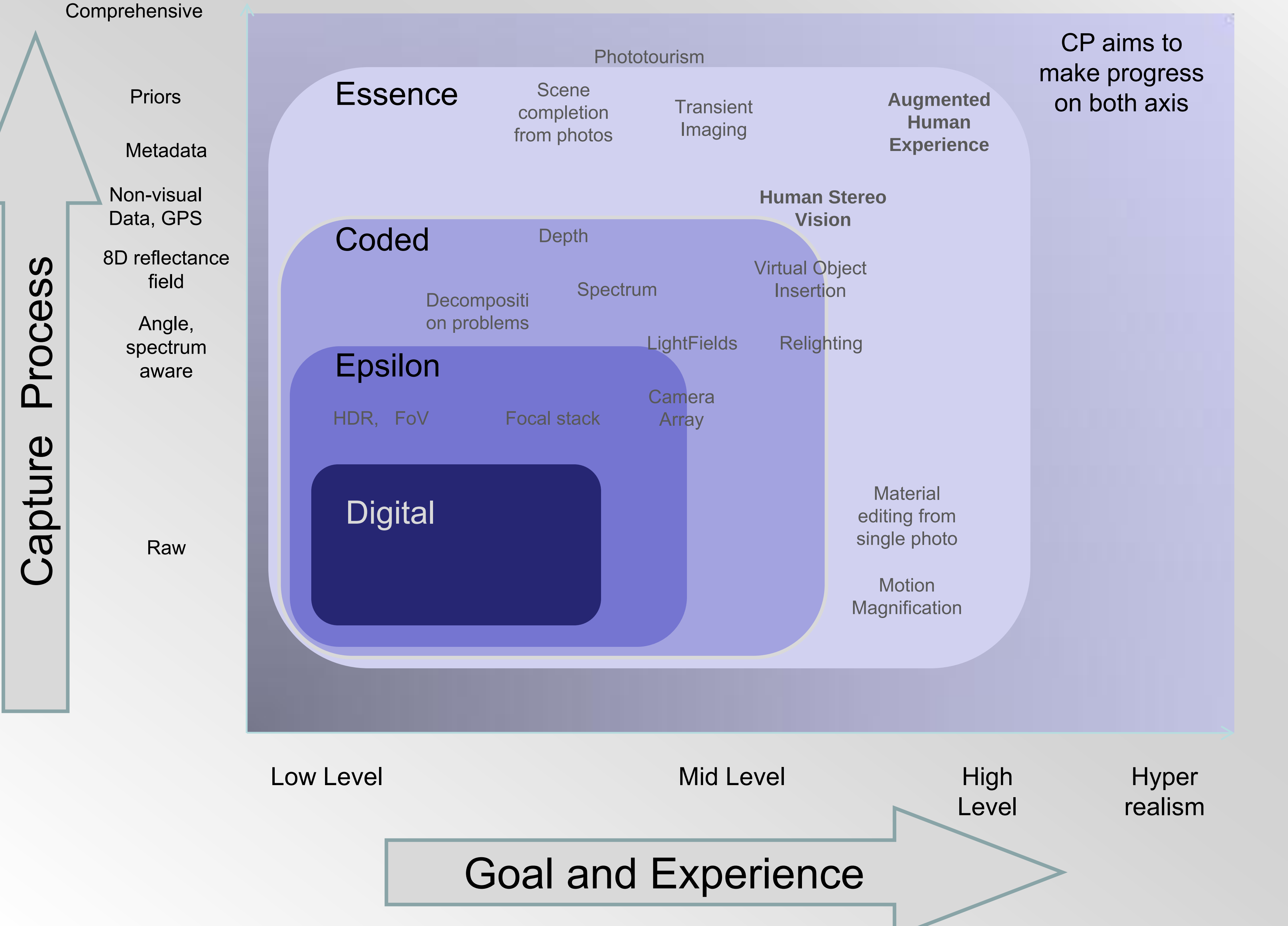
[Raskar and Tumblin]

captures a machine-readable representation of our world to
hyper-realistically synthesize the essence of our visual experience.

1. Epsilon Photography
   - Low-level vision: Pixels
   - Multi-photos by perturbing camera parameters
   - 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
   - ‘Scene analysis’

3. Essence Photography
   - High-level understanding
     - Not mimic human eye
     - Beyond single view/illum
   - ‘New artform’

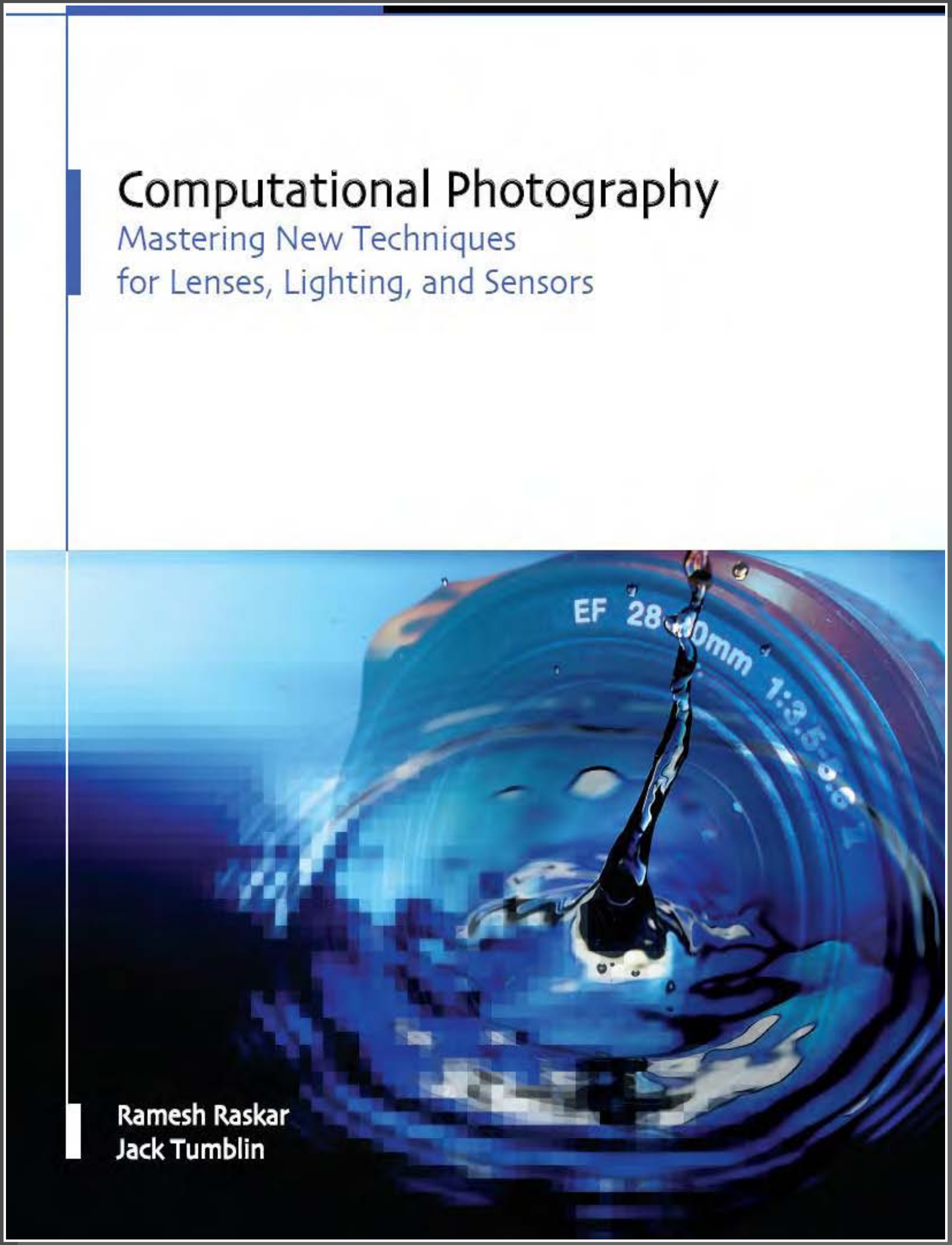

Comprehensive
Priors
Metadata
Non-visual Data, GPS
8D reflectance field
Angle, spectrum aware
Raw
Capture Process
CP aims to make progress on both axis
Phototourism
Essence
Scene completion from photos
Transient Imaging
Augmented Human Experience
Human Stereo Vision
Coded
Depth
Virtual Object Insertion
Spectrum
Decompositi on problems
LightFields
Relighting
Epsilon
Camera Array
HDR, FoV
Focal stack
Digital
Material editing from single photo
Motion Magnification
Low Level
Mid Level
High Level
Hyper realism
Goal and Experience

																Coded Photography
	Epsilon Photography															
Goals --> Tools	V	Dynamic Range	Resolution	Color Sensing	FOV/Zoom	Noise	Frame rate	Angular sensitivity/ Focus/Lightfield	Motion	Location	Depth per pixel (shape)	Albedo/reflectance/BTF (reflectance)	Regions and Boundaries F/B matting (regions)	Direct/Global/Descattering Specular/Diffuse (light transport)	Relighting	Glare, Reflection/Transmission
Optics																
Camera array and Co-axial cameras	Varying exposure, Tombo	Each cam with diff narrow fov	Each cam with diff color filter	Each cam with diff narrow fov		Staggered shutter	Synthetic Aperture,			Stereo, Multi-baseline Stereo		McGuire2005, SAMP			
Lenses	Horstmeyer2009		Kodacolor	Stermer08			Focus bracketing, Image Destabilization		Bokode	Depth from Focus/Defocus,					
Aperture/Attenuation	Braketing	Mohan'08					Coded Aperture (Veeraraghavan 07)	Lensless Imaging		Coded Aperture (Levin et al.)					Talvala2007
Mirrors/Catadioptic		Nalwa1996		Omnidirectional			Unger2003, Levoy2004			Cone Mirrors (Kuthirummal '06)	Kaleidoscope2003		Lamond2009		
Color filters			Time sequential color filters	Generalized Mosaic						Sig08 color filters in lens					
Polarization				Generalized Mosaic									Schechner 01		Schechner 00
NonstdPerspective		GaoAhuja2006													
Illumination															
Presence/absence/duration					Flash/Noflash pairs			Motion Freeze				Flash-matting (coarse depth?)			Agrawal05 (reflection layer)
Brightness	Flash HDR (Agrawal05)									Light-fall-off Stereo					
Color			Park 2007							Single-shot, colored structured lighting					
Position/Direction										Flying spot	Dana 1999	Multi-flash camera		LightWaving (Mohan05)	
Space Modulation		Flying spot					Zhang2006			Structured Light (laser striping, swept-plane shadows)		Vaquero2009	Nayar06, Levoy Confocal Illum	Light Stage	
Time Modulation								Strobing, baseball Theobalt2004		Structured Light (Gray codes, binary, phase-shifting), Time-of-flight				Light Stage, Dome	

- Ramesh Raskar and
  Jack Tumblin

- Book Publishers: A K Peters

- ComputationalPhotography.org



Goals

- Change the rules of the game
  - Emerging optics, illumination, novel sensors
  - Exploit priors and online collections
- Applications
  - Better scene understanding/analysis
  - Capture visual essence
  - Superior Metadata tagging for effective sharing
  - Fuse non-visual data
    - Sensors for disabled, new art forms, crowdsourcing, bridging cultures

Vein Viewer (Luminetx)

Locate subcutaneous veins

Courtesy of Luminetx Technologies Corporation. Used with permission.

Vein Viewer (Luminetx)

Near-IR camera locates subcutaneous veins and project their location onto the surface of the skin.

Coaxial IR camera
+ Projector

Courtesy of Luminetx Technologies Corporation. Used with permission.

Beyond Visible Spectrum

Two images removed due to copyright restrictions.

RedShift

Cedip

- Format
  - 4 (3) Assignments
    - Hands on with optics, illumination, sensors, masks
    - Rolling schedule for overlap
    - We have cameras, lenses, electronics, projectors etc
    - Vote on best project
  - Mid term exam
    - Test concepts
  - 1 Final project
    - Should be a Novel and Cool
    - Conference quality paper
    - Award for best project
  - Take 1 class notes
  - Lectures (and guest talks)
  - In-class + online discussion

- If you are a listener
  - Participate in online discussion, dig new recent work
  - Present one short 15 minute idea or new work

- Credit
  - Assignments: 40%
  - Project: 30%
  - Mid-term: 20%
  - Class participation: 10%

- Pre-reqs
  - Helpful: Linear algebra, image processing, think in 3D
  - We will try to keep math to essentials, but complex concepts

What is the emphasis?

- Learn fundamental techniques in imaging
  - In class and in homeworks
  - Signal processing, Applied optics, Computer graphics and vision, Electronics, Art, and Online photo collections
  - This is not a discussion class
- Three Applications areas
  - Photography
    - Think in higher dimensions 3D, 4D, 6D, 8D, thermal IR, range cam, lightfields, applied optics
  - Active Computer Vision (real-time)
    - HCI, Robotics, Tracking/Segmentation etc
  - Scientific Imaging
    - Compressive sensing, wavefront coding, tomography, deconvolution, psf
  - But the 3 areas are merging and use similar principles

Pre-reqs

- Two tracks:
  - Supporting students with varying backgrounds
  - A. software-intensive (Photoshop/HDRshop maybe ok)
    - But you will actually take longer to do assignments
  - B. software-hardware (electronics/optics) emphasis.

- Helpful:
  - Watch all videos on http://raskar.info/photo/
  - Linear algebra, image processing, think in 3D
  - Signal processing, Applied optics, Computer graphics and vision, Electronics, Art, and Online photo collections

- We will try to keep math to essentials, but introduce complex concepts at rapid pace

- Assignments versus Class material
  - Class material will present material with varying degree of complexity
  - Each assignments has sub-elements with increasing sophistication
  - **You can pick your level**

- Assignments:
  - You are encouraged to program in Matlab for image analysis
  - You may need to use C++/OpenGL/Visual programming for some hardware assignments
- Each student is expected to prepare notes for one lecture
  - These notes should be prepared and emailed to the instructor no later than the following Monday night (midnight EST). Revisions and corrections will be exchanged by email and after changes the notes will be posted to the website before class the following week.
  - 5 points

2	Sept 18th	Modern Optics and Lenses, Ray-matrix operations
3	Sept 25th	Virtual Optical Bench, Lightfield Photography, Fourier Optics, Wavefront Coding
4	Oct 2nd	**Digital Illumination**, Hadamard Coded and Multispectral Illumination
5	Oct 9th	**Emerging Sensors**: High speed imaging, 3D range sensors, Femto-second concepts, Front/back illumination, Diffraction issues
6	Oct 16th	Beyond Visible Spectrum: Multispectral imaging and Thermal sensors, Fluorescent imaging, 'Audio camera'
7	Oct 23rd	Image Reconstruction Techniques, Deconvolution, Motion and Defocus Deblurring, Tomography, Heterodyned Photography, Compressive Sensing
8	Oct 30th	Cameras for Human Computer Interaction (HCI): 0-D and 1-D sensors, Spatio-temporal coding, Frustrated TIR, Camera-display fusion
9	Nov 6th	Useful techniques in Scientific and Medical Imaging: CT-scans, Strobing, Endoscopes, Astronomy and Long range imaging
10	Nov 13th	Mid-term Exam, Mobile Photography, Video Blogging, Life logs and Online Photo collections
11	Nov 20th	Optics and Sensing in Animal Eyes. What can we learn from successful biological vision systems?
12	Nov 27th	Thanksgiving Holiday (No Class)
13	Dec 4th	Final Projects

Topics not covered

- Only a bit of topics below
- Art and Aesthetics
    - 4.343 Photography and Related Media
- Software Image Manipulation
    - Traditional computer vision,
    - Camera fundamentals, Image processing, Learning,
        - 6.815/6.865 Digital and Computational Photography
- Optics
    - 2.71/2.710 Optics
- Photoshop
    - Tricks, tools
- Camera Operation
    - Whatever is in the instruction manual

Courses related to CompCamera

- Spring 2010:
  - Camera Culture Seminar [Raskar, Media Lab]
    - Graduate seminar
    - Guest lectures + in class discussion
    - Homework question each week
    - Final survey paper (or project)
    - *CompCamera class: hands on projects, technical details*
  - Digital and Computational Photography [Durand, CSAIL]
    - Emphasis on software methods, Graphics and image processing
    - *CompCamera class: hardware projects, devices, beyond visible spectrum/next gen cameras*
  - Optics [George Barbastathis, MechE]
    - Fourier optics, coherent imaging
    - *CompCamera class: Photography, time-domain, sensors, illumination*
  - Computational Imaging (Horn, Spring 2006)
    - Coding, Nuclear/Astronomical imaging, emphasis on theory

Questions ..

- Brief Introductions
- Are you a photographer ?
- Do you use camera for vision/image processing? Real-time processing?
- Do you have background in optics/sensors?

- Name, Dept, Year, Why you are here

2nd International Conference on Computational Photography

Papers due November 2, 2009

iccp 10

International Conference on Computational Photography

March 26-27, 2010

MIT, Cambridge, MA

Program Chairs

Kyros Kutulakos, U. Toronto

Rafael Piestun, U. Colorado

Ramesh Raskar, MIT

Finance Chair

Yoav Schechner, Technion

Local Arrangements Chair

Sylvain Paris, Adobe

Online Activities Chair

Neel Joshi, Microsoft

Program Committee

(Vision / Graphics)

A. Agrawal, MERL

M. Cohen, Microsoft

A. Efros, CMU

P. Favaro, Heriot Watt U.

S. Hiura, U. Osaka

H. Lensch, MPI Informatik

A. Levin, Weizmann Inst.

M. Levoy, Stanford

S. Narasimhan, CMU

S. Nayar, Columbia U.

S. Paris, Adobe

(Optics)

D. Brady, Duke U.

J. Fienup, U. Rochester

The field of Computational Photography seeks to create new photographic functionalities and experiences that go beyond what is possible with traditional cameras and image processing tools. Submissions on the following topics are encouraged:

Computational Cameras: The use of optical coding followed by computational decoding to produce new or enhanced images and videos. Examples include catadioptric, coded aperture, integral/plenoptic, coded exposure, lensless, assorted pixel, compressive, holographic and depth imaging. Novel computational image detectors that facilitate the creation of new images are also included.

Multiple Images and Camera Arrays: The use of multiple images captured sequentially or simultaneously followed by processing to produce new or enhanced images. Examples include mosaicing, creation of collages and montages, refocusing, and light field rendering. Also included are the use of multiple images to achieve high dynamic range, extended depth of field, super-resolution, denoising, multispectral imaging and polarization imaging.

Computational Illumination: The use of programmable light sources to capture images followed by processing to produce new or enhanced images. Examples include structured light for depth/normal estimation, image based relighting, flash/no-flash methods for image enhancements, separation of reflection components, detection of material properties and light transport measurement and manipulation.

Advanced Image and Video Processing: The use of innovative computational methods to break the fundamental limits of traditional image processing and produce new or enhanced images. Examples include the use of image priors for enhancement, image matting, image filling, and view interpolation.

Scientific Photography and Videography: The use of imaging systems to gather quantitative information about physical systems and processes as diverse as individual cells and galaxies. Examples include application in microscopy, biomedical imaging, remote sensing and astronomy.

Important Dates

Submission of full paper	November 2, 2009
Notification of acceptance	February 2, 2010
Conference	March 26-27, 2010

detailed submission

/iccp10

http://cameraculture.media.mit.edu/iccp10

Writing a Conference Quality Paper

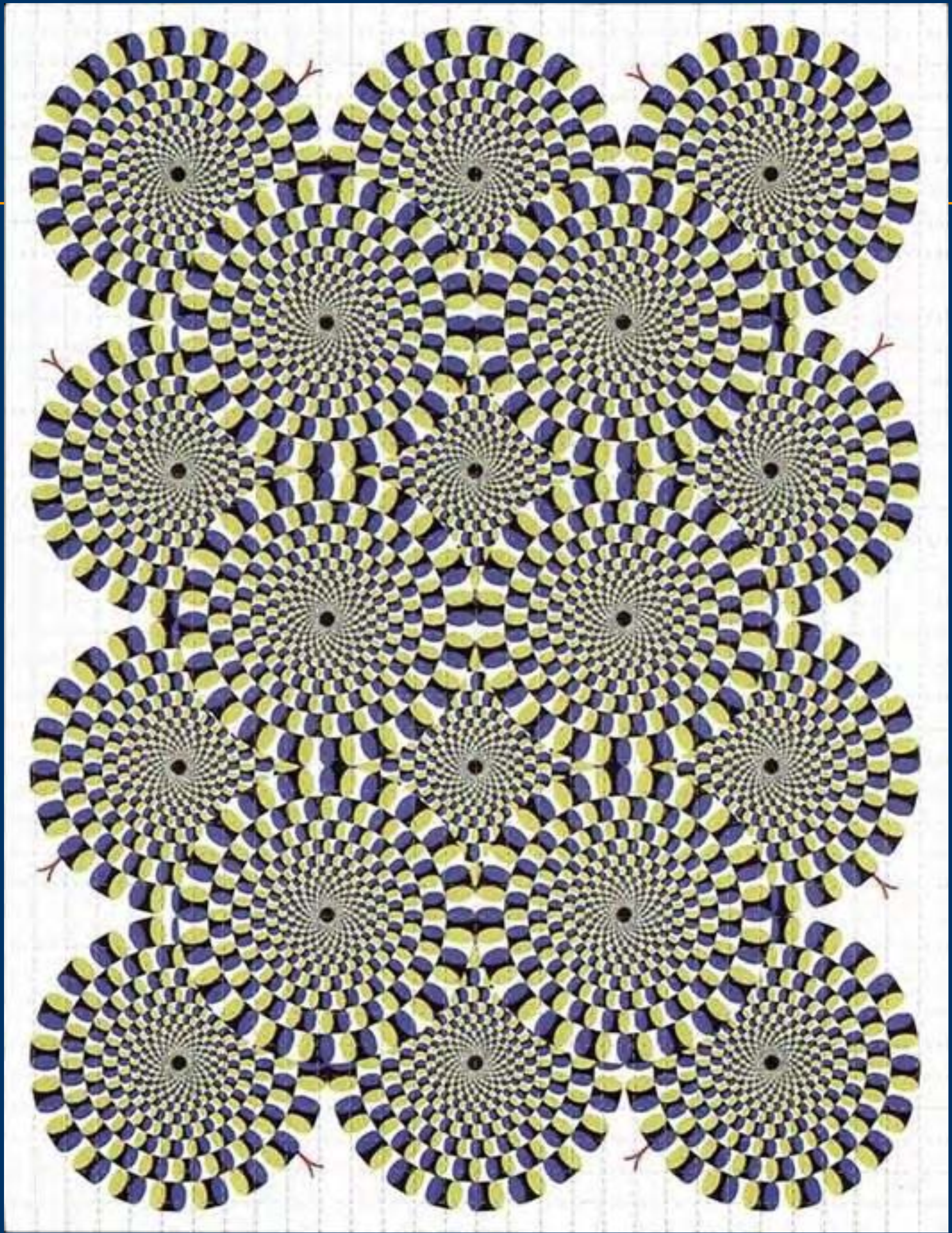
- How to come up with new ideas
  - See slideshow
    http://www.slideshare.net/cameraculture/how-to-come-up-with-new-ideas-raskar-feb09
- Developing your idea
  - Deciding if it is worth persuing
  - http://en.wikipedia.org/wiki/George_H._Heilmeier#Heilmeier.27s_Catechism
  - What are you trying to do? How is it done today, and what are the limits of current practice? What's new in your approach and why do you think it will be successful? Who cares? If you're successful, what difference will it make? What are the risks and the payoffs? How much will it cost? How long will it take?
- Last year outcome
  - 3 Siggraph/ICCV submissions, SRC award, 2 major research themes

How to quickly get started writing a paper

- Abstract
- 1. Introduction
- Motivation
- Contributions** (For the first time, we have shown that xyz)
- Related Work
- Limitations and Benefits
- 2. Method
- (For every section as well as paragraph, first sentence should be the 'conclusion' of what that section or paragraph is going to show)
- 3. More Second Order details (Section title will change)
- 4. Implementation
- 5. Results
- Performance Evaluation
- Demonstration
- 6. Discussion and Issues
- Future Directions
- 7. Conclusion

Casio EX F1

- What can it do?
  - Mostly high speed imaging
  - 1200 fps
  - Burst mode
- Déjà vu (Media Lab 1998) and Moment Camera (Michael Cohen 2005)
- HDR
- Movie



Cameras and Photography

Art, Magic, Miracle

Topics

- Smart Lighting
  - Light stages, Domes, Light waving, Towards 8D
- Computational Imaging outside Photography
  - Tomography, Coded Aperture Imaging
- Smart Optics
  - Handheld Light field camera, Programmable imaging/aperture
- Smart Sensors
  - HDR Cameras, Gradient Sensing, Line-scan Cameras, Demodulators
- Speculations

Debevec et al. 2002: ‘Light Stage 3’

Image removed due to copyright restrictions.
See Debevec, P., et al. “A Lighting Reproduction Approach to Live-Action Compositing.” *SIGGRAPH 2002 Proceedings*.

Image-Based Actual Re-lighting

Debevec et al., SIGG2001

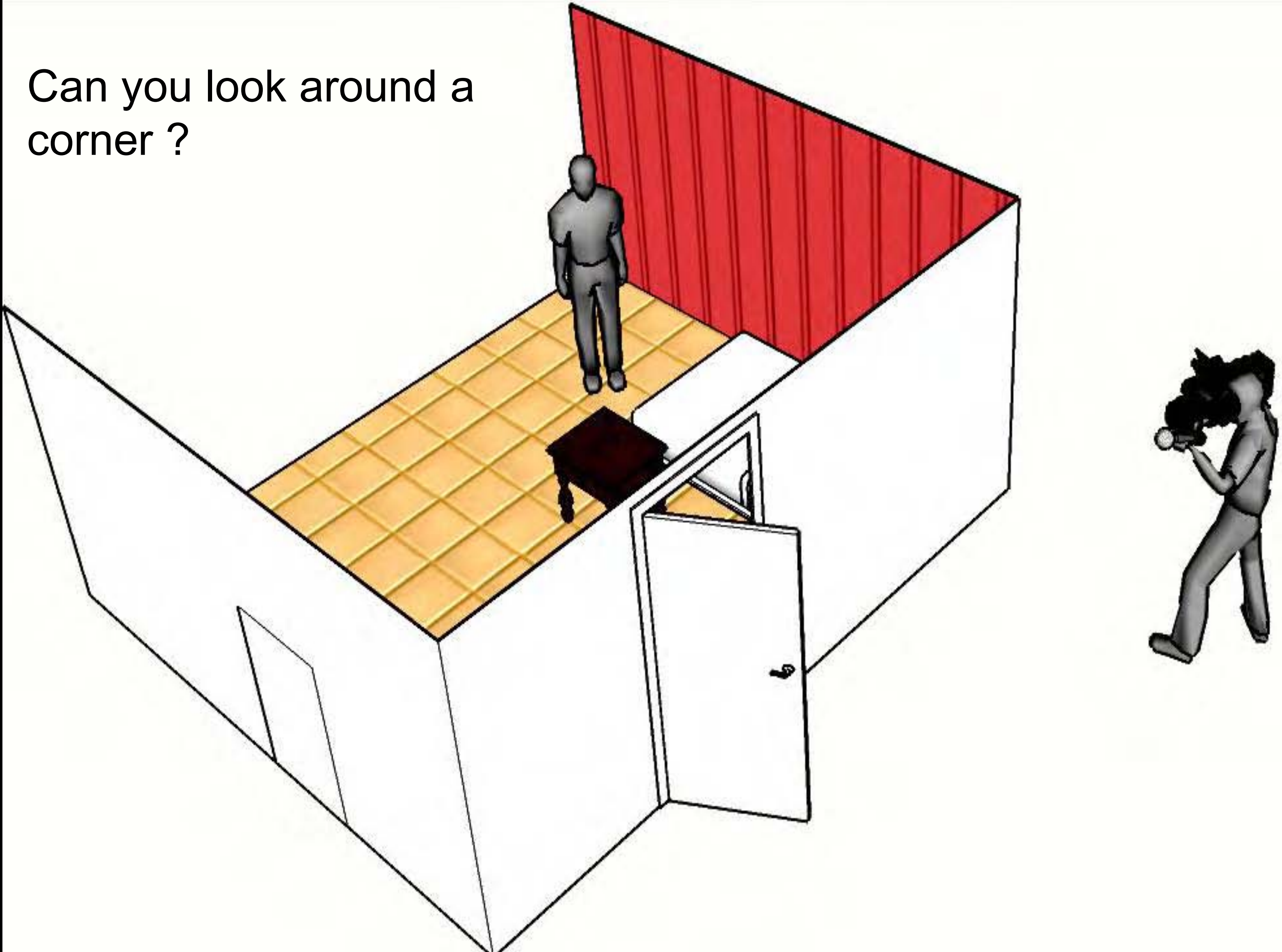
Film the background in Milan, measure incoming light

Light the actress in Los Angeles

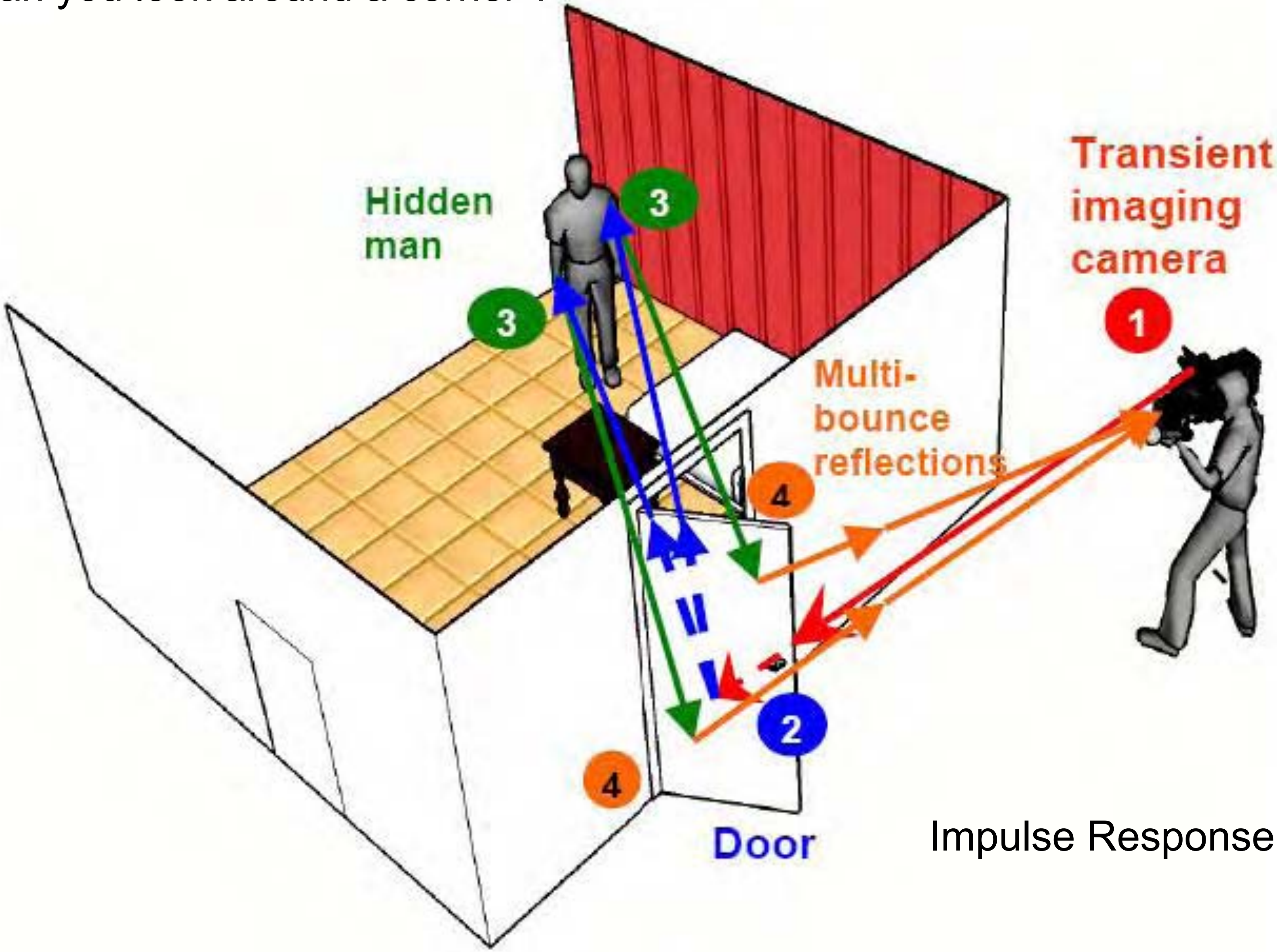
Matte the background

Matched LA and Milan lighting.

Can you look around a corner ?



Can you look around a corner ?

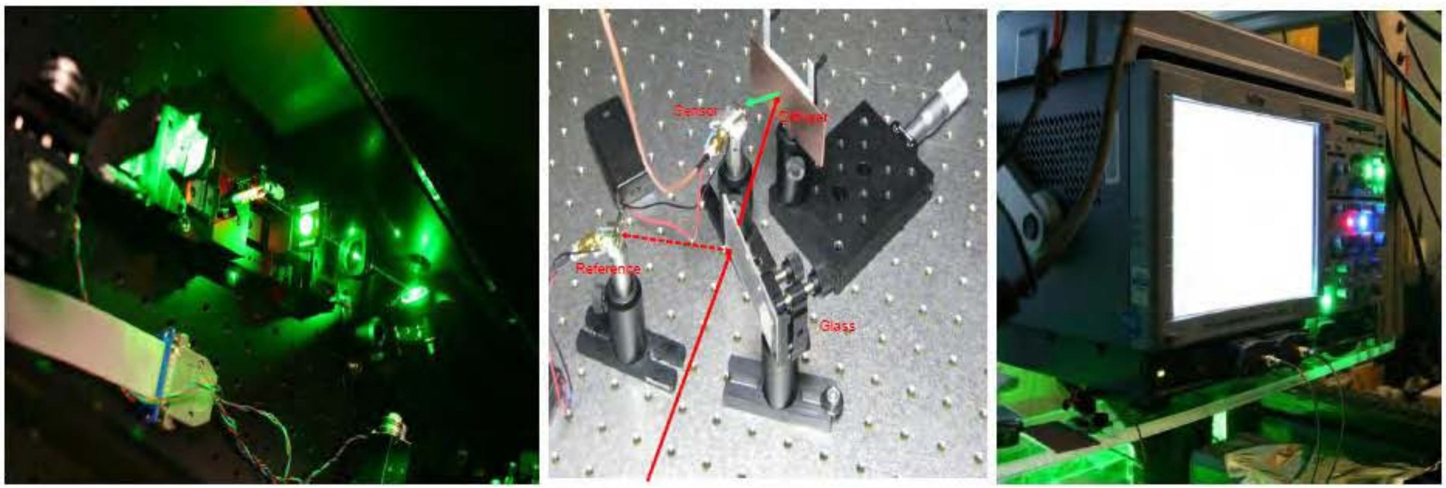


Impulse Response of a Scene

cameraculture.media.mit.edu/femtotransientimaging

Kirmani, Hutchinson, Davis, Raskar 2009
Oral paper at ICCV'2009, Oct 2009 in Kyoto

Preliminary hardware prototype of the proposed Transient imaging camera



We successfully built the first hardware prototype to experimentally validate the Transient light transport theory. This is only a preliminary setup and we have used it to conduct several proof-of-concept experiments. It includes a femto-second laser source (left), the small scene composed of the ultra-fast detector, few diffused and specular patches and the ultra-fast sensor (center). The oscilloscope (right) digitizes the received light signal which is then processed by our inversion algorithm.

Femtosecond Laser as Light Source
Pico-second detector array as Camera

Are <u>BOTH</u> a 'photograph'?

http://research.famsi.org/kerrmaya.html

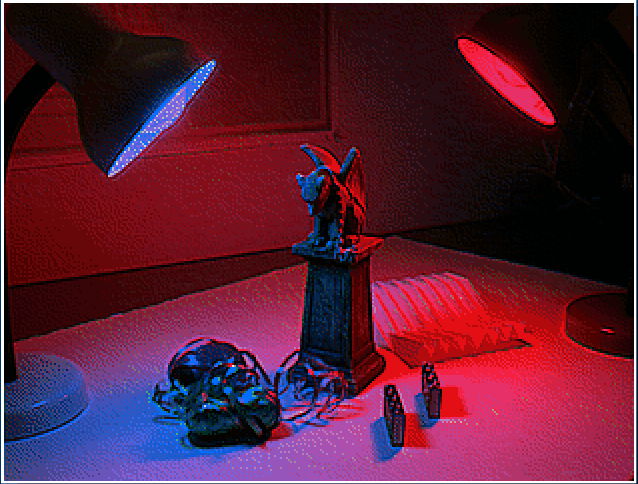
Rollout Photographs © Justin Kerr:

Slide idea: Steve Seitz

Part 2:
Fast Forward Preview

Synthetic Lighting

Paul Haeberli, Jan 1992

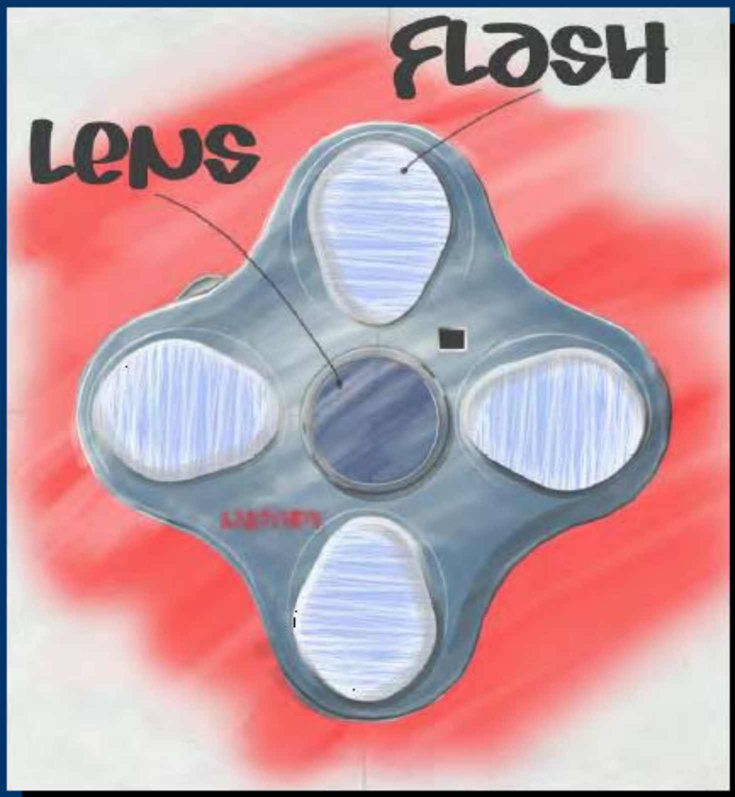


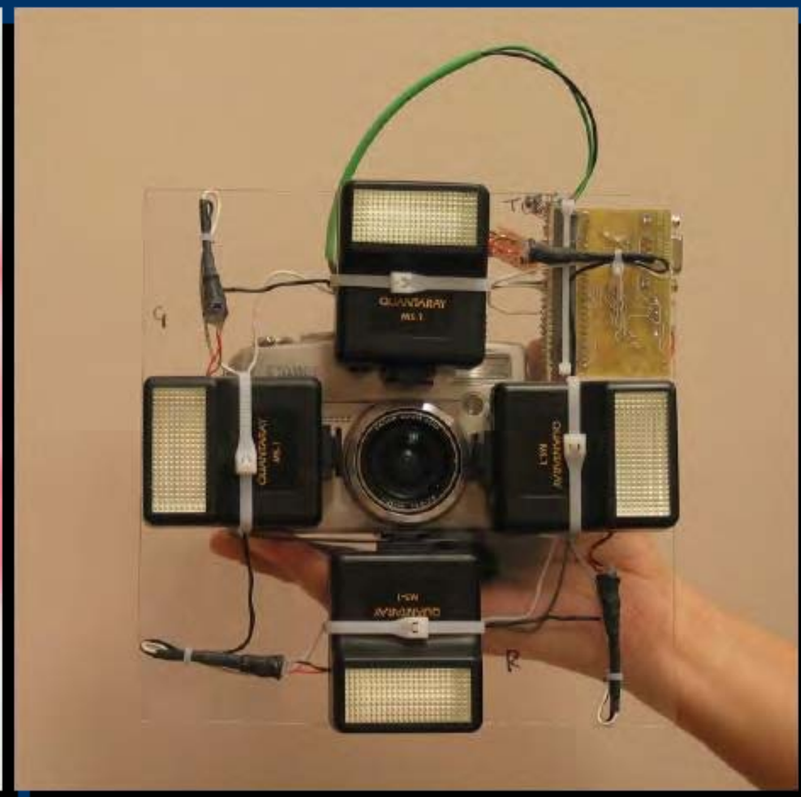
Homework

- Take multiple photos by changing lighting
- Mix and match color channels to relight

- Due Sept 19th

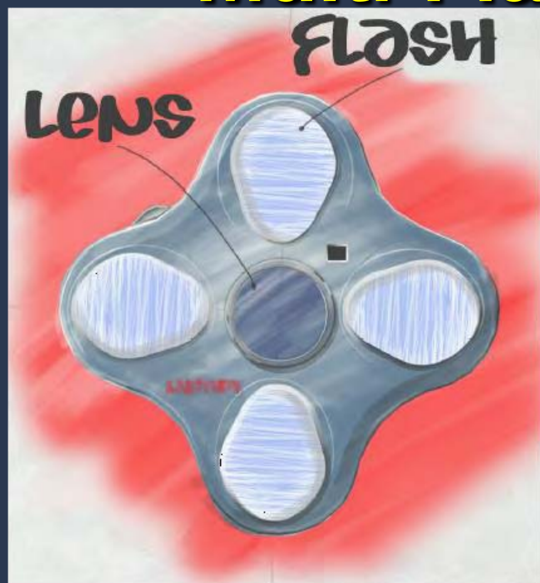
Depth Edge Camera

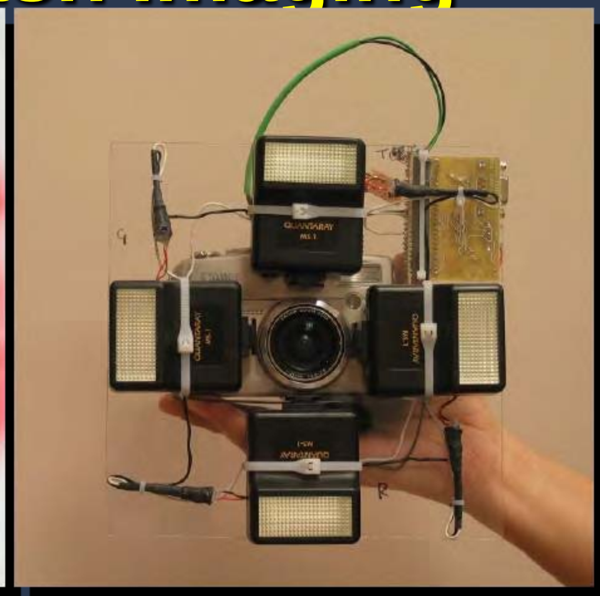




Courtesy of MERL. Used with permission.

Non-photorealistic Camera: Depth Edge Detection and Stylized Rendering using Multi-Flash Imaging



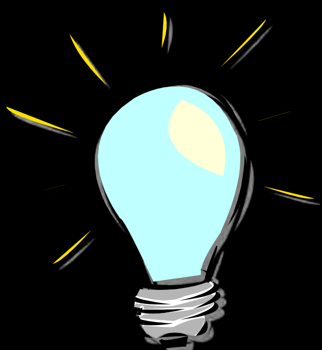


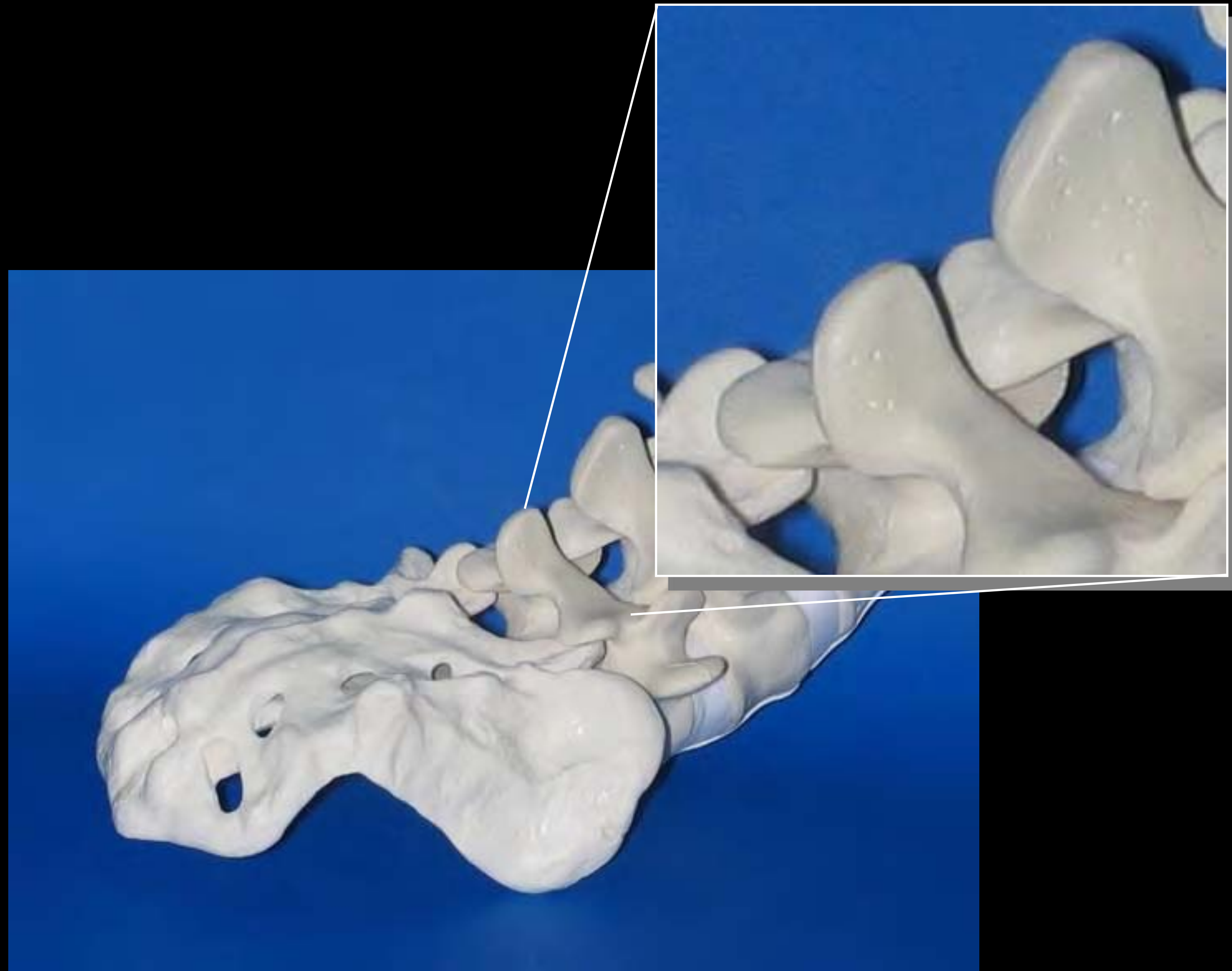
Ramesh Raskar, Karhan Tan, Rogerio Feris, Jingyi Yu, Matthew Turk

Mitsubishi Electric Research Labs (MERL), Cambridge, MA

U of California at Santa Barbara

U of North Carolina at Chapel Hill





Courtesy of MERL. Used with permission.

Courtesy of MERL. Used with permission.

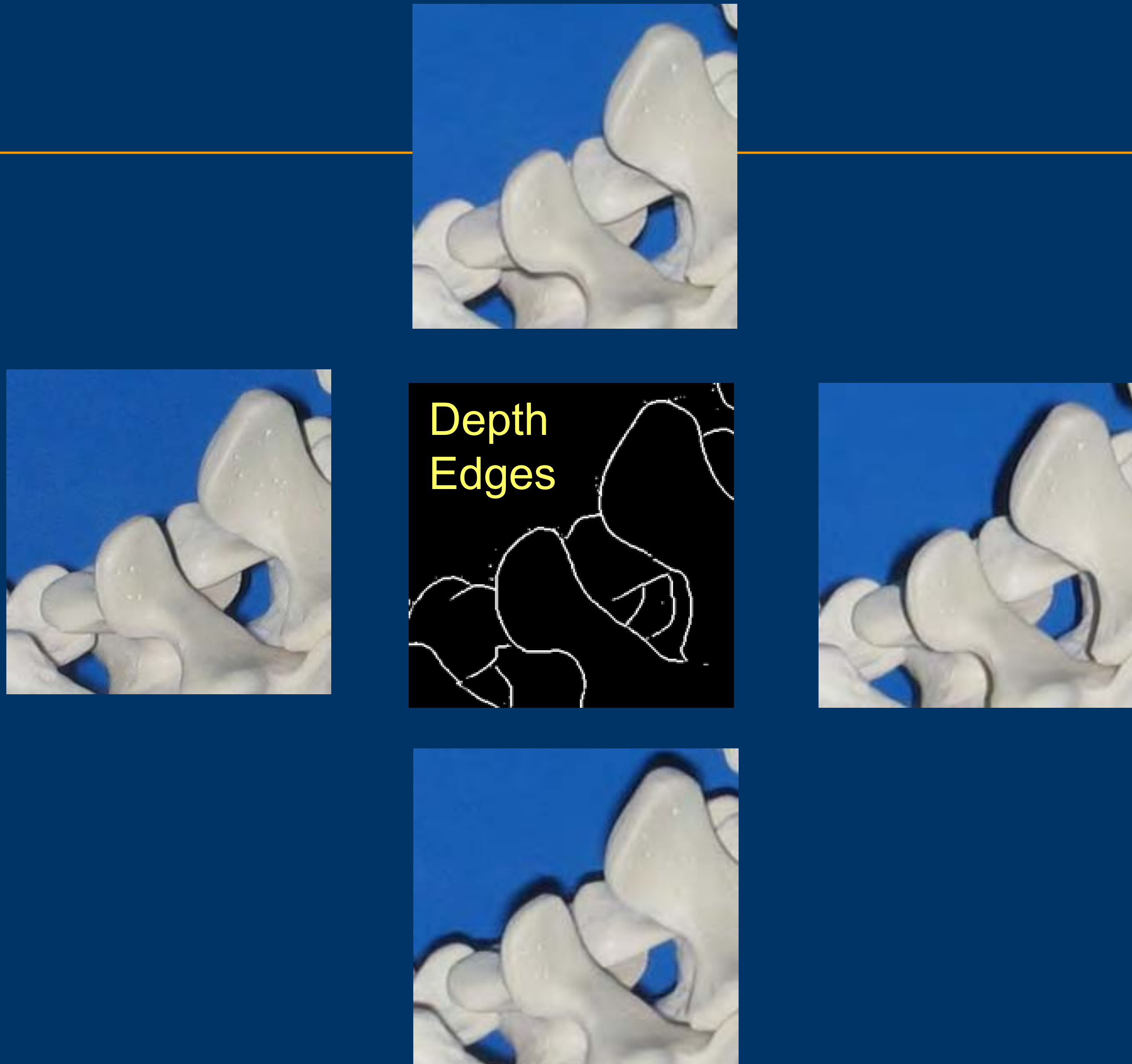
Courtesy of MERL. Used with permission.

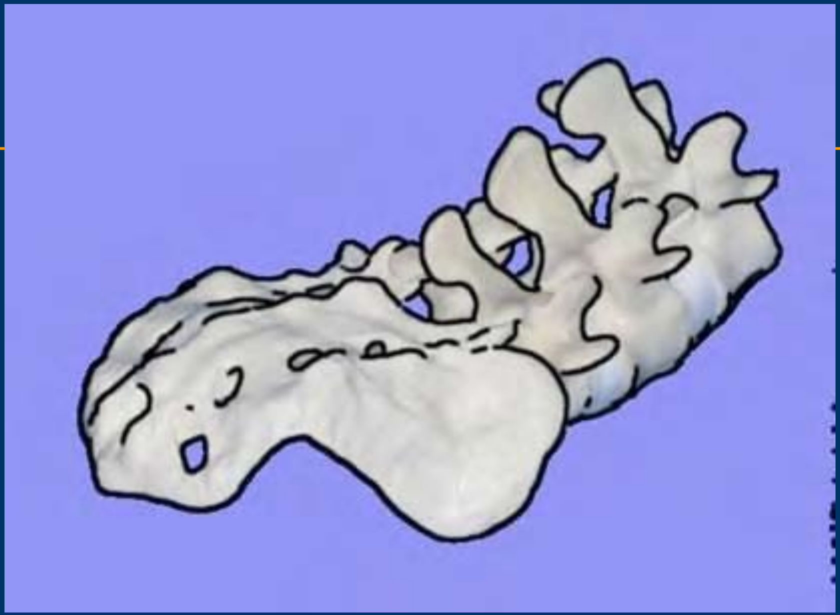
Depth Discontinuities

Courtesy of MERL. Used with permission.

Internal and external

Shape boundaries, Occluding contour, Silhouettes


Depth
Edges



Courtesy of MERL. Used with permission.

Participatory Urban Sensing

Deborah Estrin talk yesterday

Static/semi-dynamic/dynamic data

A. City Maintenance

-Side Walks

B. Pollution

-Sensor network

C. Diet, Offenders

-Graffiti

-Bicycle on sidewalk

Image removed due to copyright restrictions.

Future ..

Citizen Surveillance
Health Monitoring

$(\text{Erin Brockovich})^n$

http://research.cens.ucla.edu/areas/2007/Urban_Sensing/

Crowdsourcing

Object Recognition
Fakes
Template matching

Screenshot removed due to copyright restrictions.

Amazon Mechanical Turk:
Steve Fossett search

Screenshot removed due to copyright restrictions.

ReCAPTCHA=OCR

Screenshot removed due to copyright restrictions.

See Howe, J. "The Rise of Crowdsourcing." *WIRED Magazine*, June 2006.
http://www.wired.com/wired/archive/14.06/crowds.html

Community Photo Collections

U of Washington/Microsoft: Photosynth

Photos removed due to copyright restrictions.

See the University of Washington / Microsoft Photo Tourism site:
http://phototour.cs.washington.edu/

GigaPixel Images

Microsoft HDView

Photo collage removed due to copyright restrictions.

http://www.xrez.com/owens_giga.html

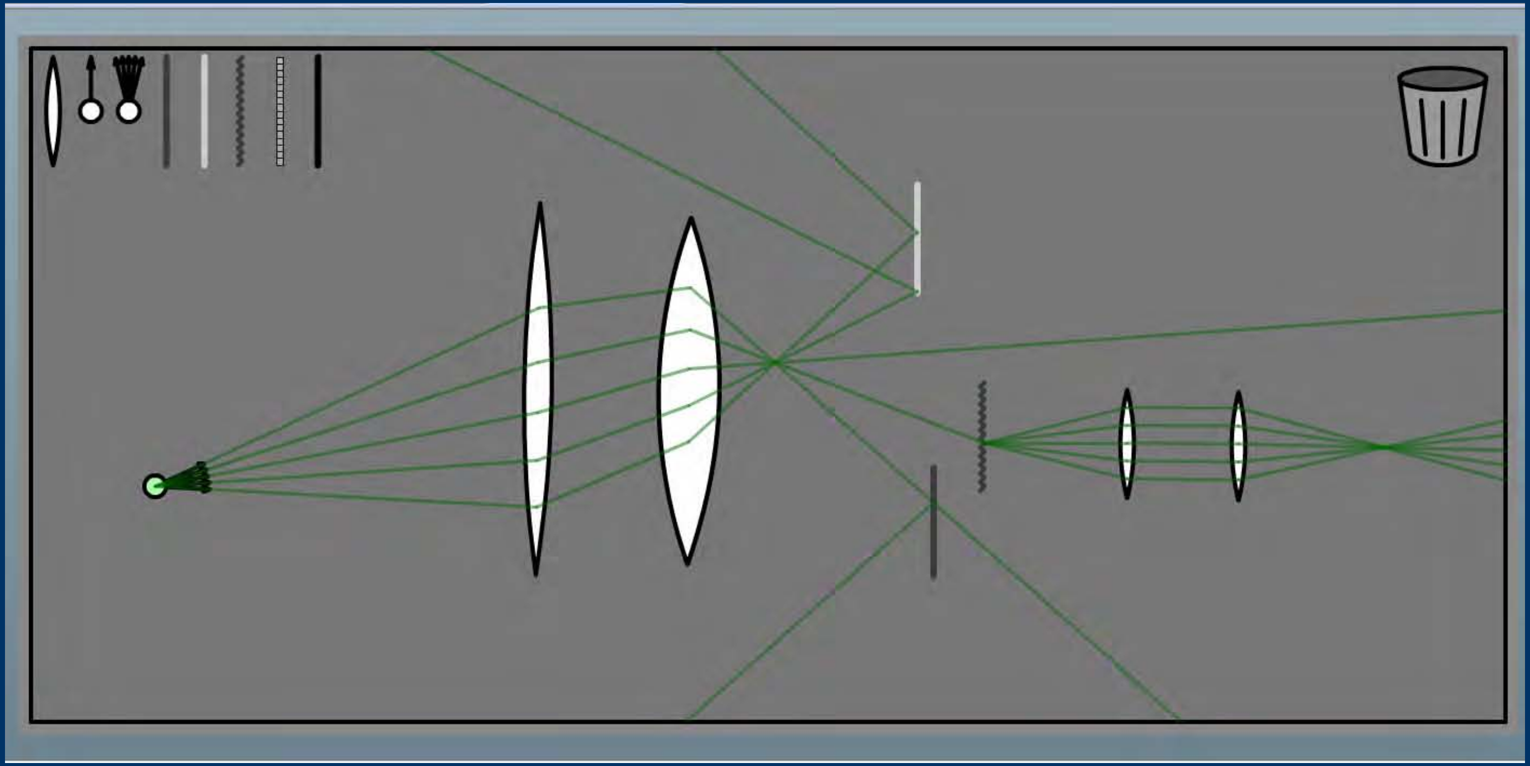
http://www.gigapxl.org/

Optics

- It is all about rays not pixels
- Study using lightfields

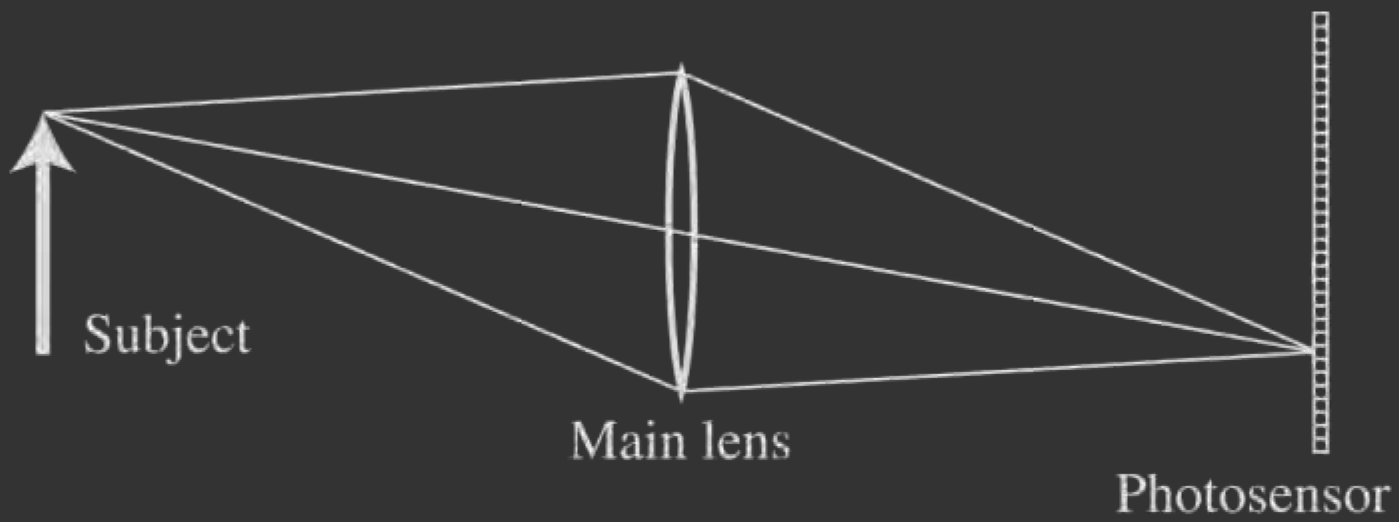
Assignment 2

- Andrew Adam's Virtual Optical Bench



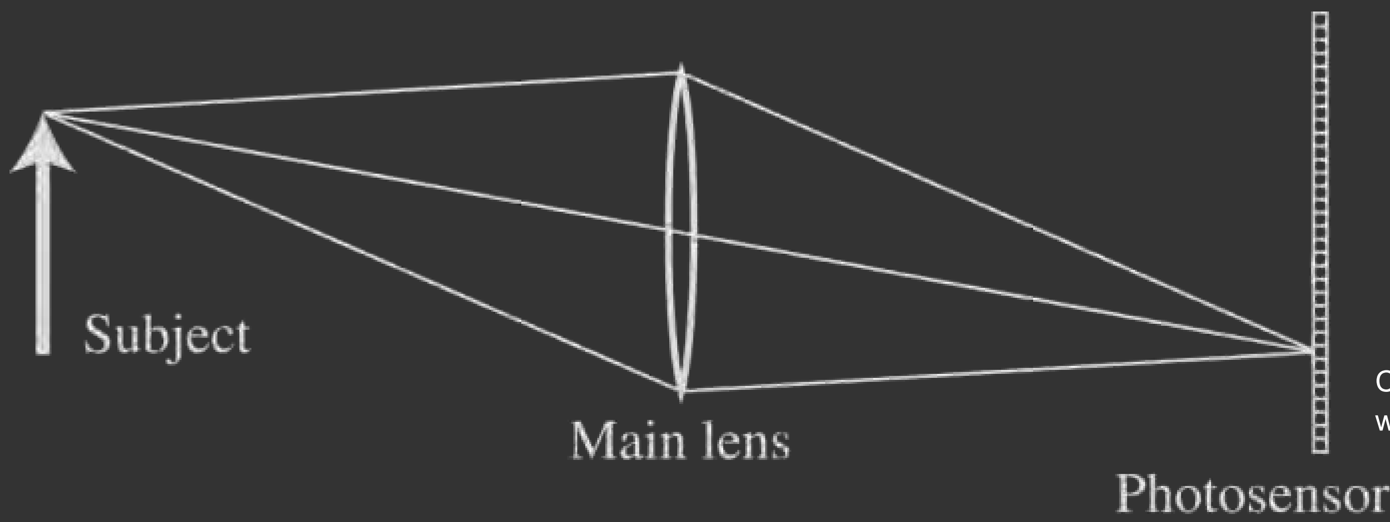
http://graphics.stanford.edu/~abadams/lenstoy.swf

Light Field Inside a Camera

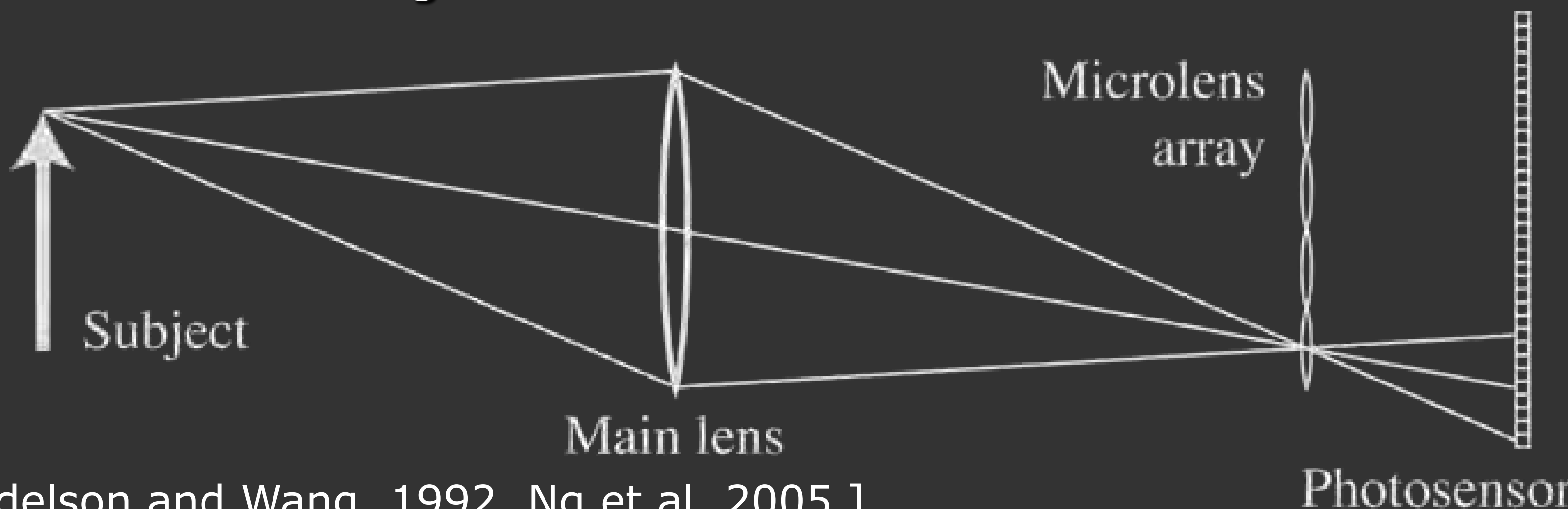


Courtesy of Ren Ng. Used with permission.

Light Field Inside a Camera



Lenslet-based Light Field camera

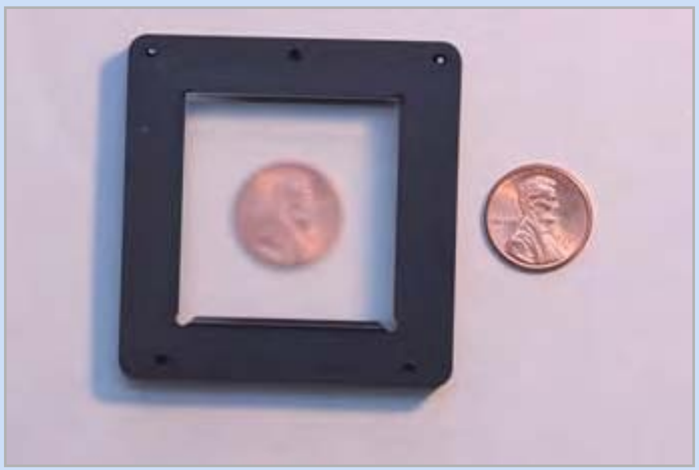


[Adelson and Wang, 1992, Ng et al. 2005]

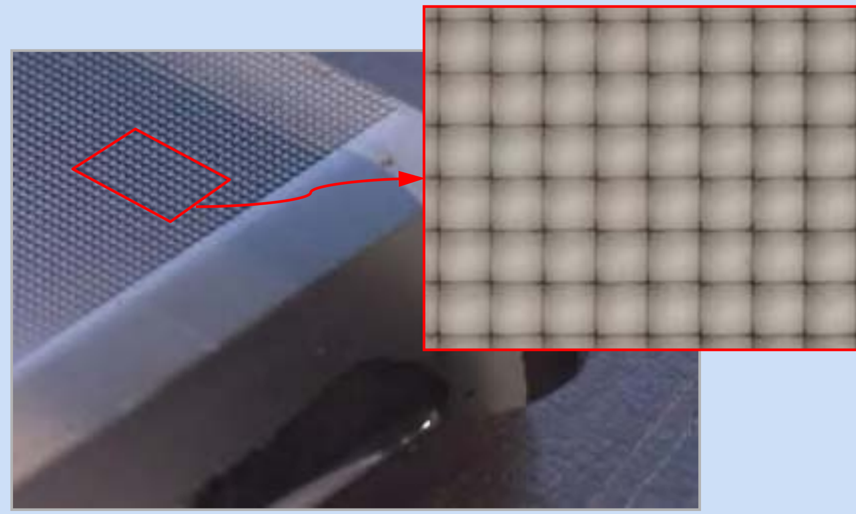
Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor



Adaptive Optics microlens array



125μ square-sided microlenses

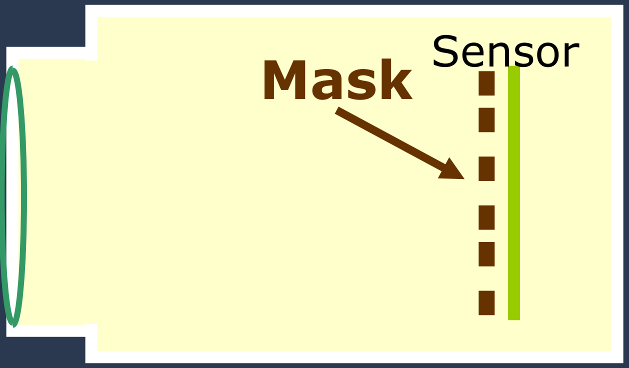
4000 4000 pixels 292 292 lenses = 14 14 pixels per lens

Digital Refocusing

[Ng et al 2005]

Can we achieve this with a <u>Mask</u> alone?

Mask based Light Field Camera

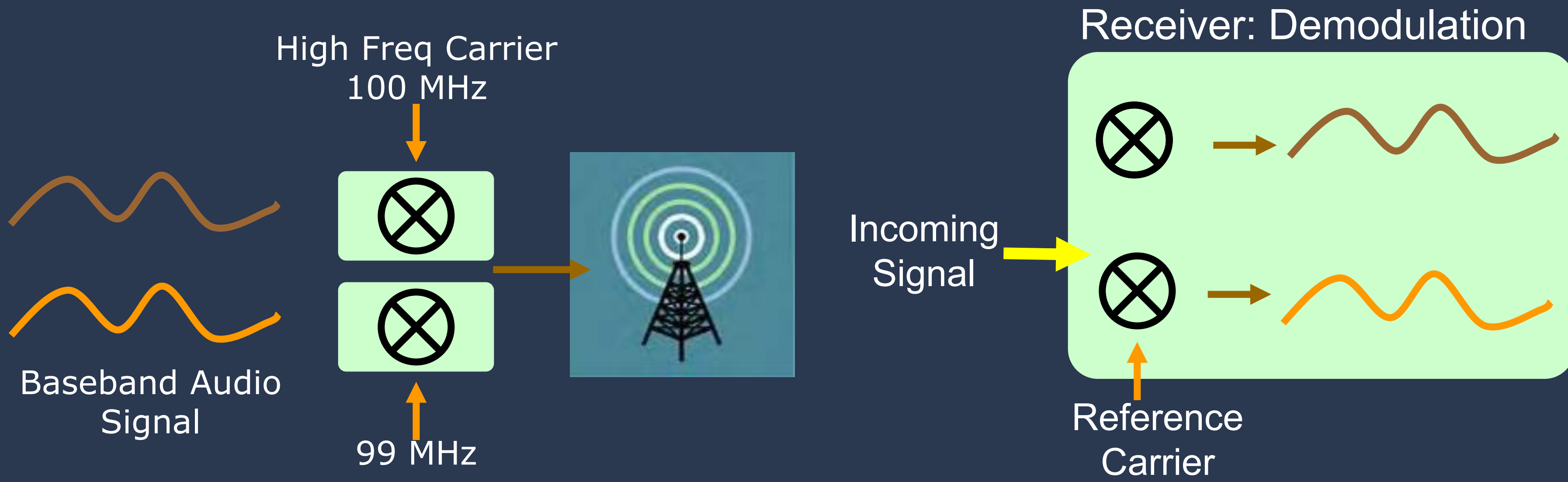


[Veeraraghavan, Raskar, Agrawal, Tumblin, Mohan, Siggraph 2007]

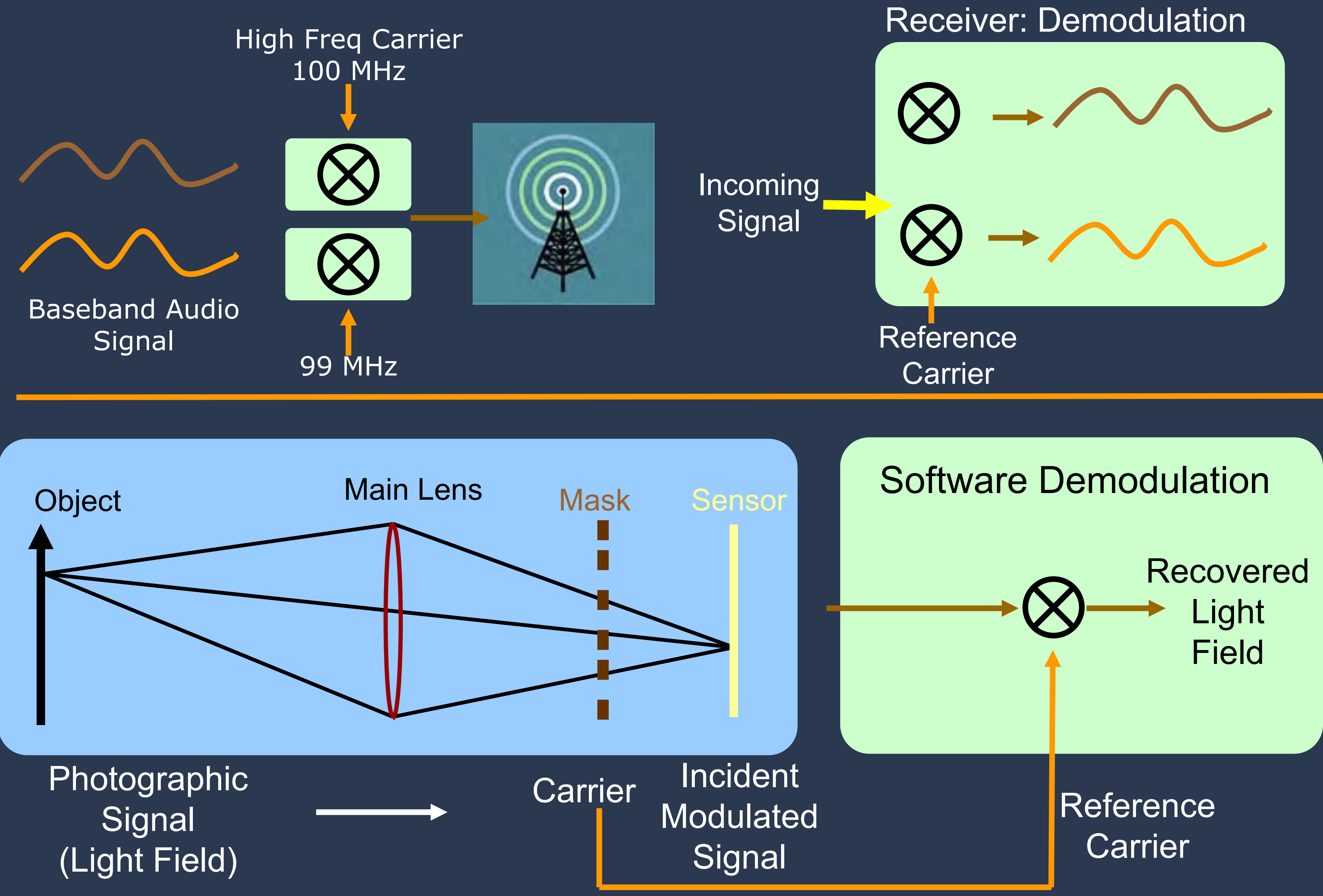
How to Capture 4D Light Field with 2D Sensor ?

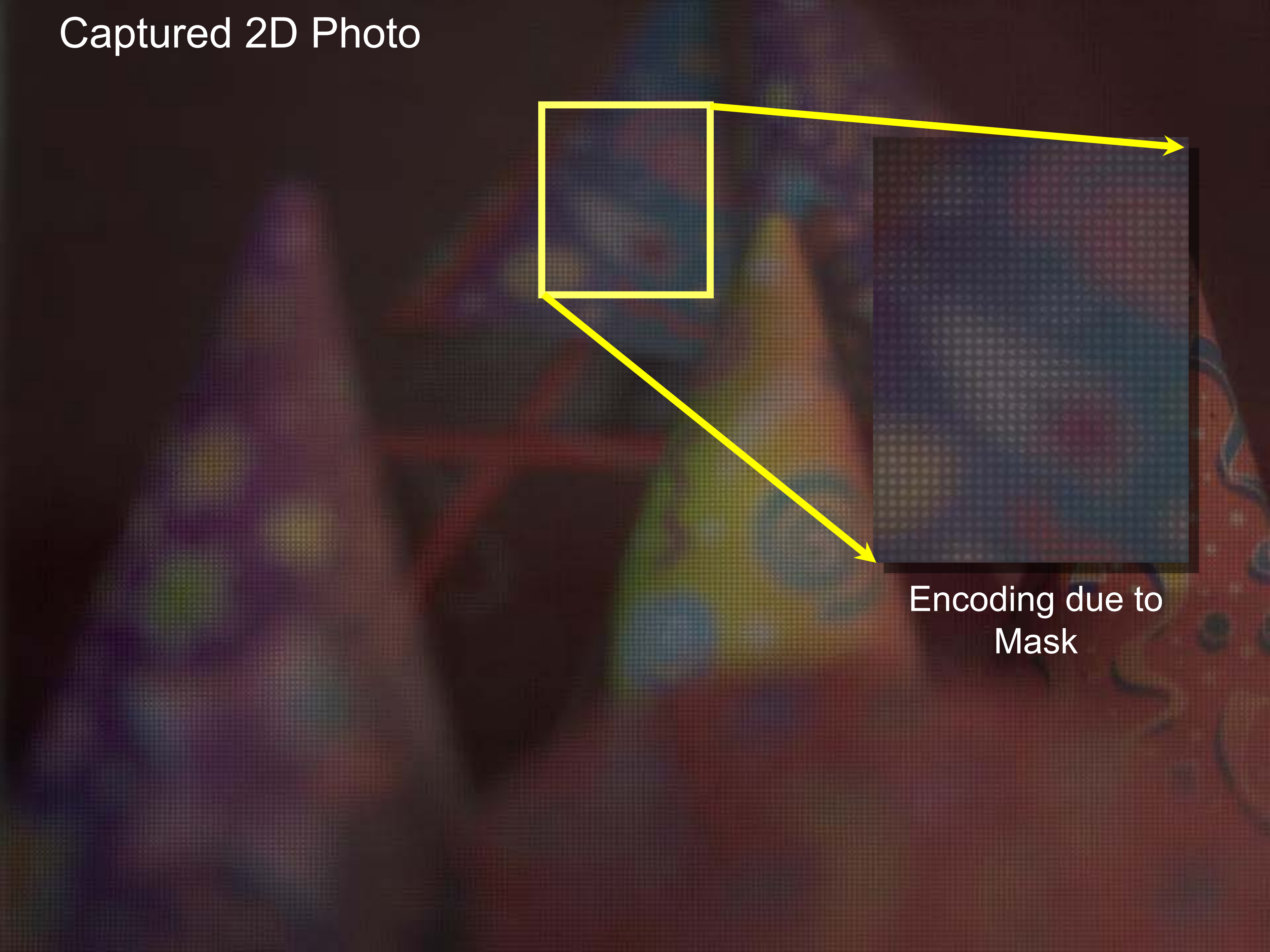
What should be the pattern of the mask ?

Radio Frequency Heterodyning

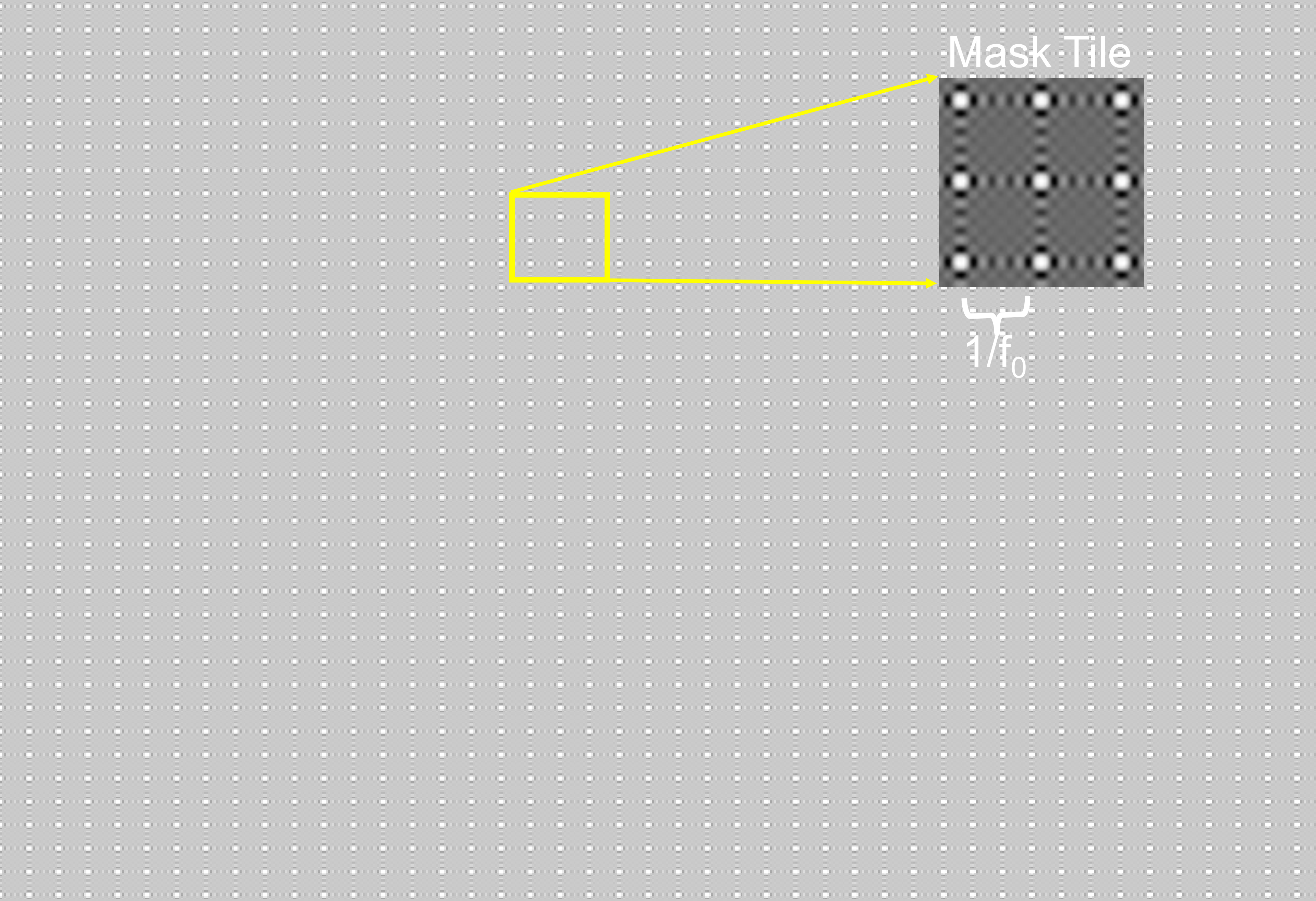


Optical Heterodyning

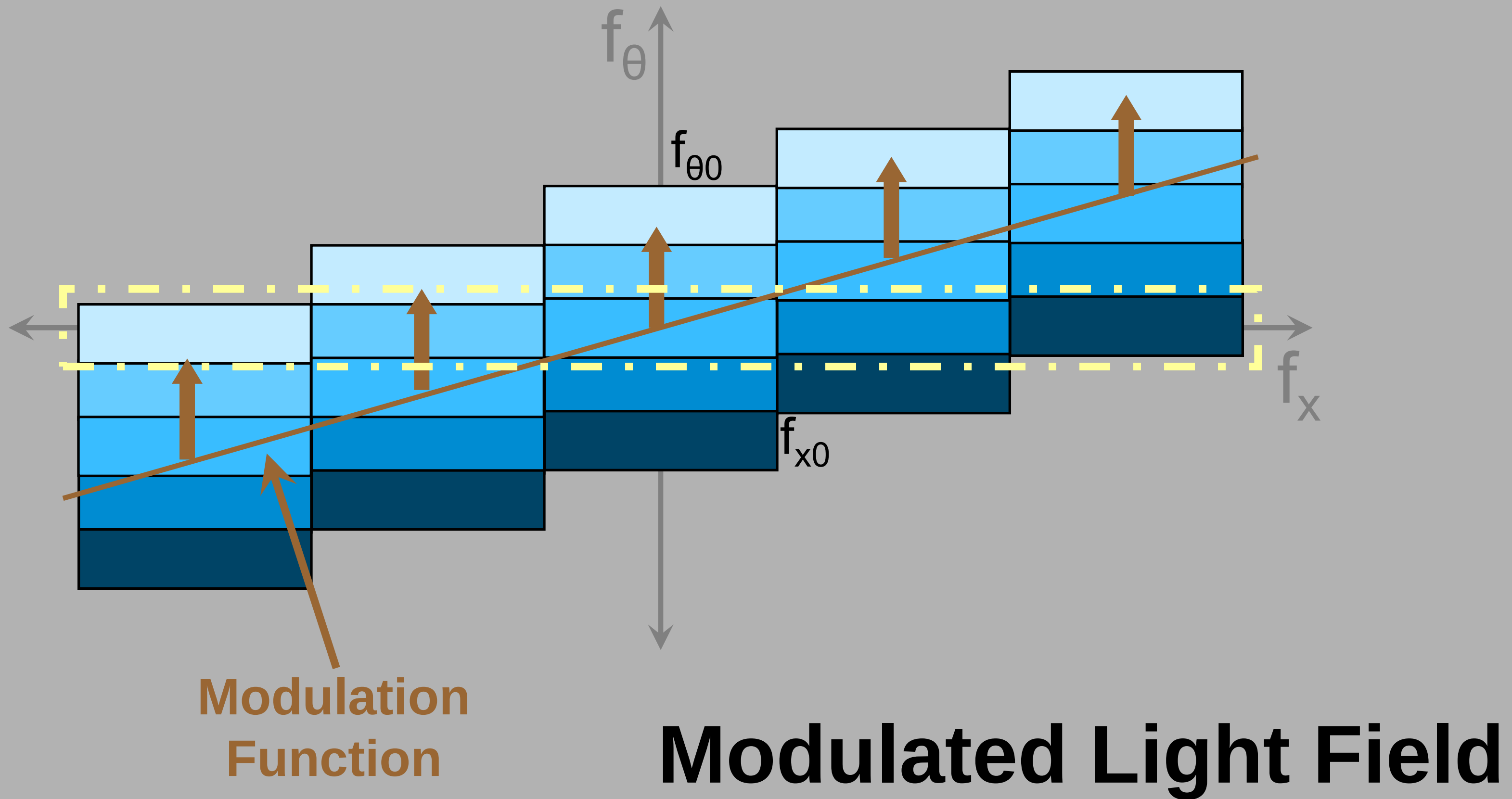



Captured 2D Photo
Encoding due to
Mask

Cosine Mask Used

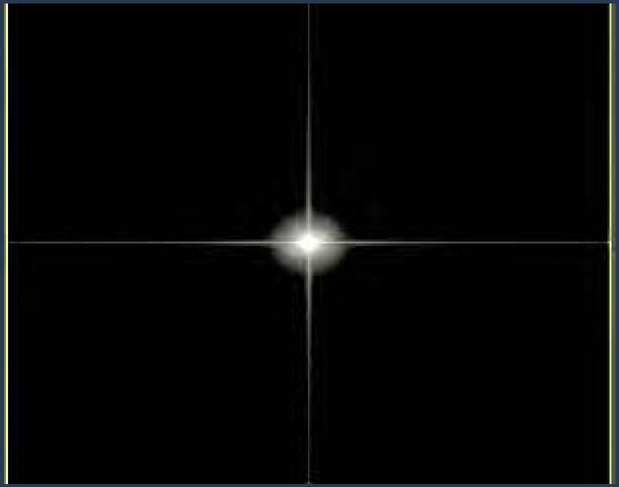


Sensor Slice captures entire Light Field



Traditional Camera Photo

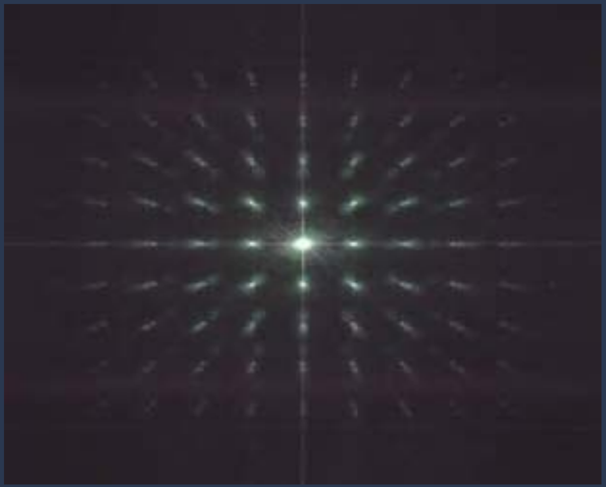
2D
FFT



Magnitude of 2D FFT

Heterodyne Camera Photo

2D
FFT



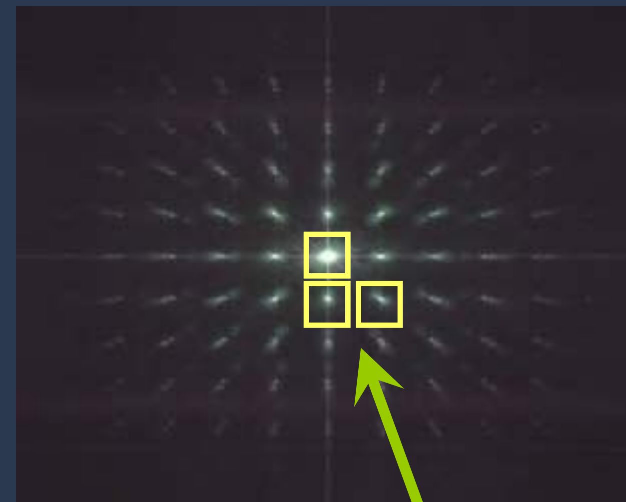
Magnitude of 2D FFT

Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D FFT

2D Fourier Transform, 1800*1800



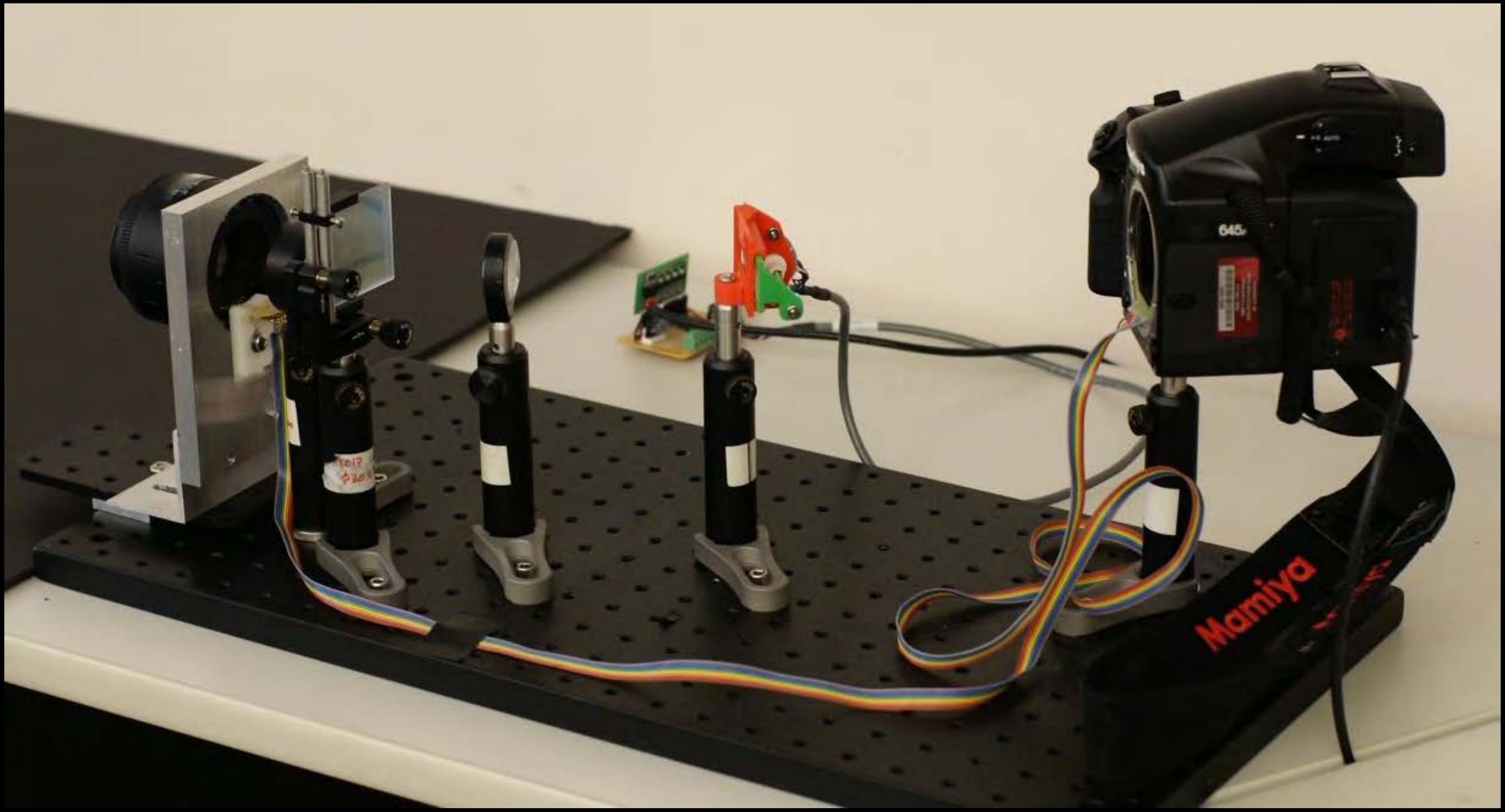
9*9=81 spectral copies

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

4D IFFT

4D Light Field
200*200*9*9

Agile Spectrum Imaging



With Ankit Mohan, Jack Tumblin [Eurographics 2008]

Lens Glare Reduction

[Raskar, Agrawal, Wilson, Veeraraghavan SIGGRAPH 2008]

Glare/Flare due to camera lenses reduces contrast

Glare Reduction/Enhancement using 4D Ray Sampling

Glare Enhanced

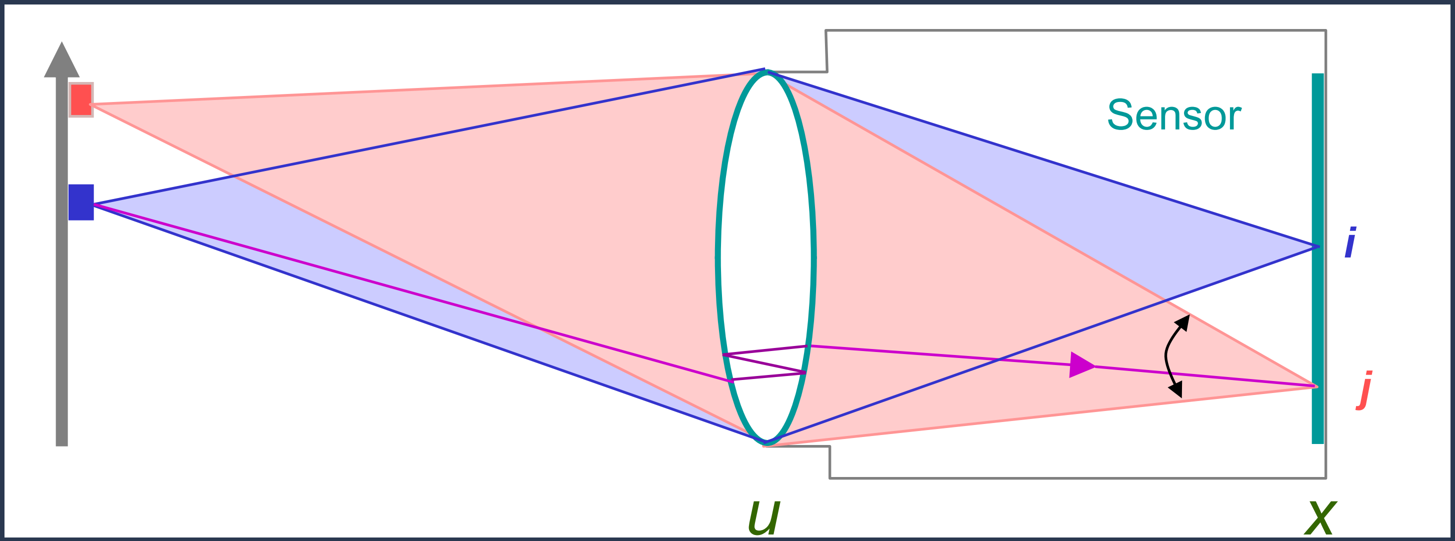
Captured

Glare Reduced

Raskar, R., et al. “Glare Aware Photography: 4D Ray Sampling for Reducing Glare Effects of Camera Lenses.” *Proceedings of SIGGRAPH 2008*.

Glare = low frequency noise in 2D

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



Long-range synthetic aperture photography

Images removed due to copyright restrictions.
See Wilburn, B., et al. “High Performance Imaging Using Large Camera Arrays.” ACM Transactions on Graphics 24, no. 3 (July 2005): 765-776 (Proceedings of ACM SIGGRAPH 2005)
http://graphics.stanford.edu/papers/CameraArray/

Levoy et al., SIGG2005

Synthetic aperture videography

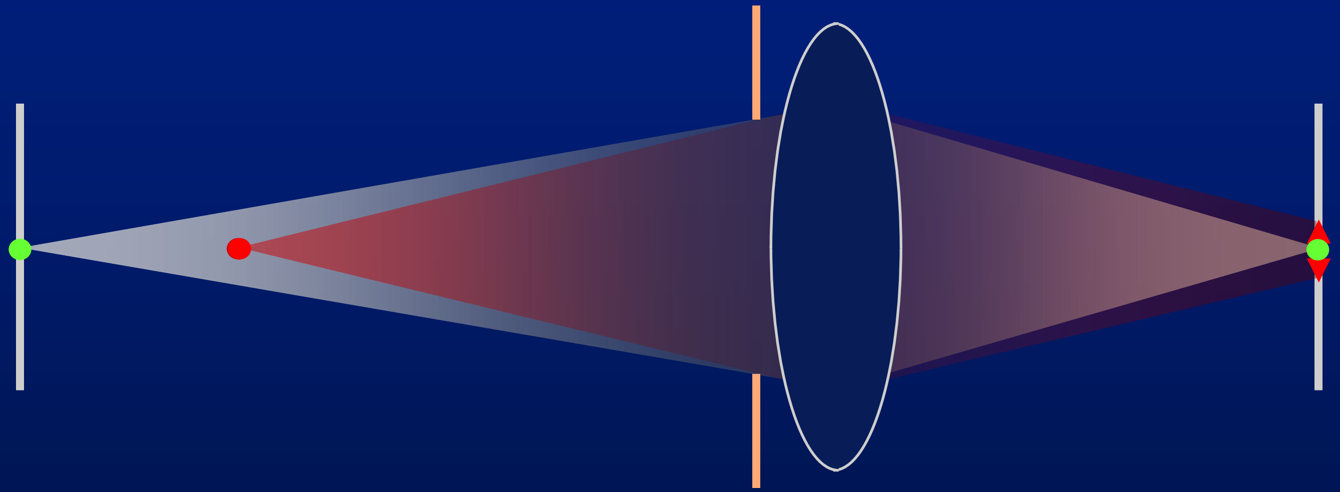
Image removed due to copyright restrictions.

Focus Adjustment: Sum of Bundles

Vaish, V., et al. "Using Plane + Parallax for Calibrating Dense Camera Arrays." *Proceedings of CVPR 2004*.

http://graphics.stanford.edu/papers/plane+parallax_calib/

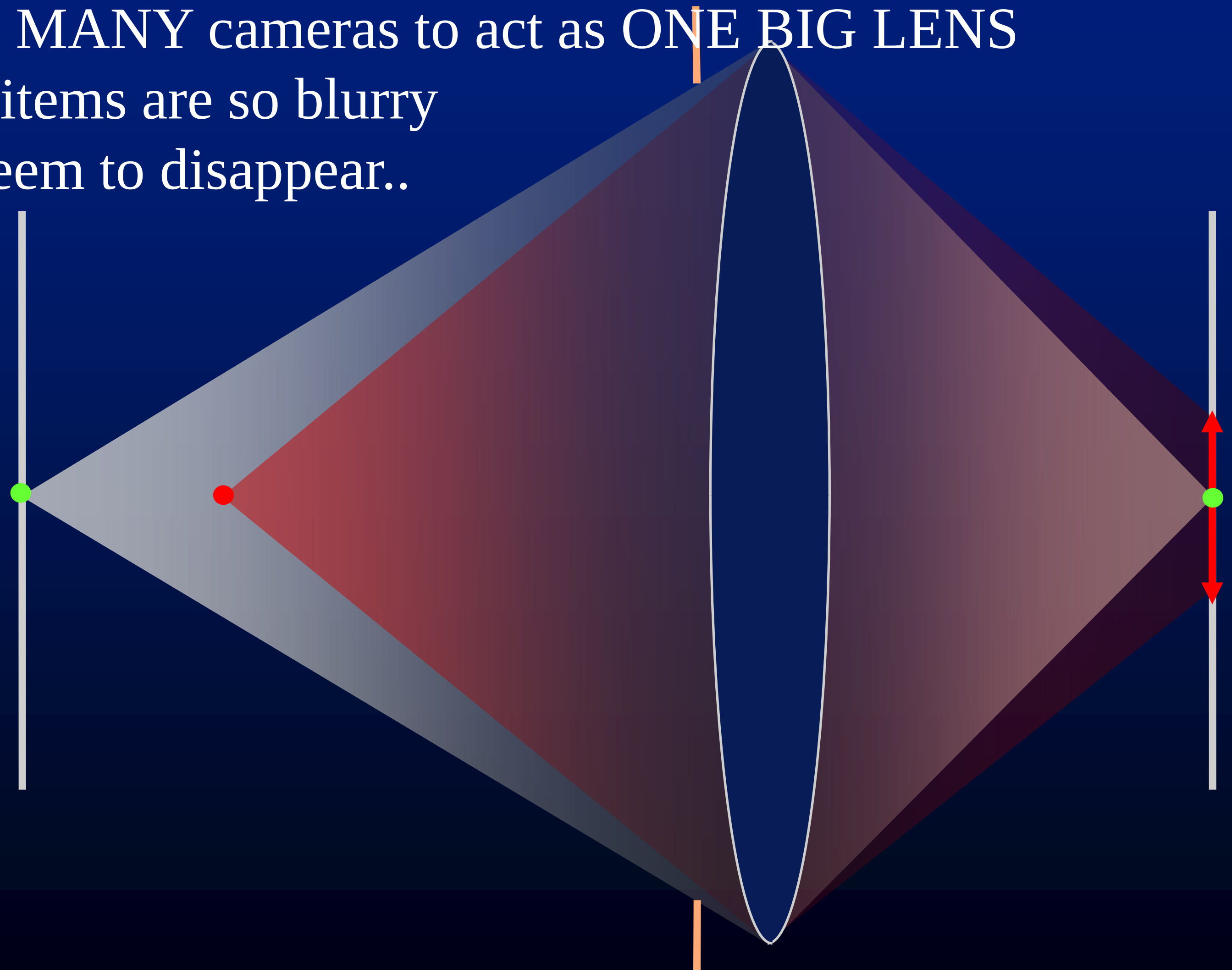
Synthetic aperture photography



Smaller aperture → → less blur, smaller circle of confusion

Synthetic aperture photography

Merge MANY cameras to act as ONE BIG LENS
Small items are so blurry
they seem to disappear..



Light field photography using a handheld plenoptic camera

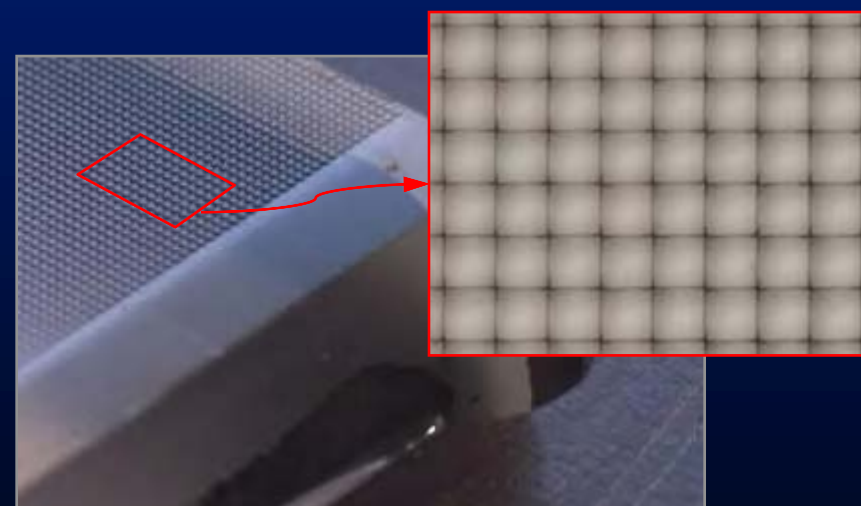
Ren Ng, Marc Levoy, Mathieu Brédif,
Gene Duval, Mark Horowitz and Pat Hanrahan

Prototype camera

Contax medium format camera

Kodak 16-megapixel sensor

Adaptive Optics microlens array



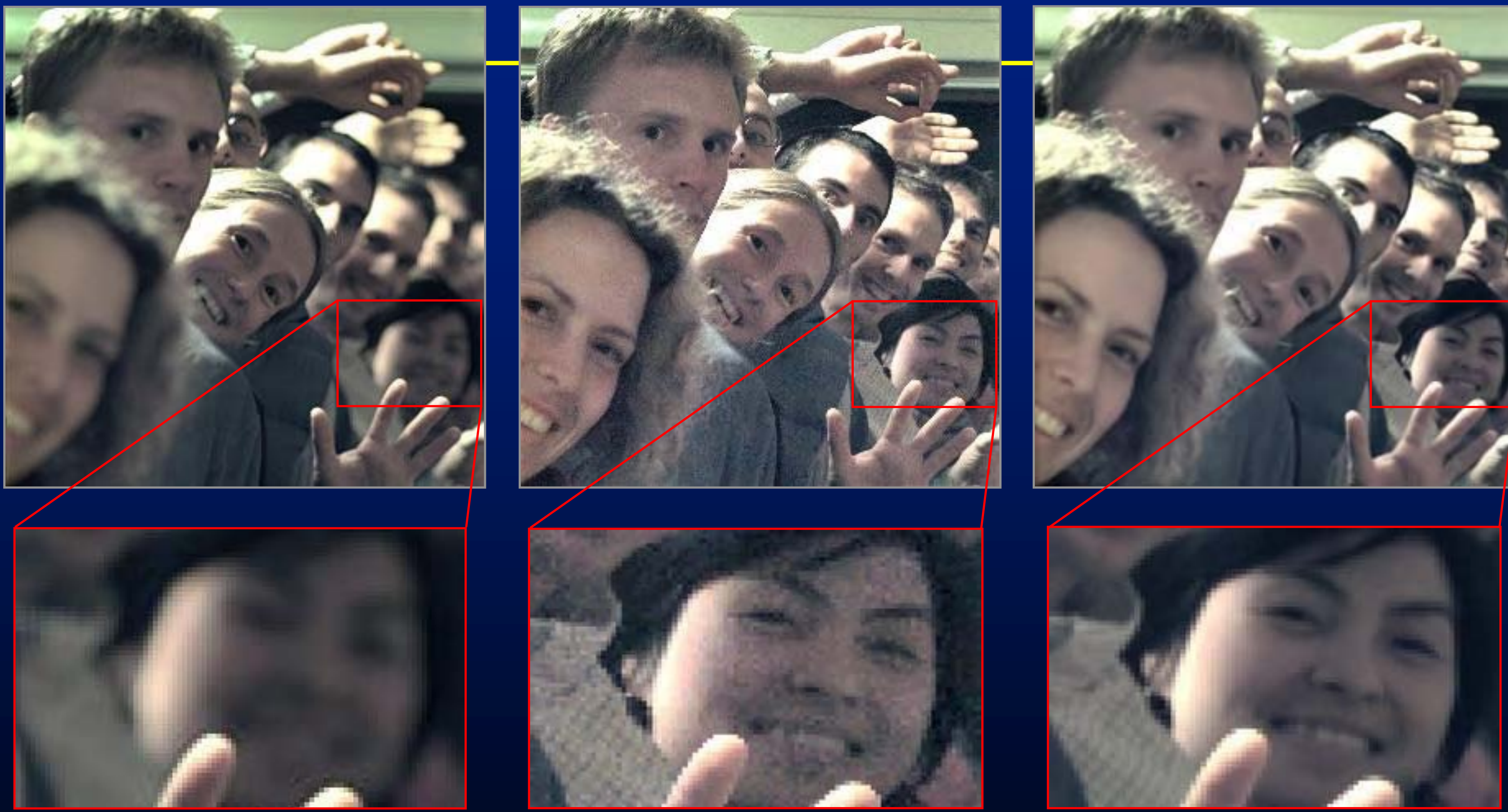
125μ square-sided microlenses

4000 4000 pixels 292 292 lenses = 14 14 pixels

Example of digital refocusing

Courtesy of Ren Ng. Used with permission.

Extending the depth of field



conventional photograph, main lens at *f* / 4

conventional photograph, main lens at *f* / 22

light field, main lens at *f* / 4, after all-focus algorithm [Agarwala 2004]

Imaging in Sciences: Computer Tomography

- http://info.med.yale.edu/intmed/cardio/imaging/techniques/ct_imaging/

Image removed due to copyright restrictions.
Diagram of CT Scanner machine.

Borehole tomography

Diagram and graph removed due to copyright restrictions.

(from Reynolds)

- receivers measure end-to-end travel time
- reconstruct to find velocities in intervening cells
- must use limited-angle reconstruction method (like ART)

Deconvolution microscopy

Two photos of fission yeast cells removed due to copyright restrictions.
See image gallery at http://www.appliedprecision.com/hires/images.asp

ordinary microscope image

deconvolved from focus stack

- competitive with confocal imaging, and much faster
- assumes emission or attenuation, but not scattering
- therefore cannot be applied to opaque objects
- begins with less information than a light field (3D vrs 4D)

Coded-Aperture Imaging

- Lens-free imaging!
- Pinhole-camera sharpness,
  without massive light loss.
- No ray bending (OK for X-ray, gamma ray, etc.)

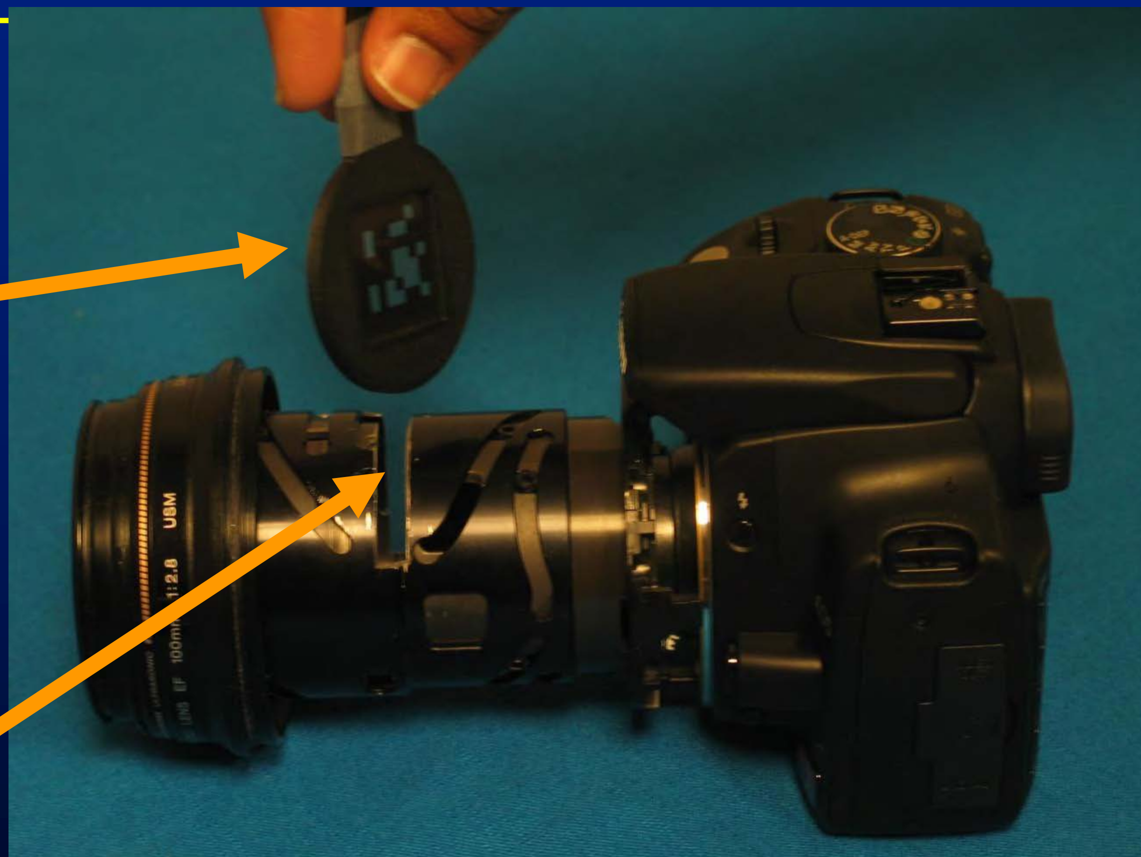
- Two elements
  - Code Mask: binary (opaque/transparent)
  - Sensor grid

- Mask autocorrelation is delta function (impulse)
- Similar to MotionSensor ?

Diagram removed due to copyright restrictions.

Mask in a Camera

Mask



Aperture

Canon EF 100 mm 1:1.28 Lens,
Canon SLR Rebel XT camera

Captured Blurred Image

Refocused Image on Person



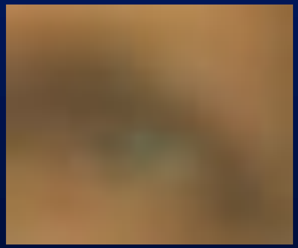
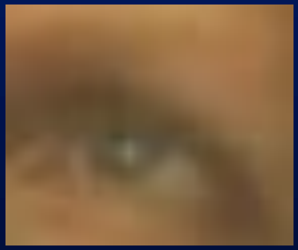
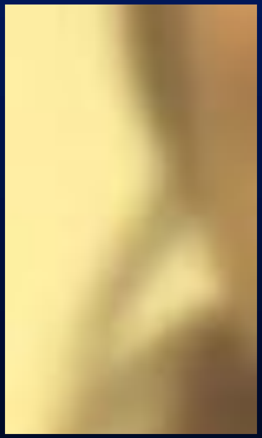
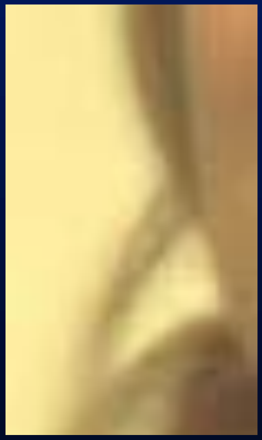
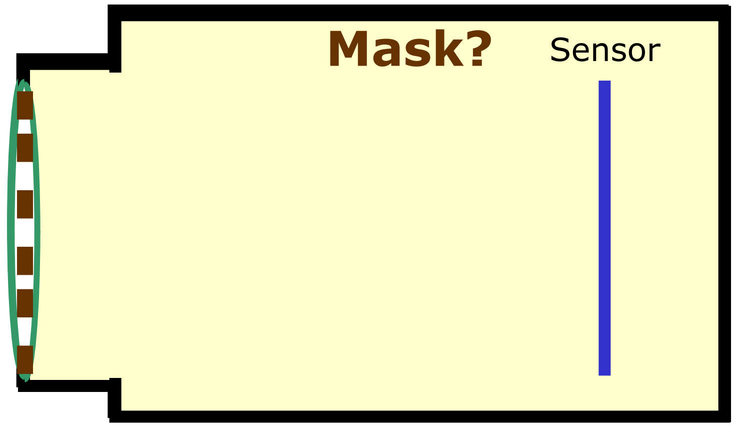
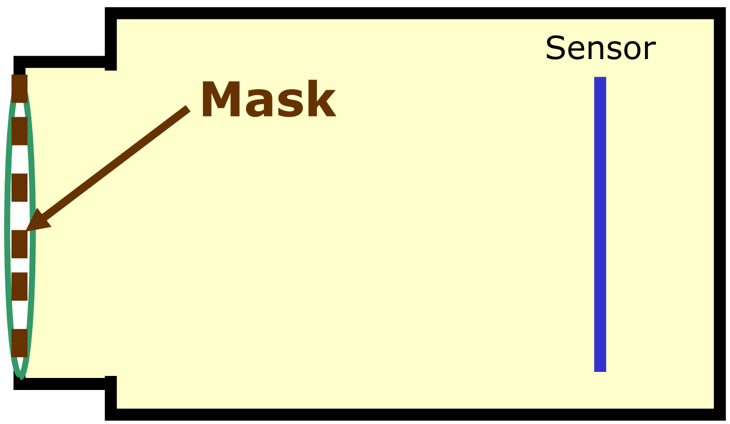





Diagram removed due to copyright restrictions.
Receptor cell and pigment cell.

Larval Trematode Worm





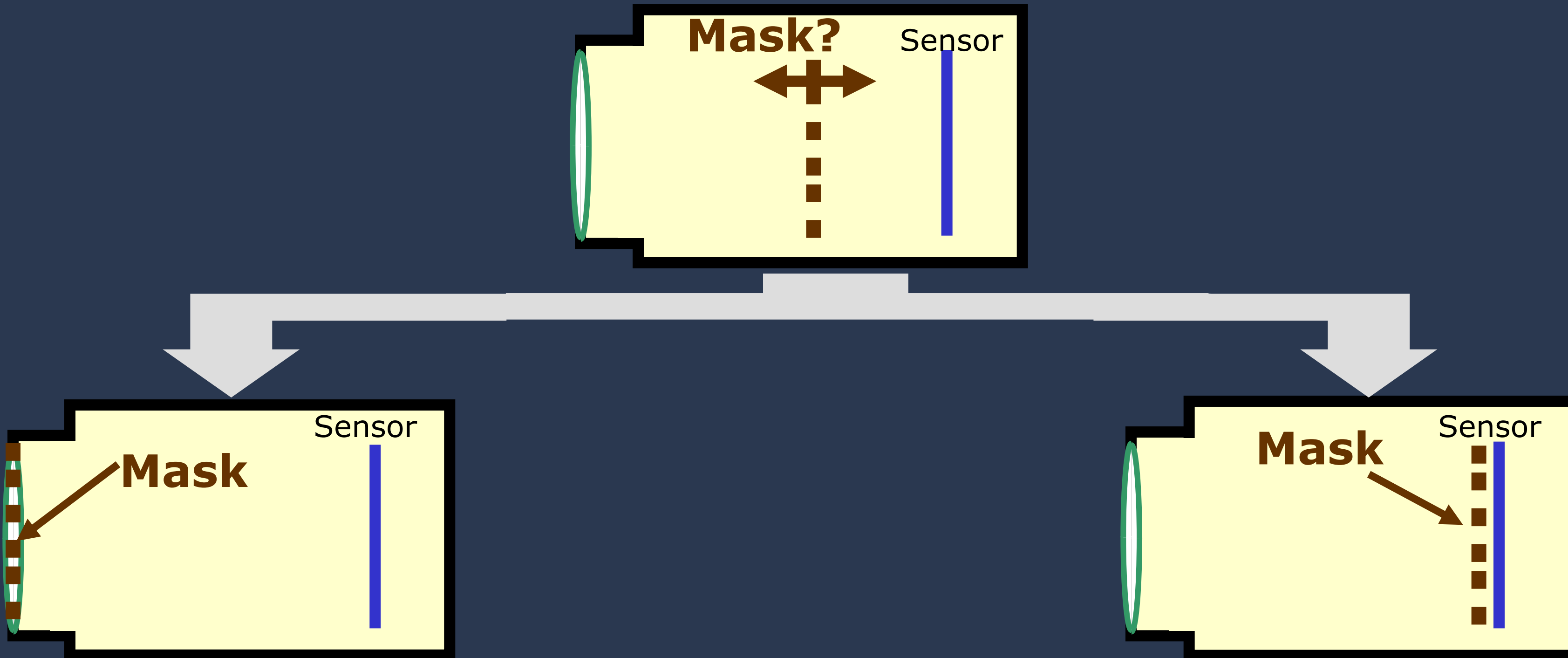
Full Resolution Digital Refocusing:

Coded Aperture Camera

4D Light Field from 2D Photo:

Heterodyne Light Field Camera

Coding and Modulation in Camera Using Masks



Coded Aperture for Full Resolution Digital Refocusing

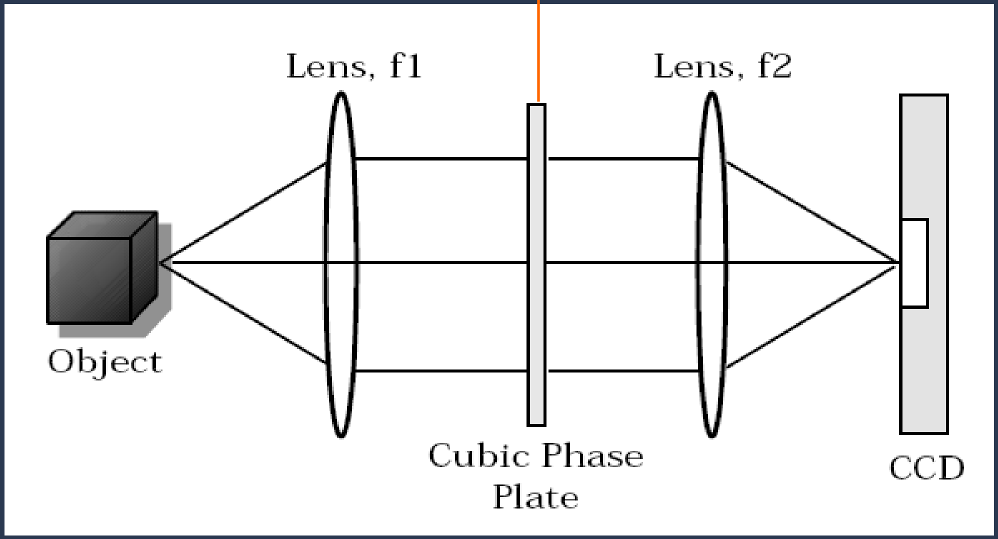
Heterodyne Light Field Camera

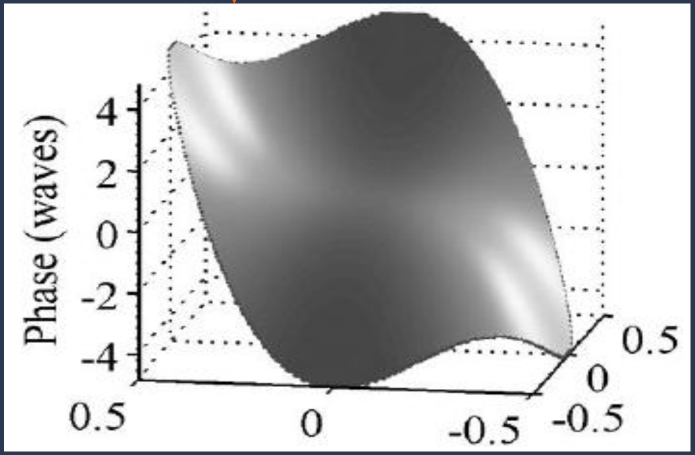
Conventional Lens: Limited Depth of Field

Open Aperture

Smaller Aperture

Wavefront Coding using Cubic Phase Plate

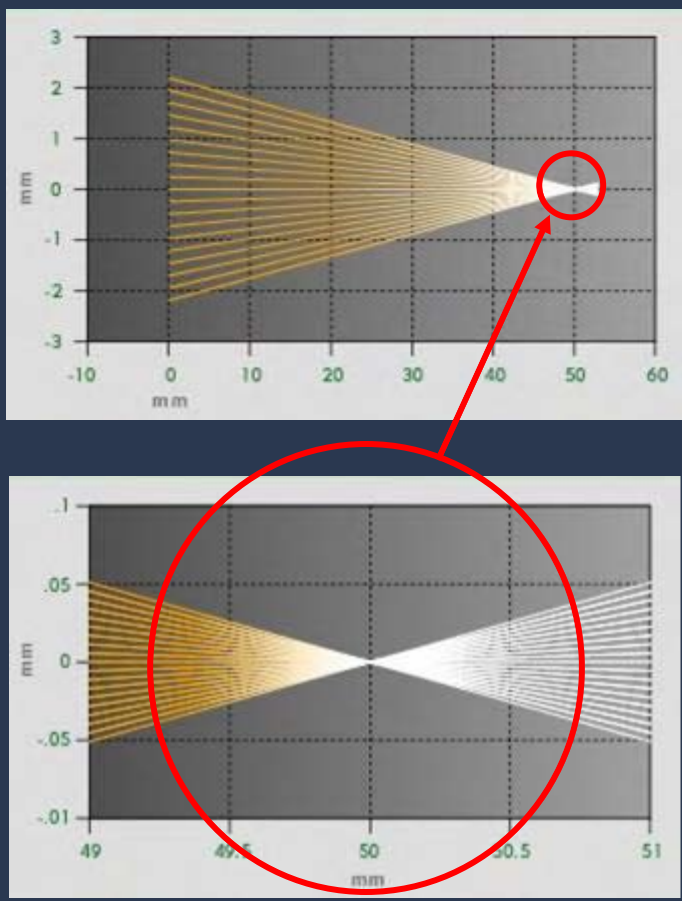




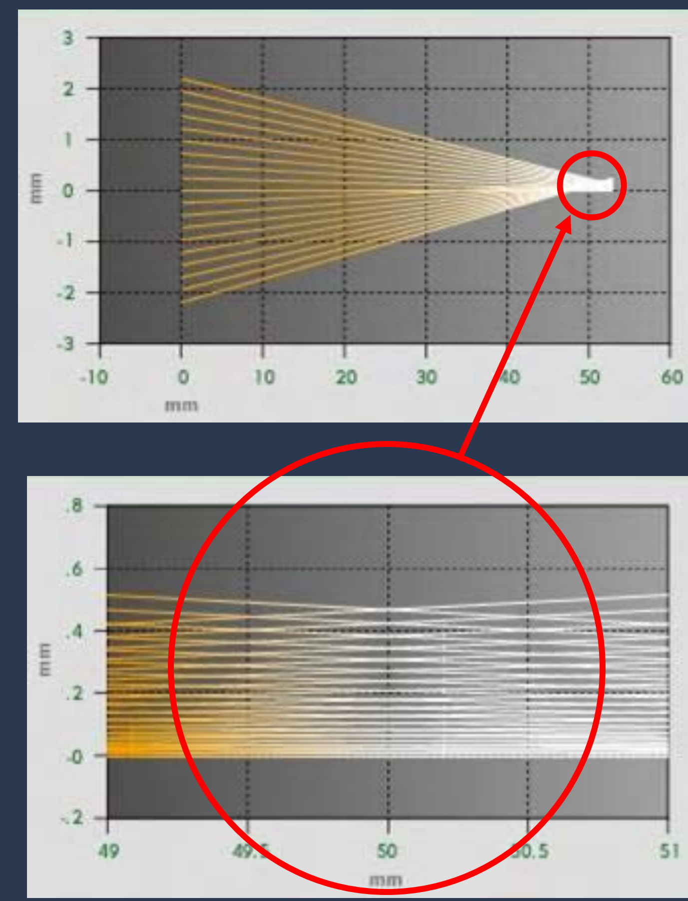
"*Wavefront Coding: jointly optimized optical and digital imaging systems*",
E. Dowski, R. H. Cormack and S. D. Sarama ,
Aerosense Conference, April 25, 2000

Depth Invariant Blur

Conventional System



Wavefront Coded System



Phase mask

Decoding depth via defocus blur

• Design PSF that changes quickly through focus so that defocus can be easily estimated
• Implementation using phase diffractive mask

(Sig 2008, Levin et al used amplitude mask)

Typical PSF changes slowly

Designed PSF changes fast

Images removed due to copyright restrictions.

R. Piestun, Y. Schechner, J. Shamir, “Propagation-Invariant Wave Fields with Finite Energy,” JOSA A **17, 294-303 (2000)**
R. Piestun, J. Shamir, “Generalized propagation invariant wave-fields,” JOSA A 15, 3039 (1998)

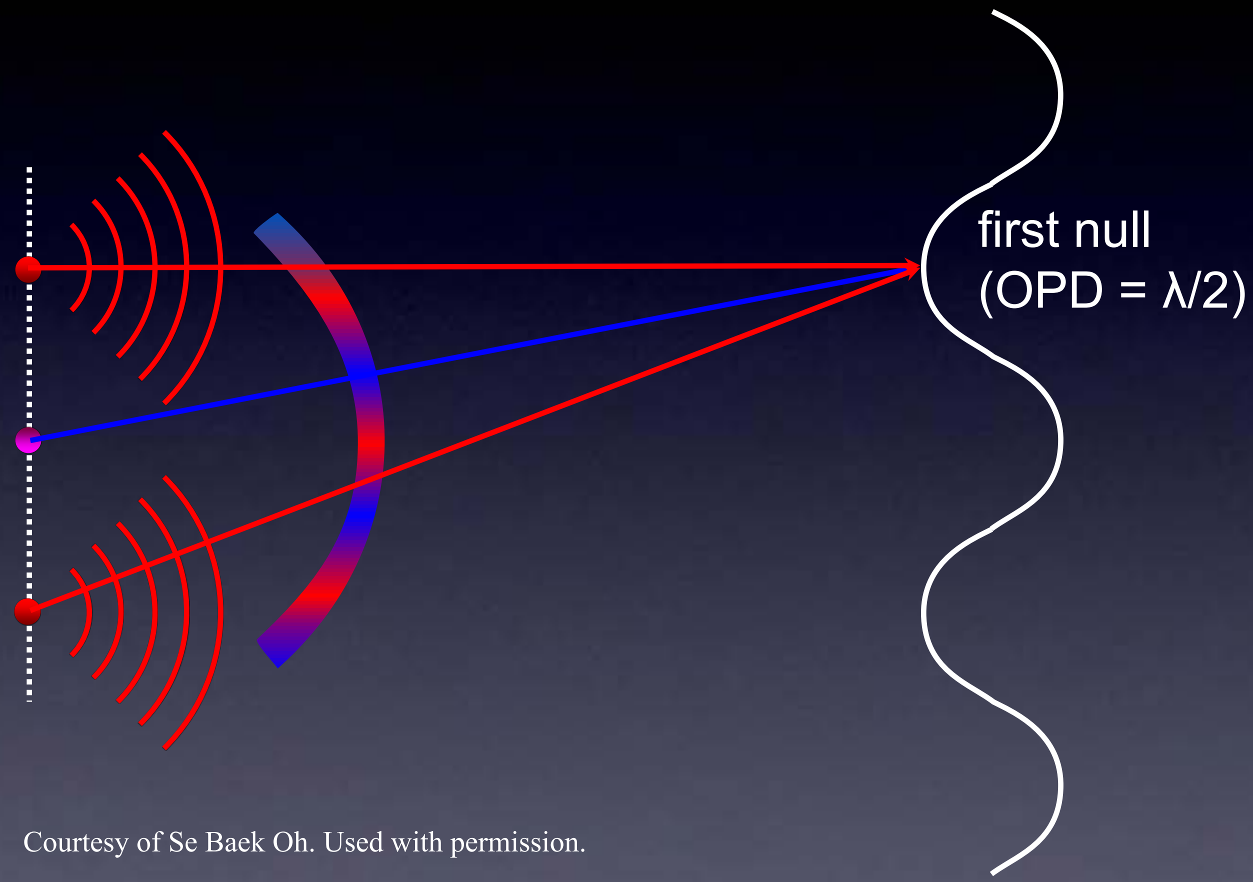
Rotational PSF

Images removed due to copyright restrictions.

R. Piestun, Y. Schechner, J. Shamir, "Propagation-Invariant Wave Fields with Finite Energy," JOSA A **17, 294-303 (2000)**
R. Piestun, J. Shamir, "Generalized propagation invariant wave-fields," JOSA A 15, 3039 (1998)

Can we deal with particle-wave duality of light with modern Lightfield theory ?

Young's Double Slit Expt



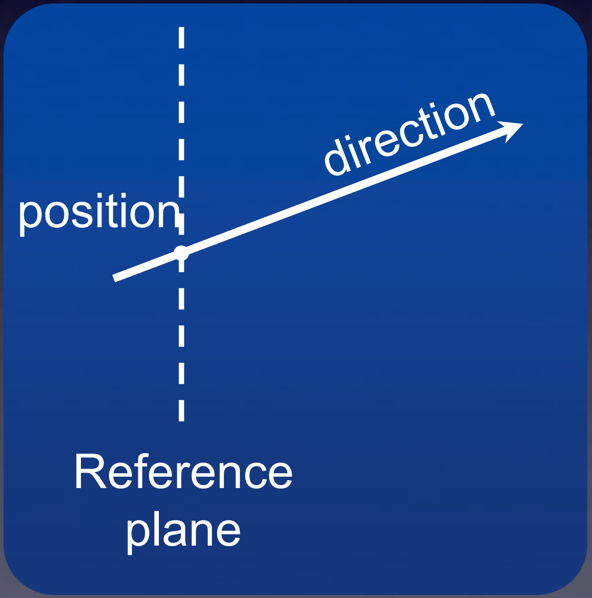
Courtesy of Se Baek Oh. Used with permission.

Diffraction and Interferences modeled using Ray representation

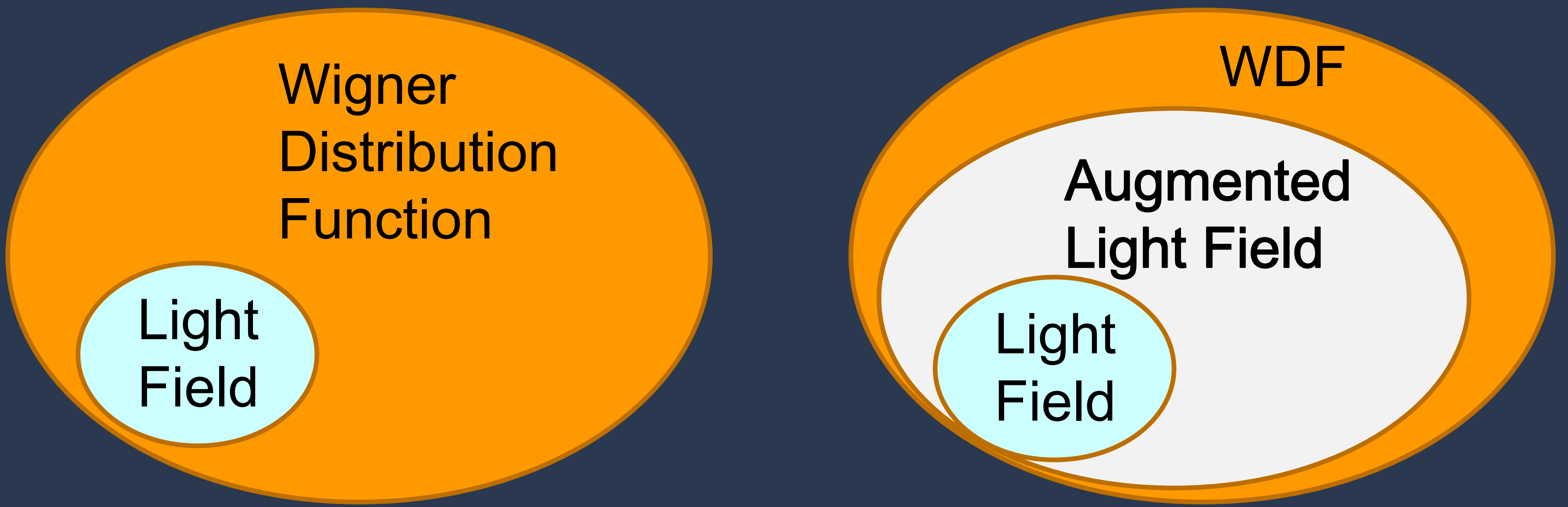
Light Fields

Goal: Representing propagation, interaction and image formation of light using purely position and angle parameters

- Radiance per ray
- Ray parameterization:
  - Position : x
  - Direction : θ



Light Fields for Wave Optics Effects



LF < WDF

Lacks phase properties
Ignores diffraction, phase masks

Radiance = Positive

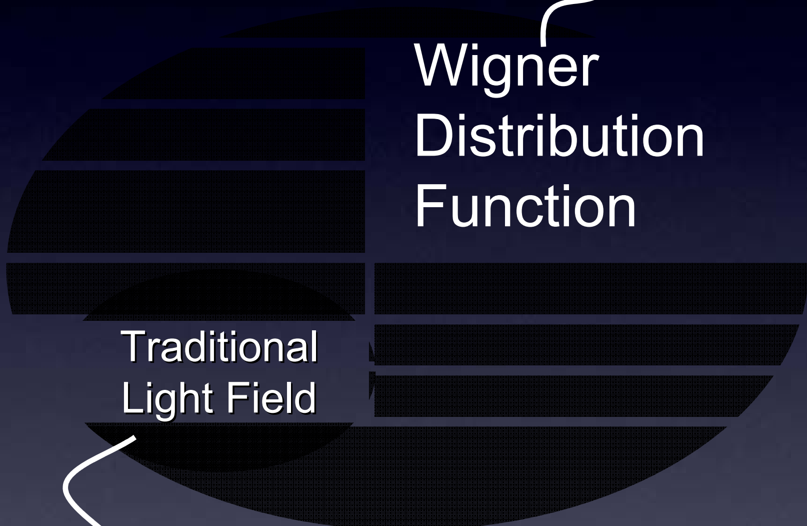
ALF ~ WDF

Supports coherent/incoherent

Radiance = Positive/Negative
Virtual light sources

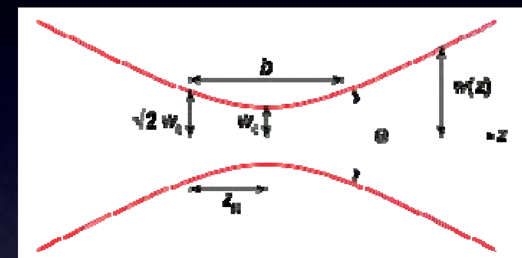
Limitations of Traditional Lightfields

rigorous but cumbersome
wave optics based

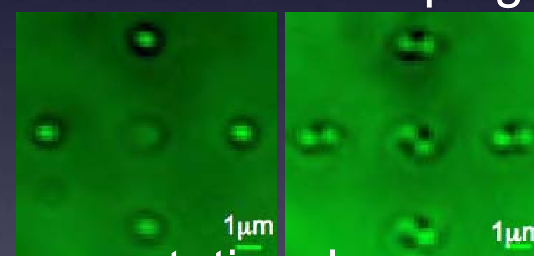


ray optics based
simple and powerful
limited in diffraction & interference

holograms



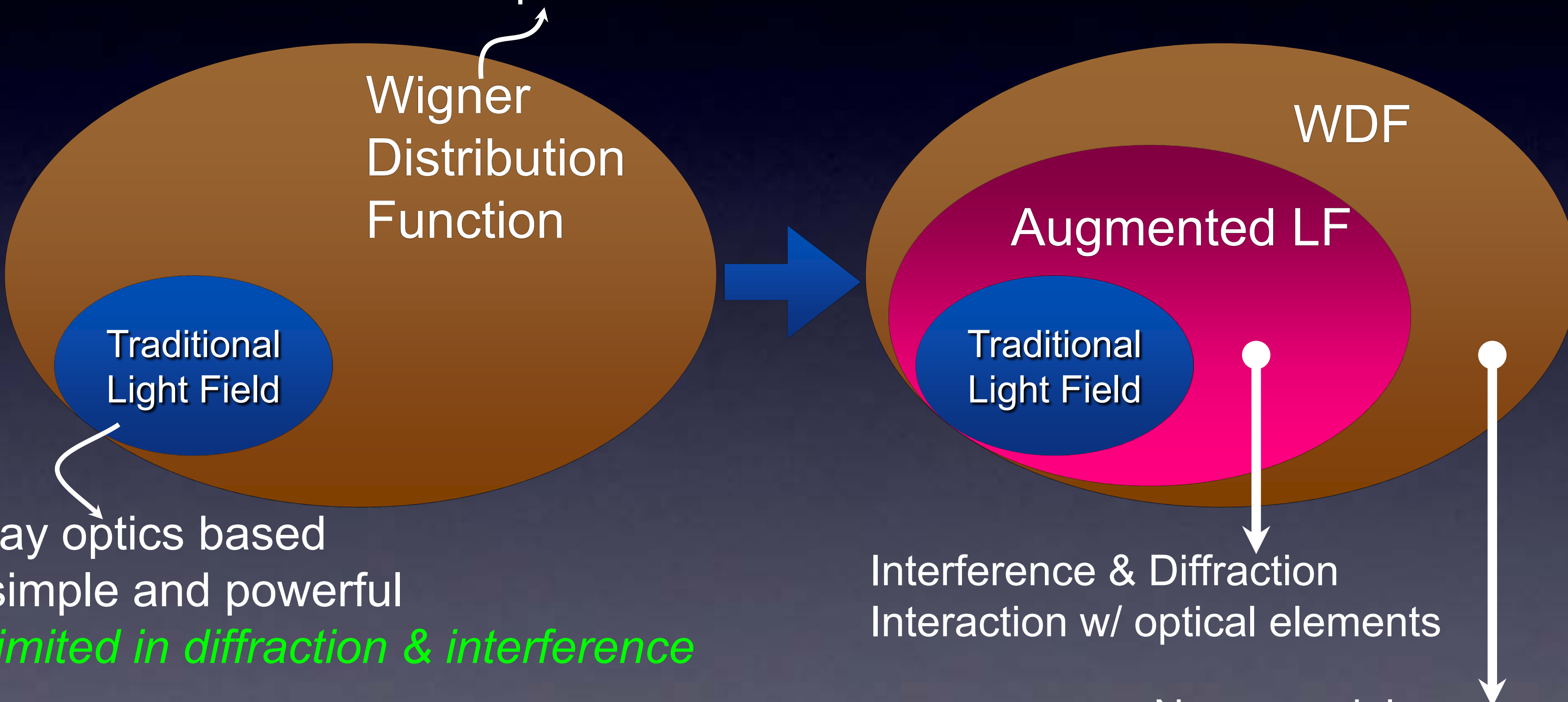
beam shaping



rotational
PSF

Example: New Representations Augmented Lightfields

rigorous but cumbersome
wave optics based



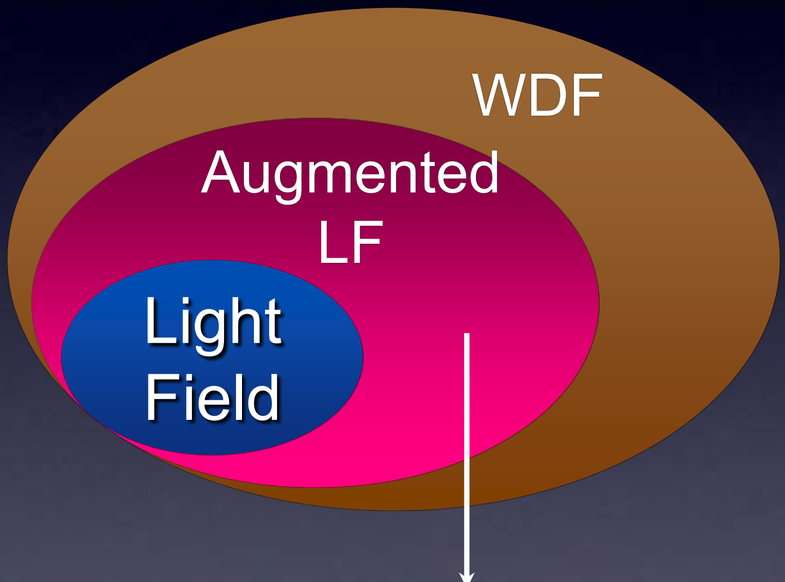
ray optics based
simple and powerful
limited in diffraction & interference

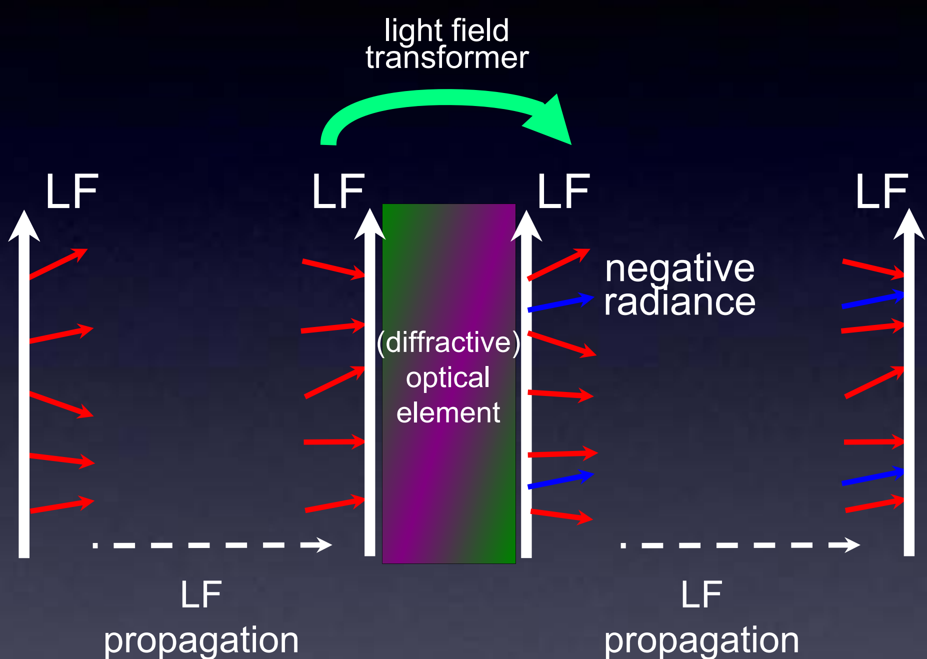
Interference & Diffraction
Interaction w/ optical elements

Non-paraxial
propagation

http://raskar.scripts.mit.edu/~raskar/lightfields/

(ii) Augmented Light Field with LF Transformer



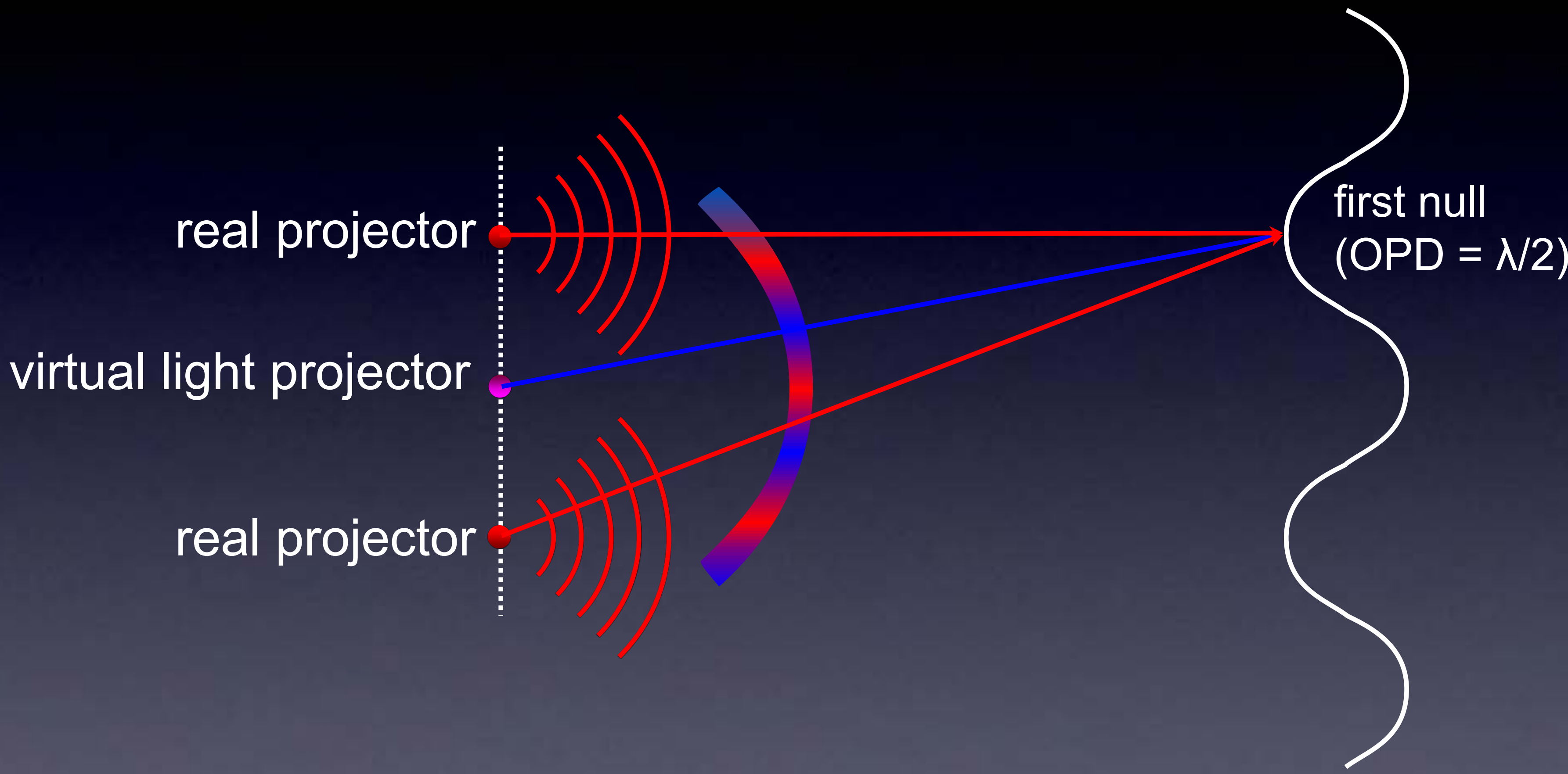


Interaction at the optical elements

Courtesy of Se Baek Oh. Used with permission.

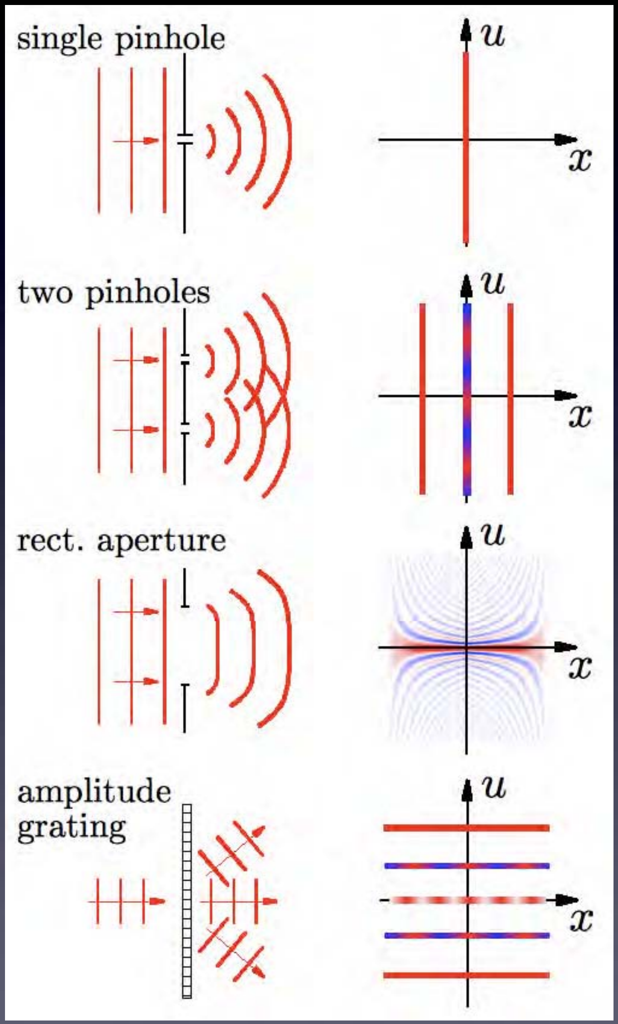
Augmenting Light Field to Model Wave Optics Effects , [Oh, Barbastathis, Raskar]

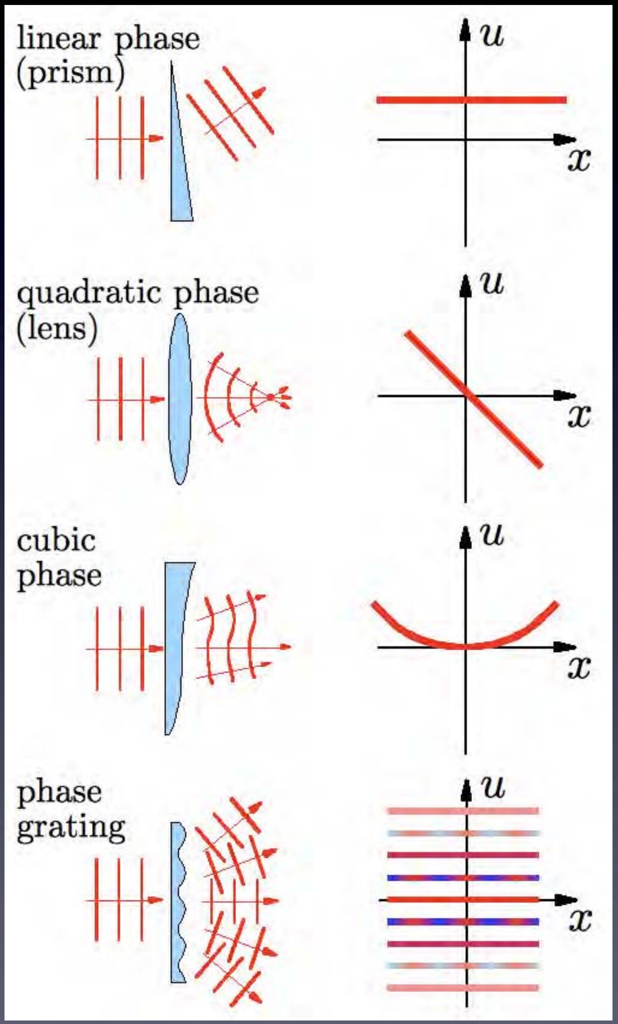
Virtual light projector with real valued (possibly <u>negative</u> radiance) along a ray



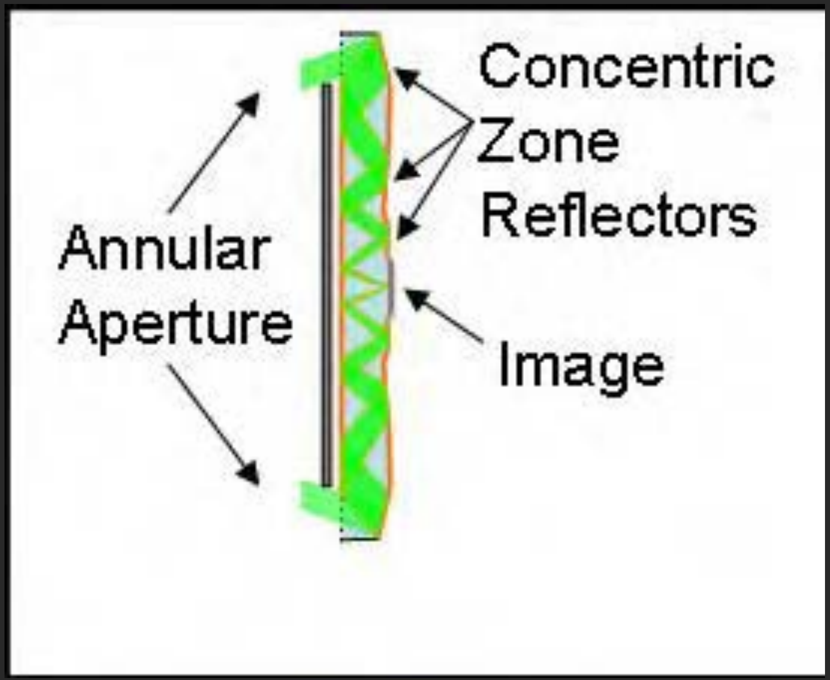
Courtesy of Se Baek Oh. Used with permission.

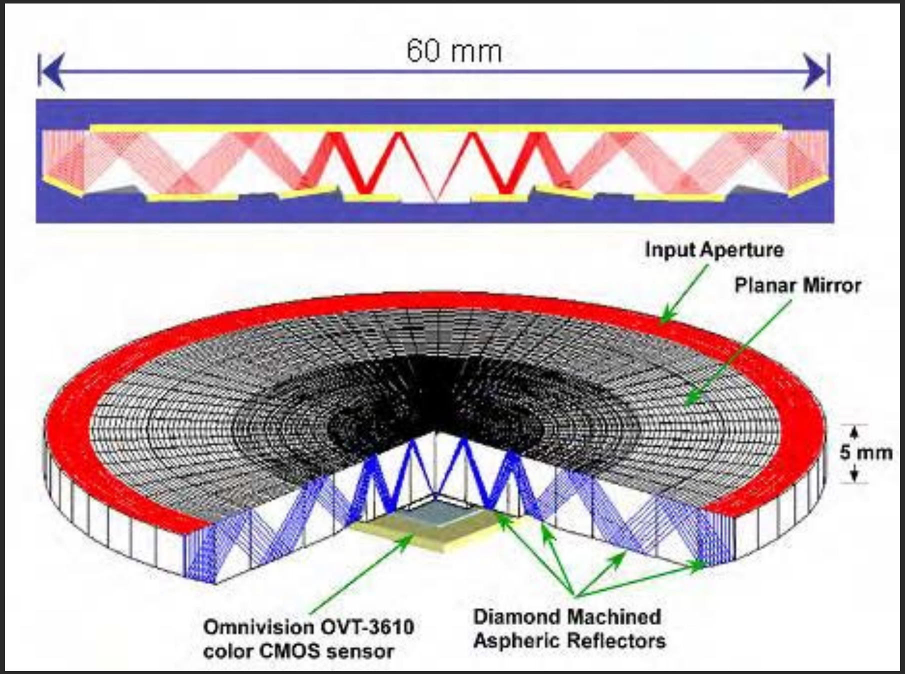
(ii) ALF with LF Transformer





"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

Slide by Shree Nayar

Gradient Index (GRIN) Optics

Refractive Index along width

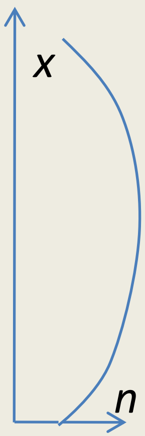


Diagram removed due to copyright restrictions.

Gradient Index 'Lens'

Continuous change of the refractive index within the optical material

Change in RI is very small, 0.1 or 0.2

Conventional Convex Lens

Constant refractive index but carefully designed geometric shape

Photonic Crystals

- ‘Routers’ for photons instead of electrons

- Photonic Crystal
  - Nanostructure material with ordered array of holes
  - A lattice of high-RI material embedded within a lower RI
  - High index contrast
  - 2D or 3D periodic structure

- Photonic band gap
  - Highly periodic structures that blocks certain wavelengths
  - (creates a ‘gap’ or notch in wavelength)

- Applications
  - ‘Semiconductors for light’: mimics silicon band gap for electrons
  - Highly selective/rejecting narrow wavelength filters (Bayer Mosaic?)
  - Light efficient LEDs
  - Optical fibers with extreme bandwidth (wavelength multiplexing)
  - Hype: future terahertz CPUs via optical communication on chip

- Image of small index of refraction gradients in a gas
- Invisible to human eye (subtle mirage effect)

Schlieren Photography

Diagram removed due to copyright restrictions.

Collimated
Light

Knife edge blocks half the light
unless
distorted beam focuses imperfectly

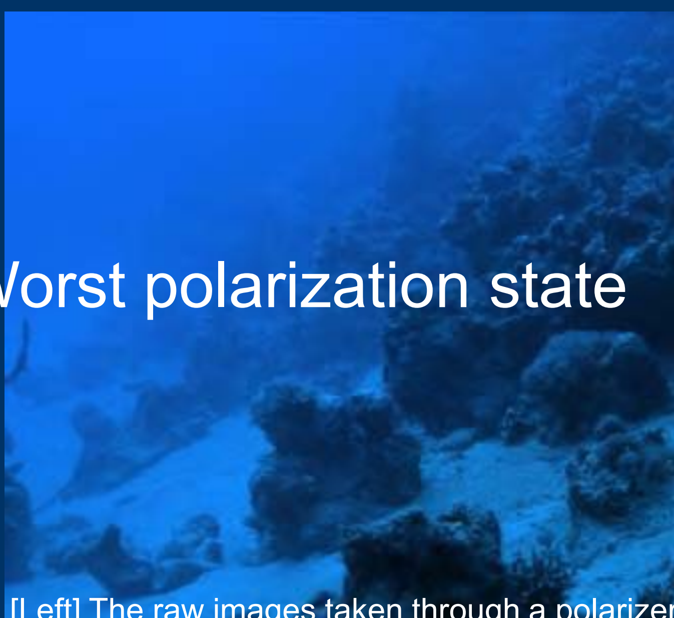
Camera

Photo removed due to copyright restrictions.
"Full-Scale Schlieren Image Reveals The Heat Coming off of a Space Heater, Lamp and Person."
http://www.mne.psu.edu/psgdl/FSSPhotoalbum/index1.htm

Varying Polarization

Yoav Y. Schechner, Nir Karpel 2005

Best polarization state



Worst polarization state

Best polarization state | Recovered image

[Left] The raw images taken through a polarizer. [Right] White-balanced results:
The recovered image is much clearer, especially at distant objects, than the raw image

Varying Polarization

- Schechner, Narasimhan, Nayar
- Instant dehazing of images using polarization

Image removed due to copyright restrictions.
See Fig. 5 in Schechner, Yoav Y., Srinivas G. Narasimhan, and Shree K. Nayar. "Polarization-based Vision Through Haze." *Applied Optics* 42, no. 3 (2003): 511-525.

Photon-x:
Polarization Bayer Mosaic for Surface normals

Images removed due to copyright restrictions.

Novel Sensors

- Gradient sensing
- HDR Camera, Log sensing
- Line-scan Camera
- Demodulating
- Motion Capture
- 3D

- Camera =
  - 0D sensors
    - Motion detector
    - Bar code scanner
    - Time-of-flight range detector (Darpa Grand Challenge)
  - 1D sensors
    - Line scan camera (photofinish)
    - Flatbed scanner
    - Fax machine
  - 2D sensors
  - 2-1/2D sensors
  - ‘3D’ sensors

Line Scan Camera: PhotoFinish 2000 Hz

Images removed due to copyright restrictions.

The CityBlock Project

Images removed due to copyright restrictions.
See http://graphics.stanford.edu/projects/cityblock/

Precursor to Google Streetview Maps

Problem: Motion Deblurring

Input Image

Source: Raskar, Agrawal and Tumblin. “Coded Exposure Photography: Motion Deblurring via Fluttered Shutter.” *Proceedings of SIGGRAPH 2006*.

Source: Raskar, Agrawal and Tumblin. “Coded Exposure Photography: Motion Deblurring via Fluttered Shutter.” *Proceedings of SIGGRAPH 2006*.

Blurred Taxi

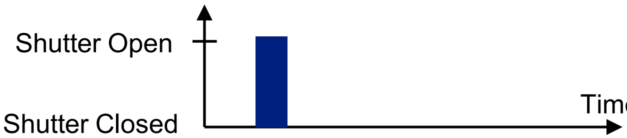
Image Deblurred by solving a linear system. No post-processing

Application: Aerial Imaging

Sharpness versus Image Pixel Brightness

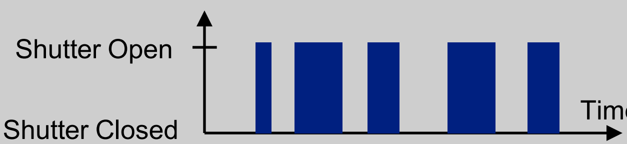
Long Exposure:
The moving camera creates smear

Short Explosure:
Avoids blur. But the image is dark



Goal: Capture <u>sharp image</u> with sufficient <u>brightness</u> using a camera on a fast moving aircraft

Solution:
Flutter Shutter



Application: Electronic Toll Booths

Monitoring Camera for detecting license plates

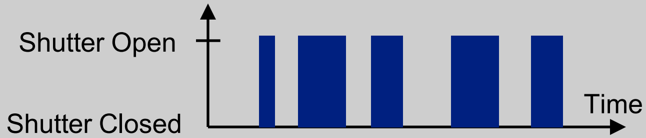
Images removed due to copyright restrictions.

Ideal exposure duration depends on car speed which is difficult to determine a-priory.

Longer exposure duration blurs the license plate image making character recognition difficult

Goal: Automatic number plate recognition from sharp image

Solution:
Sufficiently long exposure duration with fluttered shutter



Fluttered Shutter Camera

Raskar, Agrawal, Tumblin Siggraph2006

Ferroelectric shutter in front of the lens is turned opaque or transparent in a rapid binary sequence

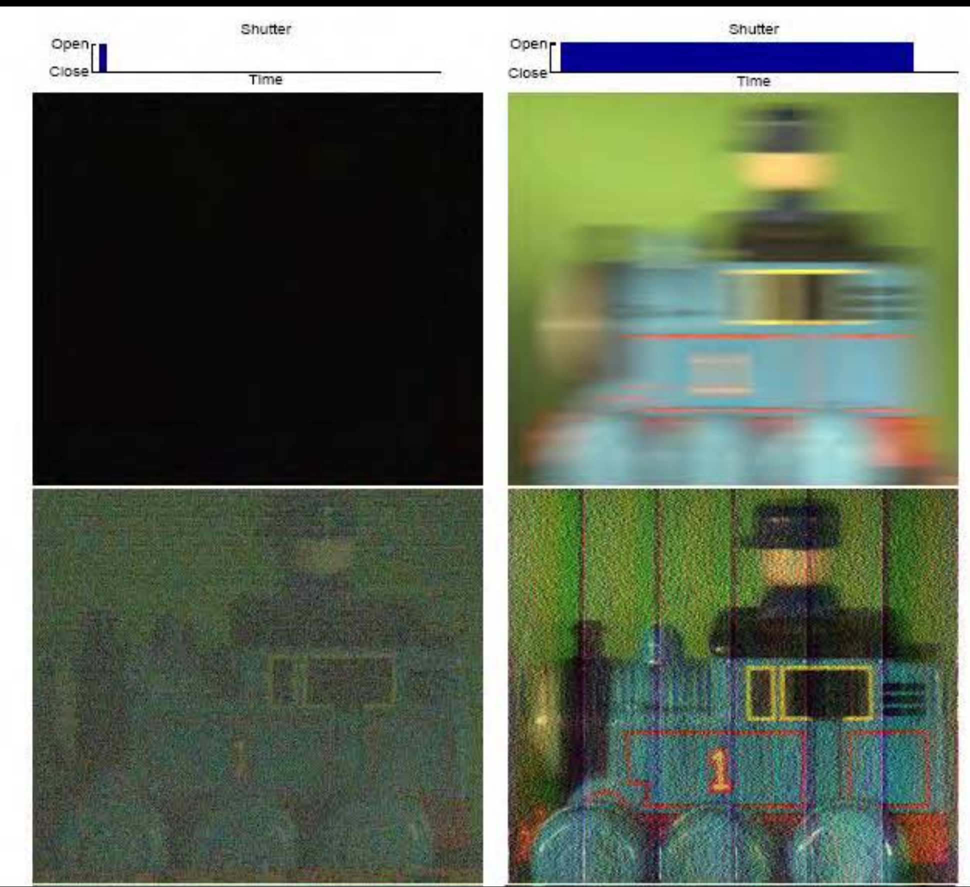
Source: Raskar, Agrawal and Tumblin. "Coded Exposure Photography: Motion Deblurring via Fluttered Shutter." *Proceedings of SIGGRAPH 2006*.

Source: Raskar, Agrawal and Tumblin. "Coded Exposure Photography: Motion Deblurring via Fluttered Shutter." *Proceedings of SIGGRAPH 2006*.

Coded Exposure Photography: Assisting Motion Deblurring using Fluttered Shutter

Raskar, Agrawal, Tumblin (Siggraph2006)

Short Exposure | Traditional | Coded



← Shutter →

← Captured Photos →

← Deblurred Results →

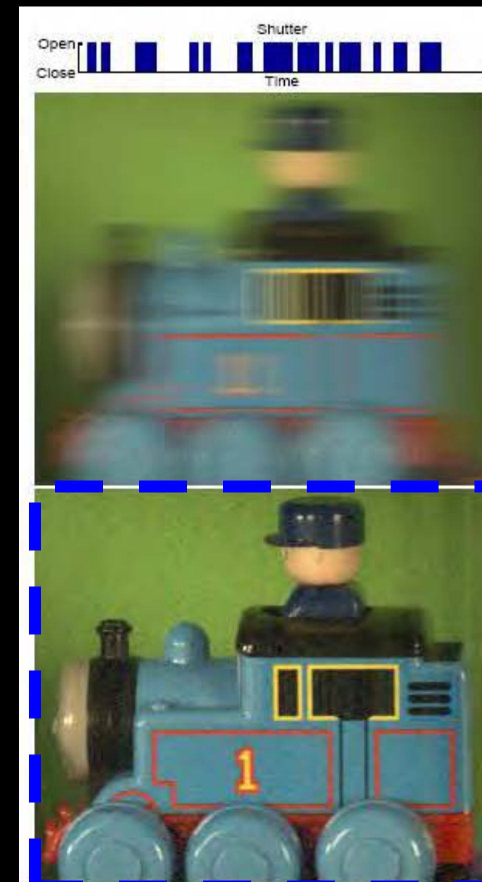


Image is dark and noisy

Result has Banding Artifacts and some spatial frequencies are lost

Decoded image is as good as image of a static scene

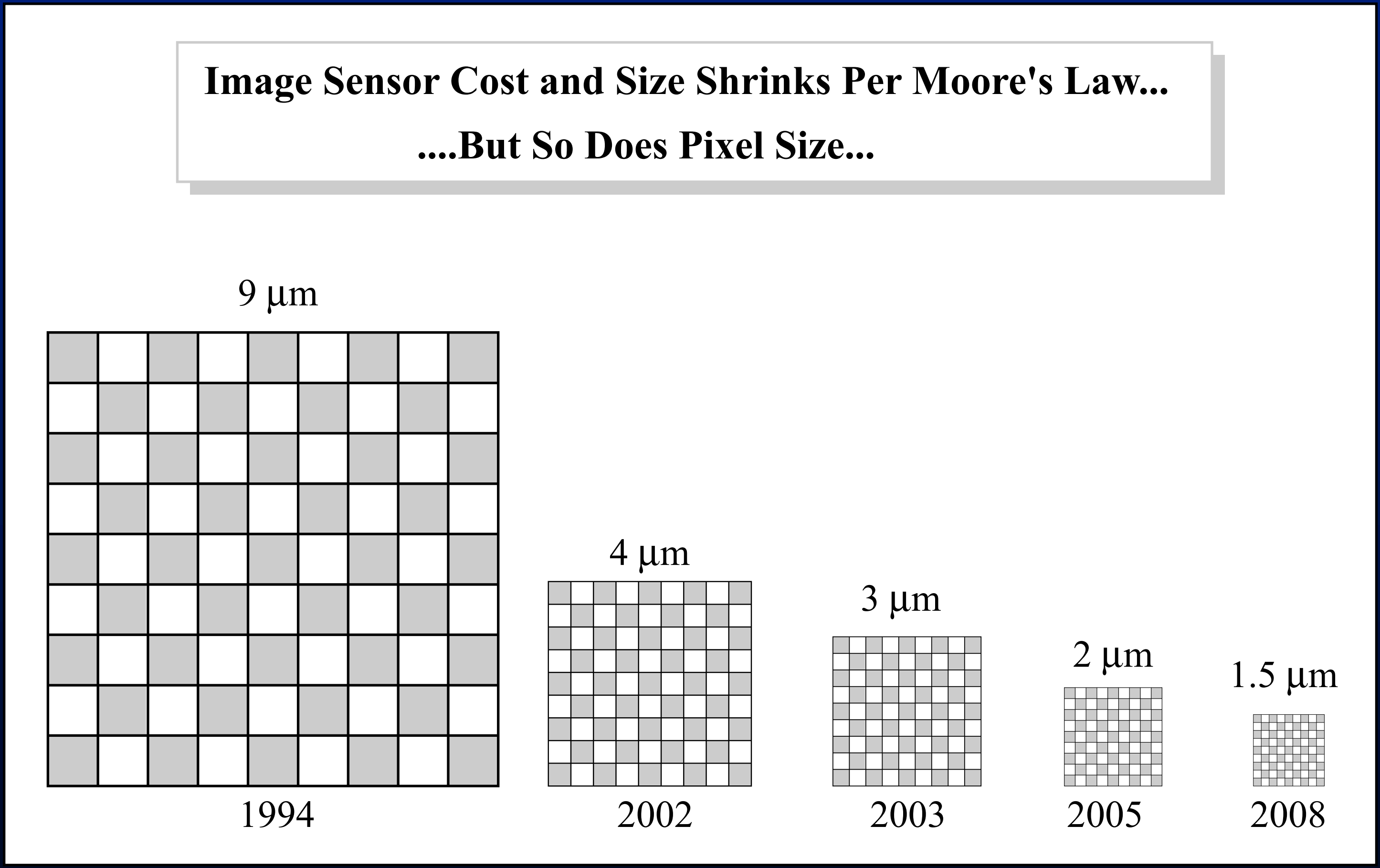
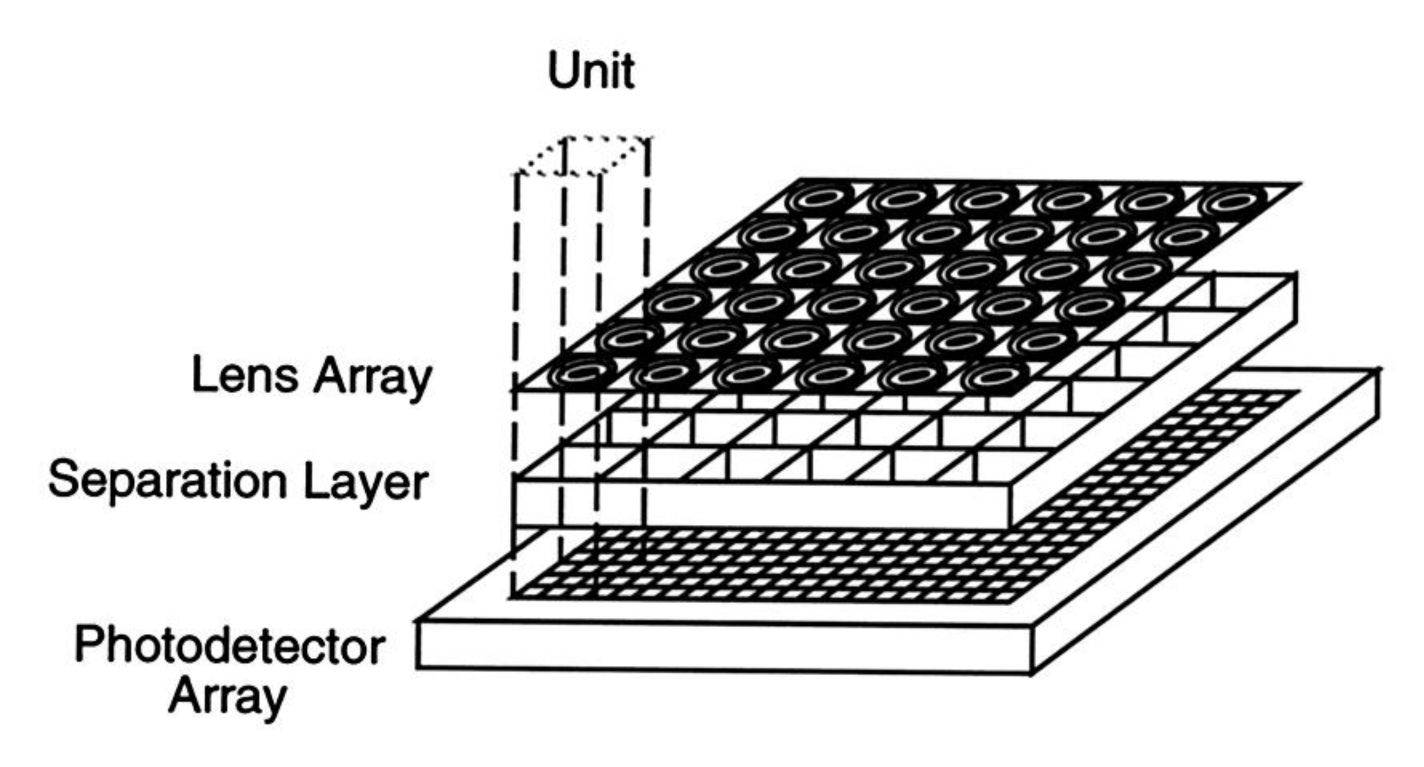


Figure by MIT OpenCourseWare. Data from Prismark and Tessera.

Compound Lens of Dragonfly

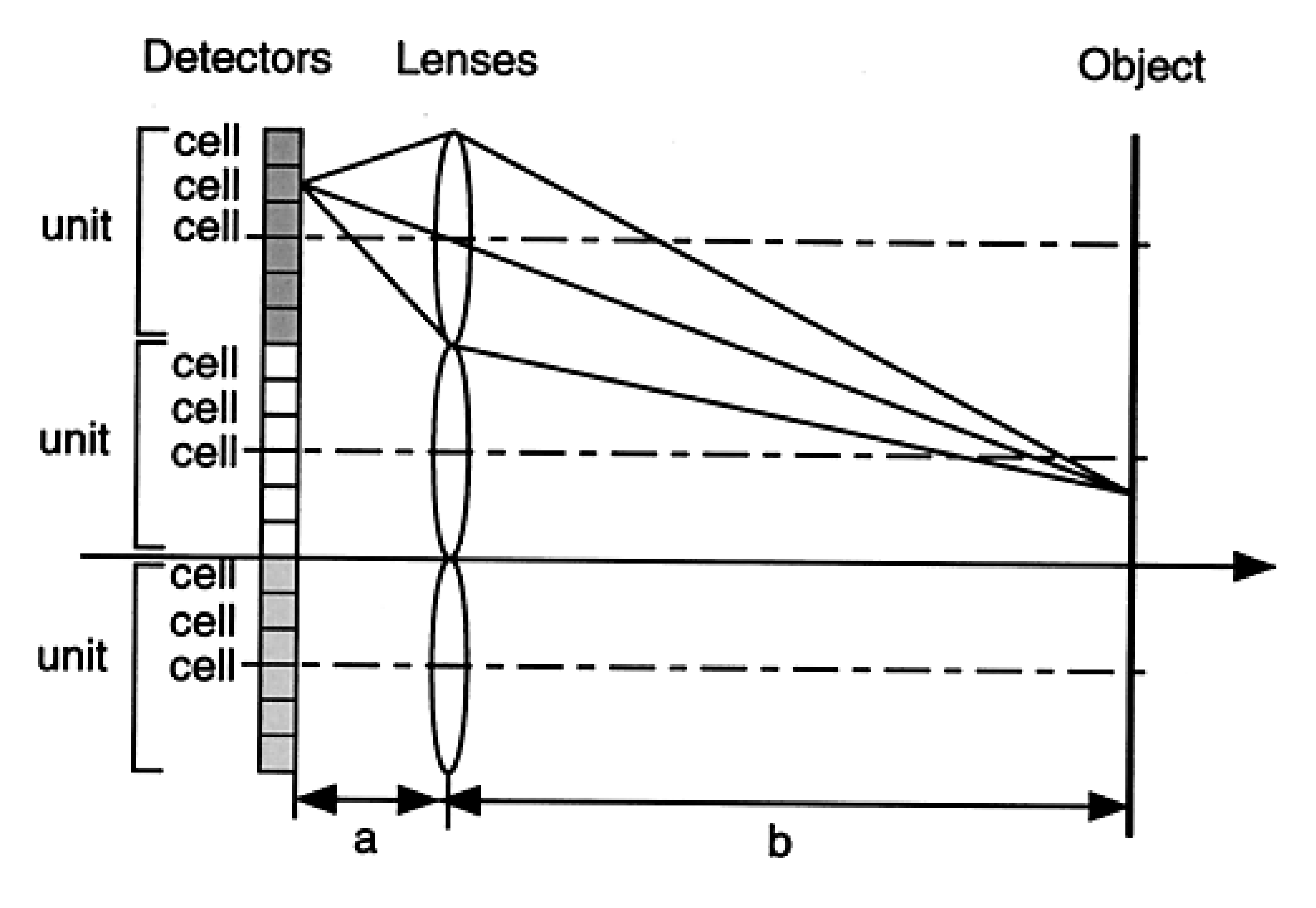
Images removed due to copyright restrictions.

TOMBO: Thin Camera (2001)



"Thin observation module by bound optics (TOMBO),"
J. Tanida, T. Kumagai, K. Yamada, S. Miyatake
Applied Optics, 2001

TOMBO: Thin Camera



ZCam (3Dvsystems),
Shuttered Light Pulse

Resolution :
1cm for 2-7 meters

Cameras for HCI

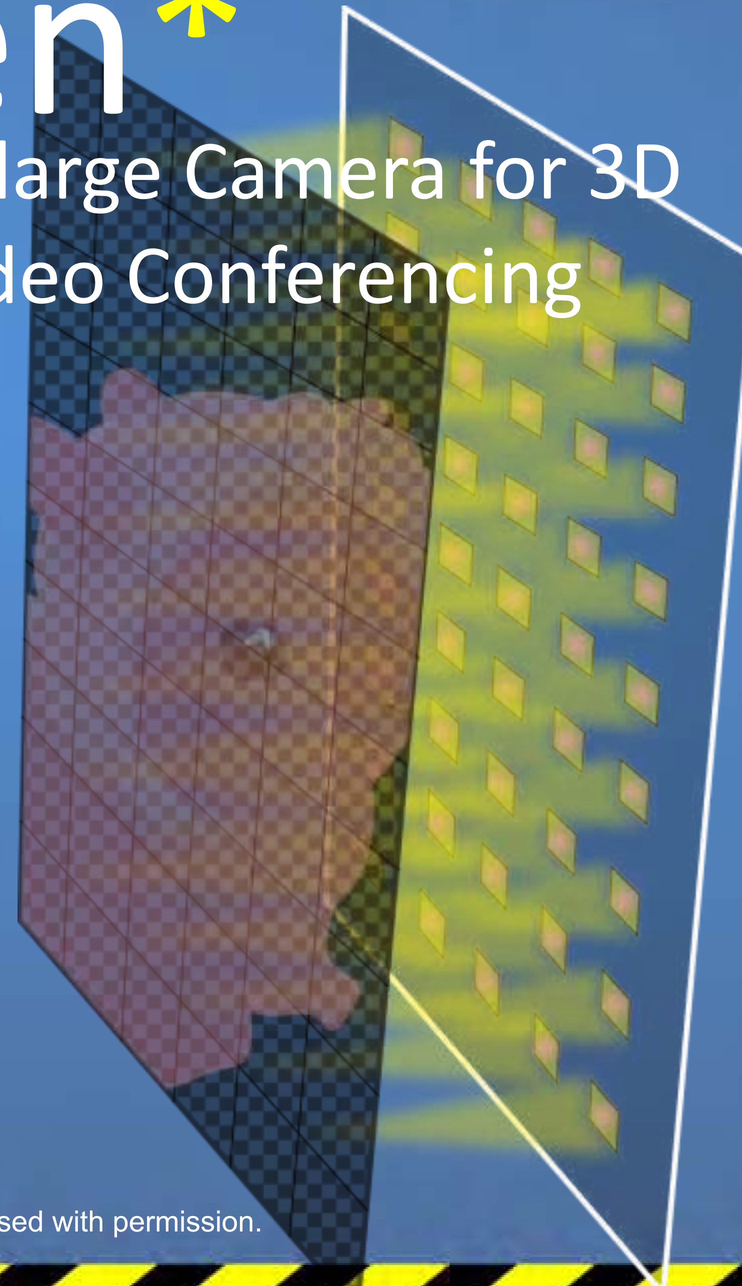
- Frustrated total internal reflection

Images removed due to copyright restrictions.

Han, J. Y. 2005. Low-Cost Multi-Touch Sensing through Frustrated Total Internal Reflection. In *Proceedings of the 18th Annual ACM Symposium on User Interface Software and Technology*

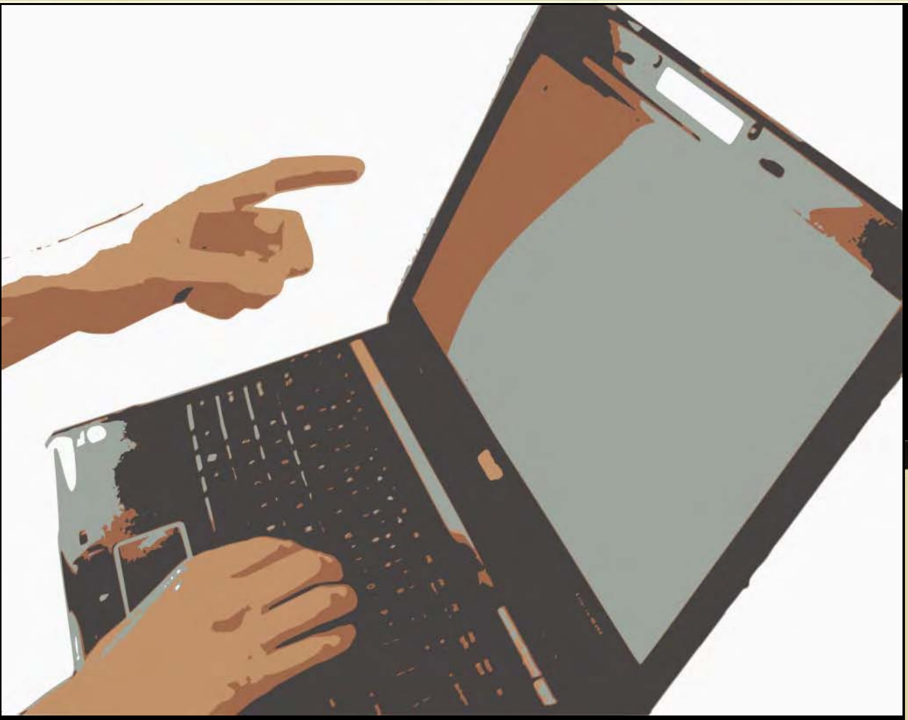
BiDi Screen*

Converting LCD Screen = large Camera for 3D Interactive HCI and Video Conferencing



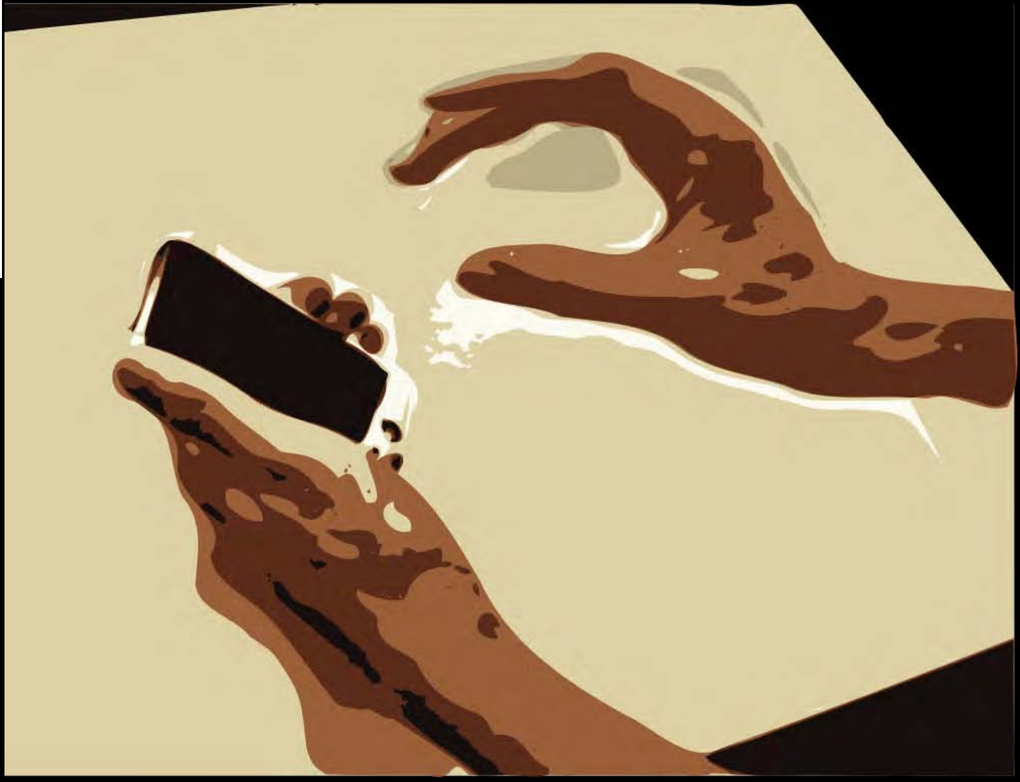
Matthew Hirsch, Henry Holtzman
Doug Lanman, Ramesh Raskar
Siggraph Asia 2009
Class Project in CompCam 2008
SRC Winner

Beyond Multi-touch: Mobile

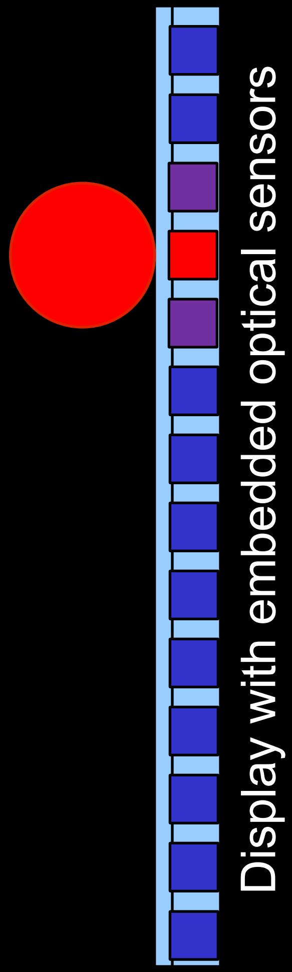


Laptops

Mobile

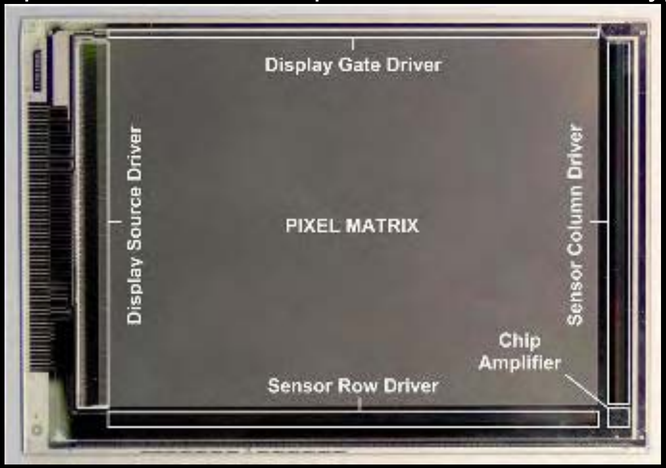


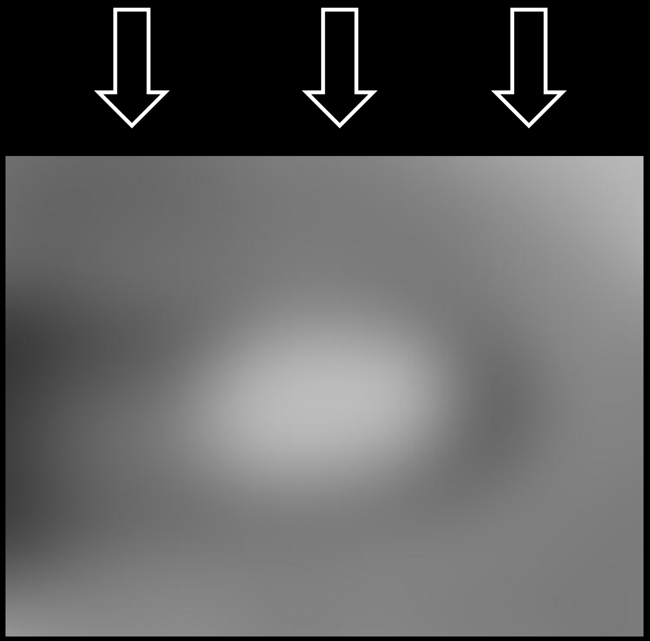
Light Sensing Pixels in LCD



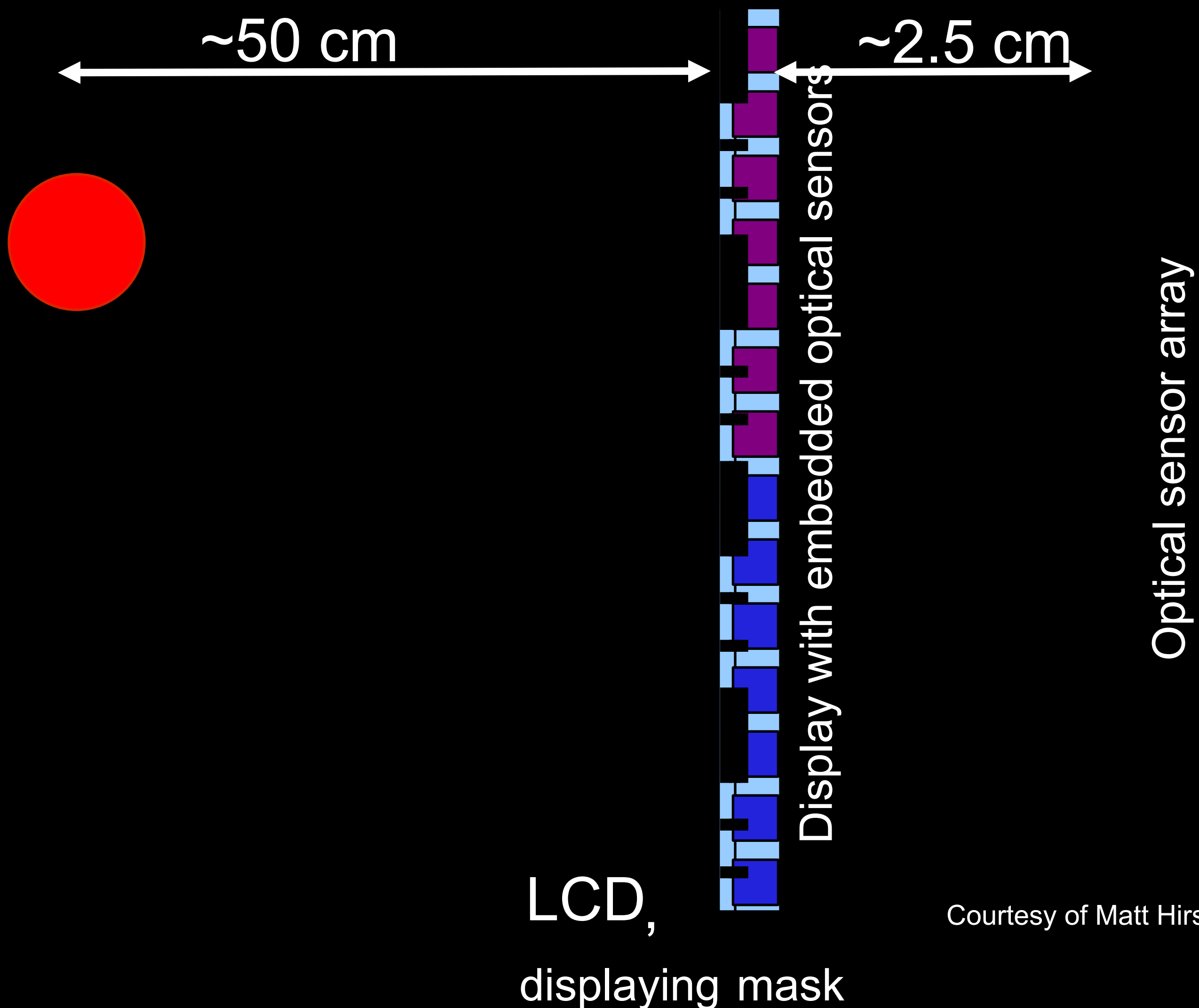
Courtesy of Matt Hirsch. Used with permission.

Sharp Microelectronics Optical Multi-touch Prototype



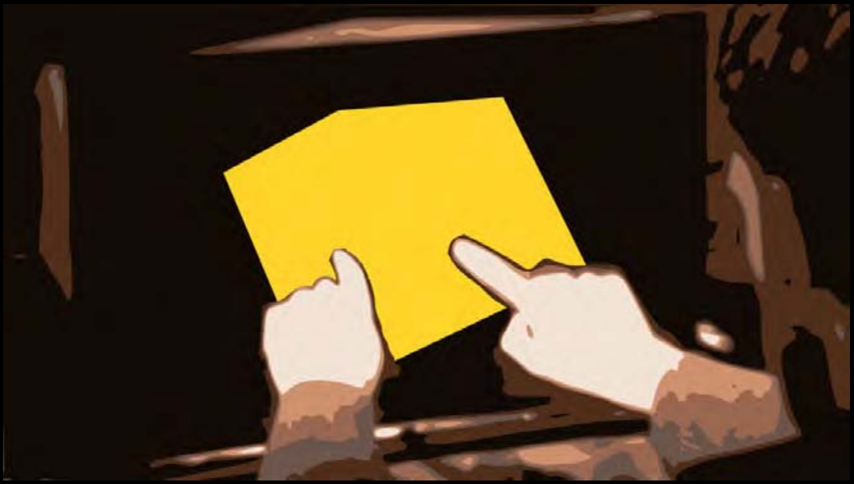


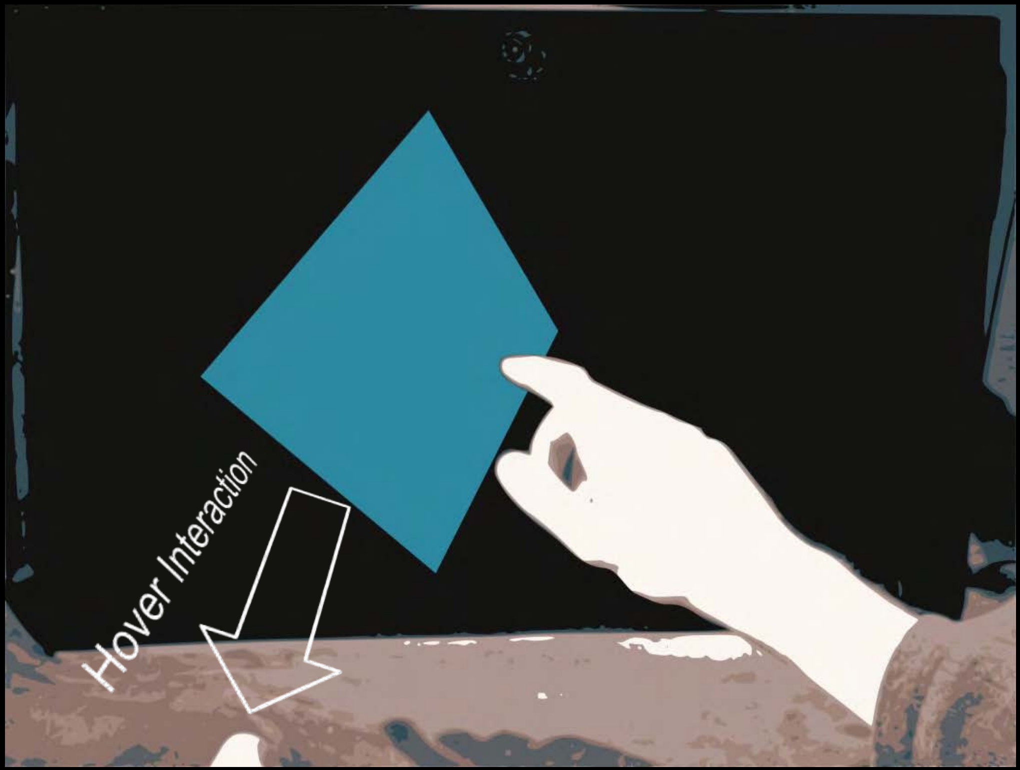
Design Overview



Beyond Multi-touch: Hover Interaction

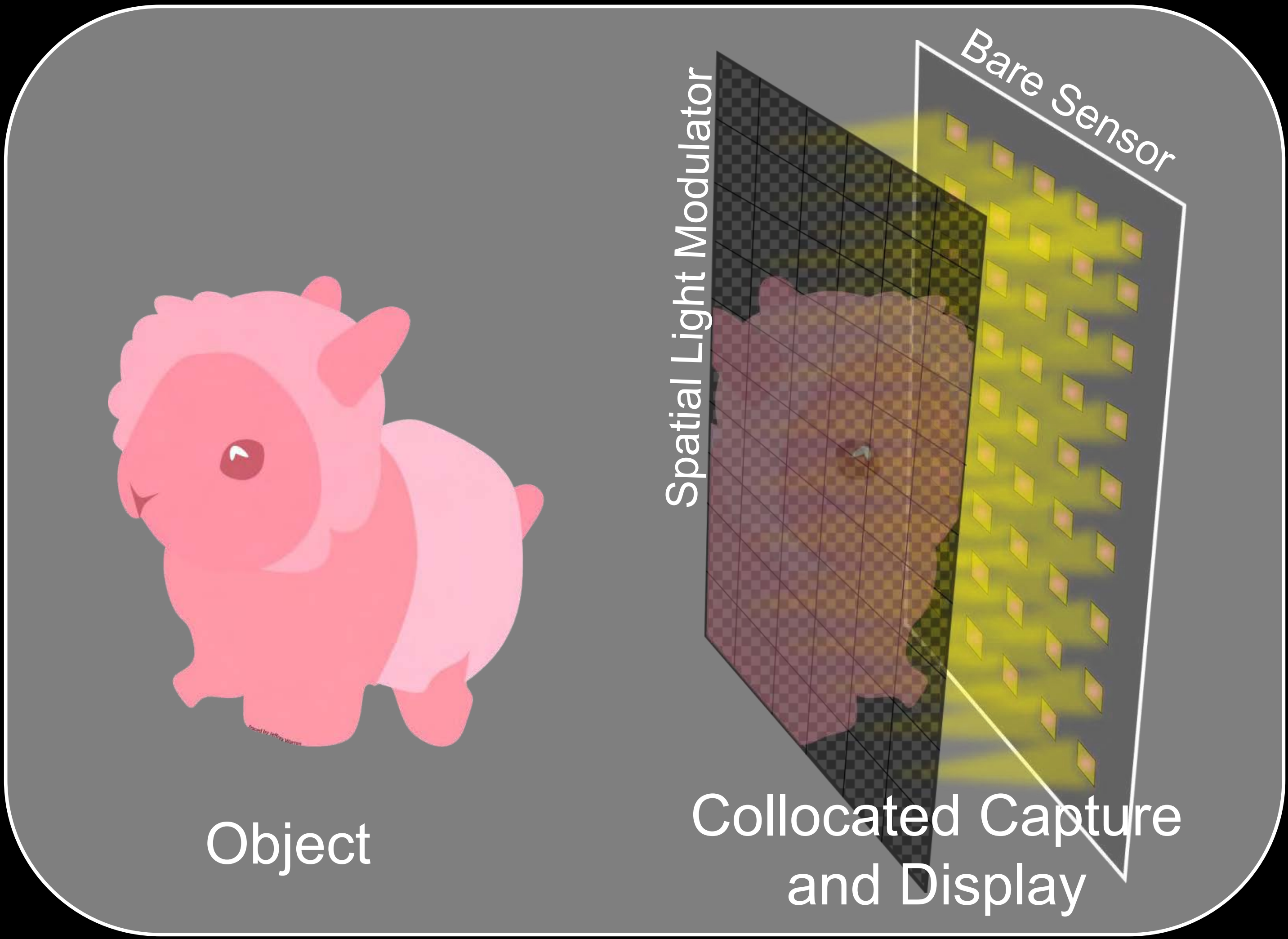
- Seamless transition of multitouch to gesture
- Thin package, LCD



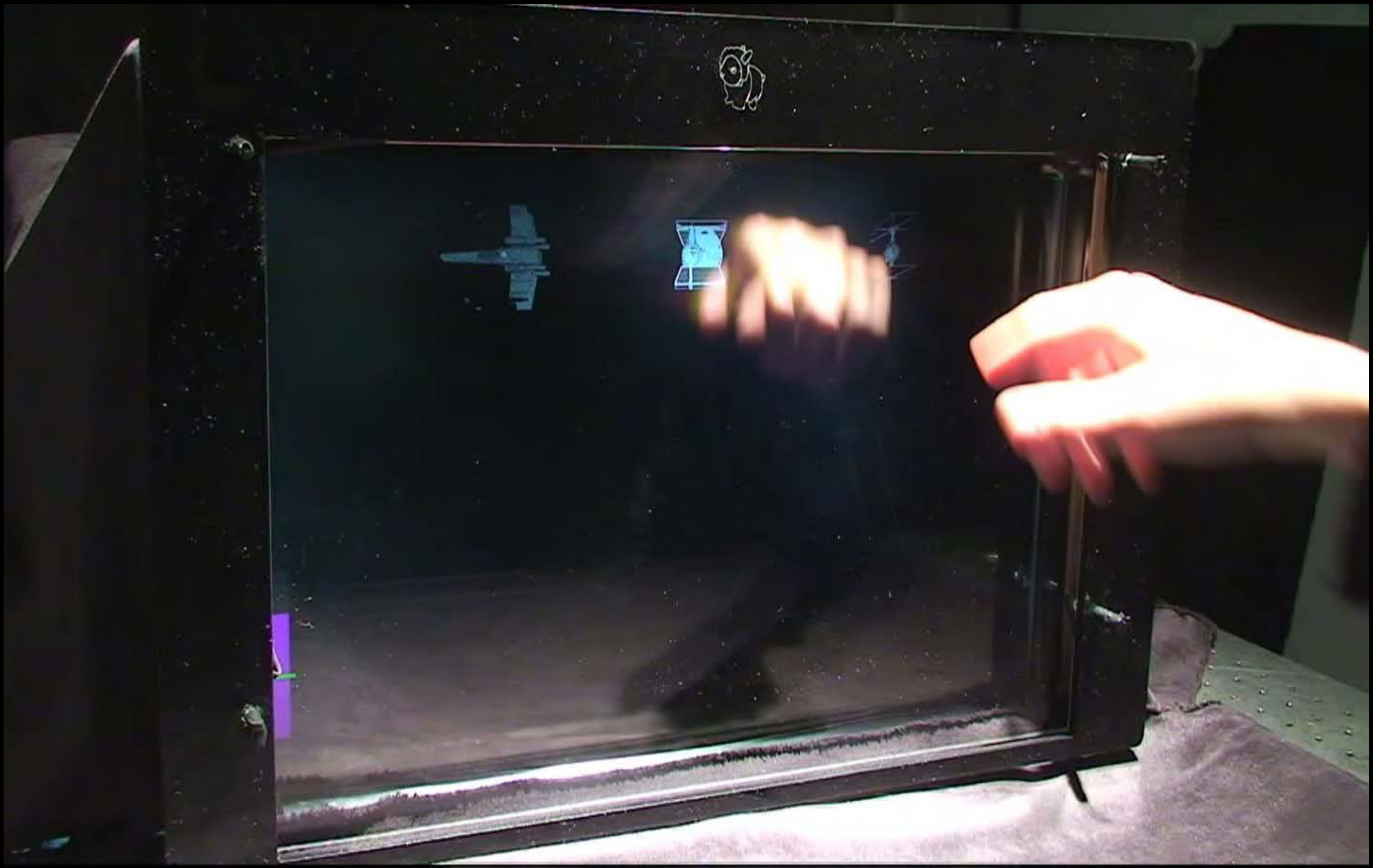


Courtesy of Matt Hirsch. Used with permission.

Design Vision

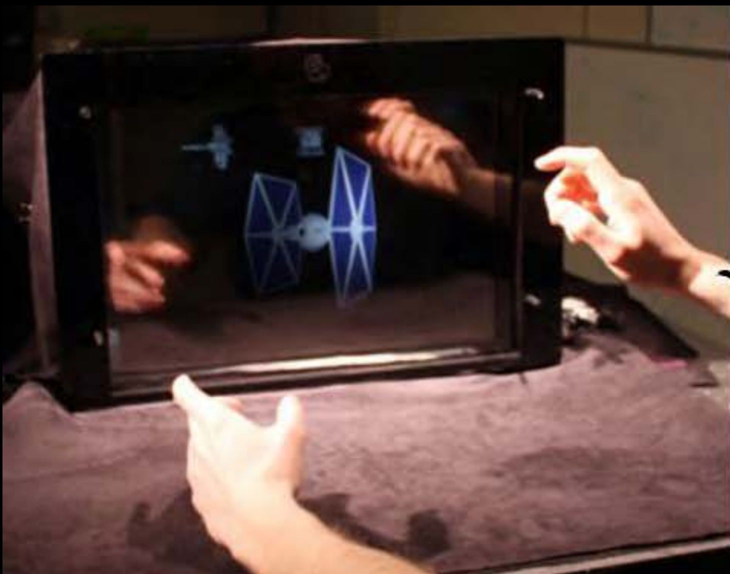


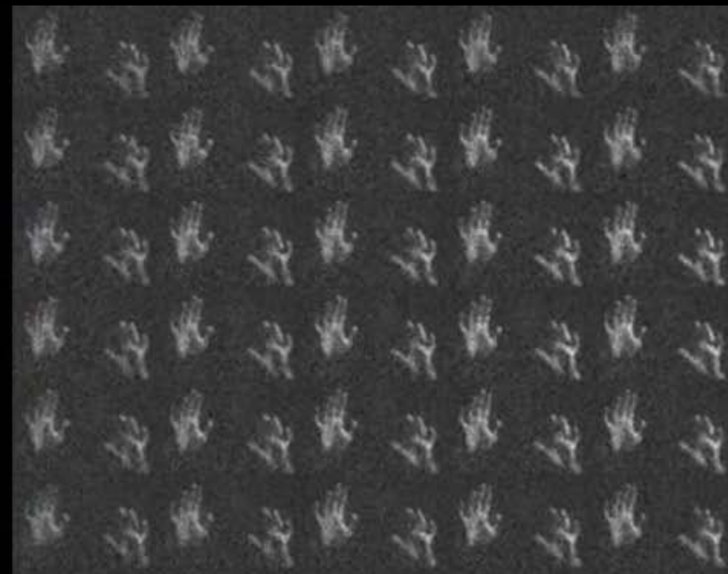
Touch + Hover using Depth Sensing LCD Sensor

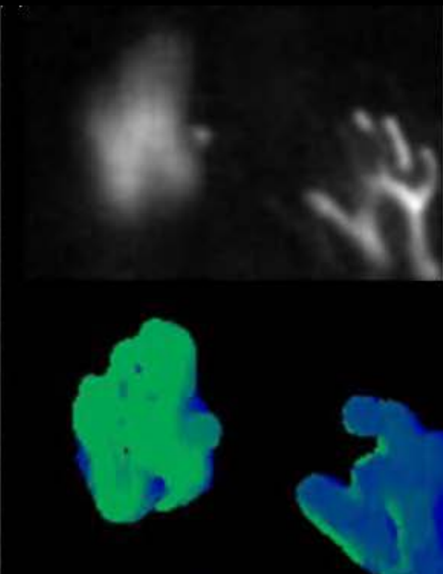


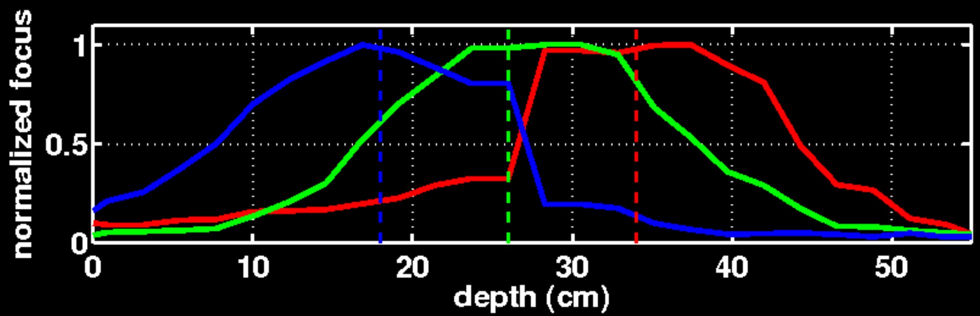
Courtesy of Matt Hirsch. Used with permission.

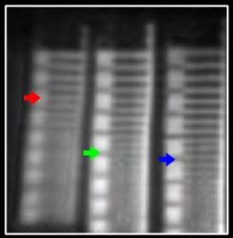
Overview: Sensing Depth from Array of Virtual Cameras in LCD











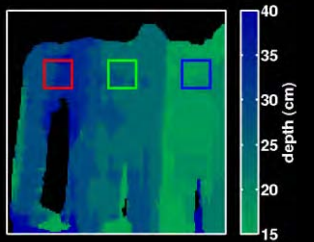
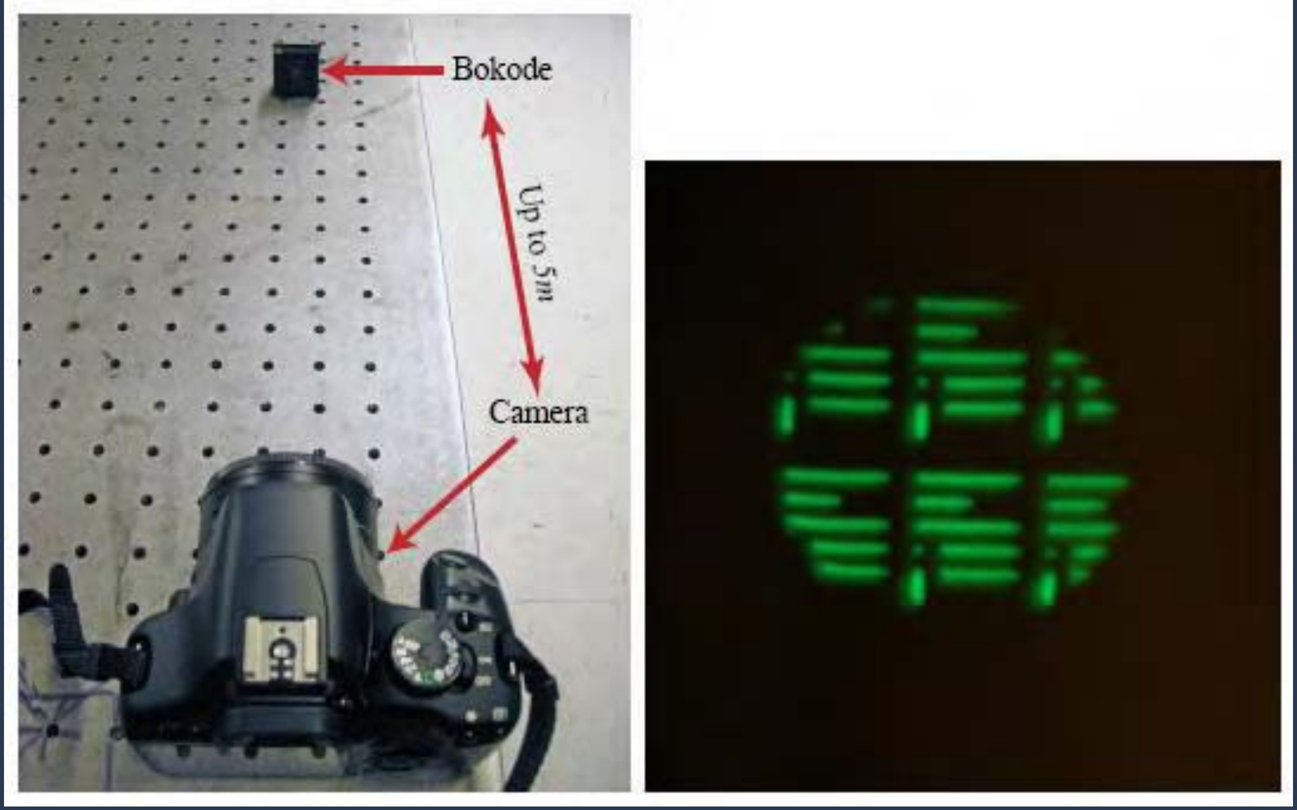


Image removed due to copyright restrictions. Schematic of ANOTO pen, from
http://www.acreo.se/upload/Publications/Proceedings/OE00/00-KAURANEN.pdf

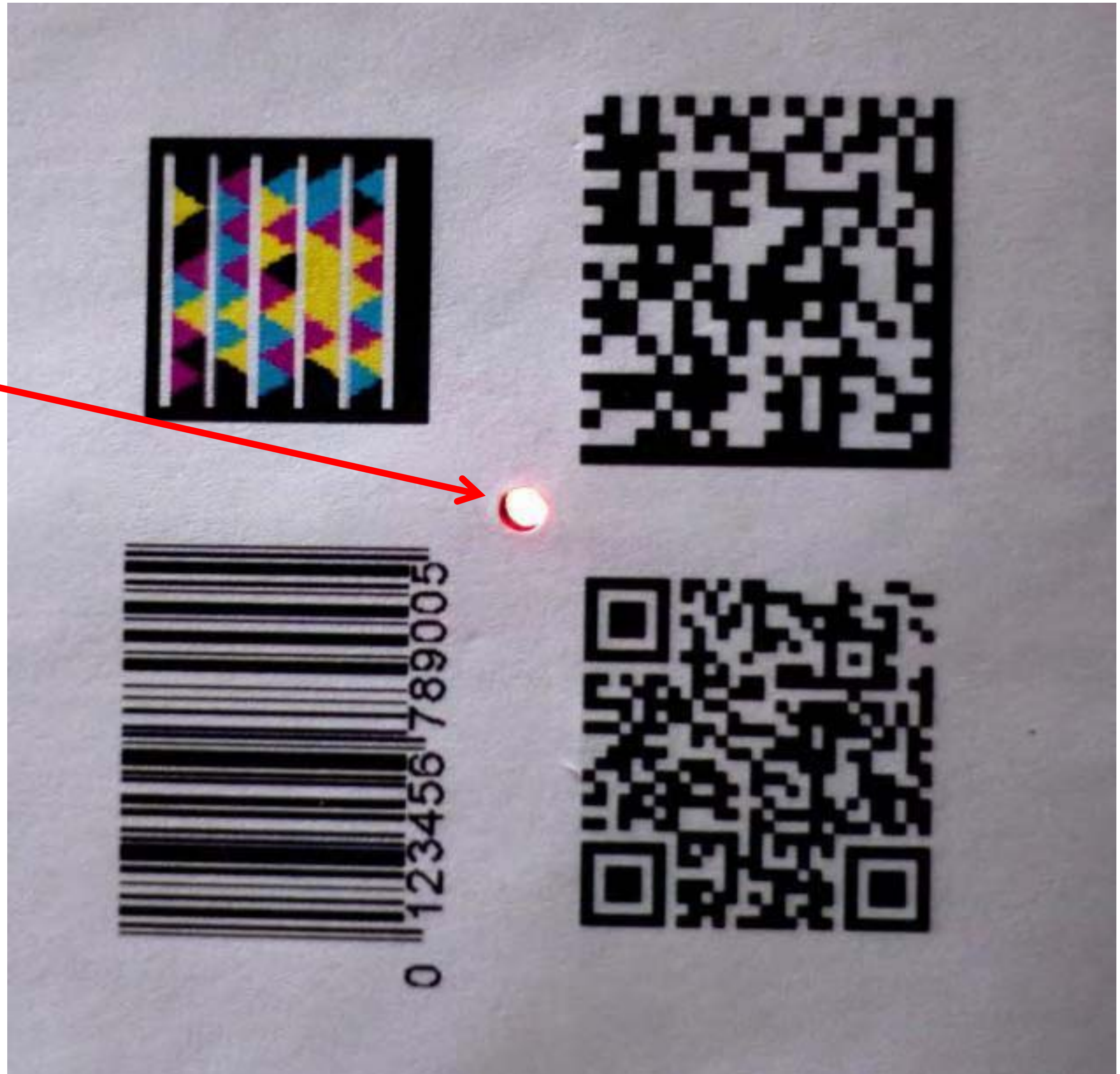
Computational Probes:
Long Distance Bar-codes

- Smart Barcode size : 3mm x 3mm
- Ordinary Camera: Distance 3 meter



Mohan, Woo,Smithwick, Hiura, Raskar
Accepted as Siggraph 2009 paper

Bokode



Mohan, A., G. Woo, S. Hiura, Q. Smithwick, and R. Raskar. “Bokode: Imperceptible Visual Tags for Camera-based Interaction from a Distance.” *Proceedings of ACM SIGGRAPH 2009*.

Barcodes

markers that assist machines in understanding the real world

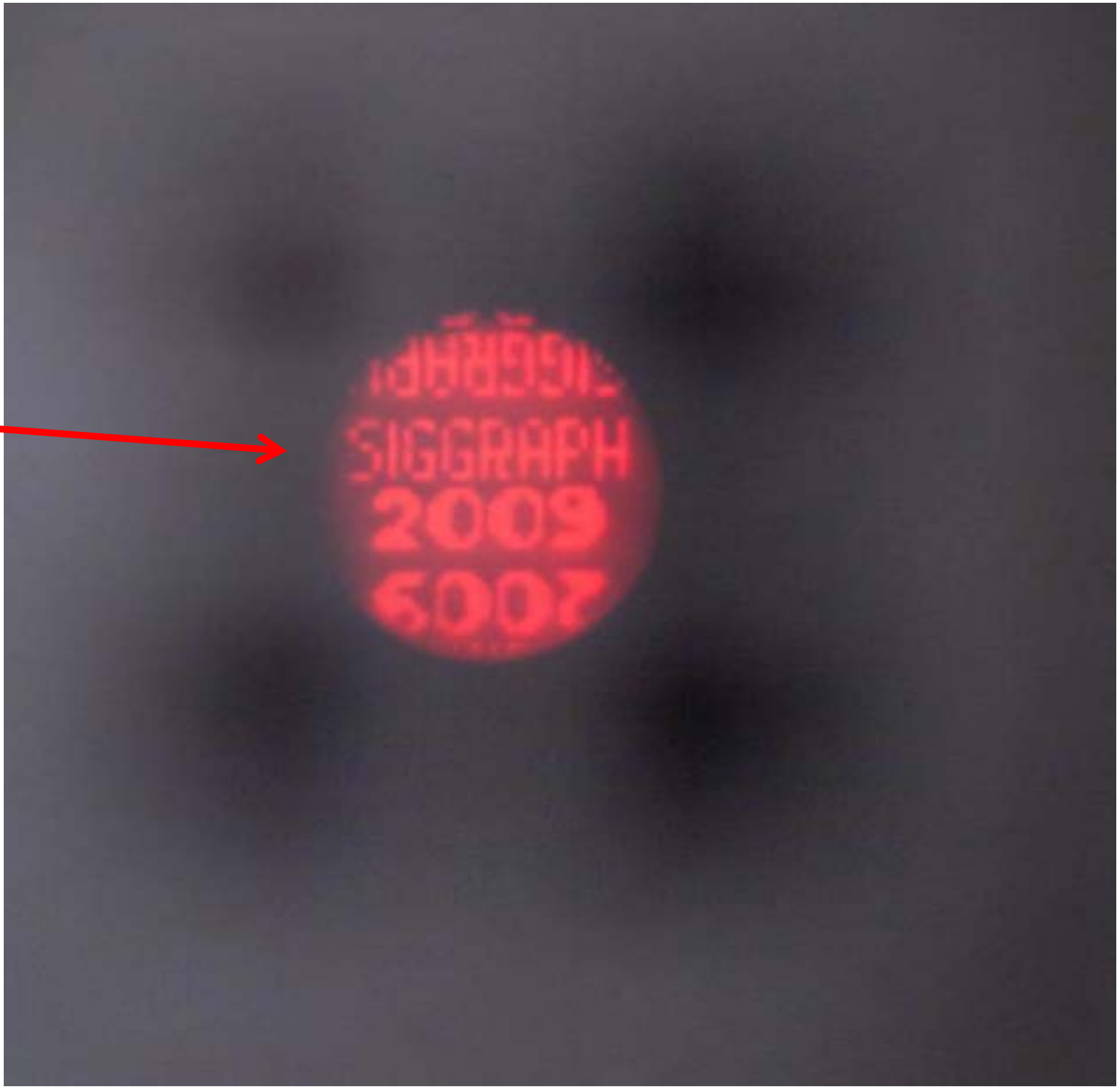
Bokode: imperceptible visual tags for camera based interaction from a distance

ankit mohan, grace woo, shinsaku hiura,
quinn smithwick, ramesh raskar

camera culture group, MIT media lab

Mohan, A., G. Woo, S. Hiura, Q. Smithwick, and R. Raskar. "Bokode: Imperceptible Visual Tags for Camera-based Interaction from a Distance." *Proceedings of ACM SIGGRAPH 2009*.

Defocus blur of Bokode



Mohan, A., G. Woo, S. Hiura, Q. Smithwick, and R. Raskar. "Bokode: Imperceptible Visual Tags for Camera-based Interaction from a Distance." *Proceedings of ACM SIGGRAPH 2009*.

Simplified Ray Diagram

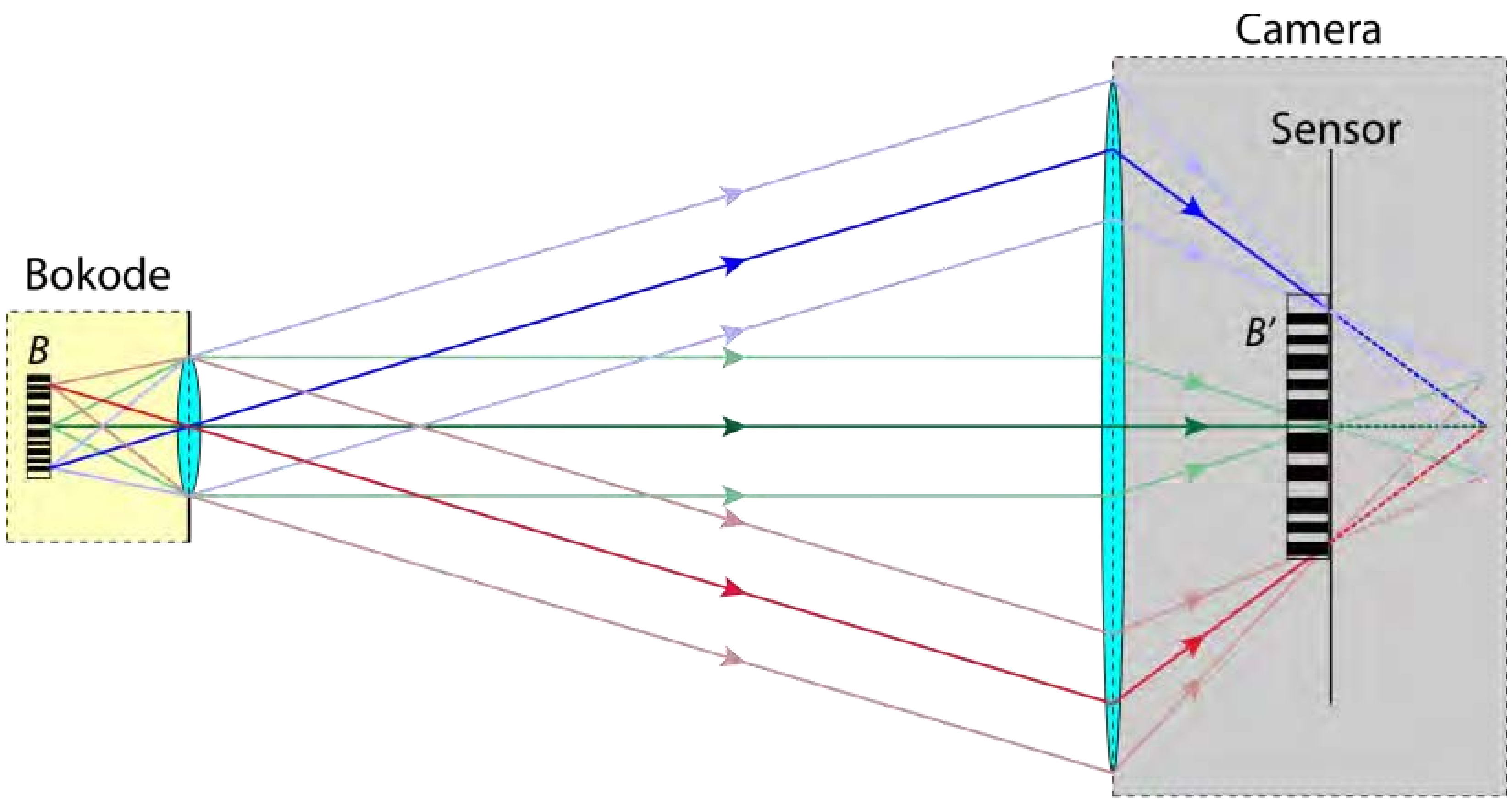
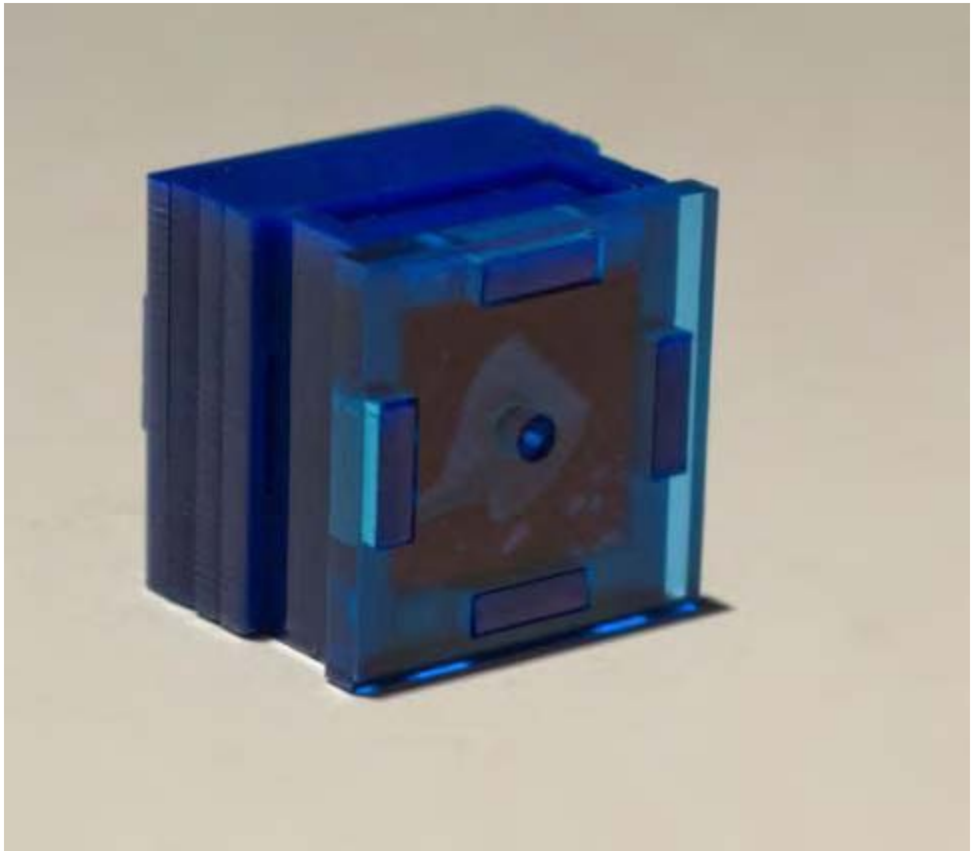


Image greatly magnified.

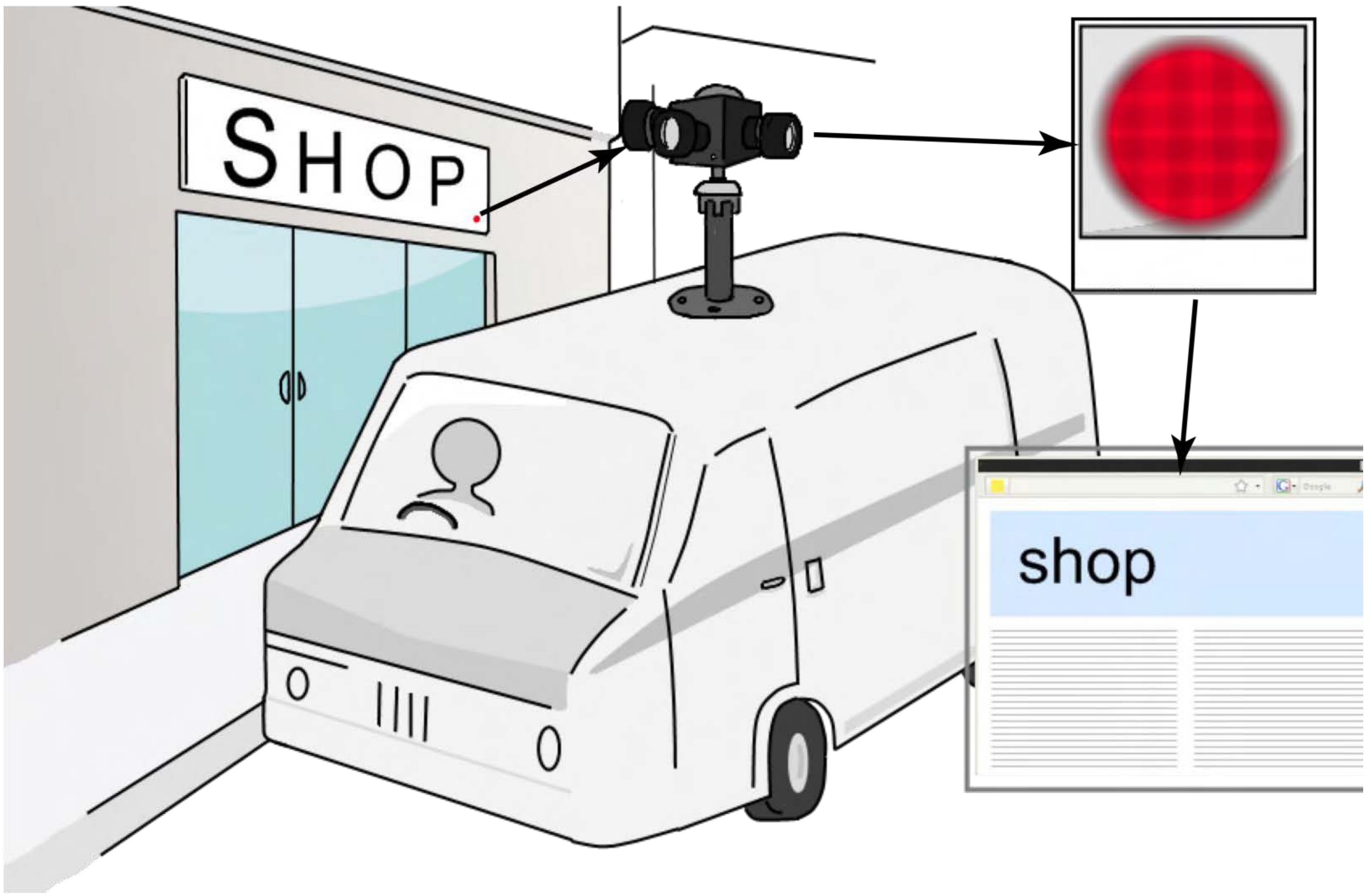
Mohan, A., G. Woo, S. Hiura, Q. Smithwick, and R. Raskar. "Bokode: Imperceptible Visual Tags for Camera-based Interaction from a Distance." *Proceedings of ACM SIGGRAPH 2009*.

Our Prototypes



Mohan, A., G. Woo, S. Hiura, Q. Smithwick, and R. Raskar. "Bokode: Imperceptible Visual Tags for Camera-based Interaction from a Distance." *Proceedings of ACM SIGGRAPH 2009*.

street-view tagging



Mohan, A., G. Woo, S. Hiura, Q. Smithwick, and R. Raskar. "Bokode: Imperceptible Visual Tags for Camera-based Interaction from a Distance." *Proceedings of ACM SIGGRAPH 2009*.

Vicon
Motion Capture

Medical Rehabilitation

Athlete Analysis

High-speed
IR Camera

Performance Capture

Biomechanical Analysis

Prakash: Lighting-Aware Motion Capture Using Photosensing Markers and Multiplexed Illuminators

R Raskar, H Nii, B de Decker, Y Hashimoto, J Summet, D Moore, Y Zhao, J Westhues, P Dietz, M Inami, S Nayar, J Barnwell, M Noland, P Bekaert, V Branzoi, E Bruns

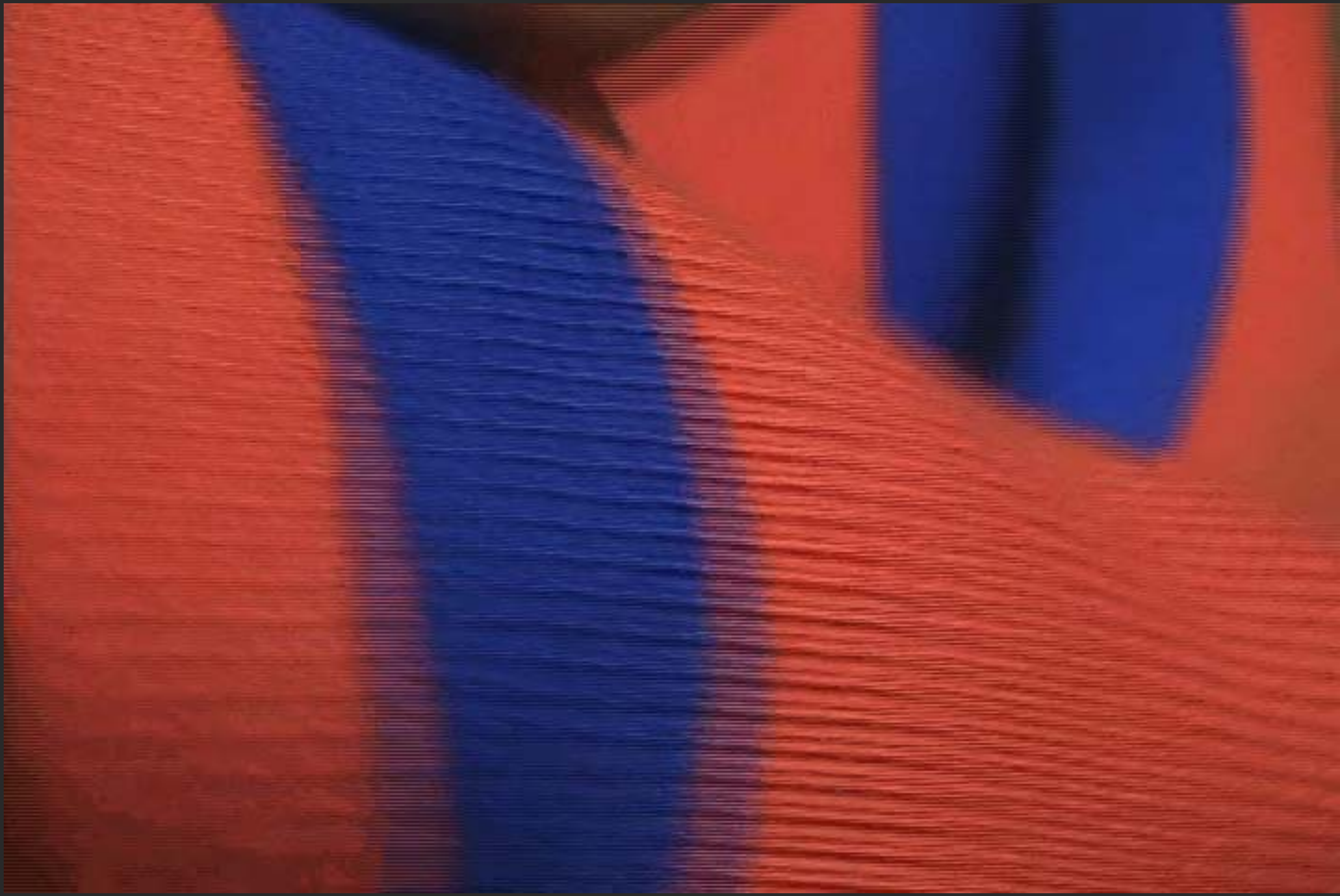
Siggraph 2007

Imperceptible Tags under clothing, tracked under ambient light

Hidden
Marker Tags

Outdoors

Unique Id



http://raskar.info/prakash

Camera-based HCI

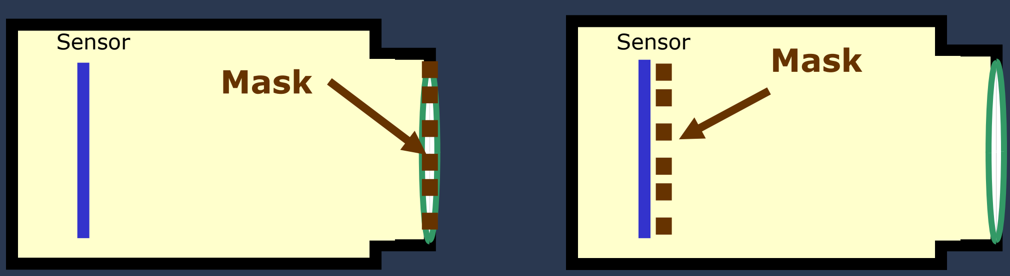
- Many projects here
  - Robotics, Speechome, Spinner, Sixth Sense

- Sony EyeToy
- Wii
- Xbox/Natal
- Microsoft Surface
  - Shahram Izadi (Microsoft Surface/SecondLight)
  - Talk at Media Lab, Tuesday Sept 22^{nd} , 3pm

Forerunners ..

Images removed due to copyright restrictions.
Diagrams of single photosensor and multiple photosensor worm "eyes."

Image removed due to copyright restrictions.
Diagram of human eye.



Tools

for

Visual Computing

Photos removed due to copyright restrictions.
Chambered eyes: nautilus, octopus, red-tailed hawk, scallop
Compound eyes: sea fan, dragonfly, krill, lobster
Optical methods: shadow, refractive, reflective

Fernald, Science [Sept 2006]

Project Assignments

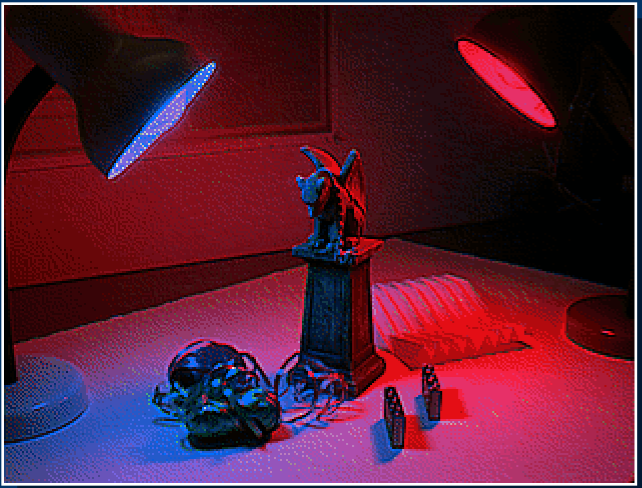
- Relighting
- Dual Photography
- Virtual Optical Bench
- Lightfield capture
  - Mask or LCD with programmable aperture
- One of
  - High speed imaging
  - Thermal imaging
  - 3D range sensing
- Final Project

Goals

- Change the rules of the game
  - Emerging optics, illumination, novel sensors
  - Exploit priors and online collections
- Applications
  - Better scene understanding/analysis
  - Capture visual essence
  - Superior Metadata tagging for effective sharing
  - Fuse non-visual data
    - Sensors for disabled, new art forms, crowdsourcing, bridging cultures

First Assignment: Synthetic Lighting

Paul Haeberli, Jan 1992



What is the emphasis?

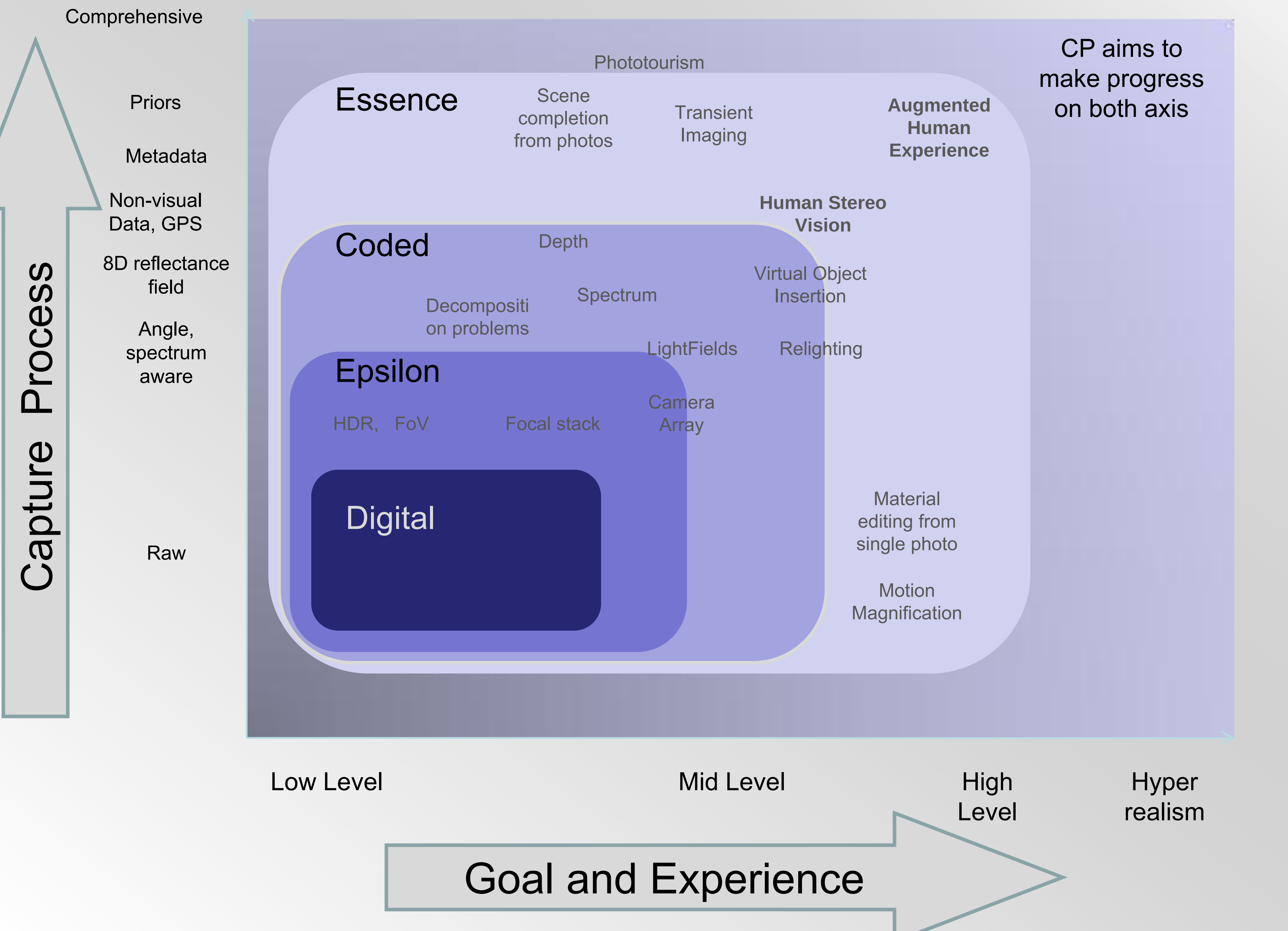
- Learn fundamental techniques in imaging
  - In class and in homeworks
  - Signal processing, Applied optics, Computer graphics and vision, Electronics, Art, and Online photo collections
  - This is not a discussion class
- Three Applications areas
  - Photography
    - Think in higher dimensions 4D, 6D, 8D, thermal, range cam, lightfields, applied optics
  - Active Computer Vision (real-time)
    - HCI, Robotics, Tracking/Segmentation etc
  - Scientific Imaging
    - Compressive sensing, wavefront coding, tomography, deconvolution, psf
  - But the 3 areas are merging and use similar principles

First Homework Assignment

- Take multiple photos by changing lighting
- Mix and match color channels to relight

- Due Sept 25th

- Need Volunteer: taking notes for next class
  - Sept 18: Sam Perli
  - Sept 25: ?


Comprehensive
Priors
Metadata
Non-visual Data, GPS
8D reflectance field
Angle, spectrum aware
Raw
Capture Process
Phototourism
CP aims to make progress on both axis
Essence
Scene completion from photos
Transient Imaging
Augmented Human Experience
Human Stereo Vision
Coded
Depth
Virtual Object Insertion
Spectrum
Decompositi on problems
LightFields
Relighting
Epsilon
Camera Array
HDR, FoV
Focal stack
Digital
Material editing from single photo
Motion Magnification
Low Level
Mid Level
High Level
Hyper realism
Goal and Experience

Computational Photography
http://raskar.info/photo/

<u>Capture</u>

- Overcome Limitations of Cameras
- Capture Richer Data
  - Multispectral
- New Classes of Visual Signals
  - Lightfields, Depth, Direct/Global, Fg/Bg separation

<u>Hyperrealistic Synthesis</u>

- Post-capture Control
- Impossible Photos
- Exploit Scientific Imaging