Femto-Photography: Trillion FPS Imaging to Look Around Corners

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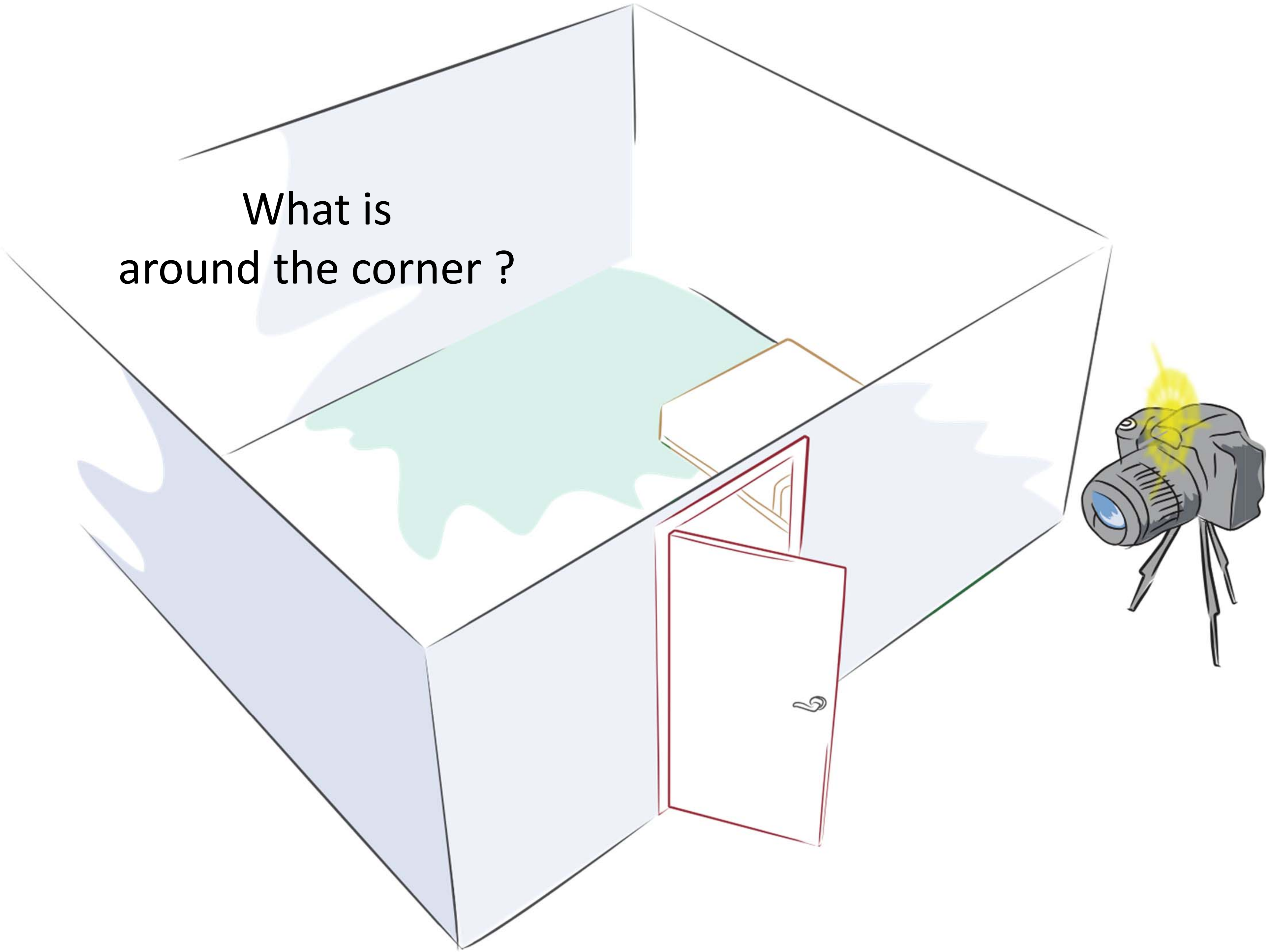
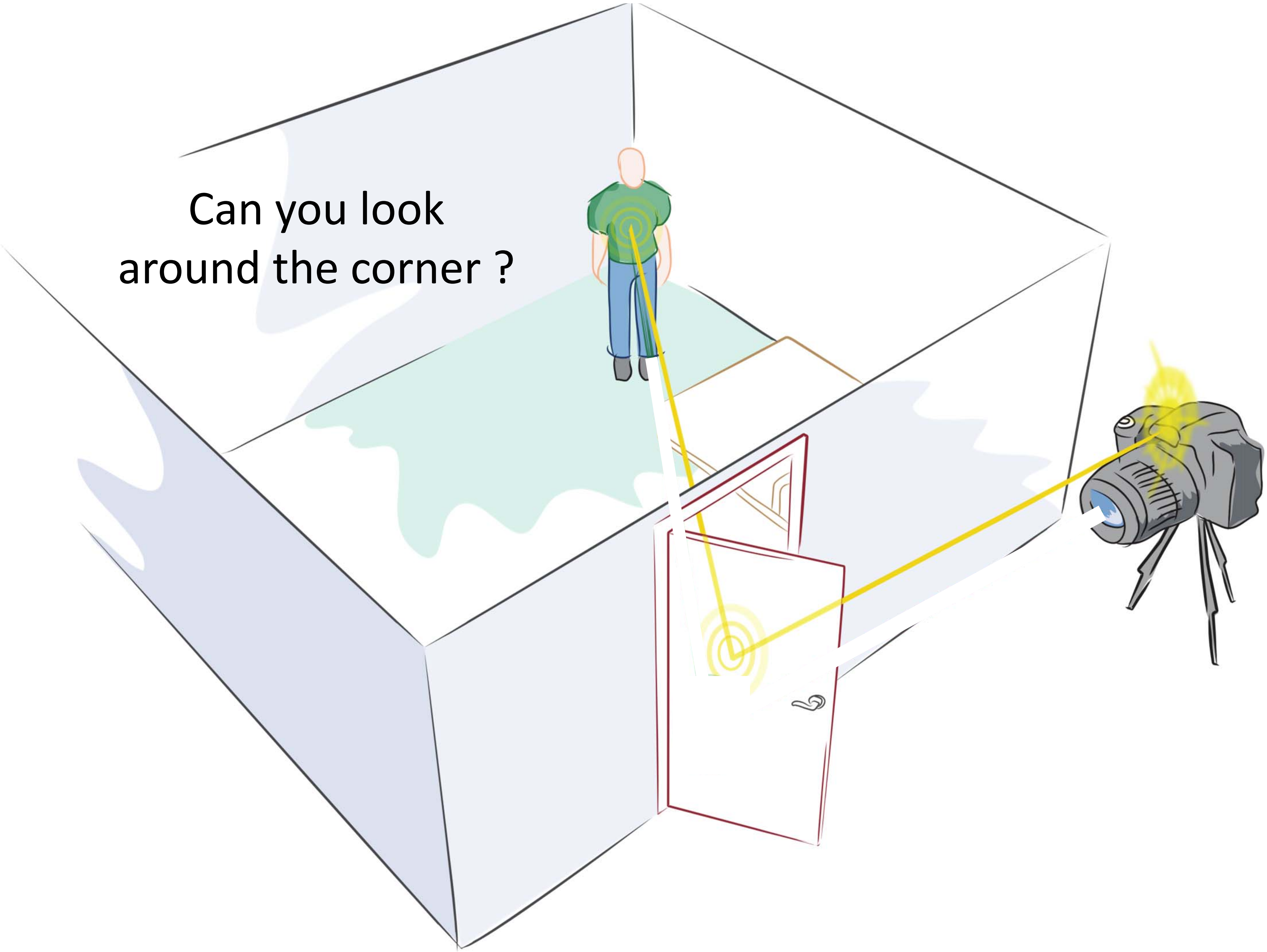
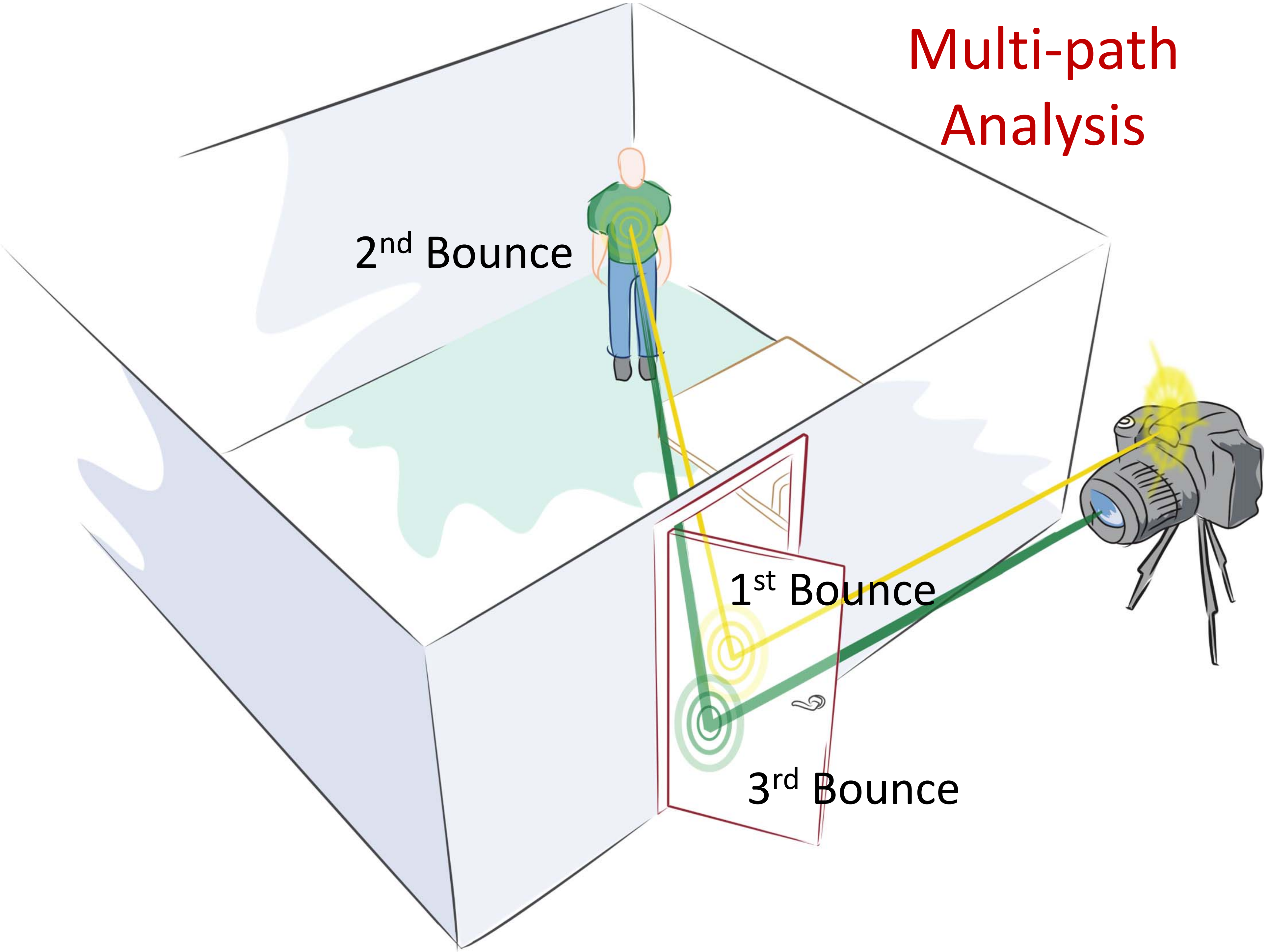

What is
around the corner ?

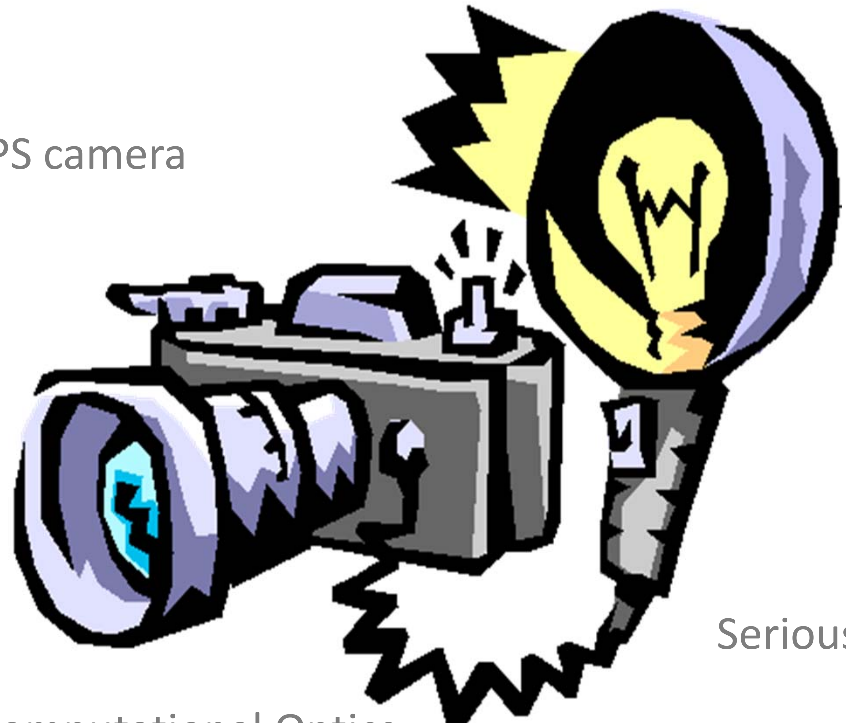

Can you look
around the corner ?

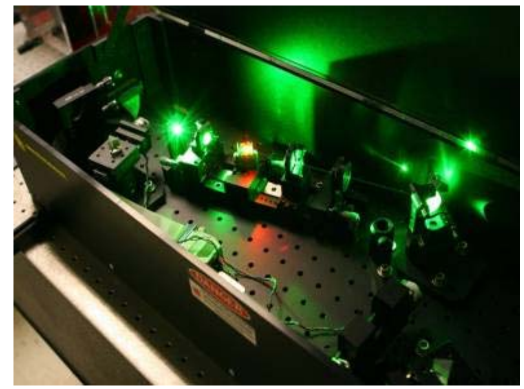

Multi-path
Analysis
2nd Bounce
1st Bounce
3rd Bounce

Femto-Photography (Transient Imaging)

FemtoFlash

Trillion FPS camera





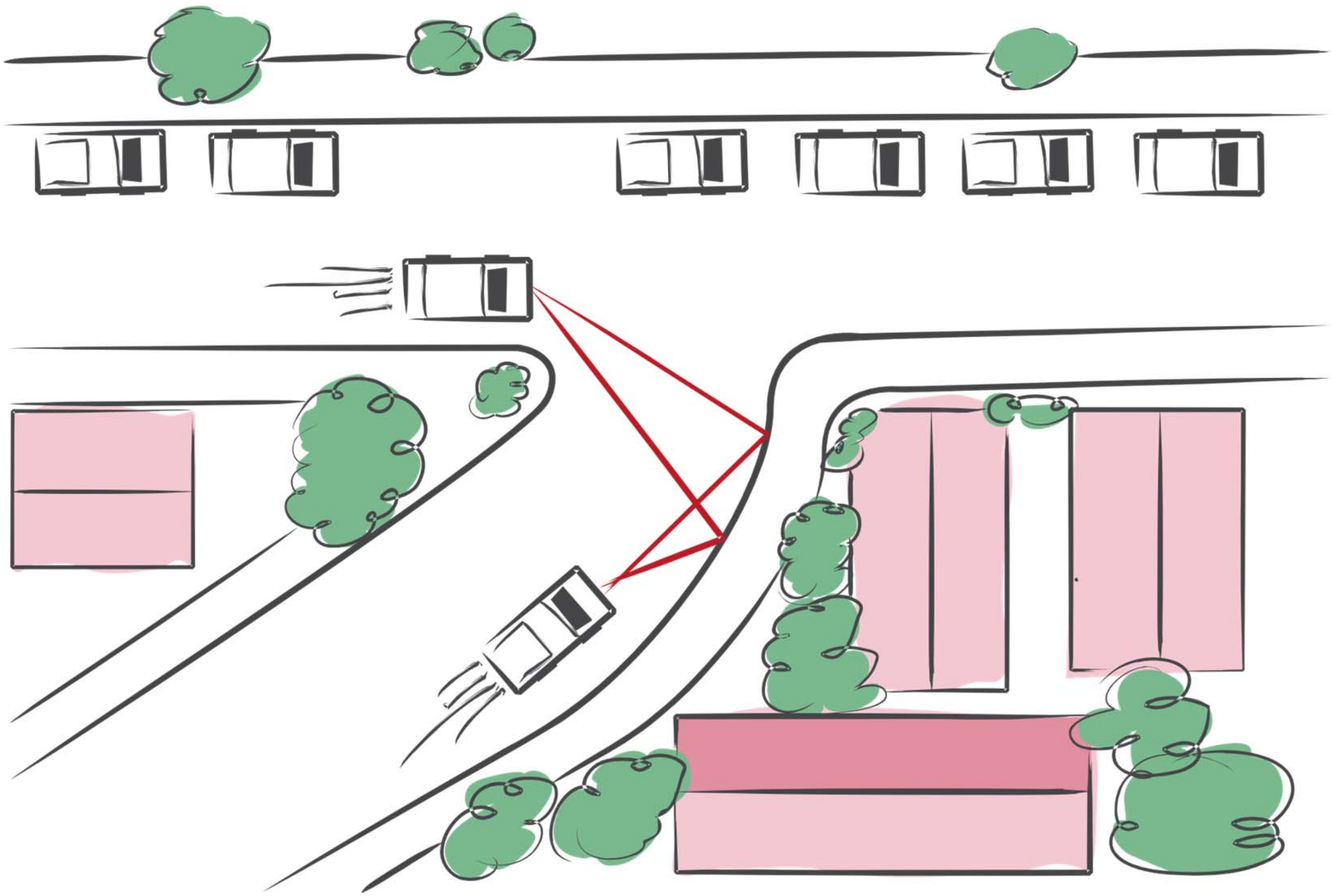
With M Bawendi,
MIT Chemistry

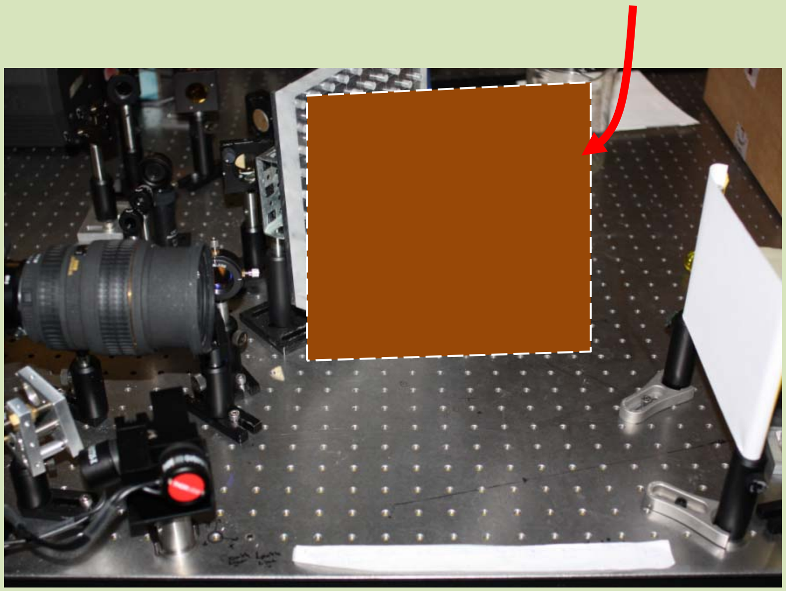
Serious Sync

Computational Optics

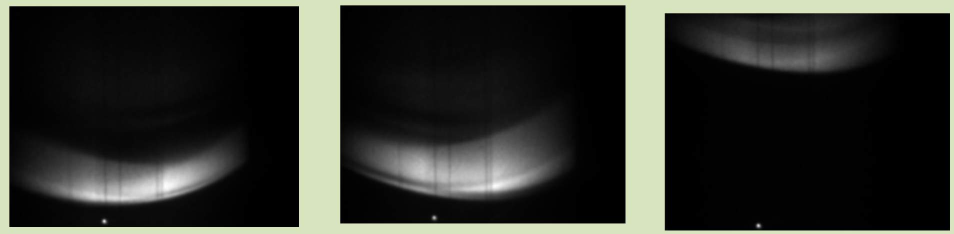
- 2011: CVPR (Pandharkar, Velten, Bardagjy, Bawendi, Raskar)
- 2009: **Marr Prize** Honorable Mention (Kirmani, Hutchinson, Davis, Raskar, ICCV'2009)
- 2008: Transient Light Transport (Raskar, Davis, March 2008)

Collision avoidance, robot navigation, …

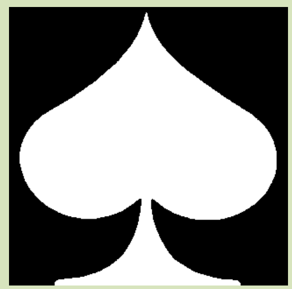




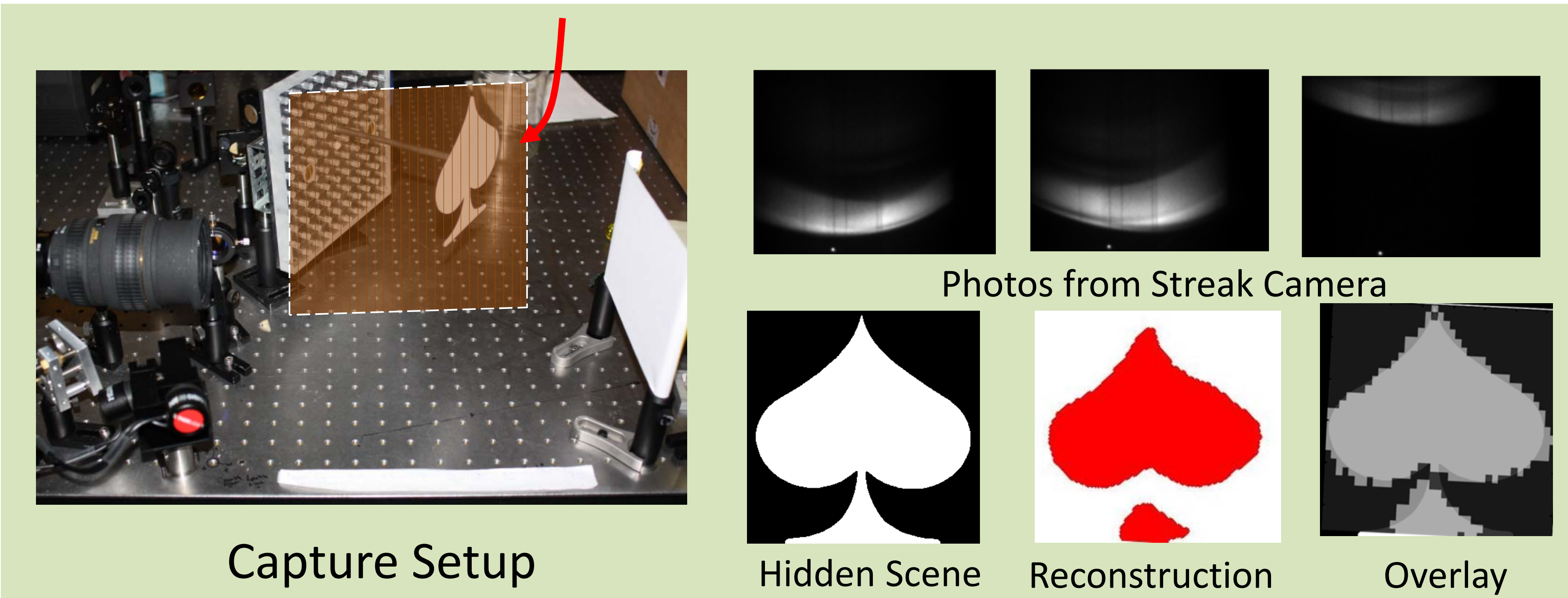
Capture Setup



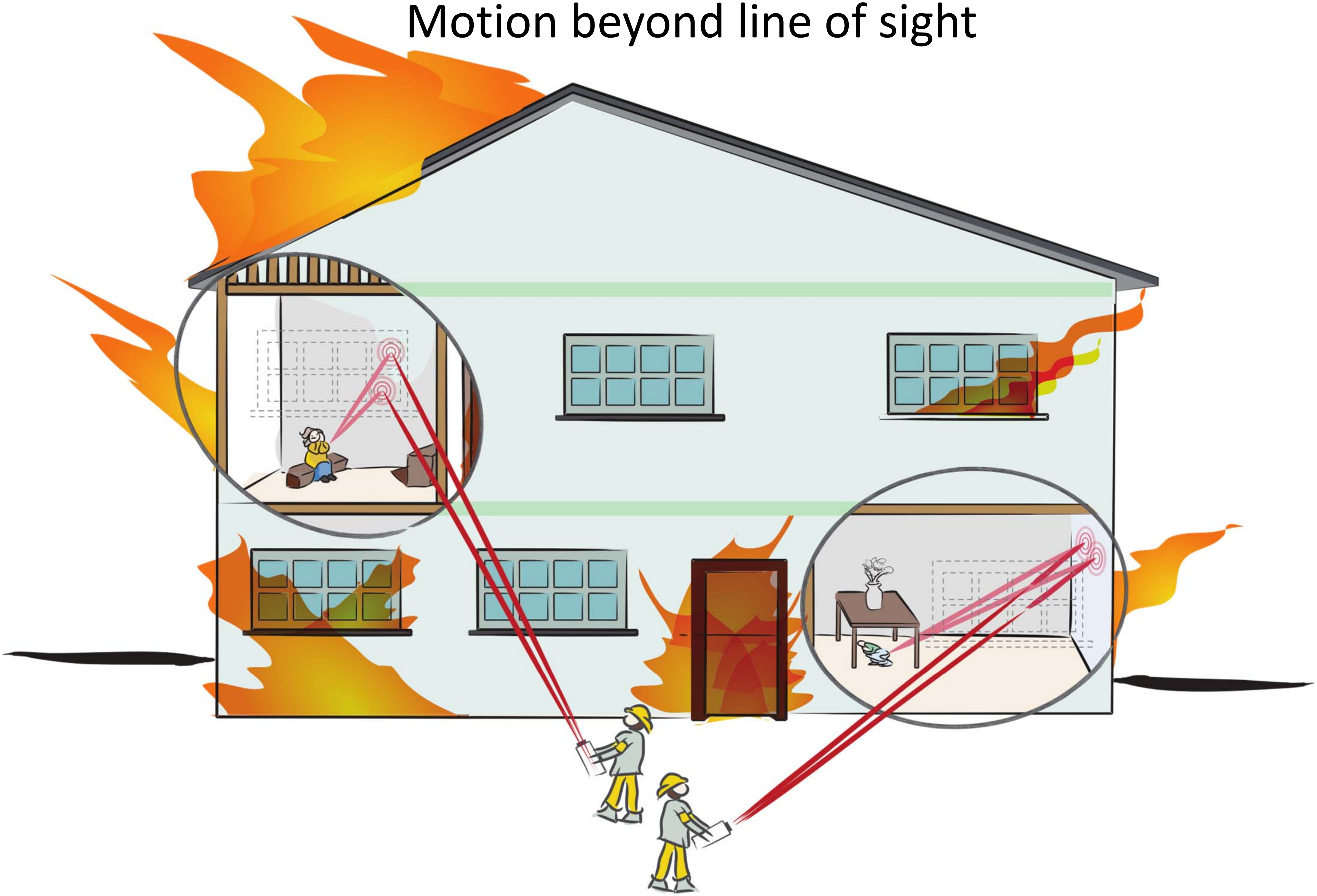
Photos from Streak Camera



Hidden Scene

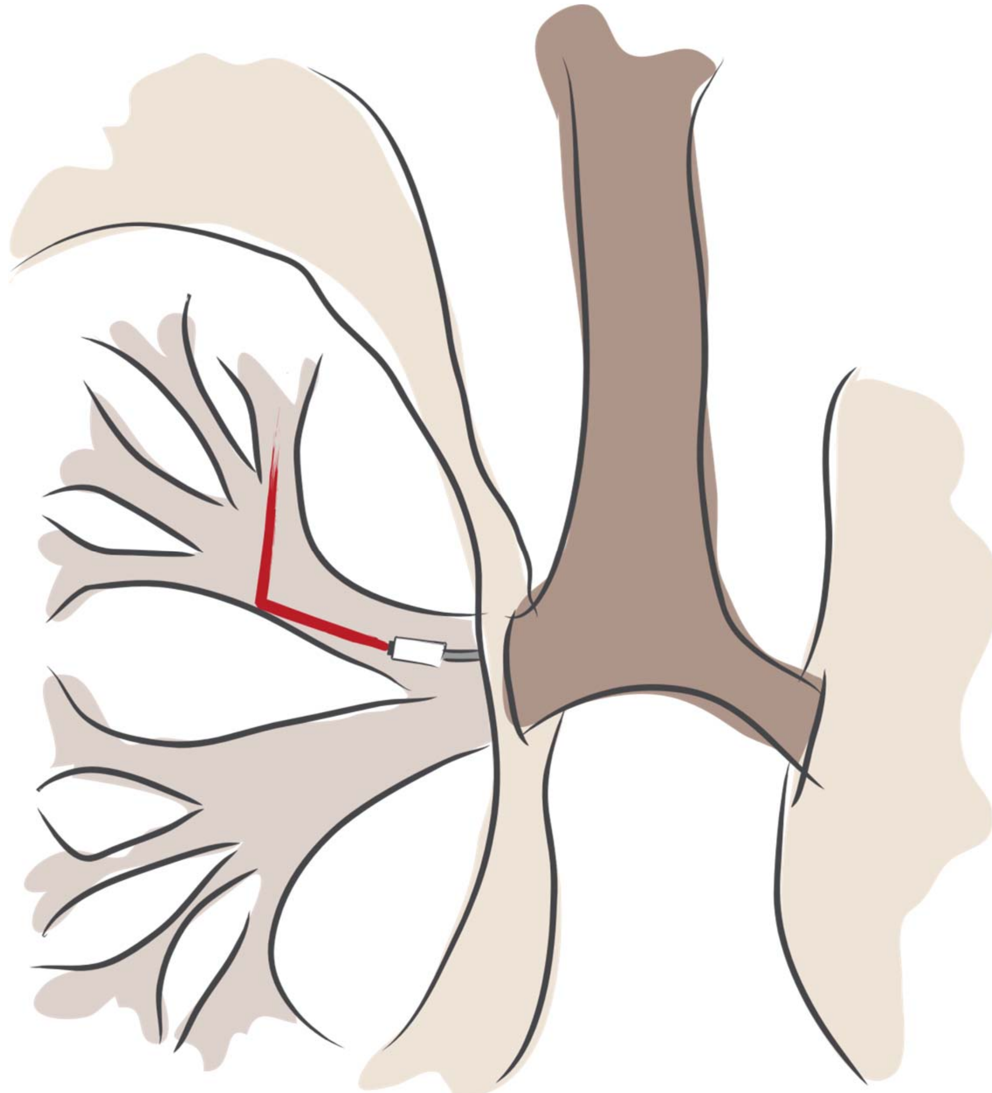

Capture Setup
Photos from Streak Camera
Hidden Scene
Reconstruction
Overlay

Motion beyond line of sight



Pandharkar, Velten, Bardagjy, Lawson, Bawendi, Raskar, CVPR 2011

…, bronchoscopies, …

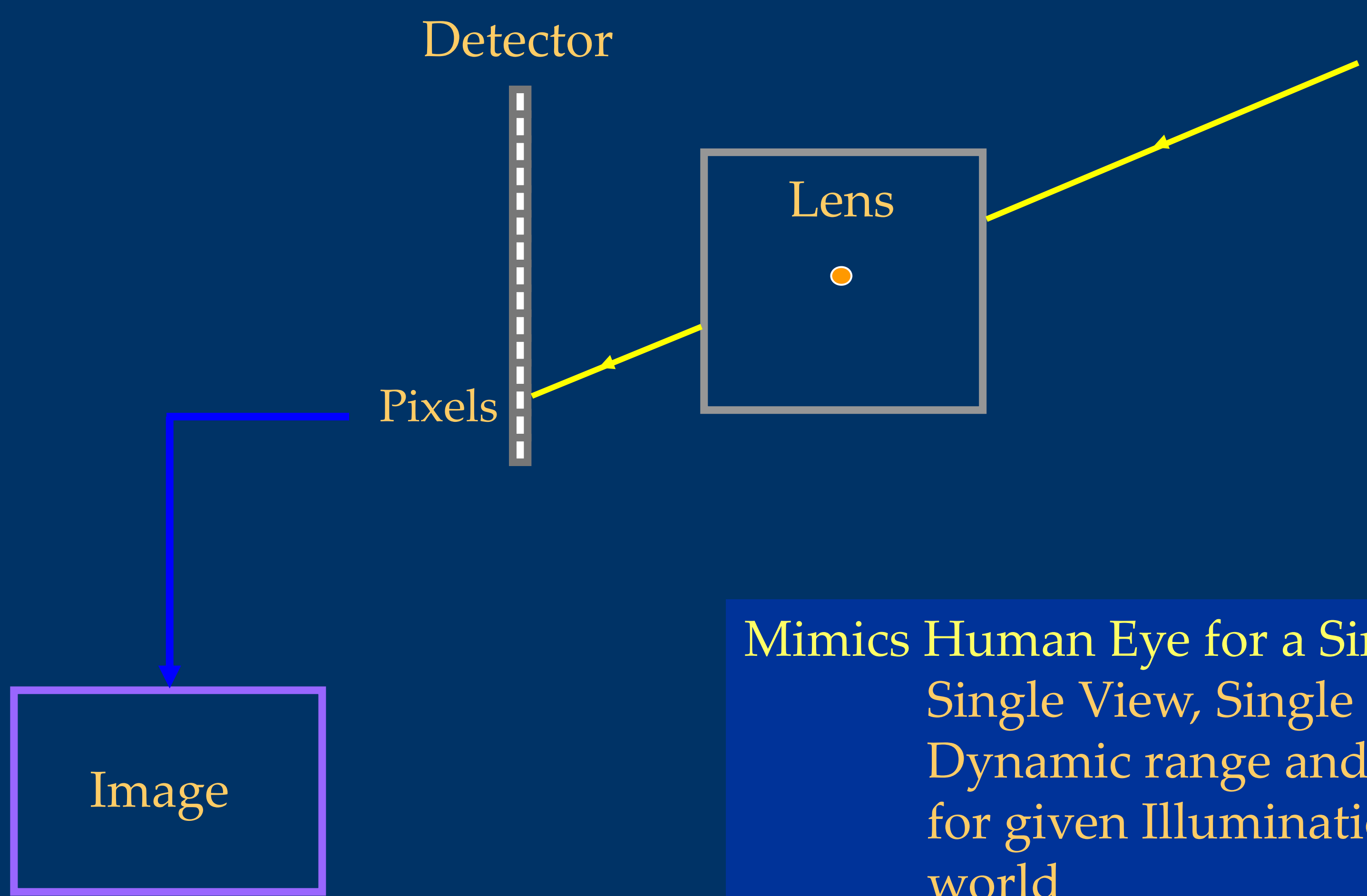


Participating Media

Team

Moungi G. Bawendi, Professor, Dept of Chemistry, MIT
James Davis, UC Santa Cruz
Andreas Velten, Postdoctoral Associate, MIT Media Lab
Rohit Pandharkar, RA, MIT Media Lab
Otkrist Gupta, RA, MIT Media Lab
Andrew Matthew Bardagjy, RA, MIT Media Lab
Nikhil Naik, RA, MIT Media Lab
Everett Lawson, MIT Media Lab
Ramesh Raskar, Asso. Prof., MIT Media Lab

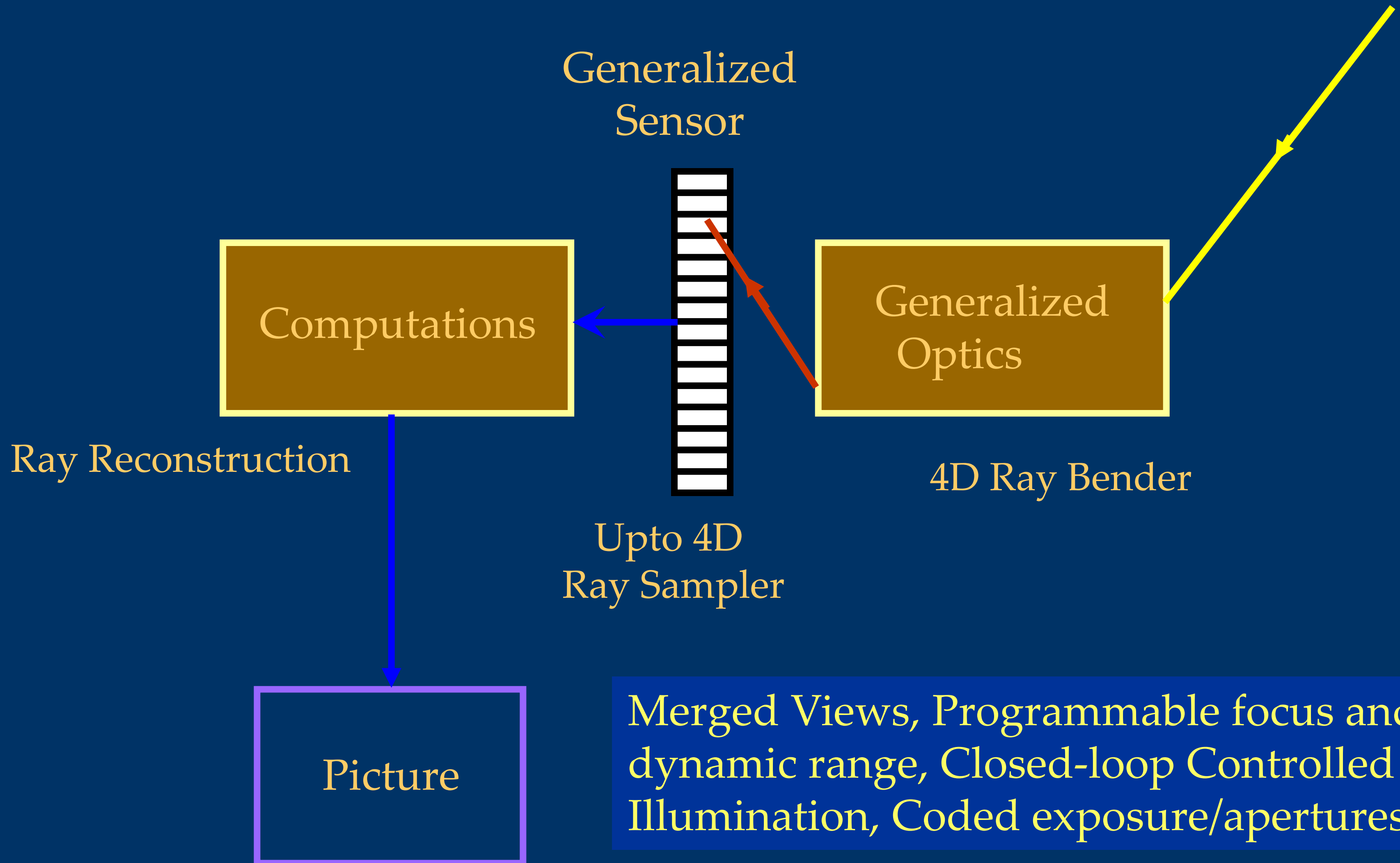
Traditional Photography



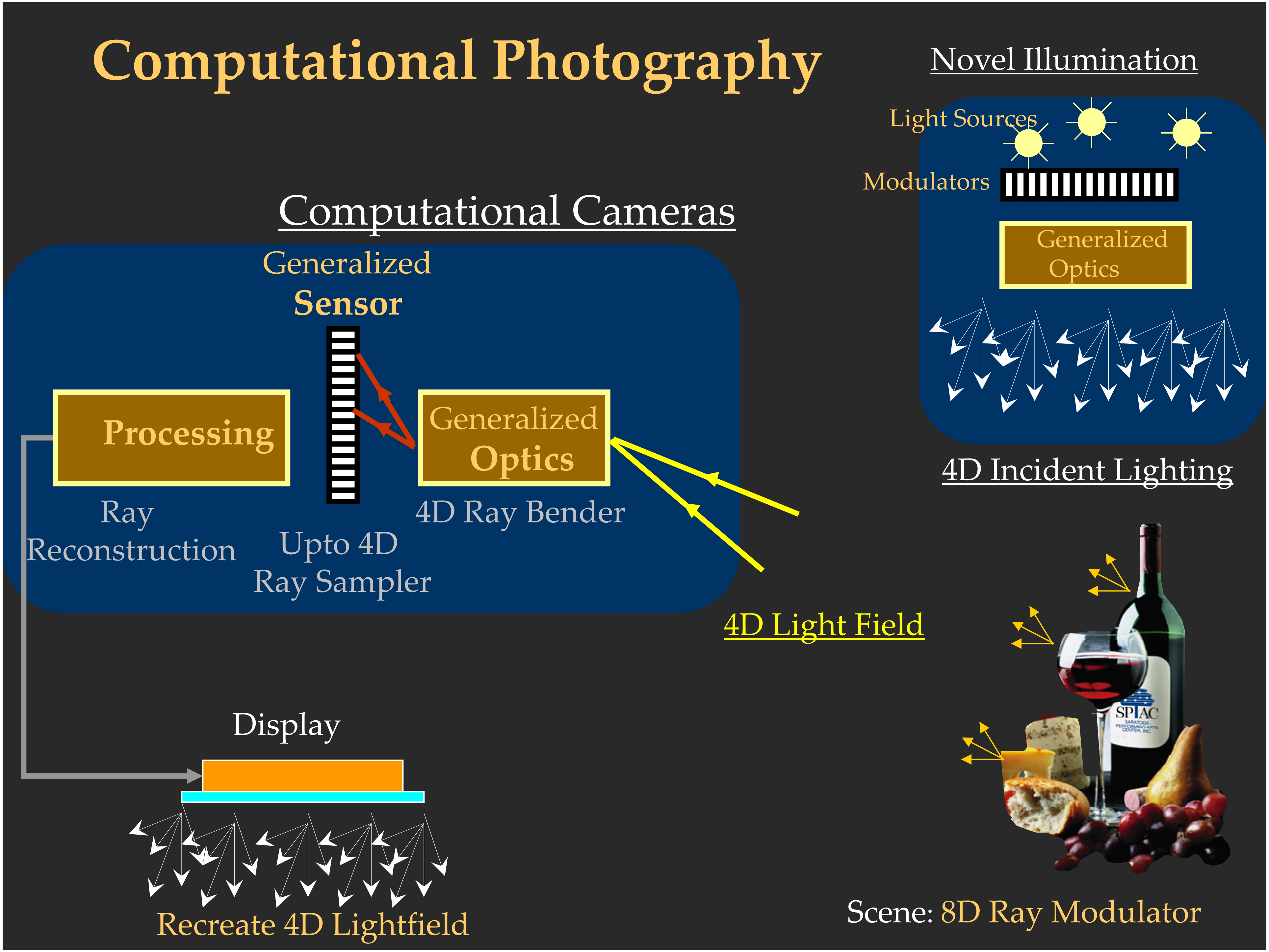
Mimics Human Eye for a Single Snapshot:
Single View, Single Instant, Fixed Dynamic range and Depth of field for given Illumination in a Static world

Courtesy: Shree Nayar

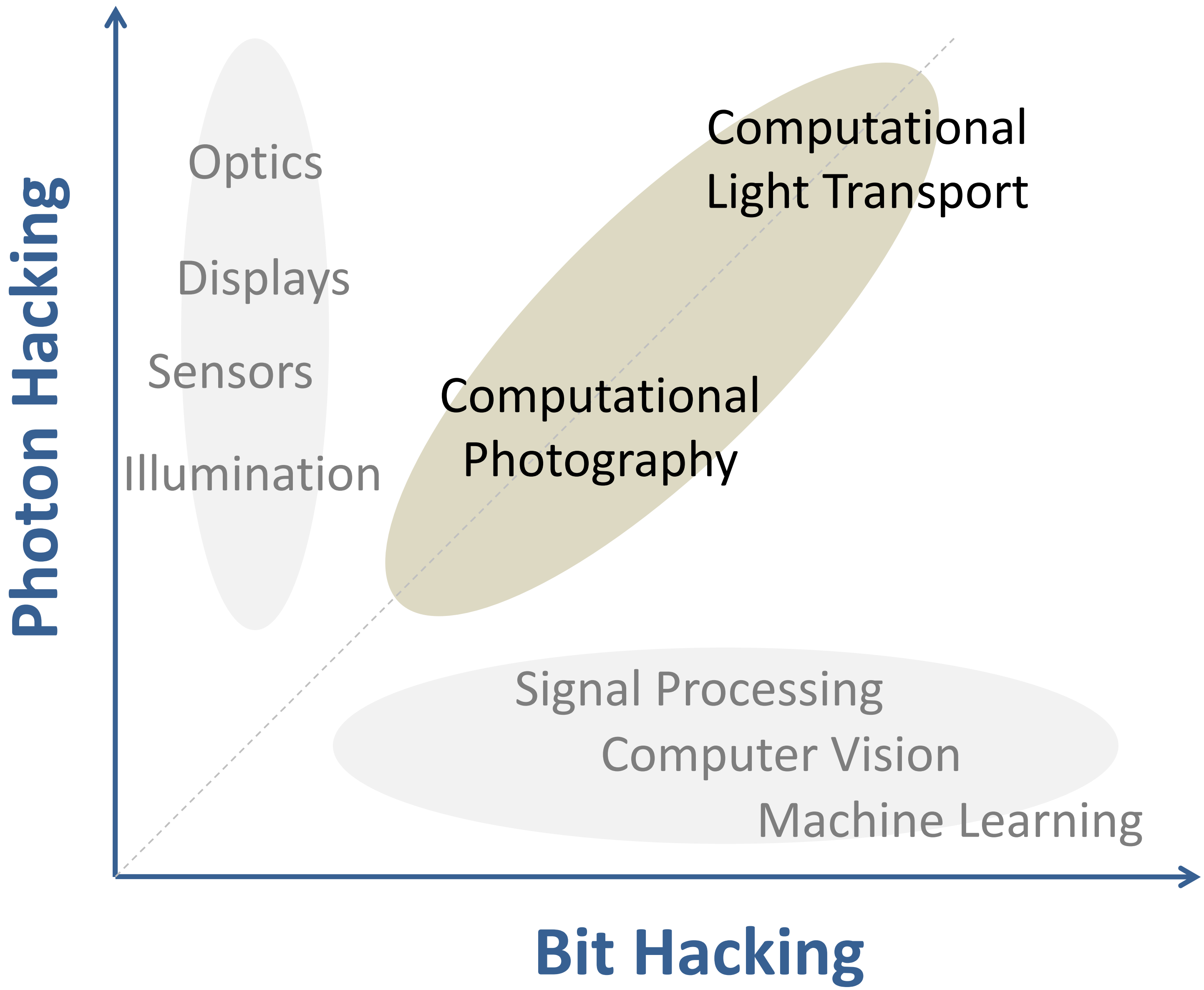
Computational Camera + Photography:
Optics, Sensors and Computations



Merged Views, Programmable focus and dynamic range, Closed-loop Controlled Illumination, Coded exposure/apertures


Computational Photography
Novel Illumination
Light Sources
Modulators
Generalized Optics
4D Incident Lighting
Computational Cameras
Generalized
Sensor
Processing
Generalized Optics
Ray Reconstruction
Upto 4D Ray Sampler
4D Ray Bender
4D Light Field
Display
Recreate 4D Lightfield
Scene: 8D Ray Modulator

Co-designing Optical and Digital Processing



Smart Cameras	Computational Camera and Photography
Pixels Images	Photons Light Fields (4D/6D/8D)
Illumination Lenses	Computational Light Transport
Image Processing	Algebraic Rank Scene Priors/sparsity Transforms (signal proc)

What is MIT Media Lab?

A Graduate Program in the Media Arts & Sciences

Houses ~150 students and 30 PIs

A Research Lab that spans across disciplines and academic/ industrial lines

65 sponsor companies,

Sponsorship = ~ Cost of 1 employee

Sponsors get free, non-exclusive licenses for ML IP

Founded in 1985 by
Nicholas Negroponte and Jerome Wiesner

2010: New Building

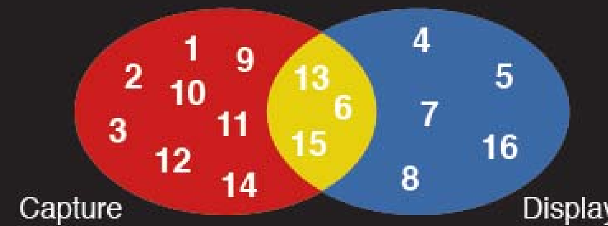
Close Ties With Industry

Our 65 corporate sponsors include some of the most creative companies in the world

Camera Culture

Ramesh Raskar
MIT Media Lab

How to create new ways to capture and share visual information.

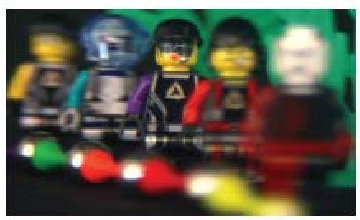


Cameras

1 Cameras of the Future

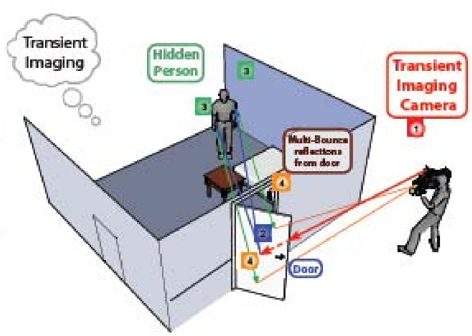
Our group conducts multi-disciplinary research in modern optics, sensors, illumination, actuators, probes, and software processing.

2 Image Destabilization



A method for obtaining SLR-like defocus (Bokeh) with a point-and-shoot camera by perturbing both the lens and the sensor during exposure.

3 Looking Around Corners

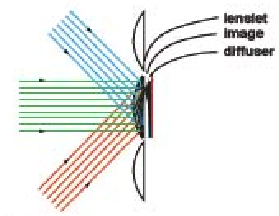


Using short laser pulses and fast detectors, we aim to build a device that can look around corners with no imaging device in the line of sight using time resolved transient imaging.

Displays

4 Slow Display

A high-resolution, ultra-low power, day/night display using programmable lasers and monostable light-reactive materials updated intentionally at a slow frame rate.

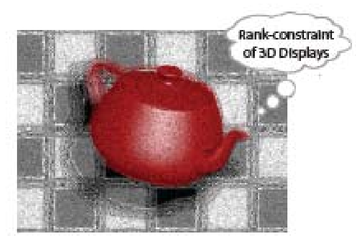


5 Living Windows I 6D Display

A completely passive display that responds to changes in viewpoint and changes in incident light conditions.

6 BiDi Screen

A thin, depth-sensing LCD for 3D interaction using light fields which supports both 2D multi-touch and unencumbered 3D gestures.



7 Glasses-free 3D HDTV

Lightfield displays with increased brightness and refresh rate by stacking a pair of modified LCD panels, exploiting rank constraint of 3D displays.

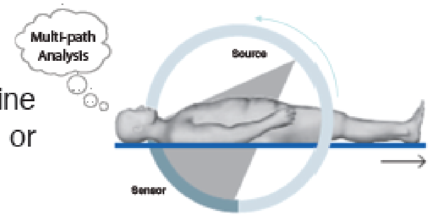
Medical Imaging

8 NETRA

Exploiting cellphone display held near eye and simple user interaction to determine the lens prescription data.

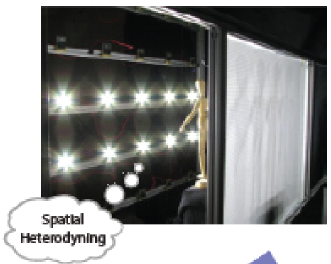
9 High-speed Tomography

A compact, fast CAT scan machine using no mechanically moving parts or synchronization.



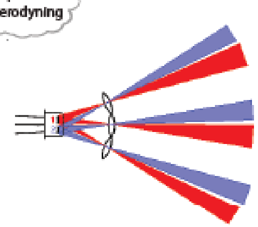
10 Shield Fields

3D reconstruction of objects from a single shot photo using spatial hetero-dyning.

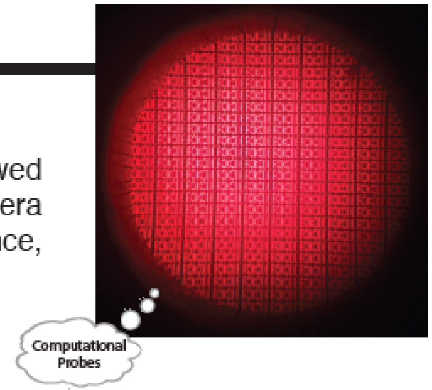


11 Blind Sight

A thermal sensing system using an array of single-bit thermal sensors cou-pled with gray-coded binary masks to track human motion while maintaining privacy.



User Interaction

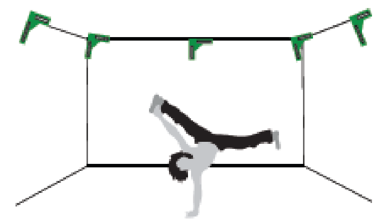


12 Bokode

Tiny barcode tags that can be viewed at large distances provide camera viewable encoding of identity, distance, and angle.

13 Second Skin

Using 3D motion tracking with real-time vibrotactile feedback aids the correction of movement and position errors to improve motor learning.



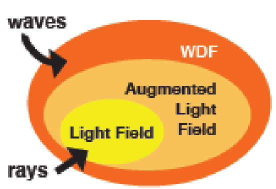
14 Vision on Tap

Bringing Computer Vision to the masses through an easily accessible web service and visual programming

Light Propagation Theory and Fourier Optics

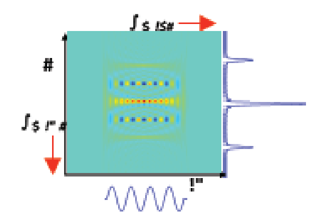
15 Augmented Light Fields

Expands light field representations to describe phase and diffraction effects by using the Wigner Distribution Func-tion.



16 View-Dependent Displays

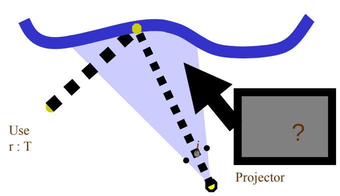
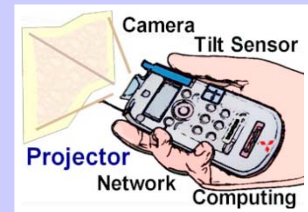
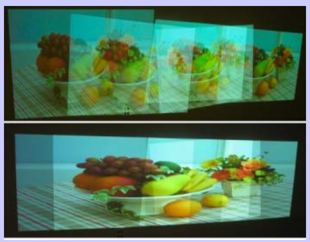
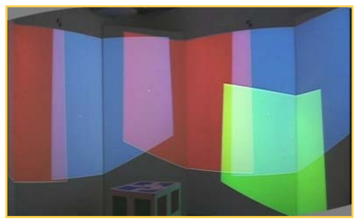
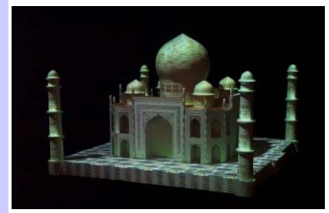
Defines connections between parallax barrier displays and holographic displays by analyzing their operations and limitations in phase space.



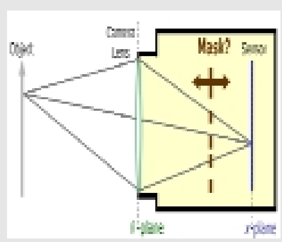
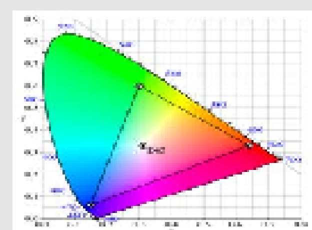
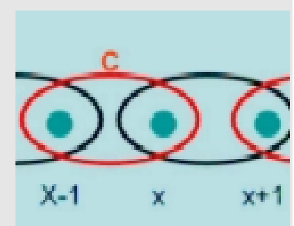
Postdoctoral Researchers: Yun Hee Kim, Douglas Lanman, Andreas Velten.
Research Assistants: Andy Bardagjy, Kevin Chiu, Otkrist Gupta, Matt Hirsch, Roarke Horstmeyer, Tyler Hutchison, Nikhil Naik, Rohit Pandharkar.

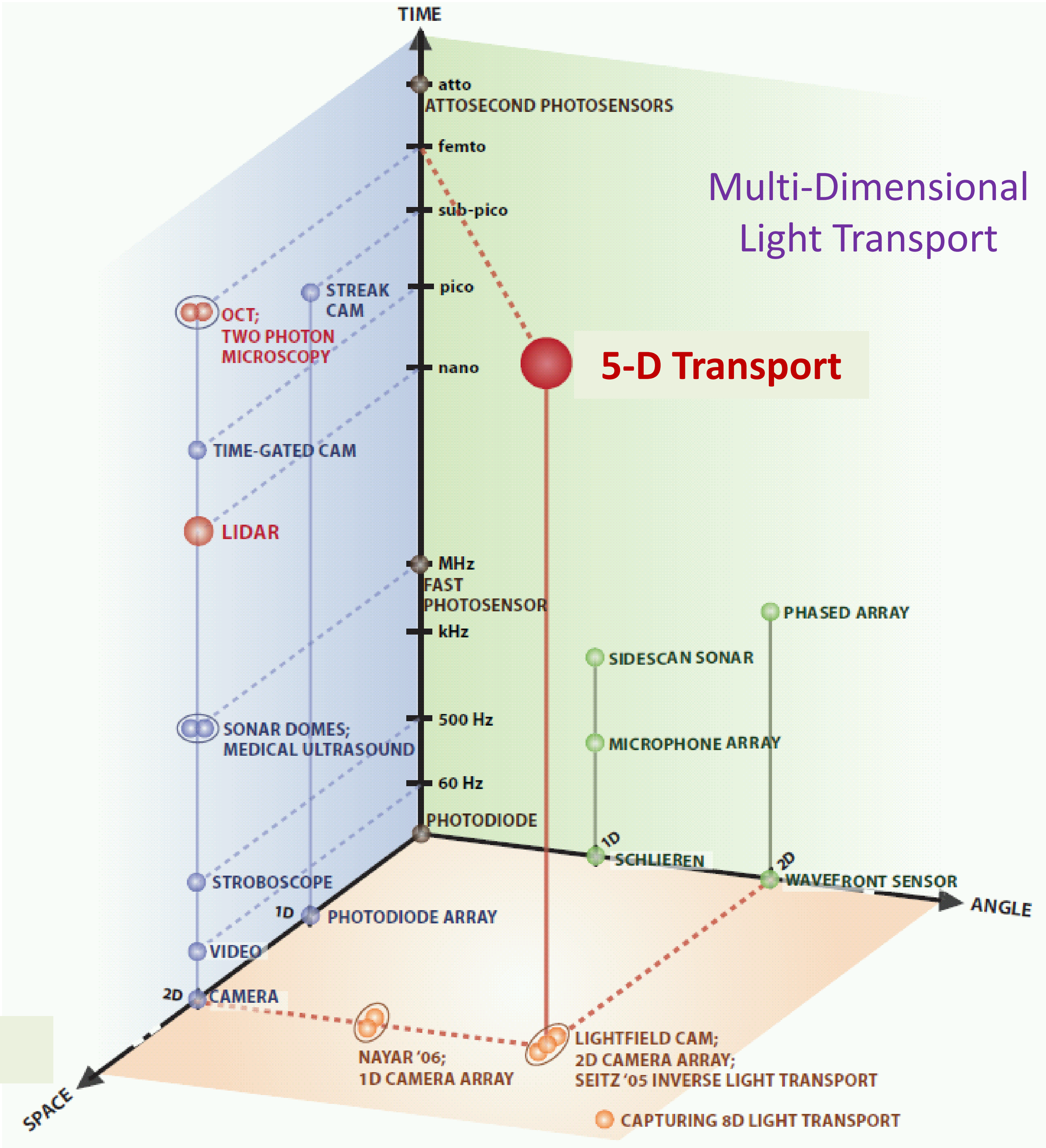
http://cameraculture.media.mit.edu

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 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

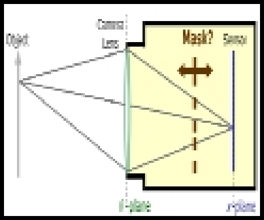

TIME
atto
ATTOSECOND PHOTOSENSORS
femto
sub-pico
pico
nano
MHz
FAST
PHOTOSENSOR
kHz
500 Hz
60 Hz
PHOTODIODE
Multi-Dimensional
Light Transport
5-D Transport
STREAK
CAM
OCT;
TWO PHOTON
MICROSCOPY
TIME-GATED CAM
LIDAR
SONAR DOMES;
MEDICAL ULTRASOUND
STROBOSCOPE
1D
PHOTODIODE ARRAY
VIDEO
2D
CAMERA
PHASED ARRAY
SIDESCAN SONAR
MICROPHONE ARRAY
1D
SCHLIEREN
2D
WAVEFRONT SENSOR
ANGLE
SPACE
NAYAR '06;
1D CAMERA ARRAY
LIGHTFIELD CAM;
2D CAMERA ARRAY;
SEITZ '05 INVERSE LIGHT TRANSPORT
CAPTURING 8D LIGHT TRANSPORT

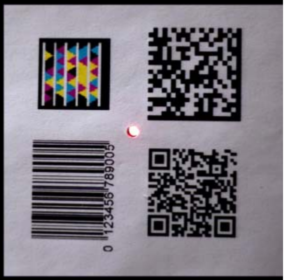
Gigapan

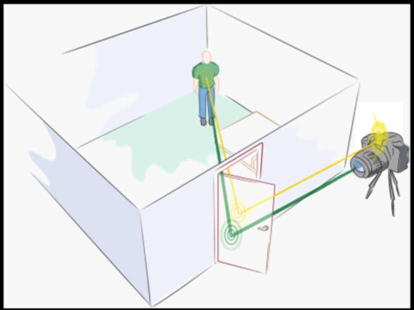
Computational Camera + Photography

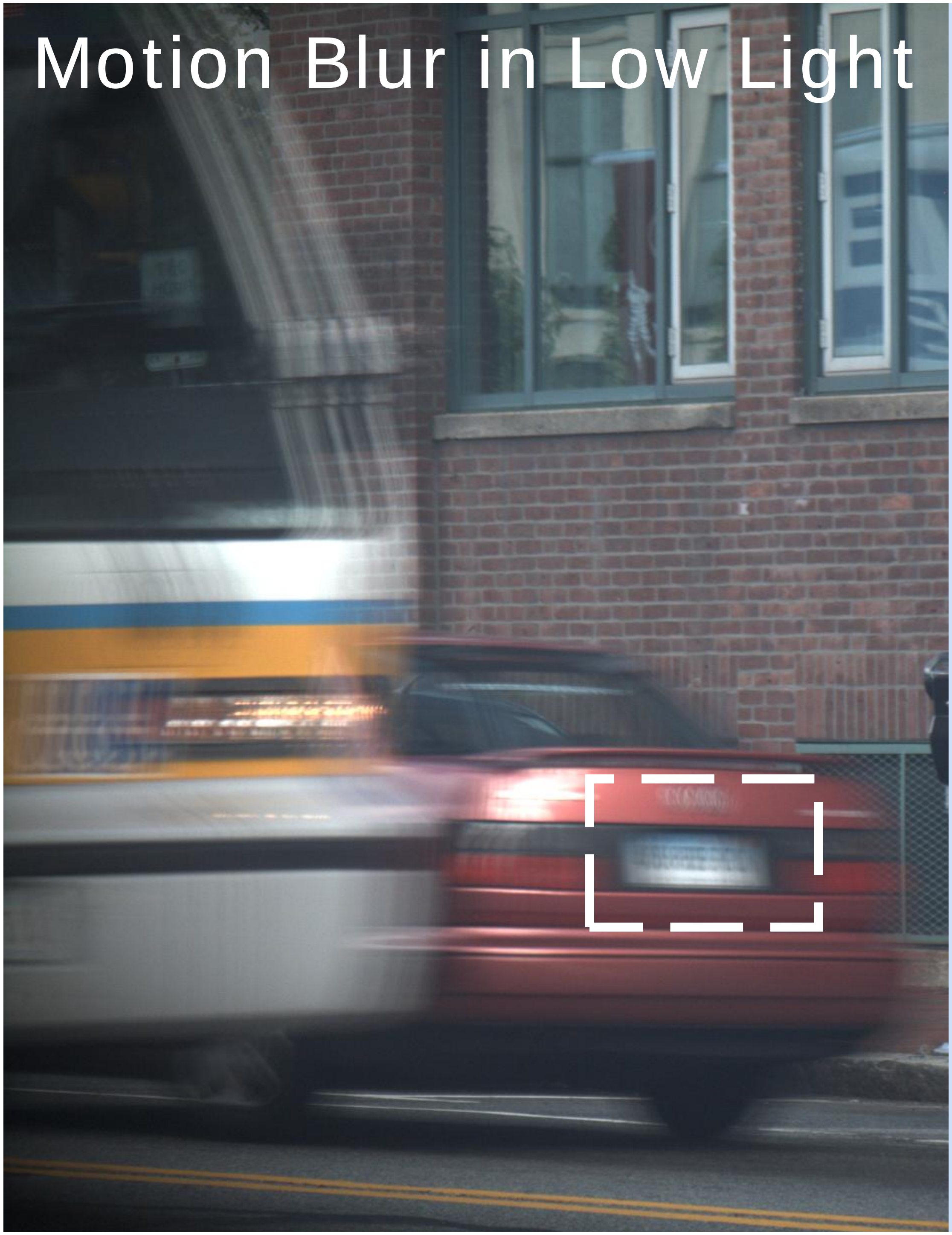
Photons not Pixels

- Time
  - Looking around a corner
  - Flutter Shutter (motion deblur)
- Space
  - LCD as virtual cameras (BiDi)
  - Mask-based Light Field Camera (depth)
- Illumination
  - Multi-flash Camera
- Computational probes
  - Bokode (long distance barcodes)

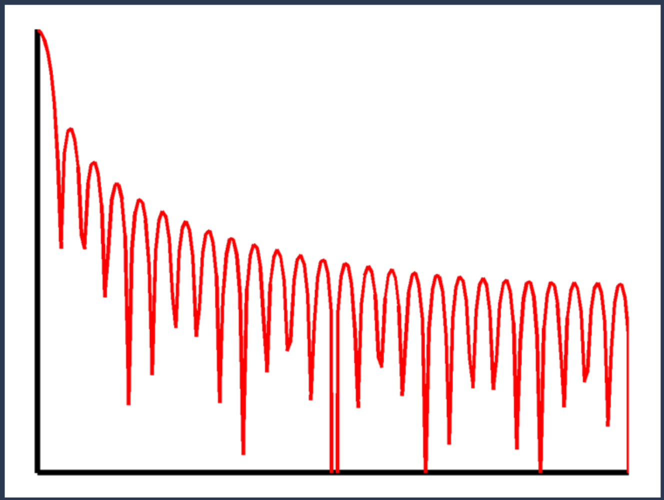




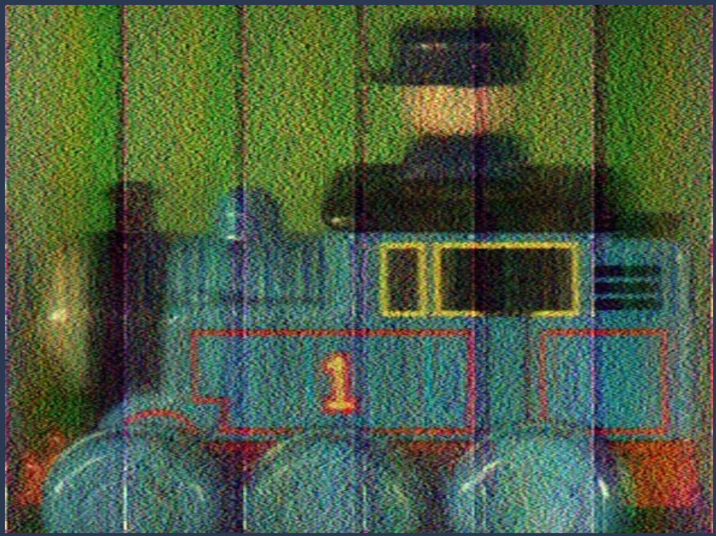



Motion Blur in Low Light

Traditional



Blurred Photo



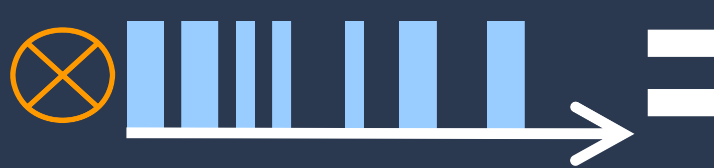
Deblurred Image

Fluttered Shutter Camera

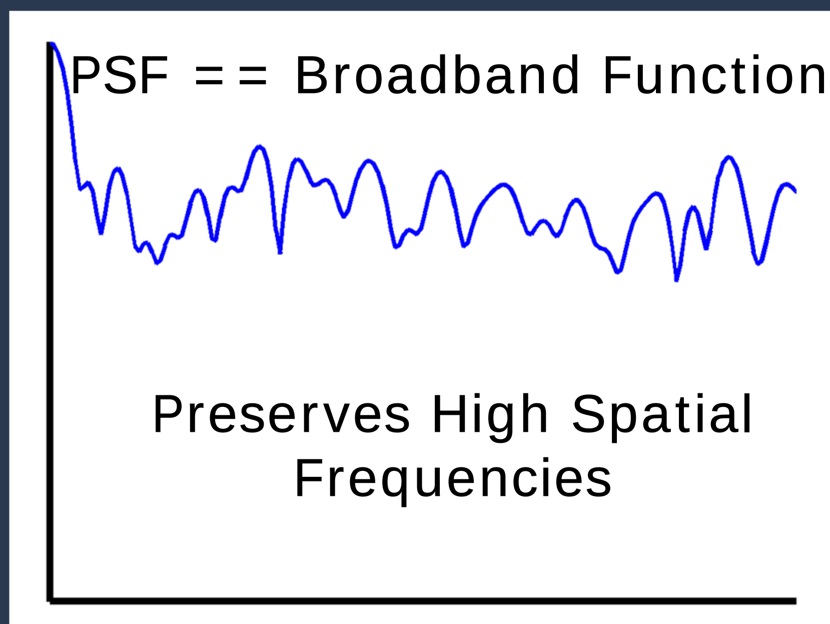
Raskar, Agrawal, Tumblin Siggraph2006

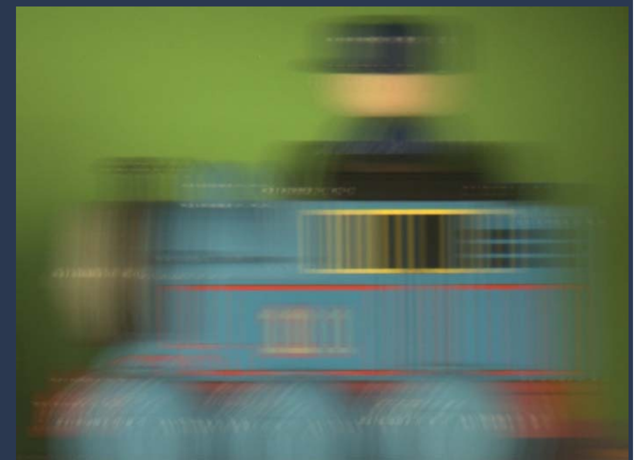
Ferroelectric shutter in front of the lens is turned opaque or transparent in a rapid binary sequence

Sharp
Photo



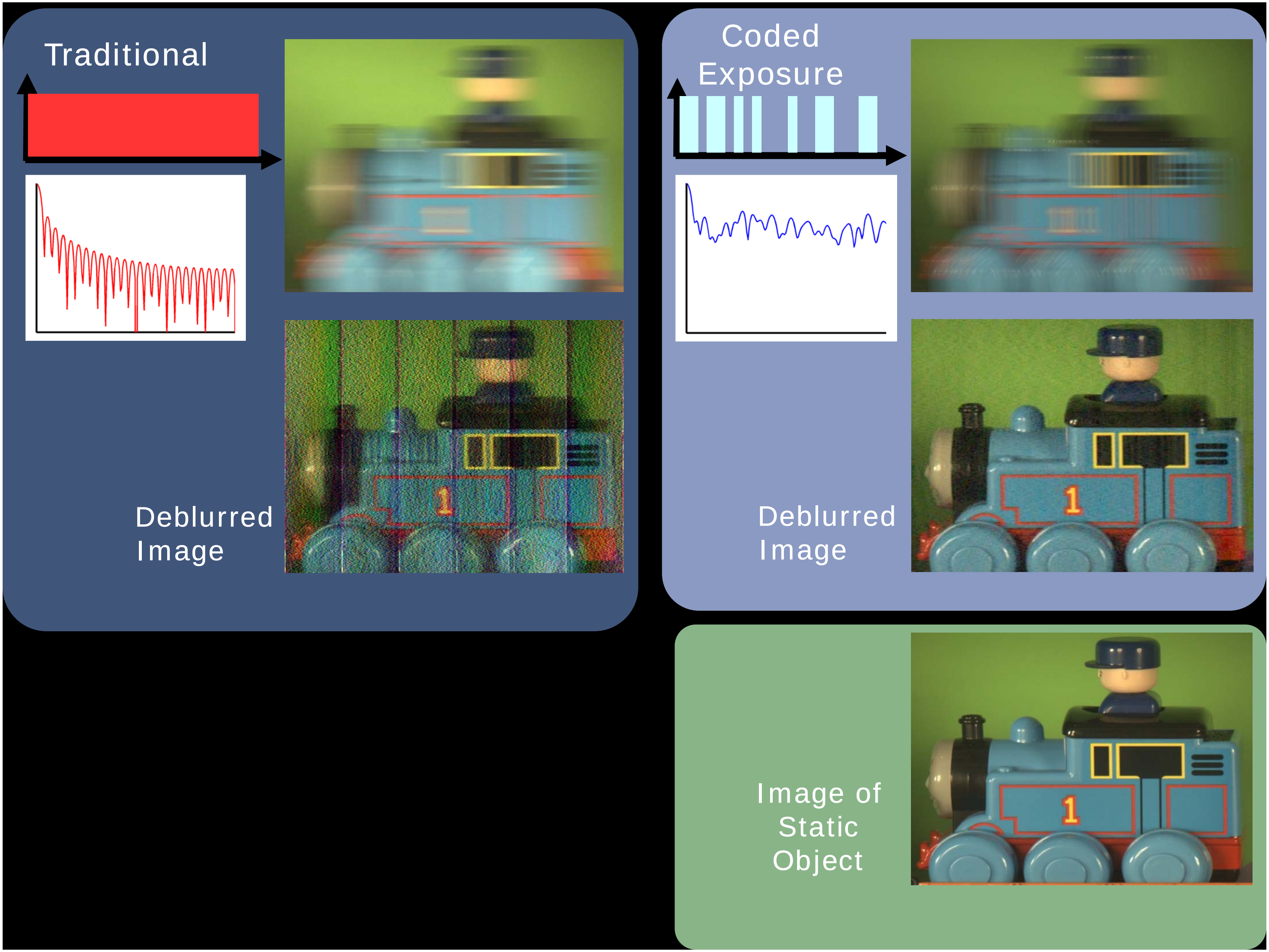
Fourier
Transform



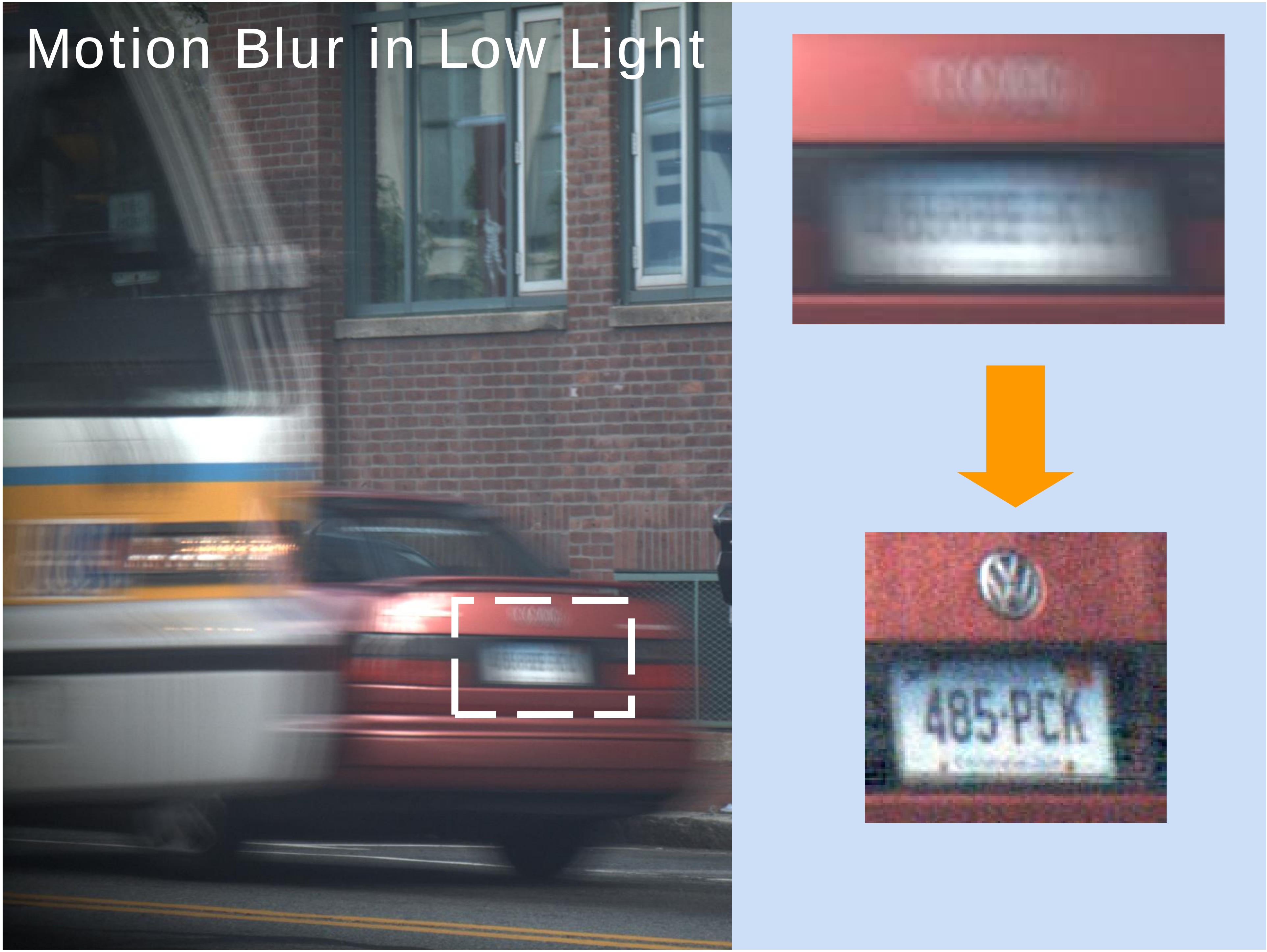


Blurred
Photo

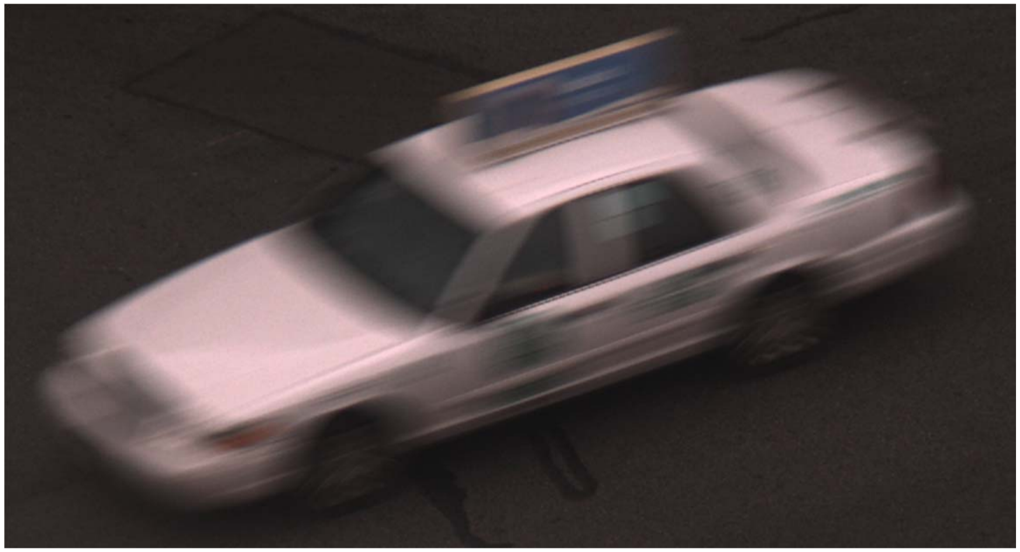
Flutter Shutter: Shutter is OPEN and CLOSED


Traditional
Deblurred Image
Coded Exposure
Deblurred Image
Image of Static Object

Motion Blur in Low Light



Varying Exposure Video:
Exploit auto-exposure mode



Blurred Photo

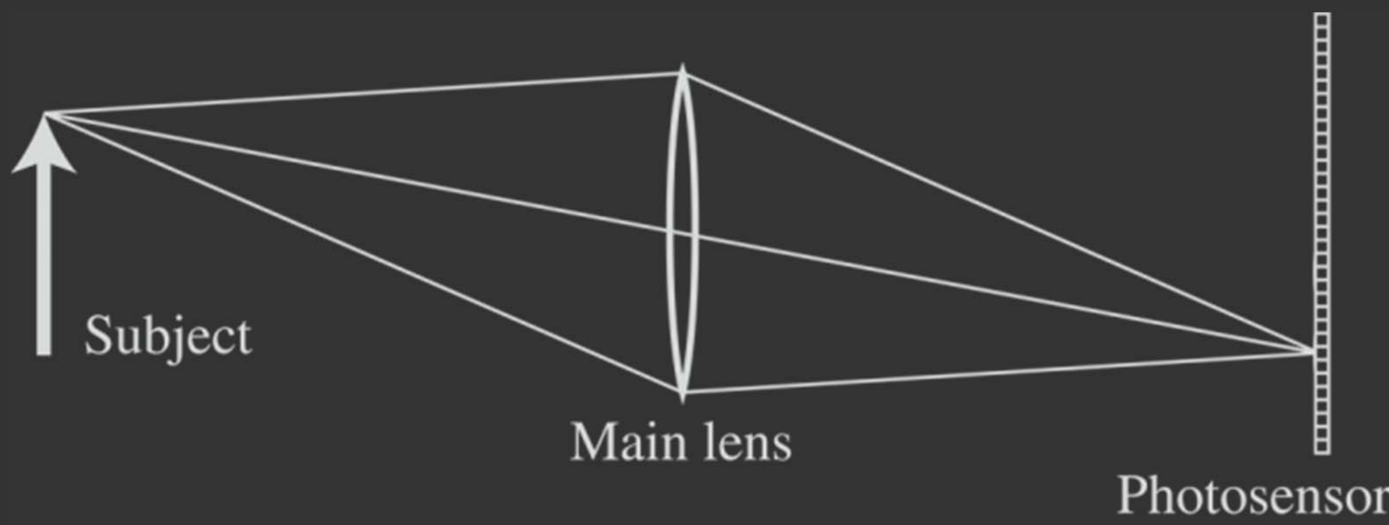
Completely automatic: (i) Segmentation, (ii) PSF estimation, (iii) deblurring

Input Photos

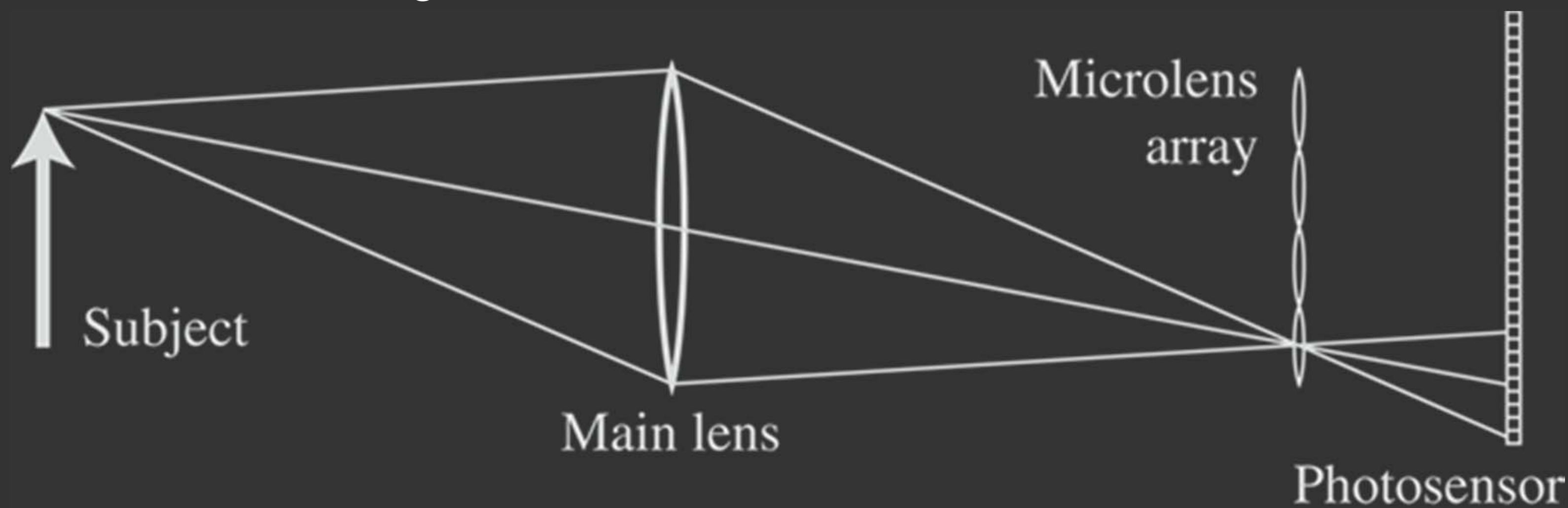
Deblurred Result

Ground Truth

Lightfield Camera for 4D Capture



Lenslet-based Light Field camera

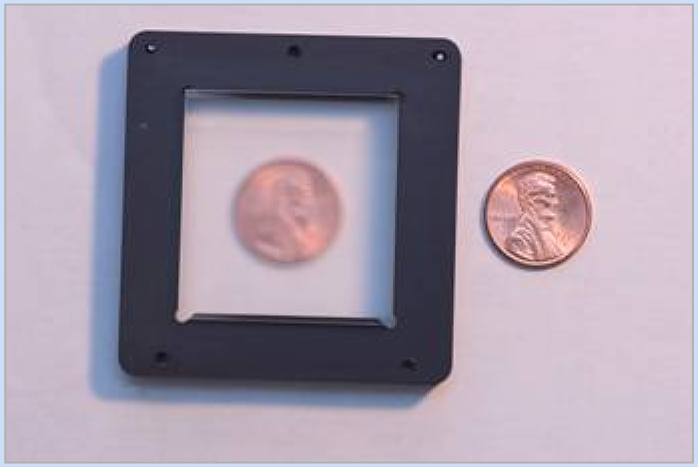


[Adelson and Wang, 1992, Ng et al. 2005]

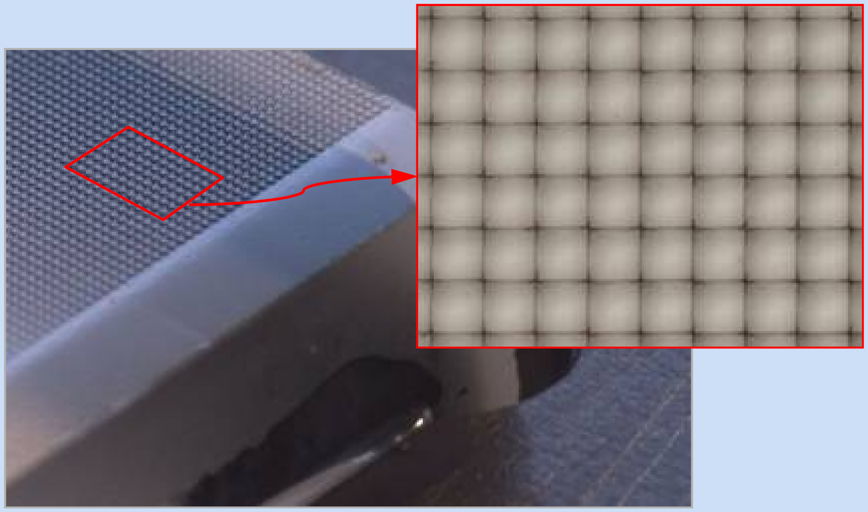
Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor



Adaptive Optics microlens array



125μ square-sided microlenses

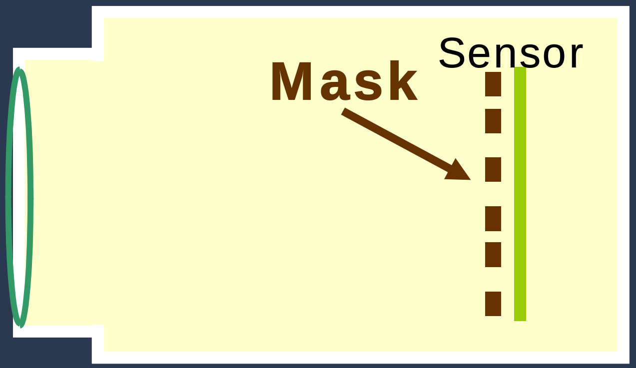
4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens

Digital Refocusing

[Ng et al 2005]

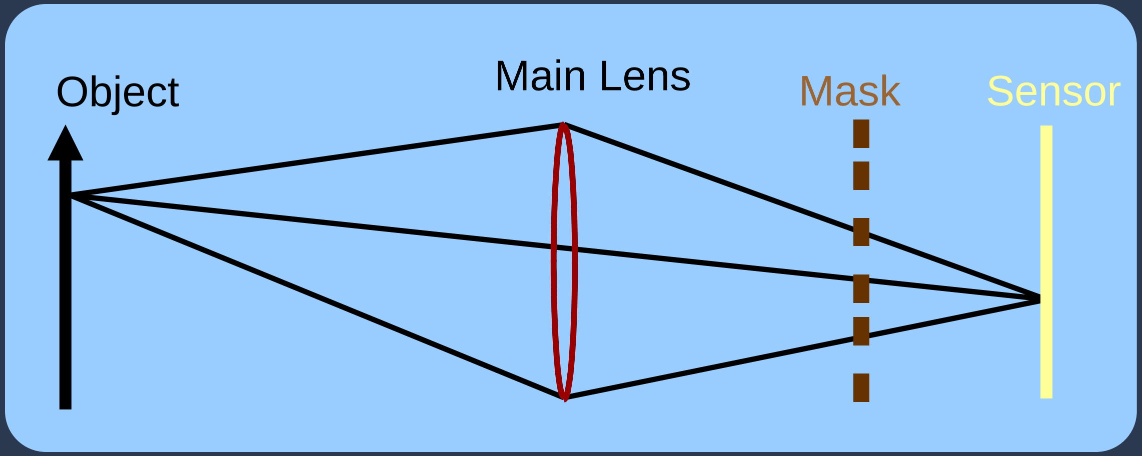
Can we achieve this with a Mask alone?

Mask based Light Field Camera



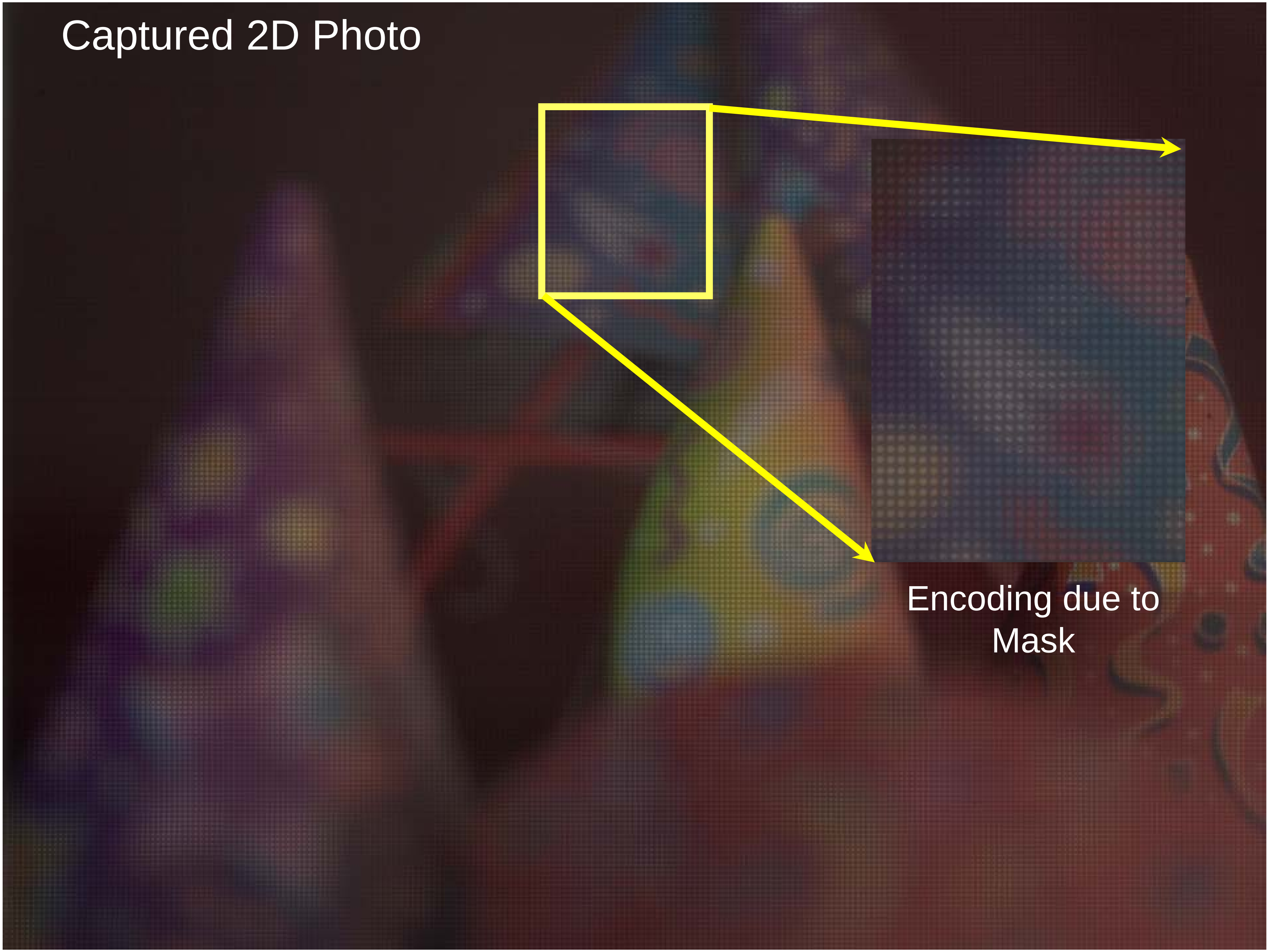
[Veeraraghavan, Raskar, Agrawal, Tumblin, Mohan, Siggraph 2007]

Spatial Heterodyning



Light Field without Additional Lenslets

Wavefront Analysis for ANY wavelength

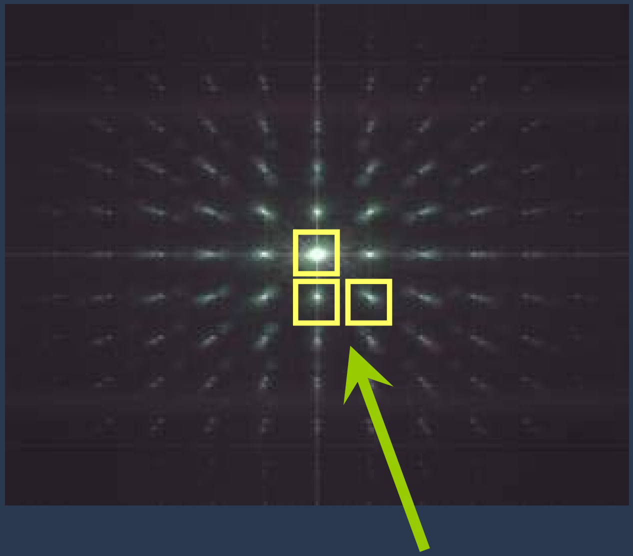

Captured 2D Photo
Encoding due to Mask

Mask-based 4D Light Field

2D Sensor Photo, 1800*1800

2D
FFT

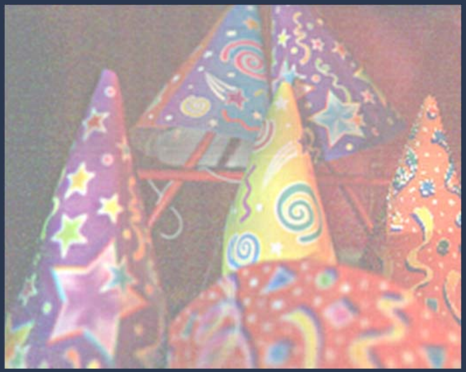
2D Fourier Transform, 1800*1800



9*9=81 spectral copies

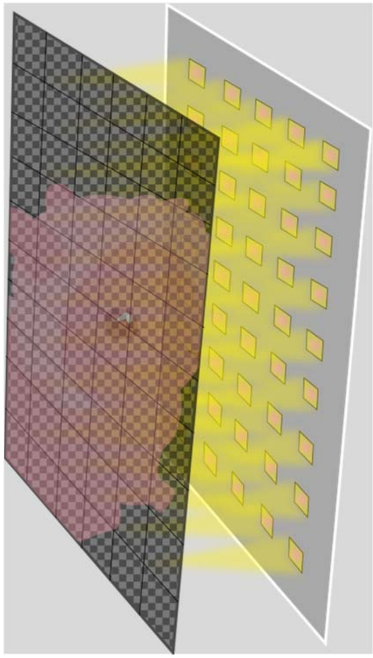
Rearrange 2D tiles into 4D planes
200*200*9*9

4D IFFT



4D Light Field → Depth
200*200*9*9

BiDi Screen: Thin LCD for touch+hover



Sensing Depth from Light Sensing LCD
By creating Array of Virtual Cameras in LCD

Hirsch, Holtzman Lanman, Raskar   Siggraph Asia 2009

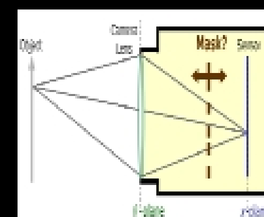
BiDi Screen: Multi-touch + Hover 3D interface

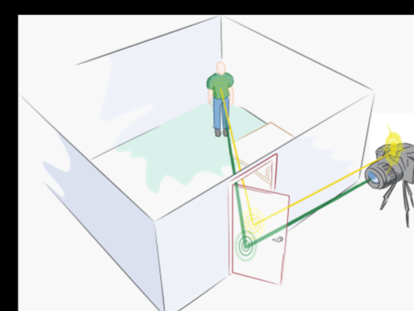
LCD = Large Area Camera

Computational Camera + Photography

Photons not Pixels

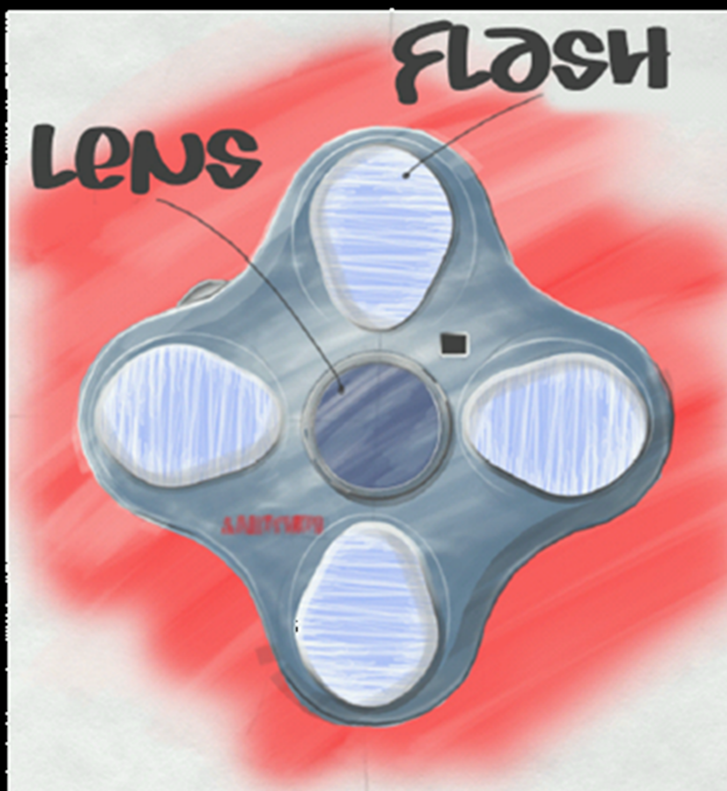
- Space
  - LCD as virtual cameras (BiDi)
  - Mask-based Light Field Camera (depth)
- Time
  - Flutter Shutter (motion deblur)
  - Looking around a corner
- Illumination
  - Multi-flash Camera
- Computational probes
  - Bokode (long distance barcodes)

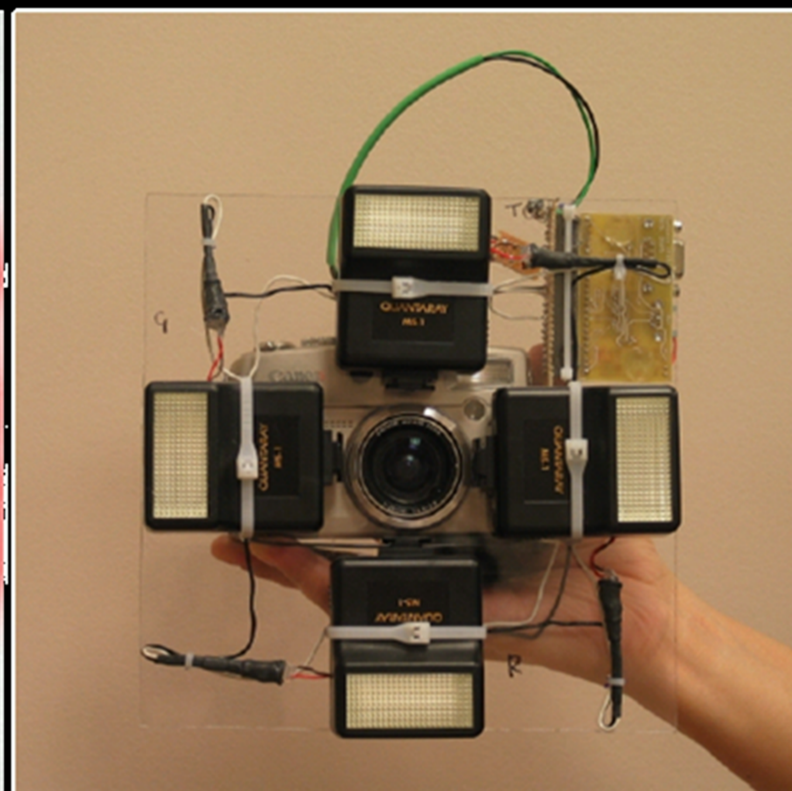


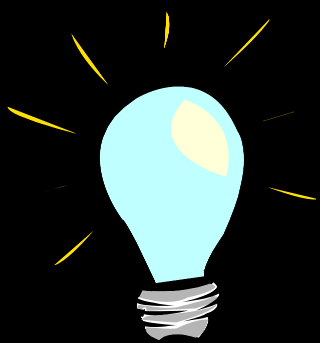
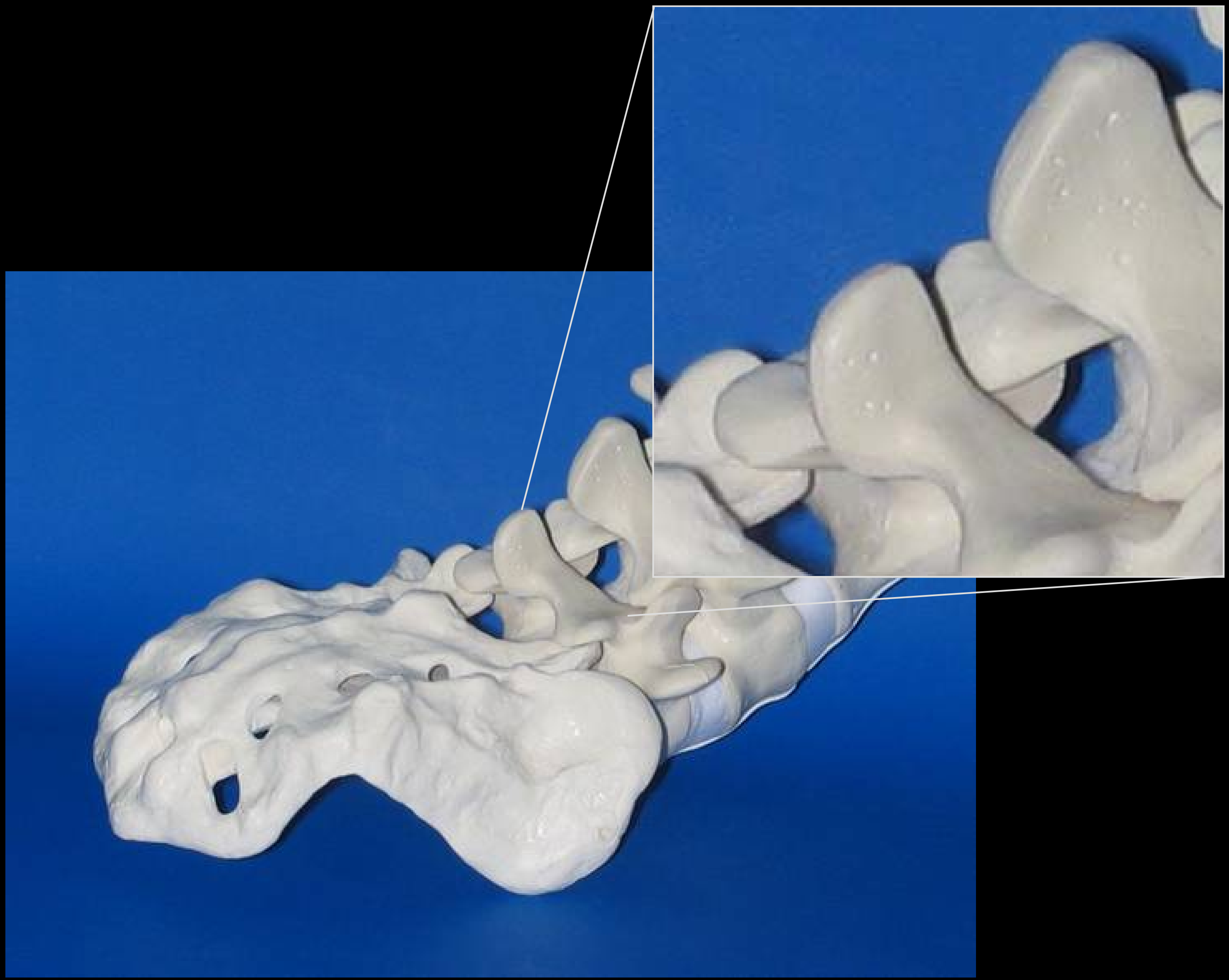


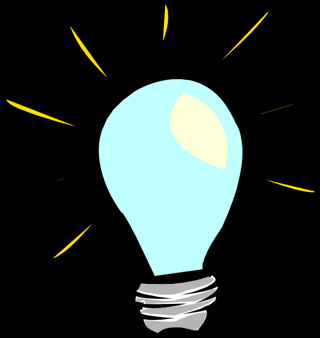
Depth Edges with MultiFlash

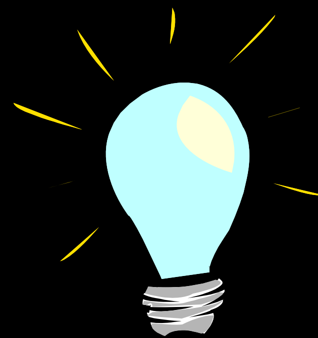
Raskar, Tan, Feris, Jingyi Yu, Turk – ACM SIGGRAPH 2004





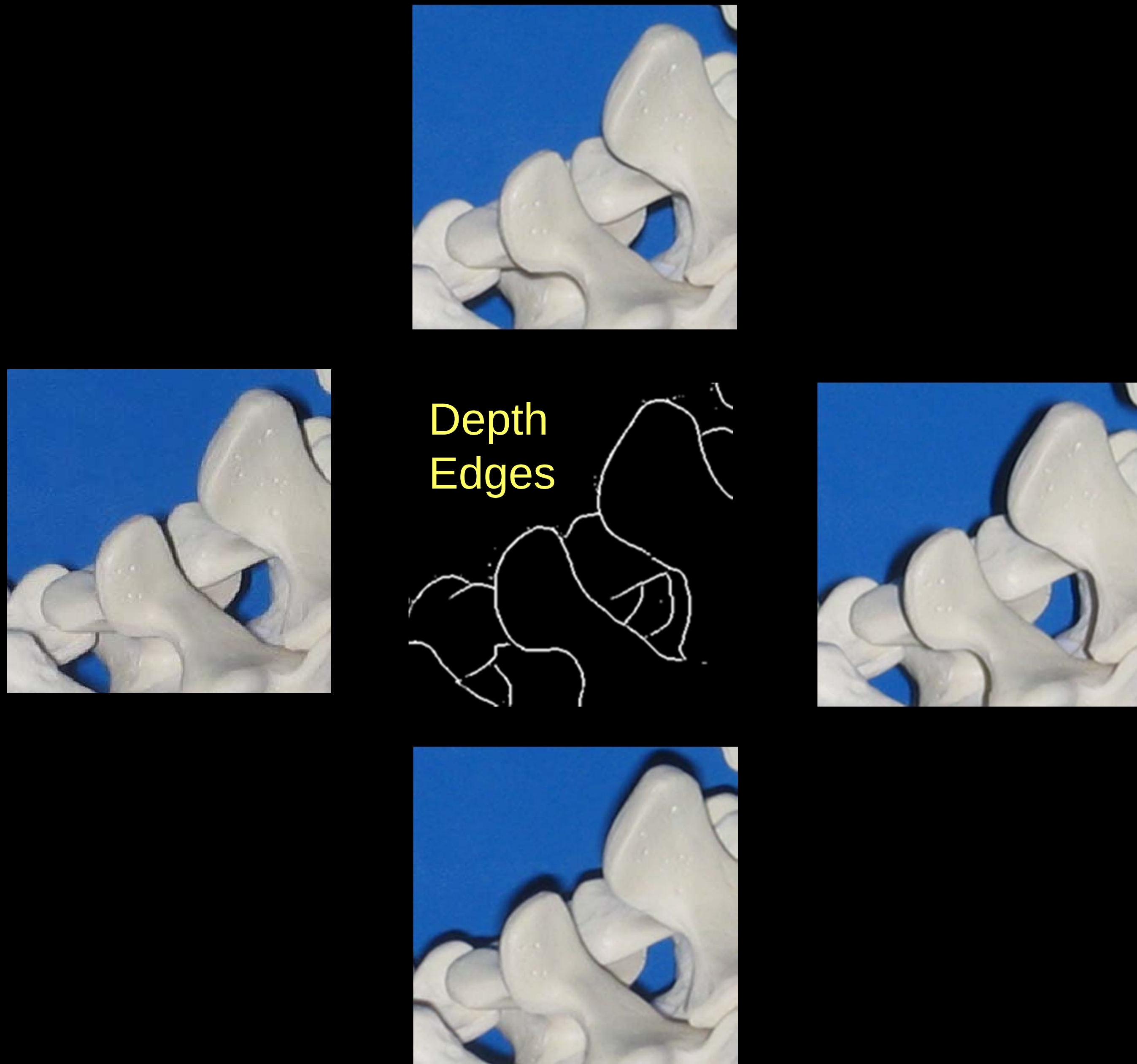







Depth Discontinuities

Internal and external
Shape boundaries, Occluding contour, Silhouettes


Depth
Edges

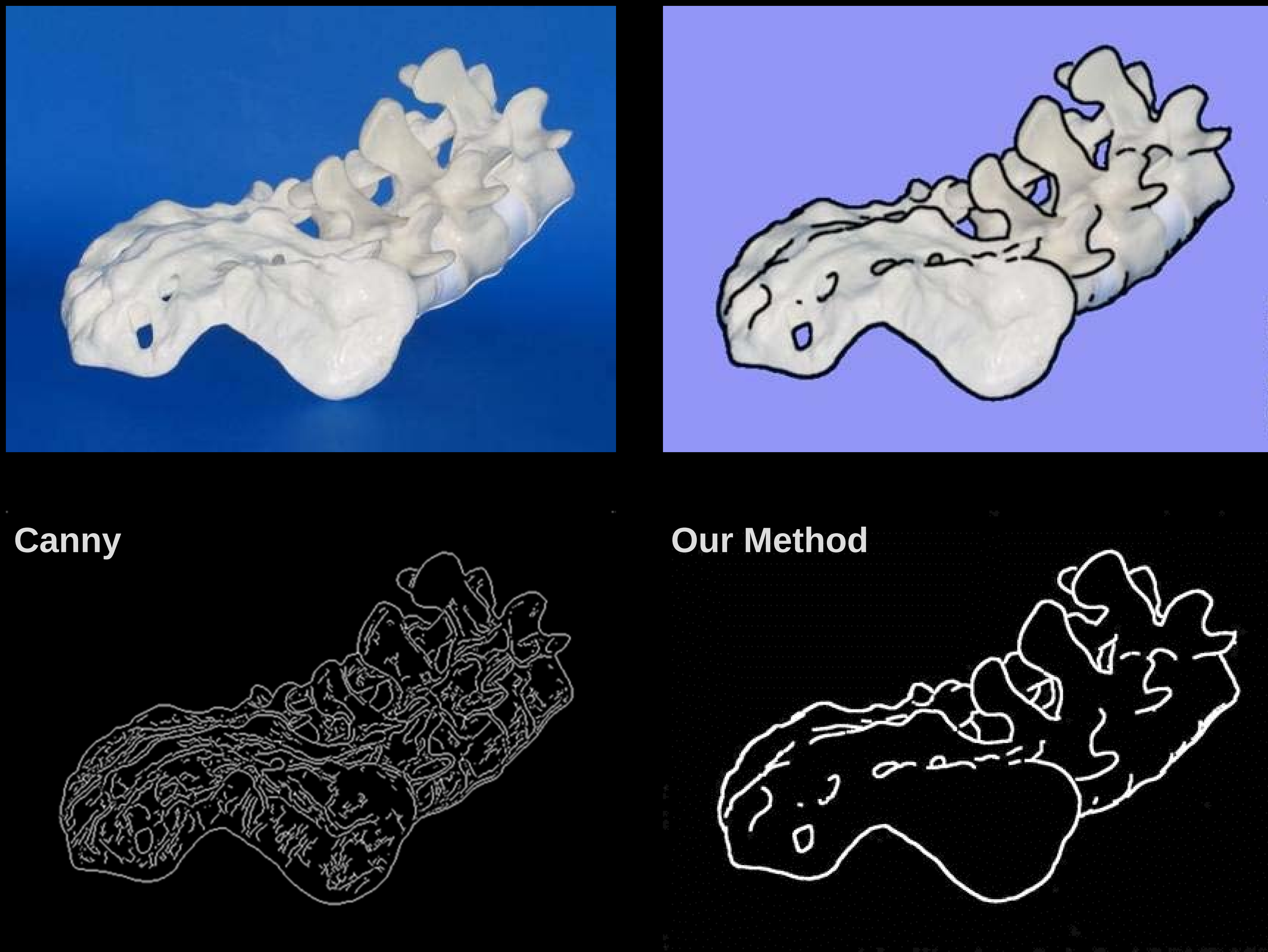

Canny
Our Method


Photo
Result
Our Method
Canny Intensity
Edge Detection

Gestures and Pose Estimation

Input Photo

Canny Edges

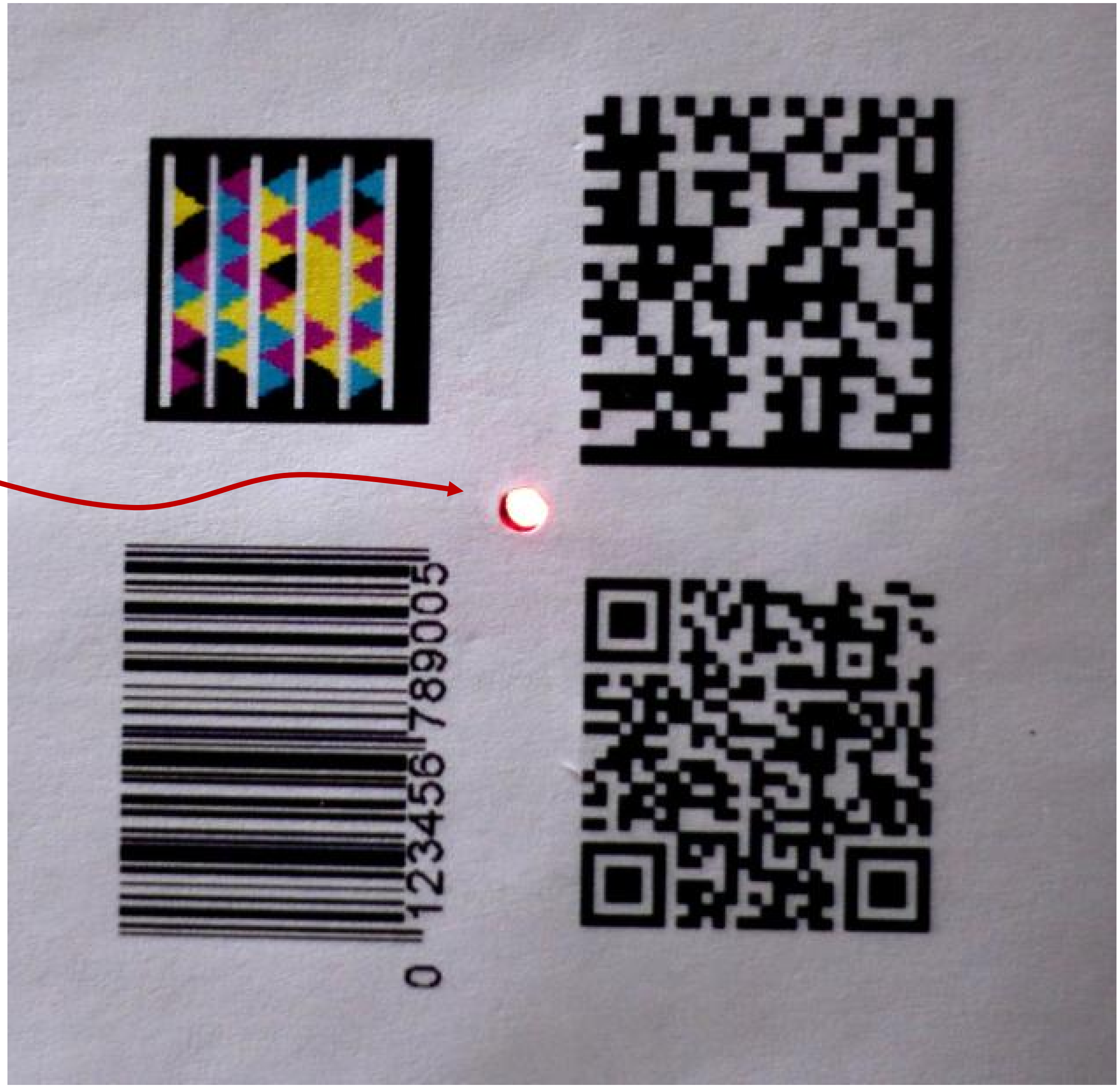
Depth Edges

Feris et al 2005

Cell Manufacturing Automation
with Mitsubishi Electric Research Labs

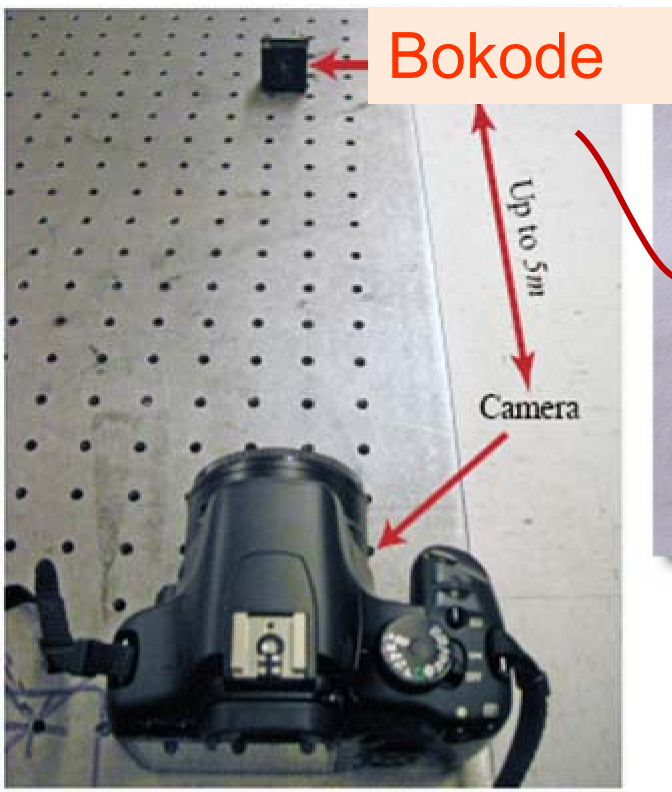
Can we shrink barcodes?

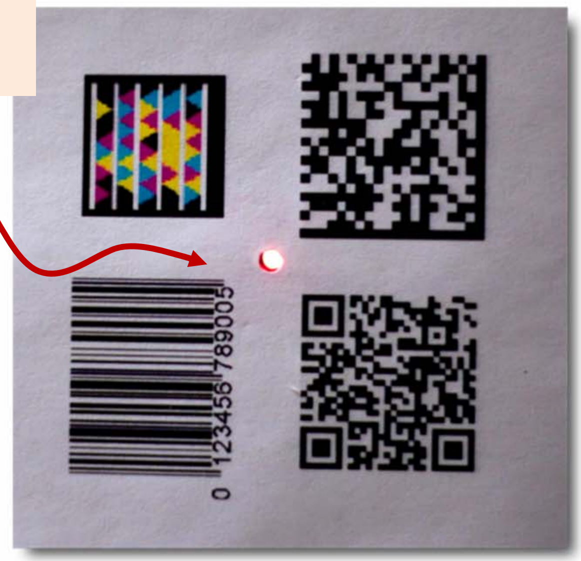
Bokode



Bokode: Long Distance Barcodes

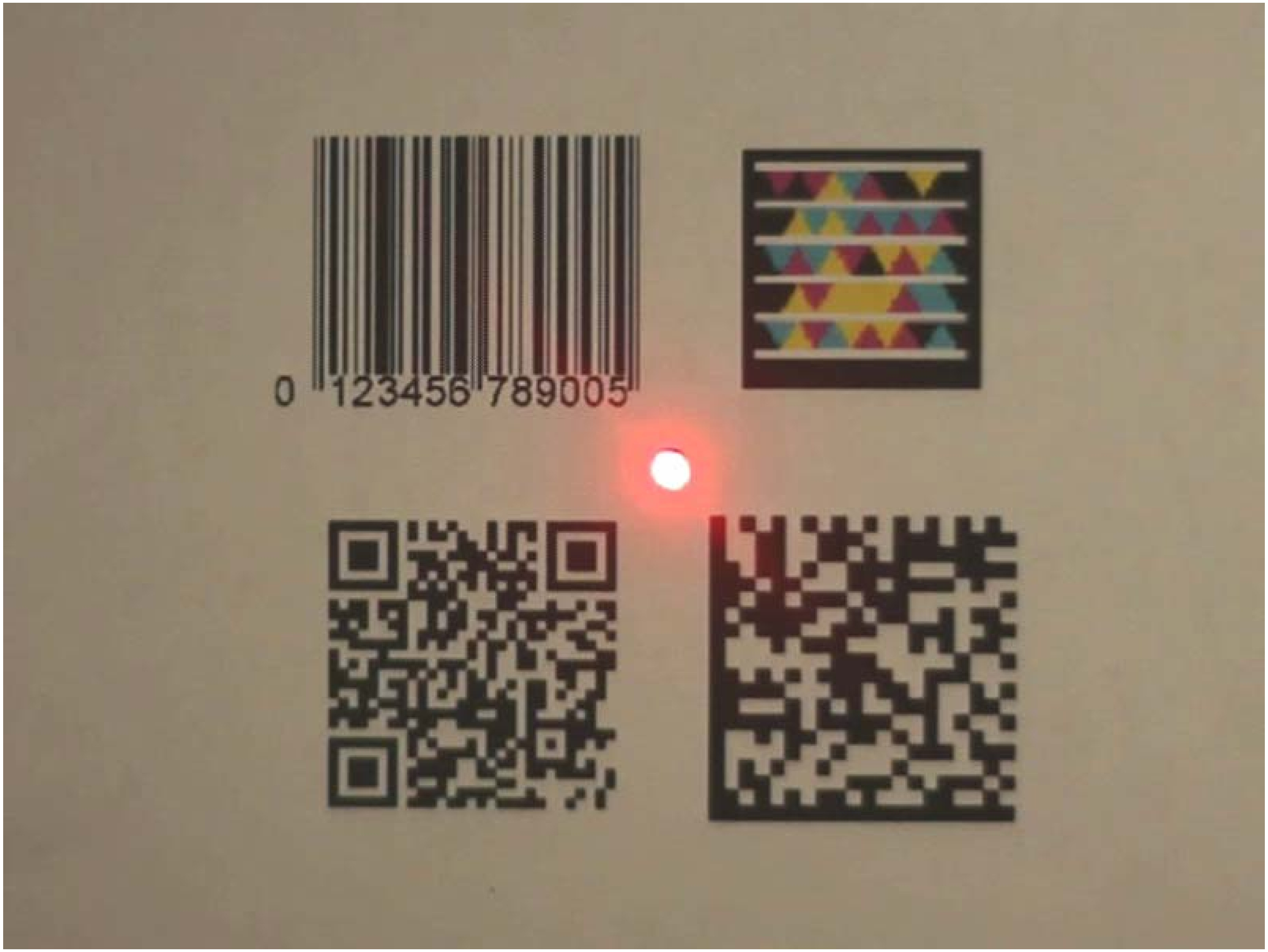
- Smart Barcode size : 3mm x 3mm
- Ordinary Camera: Distance 3 meter
- Recover using out-of-focus camera



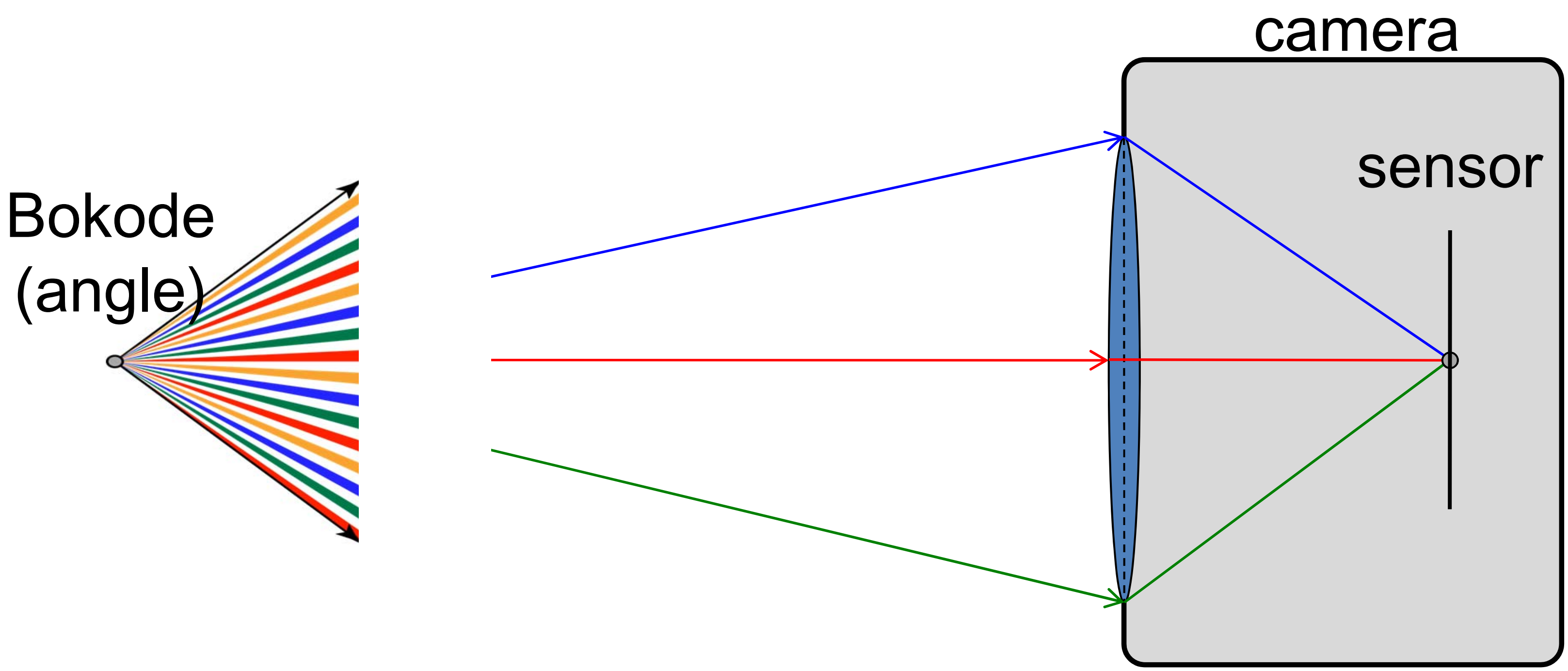


In Focus Photograph

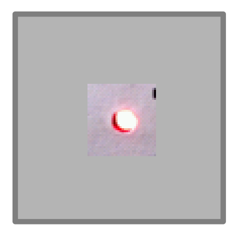
Mohan, Woo, Smithwick, Hiura, Raskar [Siggraph 2009]


0 123456 789005

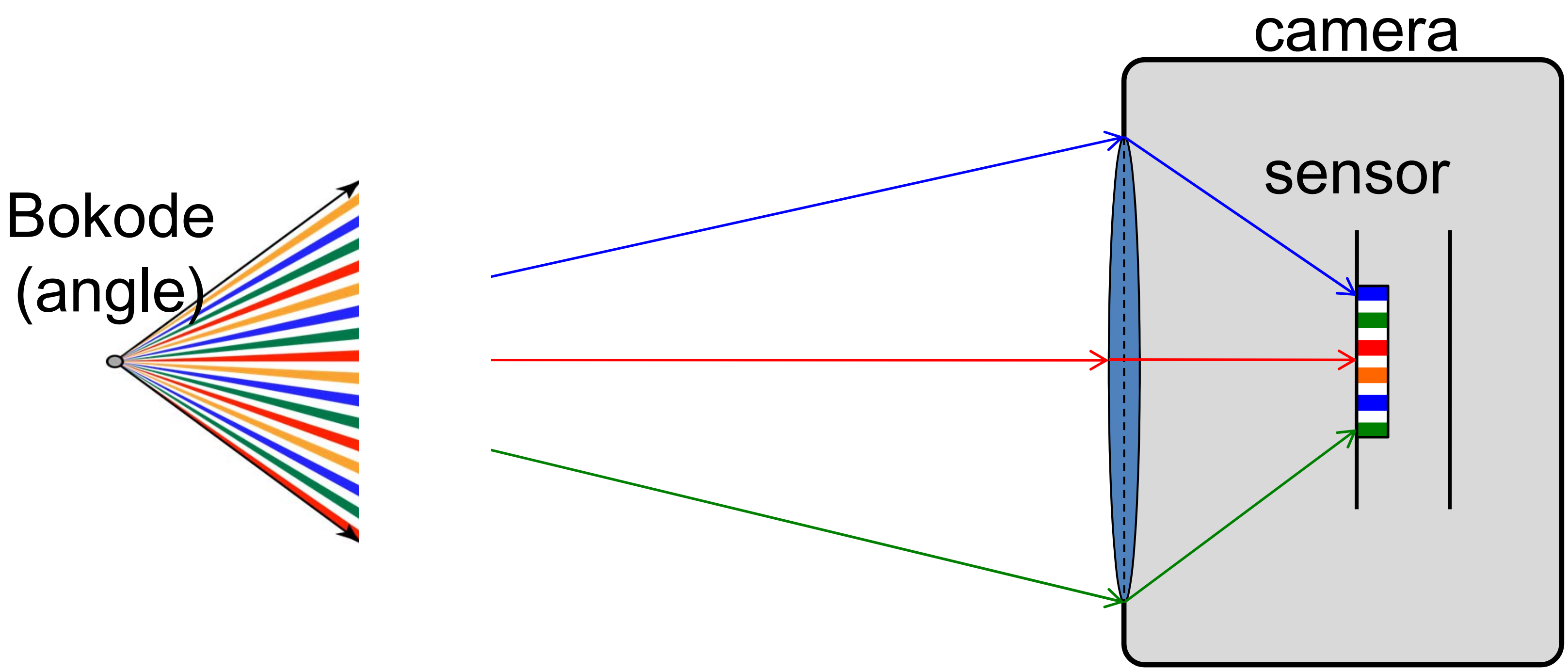
Encoding in Angle, not space, time or wavelength

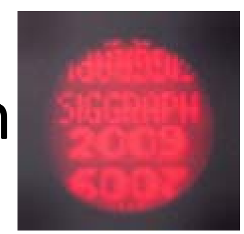


Sharp Focus



Encoding in Angle, not space, time or wavelength

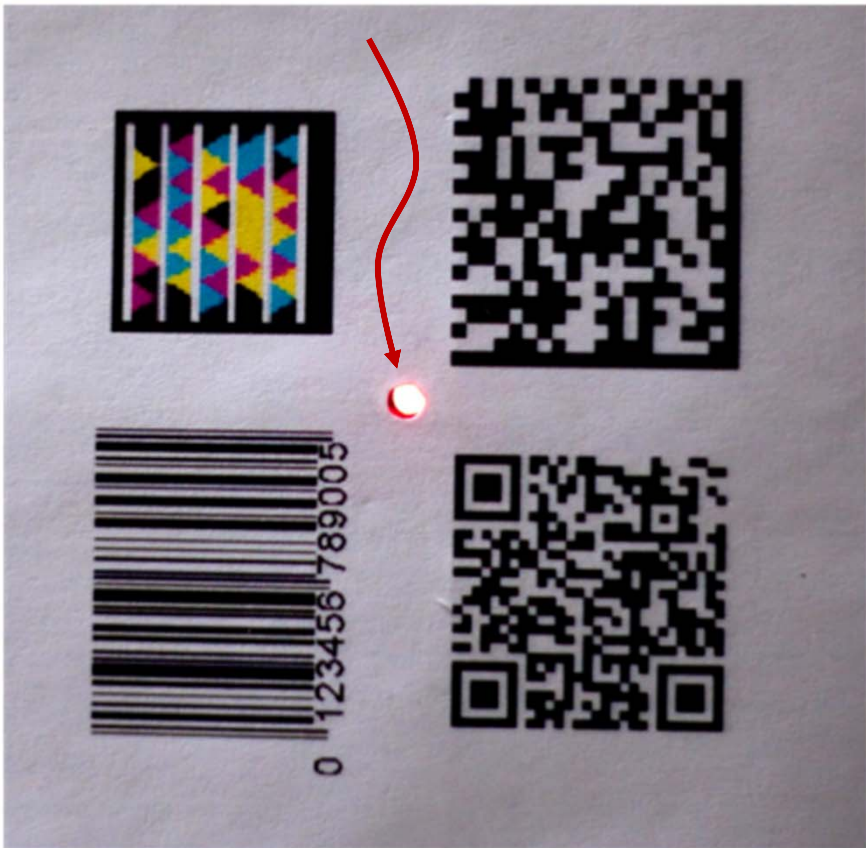


circle of confusion → circle of information 

Quote suggested by Kurt Akeley

Coding in Angle: Defocus not Zoom

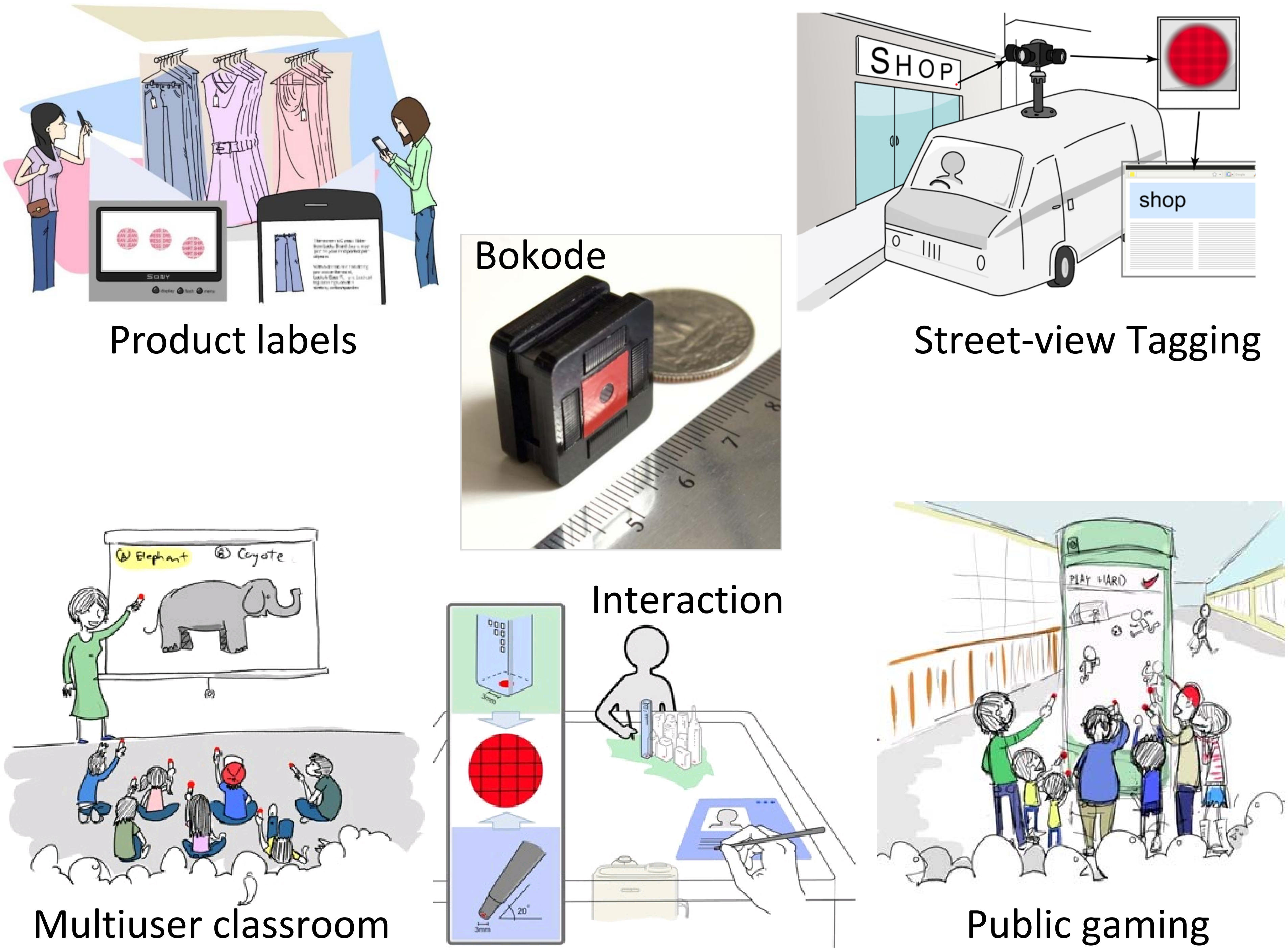
Bokode



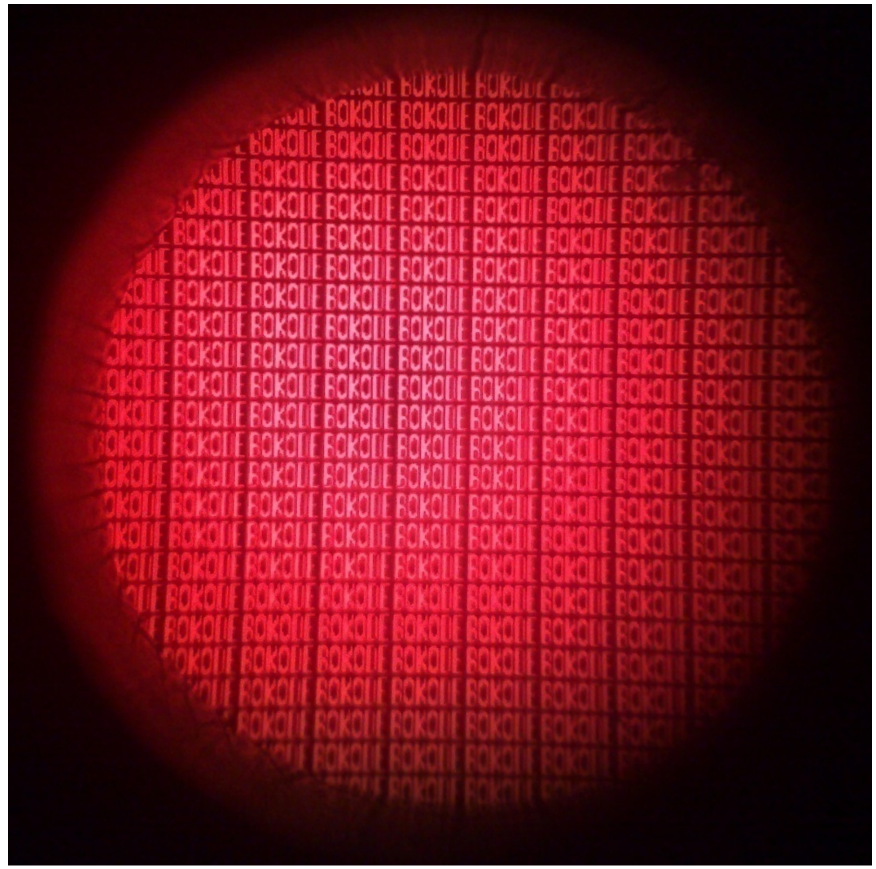
In Focus Photograph

Out of Focus Photograph

Mohan, Woo, Smithwick, Hiura, Raskar [Siggraph 2009]


Product labels
Bokode
SHOP
shop
Street-view Tagging
Elephant
Coyote
Multiuser classroom
Interaction
20°
PLAY HARD
Public gaming

Capturing Bokodes



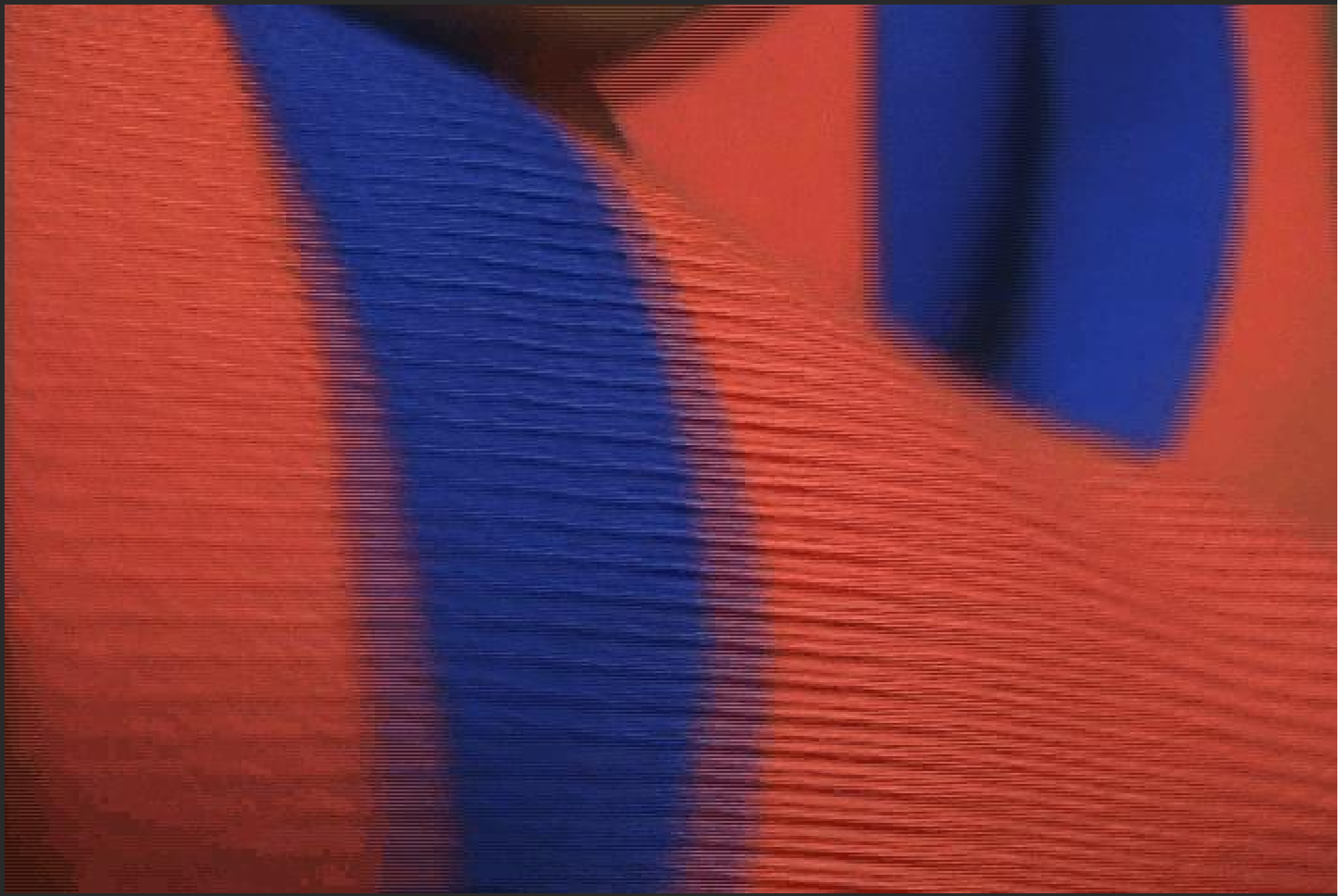
cell-phone camera
close to the Bokode
(10,000+ bytes of data)

Imperceptible Tags under clothing, tracked under ambient light

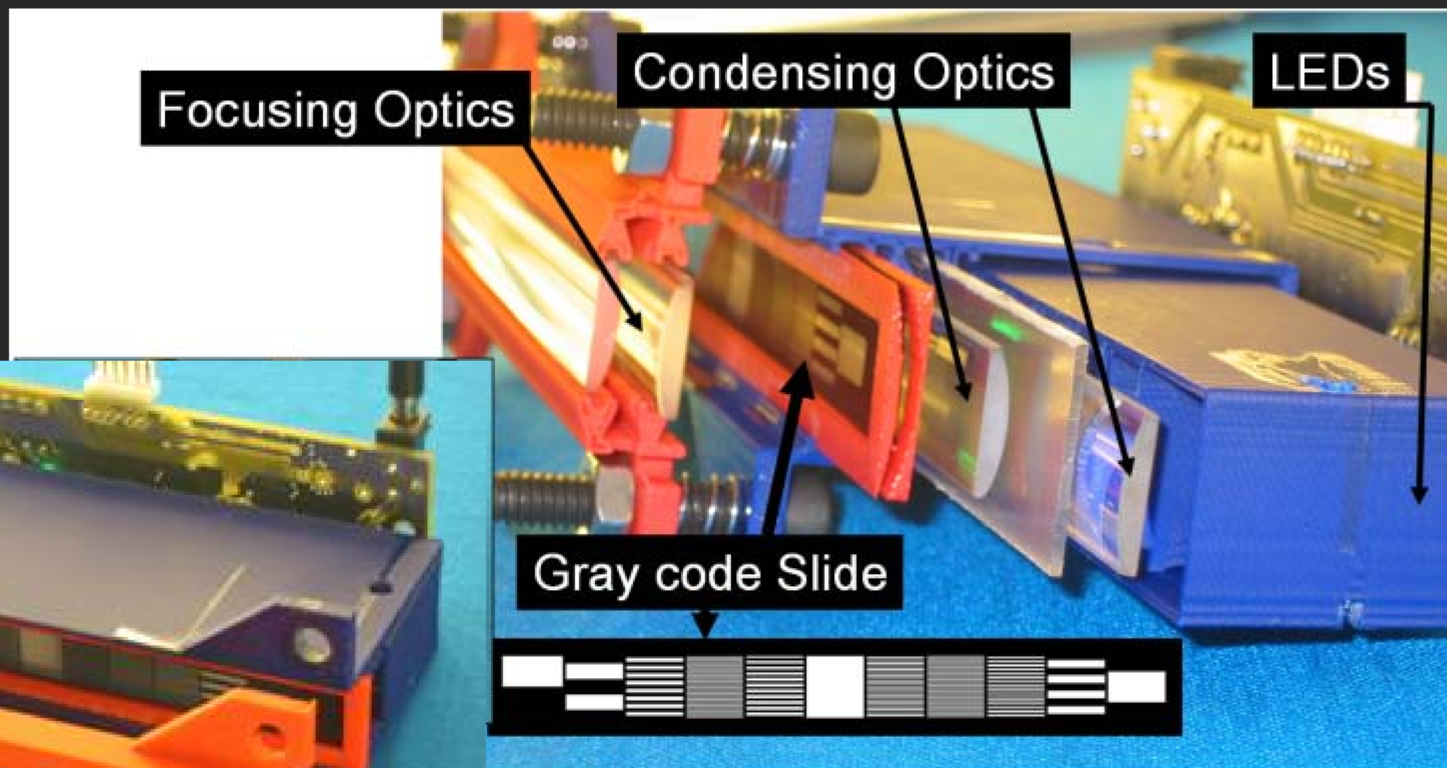
Hidden
Marker Tags

Outdoors

Unique Id

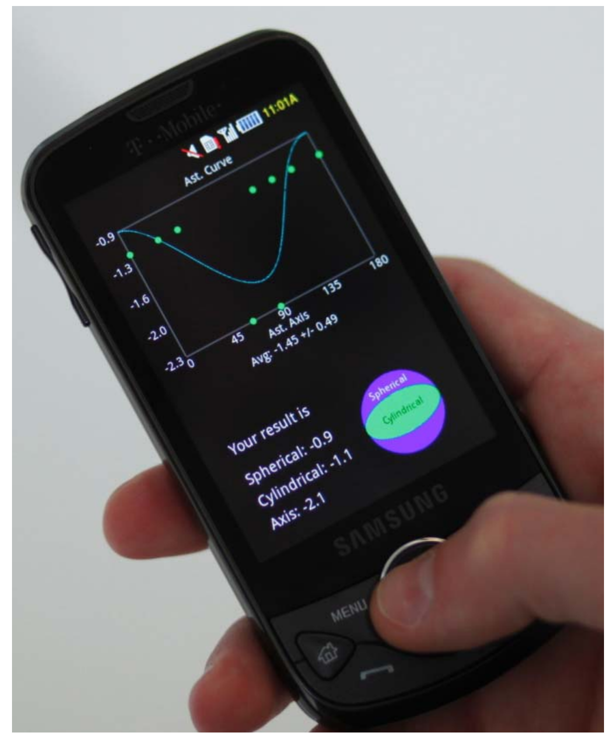


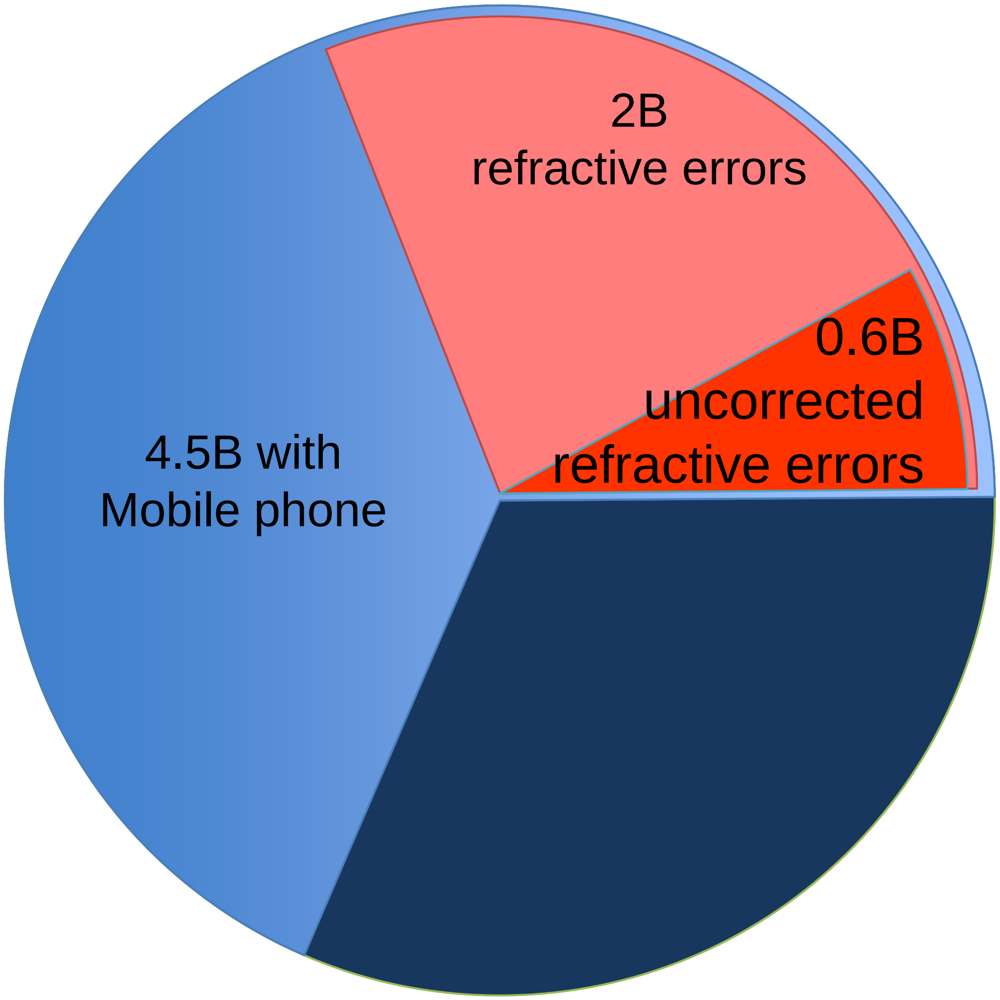
Inside of Multi-LED Emitter



NETRA:
Near **E**ye **T**ool for **R**efractive **A**ssessment

Pamplona, Mohan, Oliveira, Raskar, Siggraph 2010



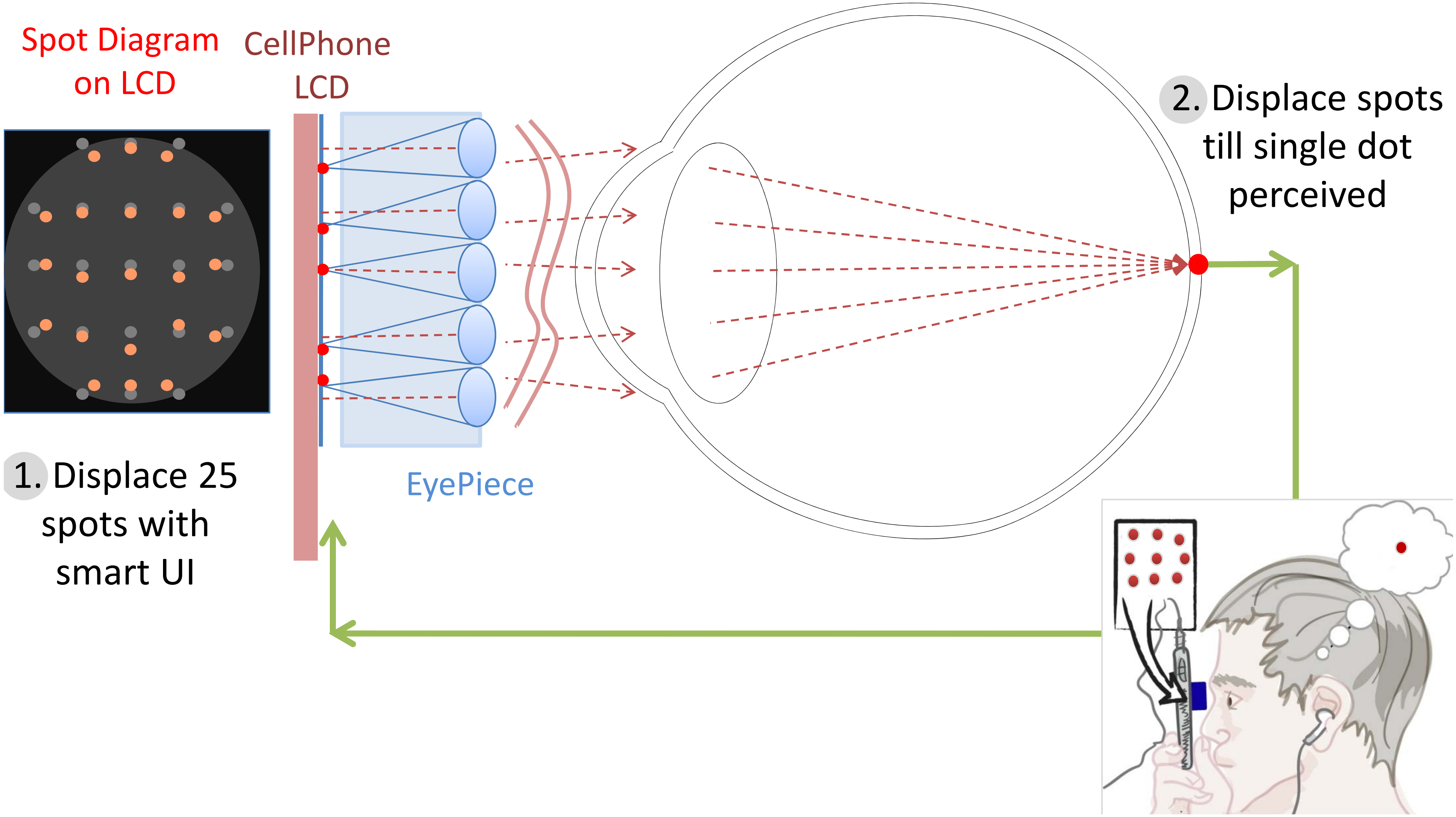


6.5 Billion people

NETRA at
LVP Eye Institute

NETRA = **Inverse** of Shack-Hartmann wavefront sensor

User interactively creates the Spot Diagram



Awards and Selection

- Vodafone Americas Foundation™ Wireless Innovation Project™ Winner$300K prize
- NASA/USAID Launch Top 10 Innovators
- World Bank 3 selected global health inv
- Google Innovation
- Deshpande Ignition Grant DESHPANDE CENTER FOR TECHNOLOGICAL INNOVATION
- MIT IDEAS (#2 award)
- International Space Station evaluation

Validation

- 0.09 D : objective precision
- ~ 0.5 D: subjective trials
- 0.3 D: IRB approved wet-stud data)

Academic Scientific Papers

- SIGGRAPH 2010
- Frontiers in Optics
- Am Acad of Optometry (AAO

Selection for Global Health Events

NASA USAID THE WORLD BANK

CNN BBC npr The New York Times New Scientist The Economist DiscoveryNews

SIGGRAPH2010 AMERICAN ACADEMY of OPTOMETRY ARVO2011 FRONTIERS IN OPTICS 2010 LASER SCIENCE XXVI mHealthSummit

Eye = Mirror of Health

Ocular Manifestation: Leading Indicator?

Convert CellPhones into Scientific Instruments


Yoon Lab, U of Rochester


Slit Lamp Exam

Retinal Scan

Direct

+

Global

[Nayar, Krishnan, Grossberg, Raskar 2006]

Trillion Frames Per Second

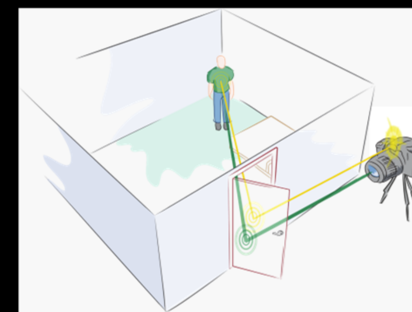
Trillion FPS

Each frame = ~2ps = 0.6 mm of Light Travel

Ripples of Waves

MIT Media Lab raskar@mit.edu http://raskar.info fb.com/cameraculture

Computational Camera + Photography



Photons not Pixels

- Time
  - Flutter Shutter (motion deblur)
  - Looking around a corner
  - Trillion FPS
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