Computational Cameras: Exploiting Spatial-Angular Temporal Tradeoffs in Photography

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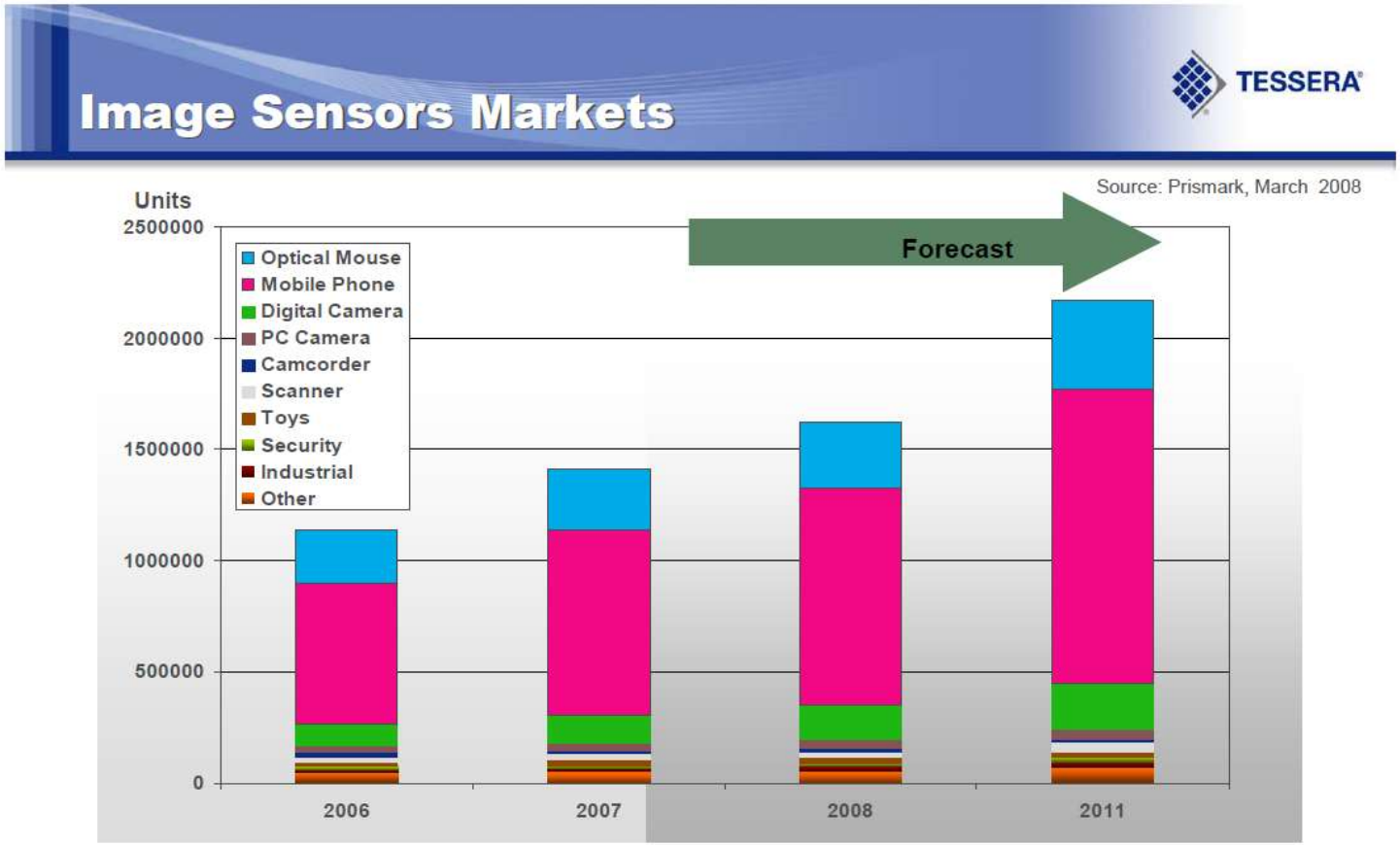
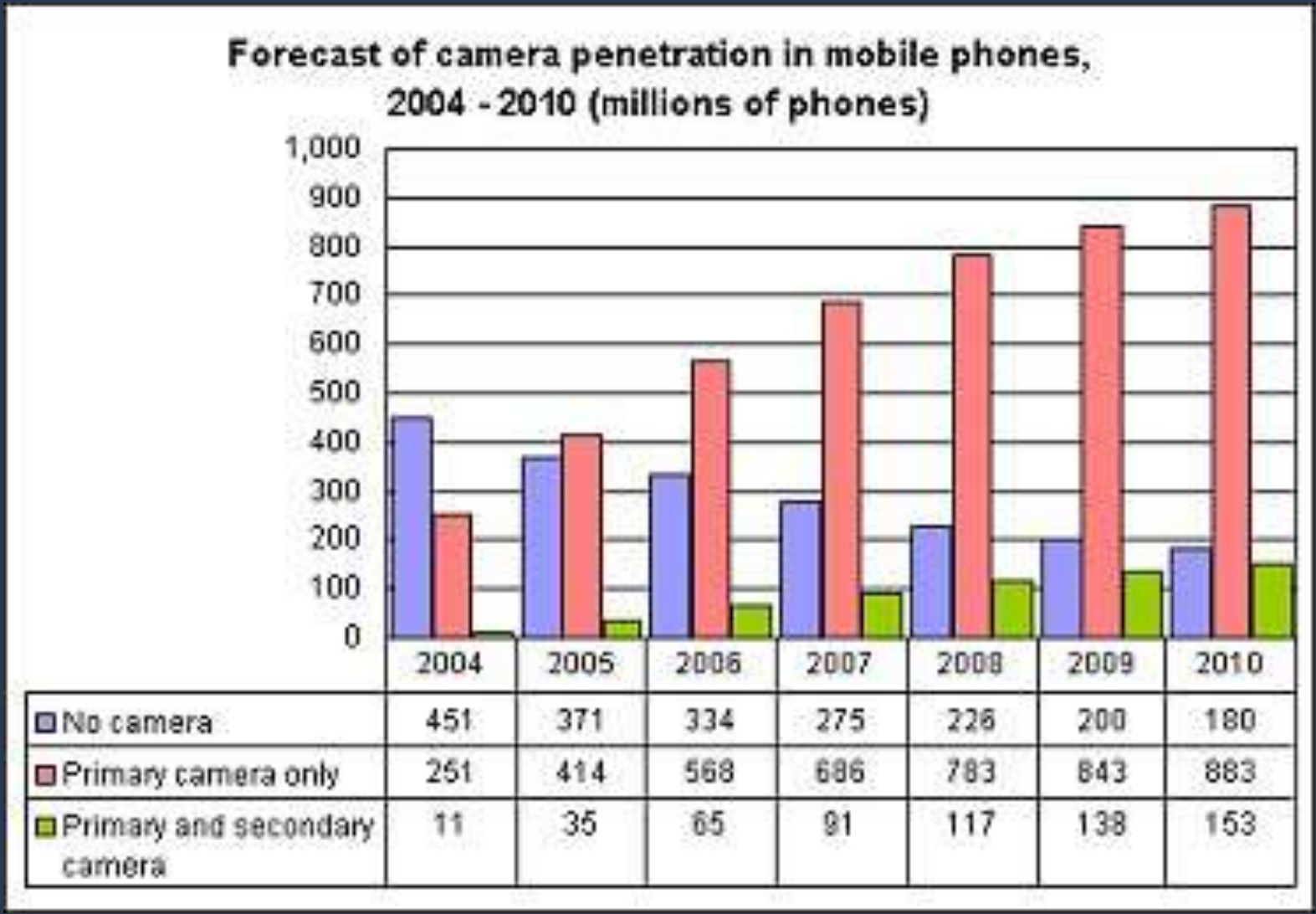
Where are the cameras?



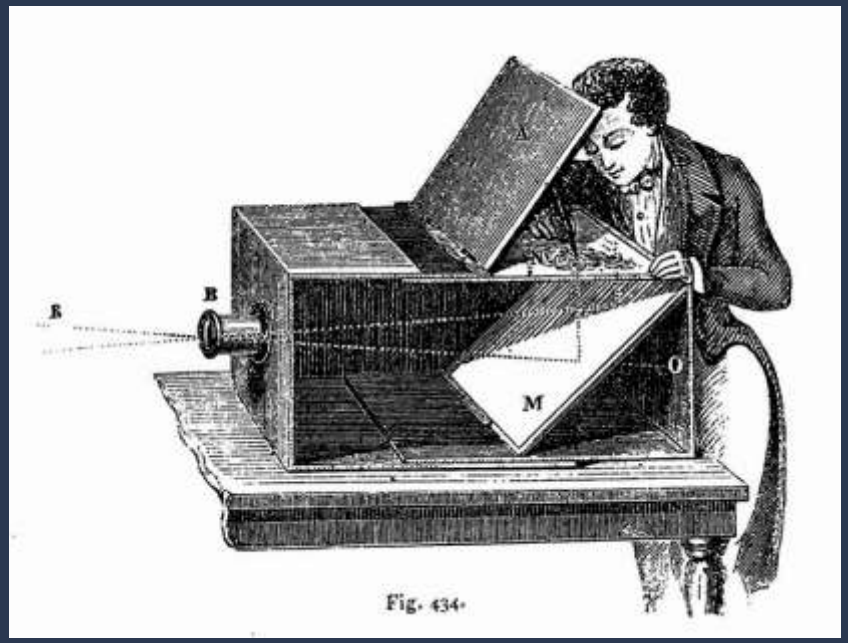
Cameras in Mobile Phones



	2004	2005	2006	2007	2008	2009	2010
No camera	451	371	334	275	226	200	180
Primary camera only	251	414	568	686	783	843	883
Primary and secondary camera	11	35	65	91	117	138	153

Source: iSuppli

Have Cameras Evolved?



Lens Based Camera Obscura, 1568

Digital Cameras

Conventional Cameras

- Tradeoffs in photography
  - Aperture size, shutter speed, ISO
- Fast lens
  - More light but low depth of field
  - Allows small shutter time
  - Macro, Wildlife, Sports
- High ISO
  - Low light scenes, but more noise

Have Projectors Evolved?

- Similar trends in form factor/Cost
  - Film/Slide projectors
  - Digital projectors
  - Pocket Projectors
  - Pico Projectors
  - Projectors in smartphones

Projector vs Cameras

- Current projectors offer capabilities far beyond current cameras
- Each projector pixel can be independently controlled
  - Allows coding and modulation of outgoing light

How about cameras where each pixel can be independently controlled?

Allow coding and modulation of incoming light?

Projectors vs Cameras

Exposure, Frame Rate, Resolution etc.

High level controls

Brightness, color temperature

Per Pixel Control?

Projectors vs Cameras

Exposure, Frame Rate, Resolution etc.

High level controls

Brightness, color temperature

Per Pixel Control?

Computational Cameras

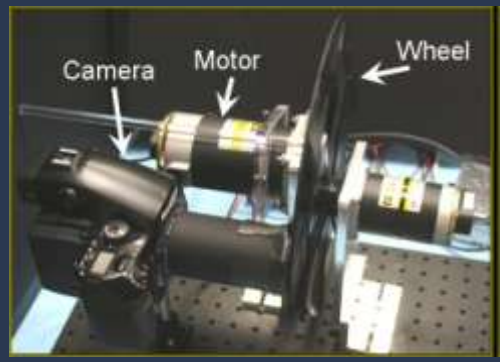
Computational Cameras

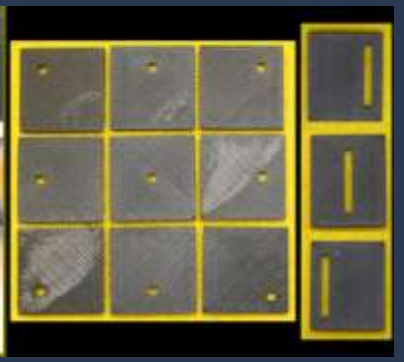
Flutter Shutter Camera

Coded Aperture

Mask based light field camera

Reinterpretable Camera





Wide Angle light field camera

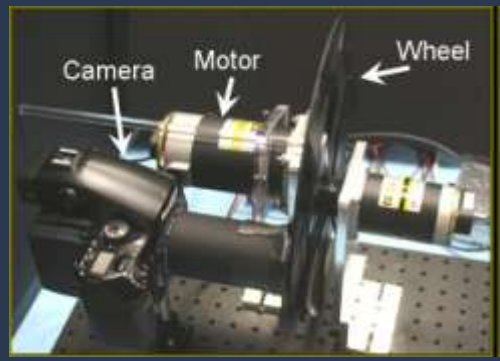
Computational Cameras

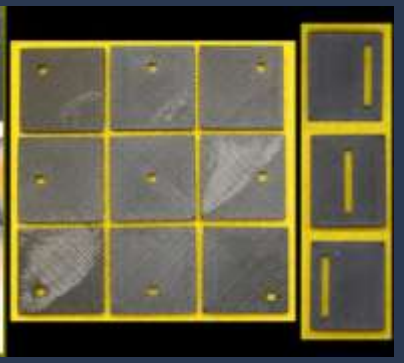
Flutter Shutter Camera

Coded Aperture

Mask based light field camera

Reinterpretable Camera



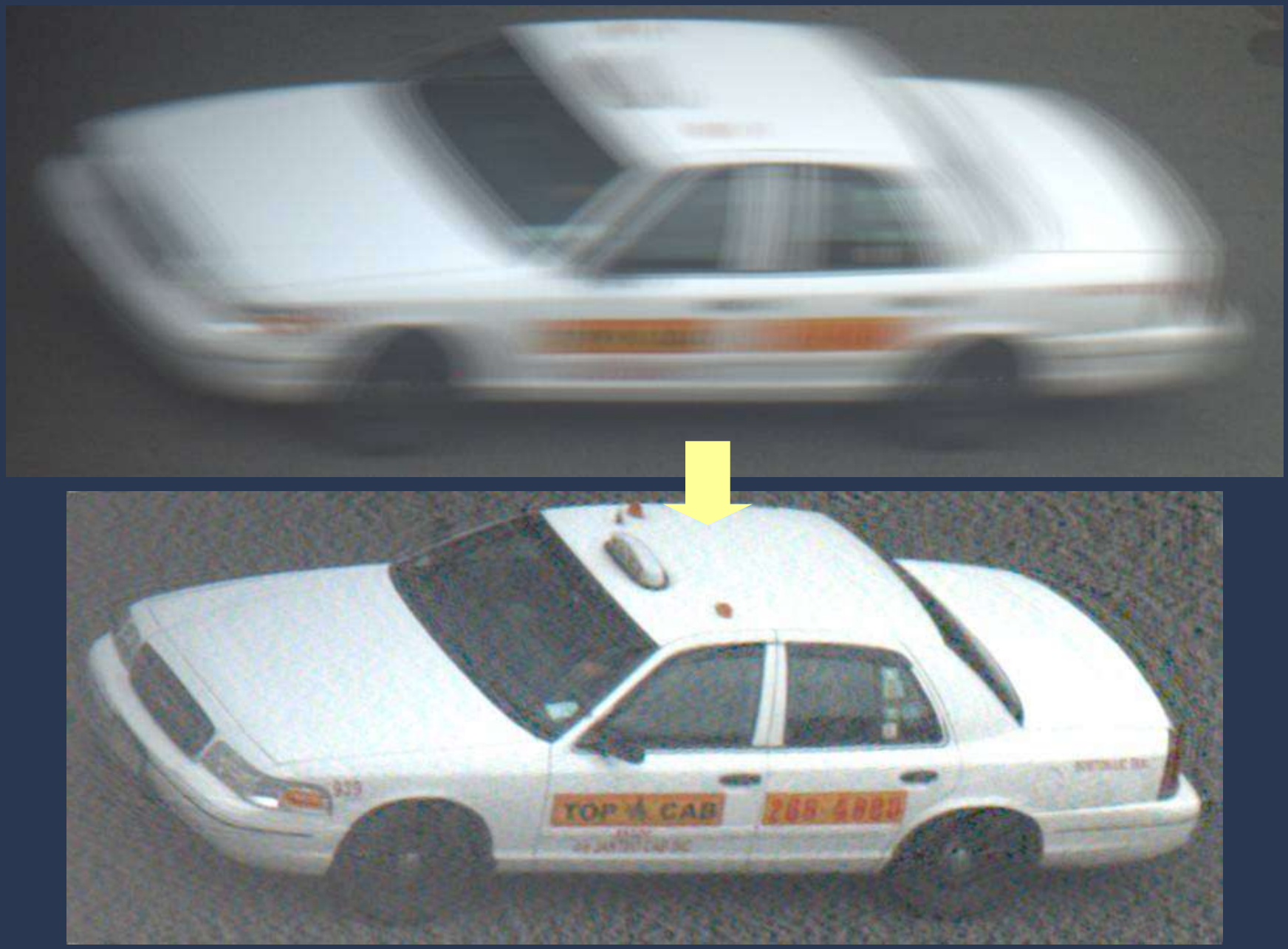


Wide Angle light field camera

Computational Cameras

Camera	Coding/Modulation Dimension
Flutter Shutter	Time (Exposure)
Coded Aperture	Space
Light Field Camera	Space and Angle
Reinterpretable Camera	Space, Time, Angle
Flexible Voxels	Space and Time

Coded Exposure [Raskar, Agrawal, Tumblin SIGGRAPH 2006]

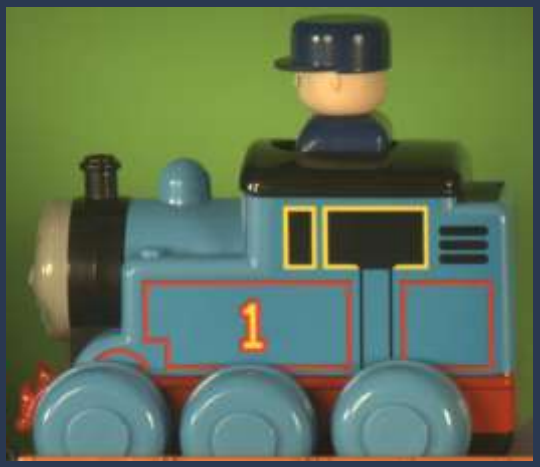


Coded Exposure (Flutter Shutter) Camera

Raskar, Agrawal, Tumblin [Siggraph2006]

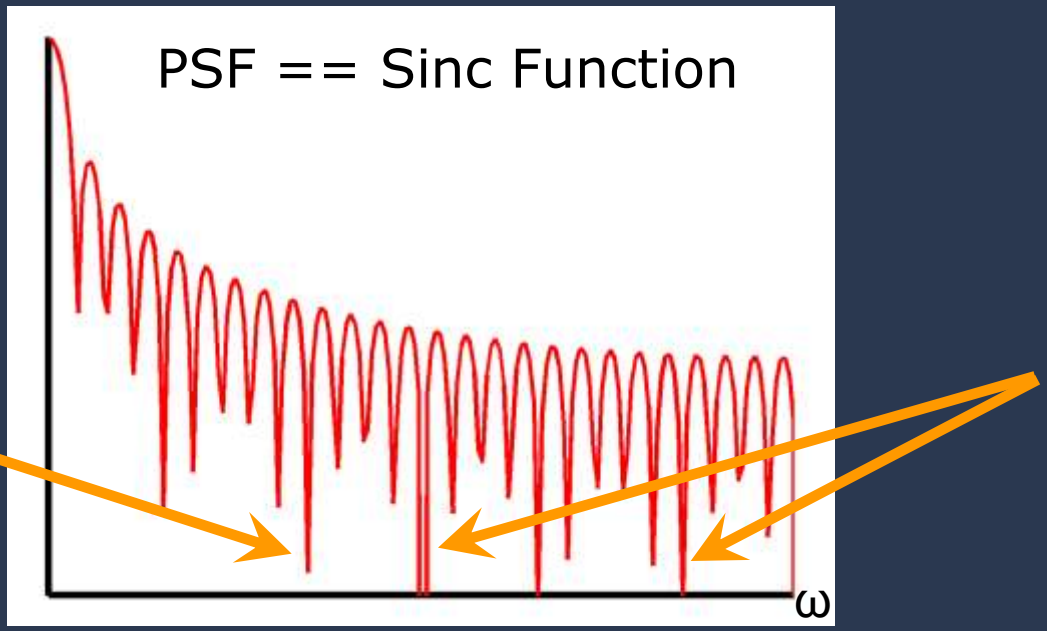
Coding in Time: Shutter is opened and closed

Blurring == Convolution

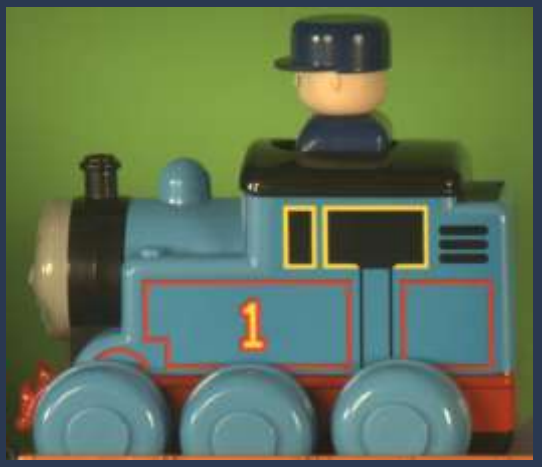


Sharp Photo

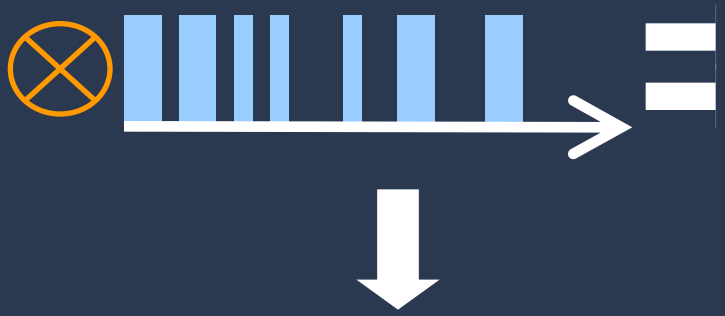
Blurred Photo



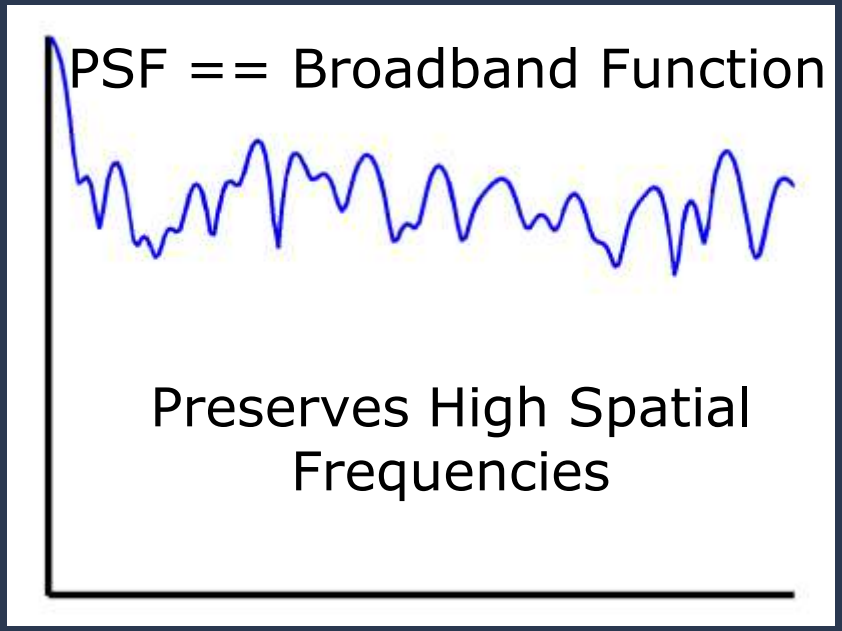
Traditional Camera: Shutter is OPEN: Box Filter



Sharp Photo

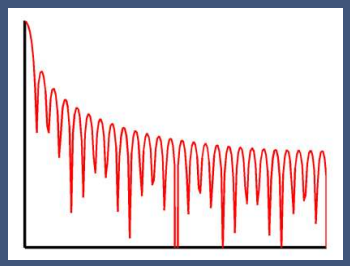


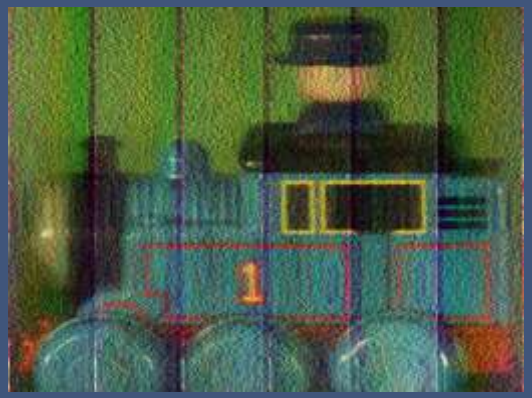
Blurred Photo



Flutter Shutter: Shutter is OPEN and CLOSED

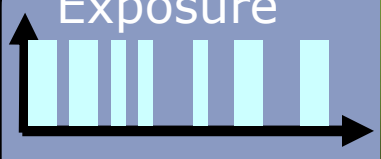
Traditional

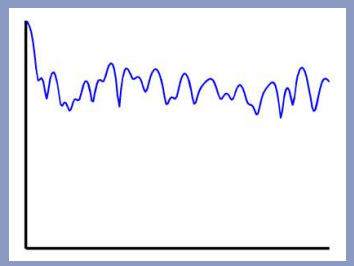


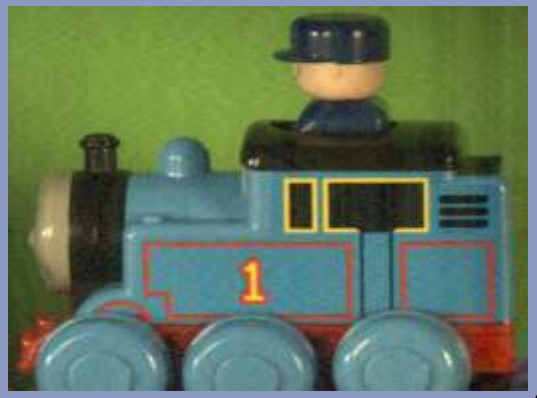


Deblurred Image

Coded Exposure

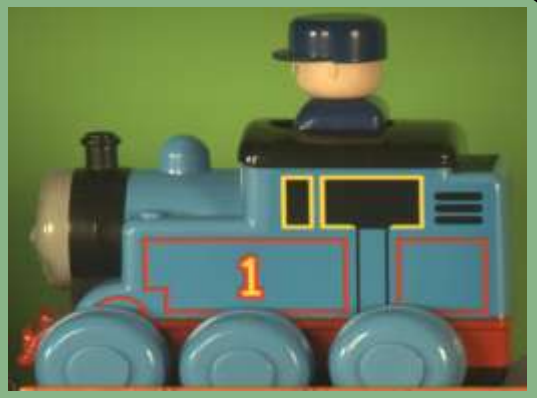






Deblurred Image

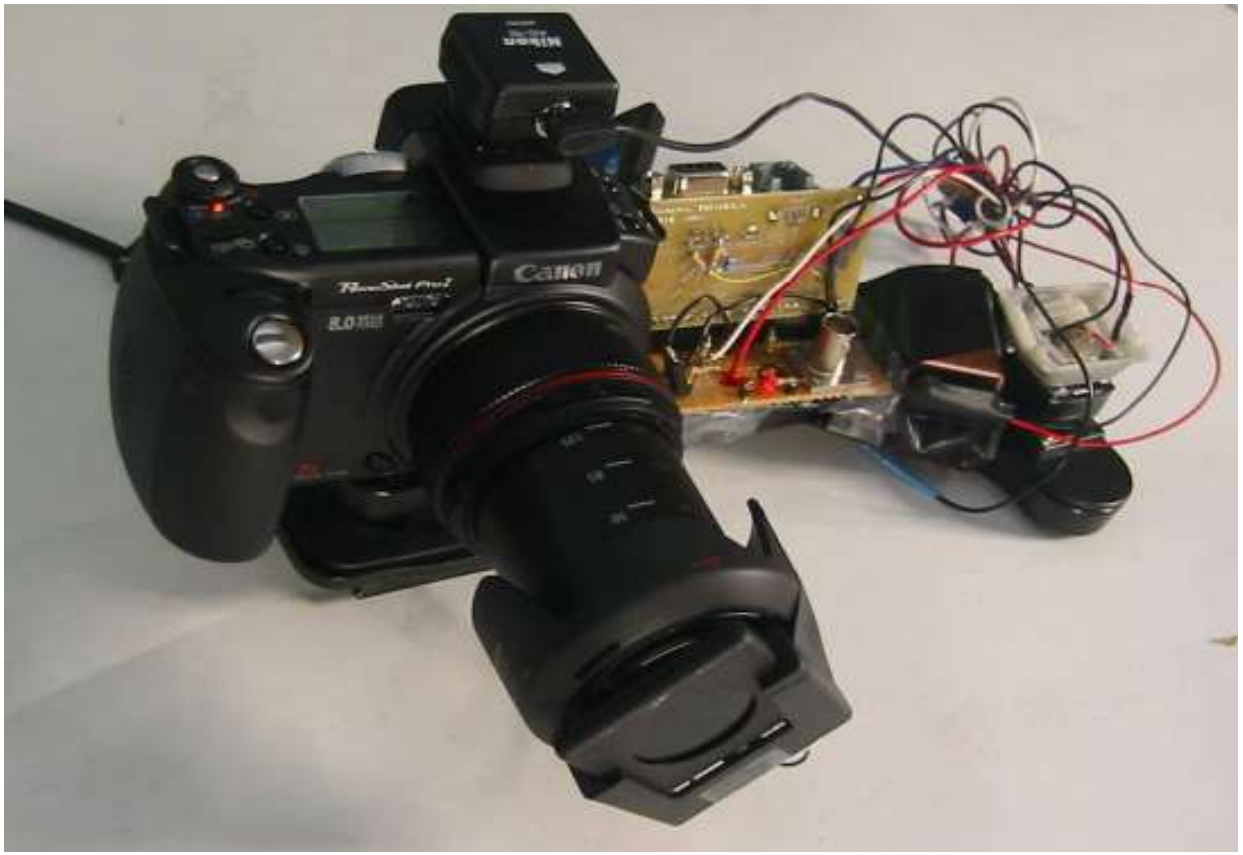
Image of Static Object



485·PCK

Coded Exposure (Flutter Shutter) Camera

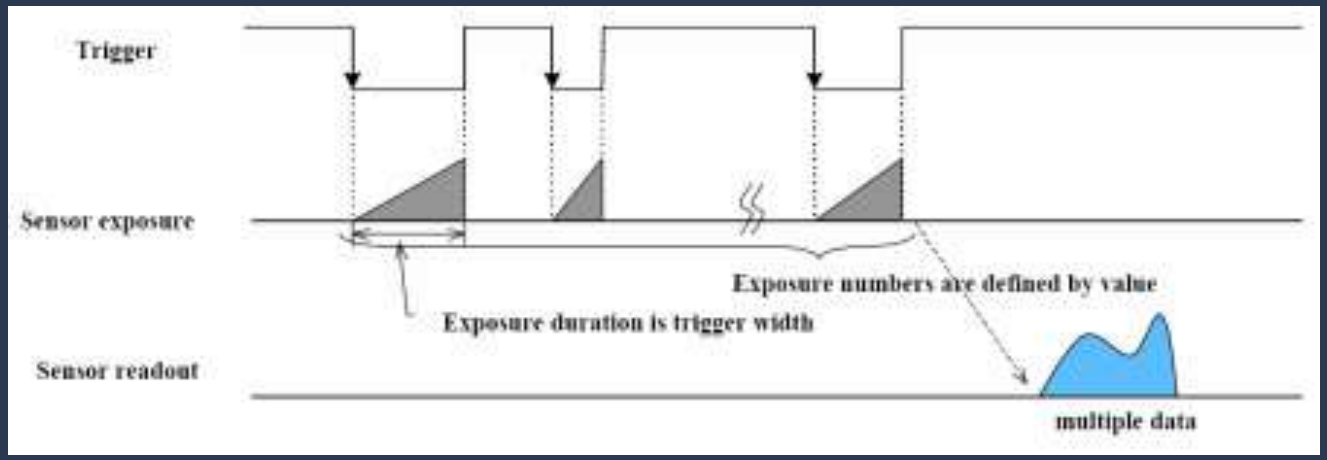
Raskar, Agrawal, Tumblin [Siggraph2006]



Coding in Time: Shutter is opened and closed

Flutter Shutter Video Camera

- Pointgrey Dragonfly2 Camera
- Use Trigger Mode 5
- On-chip, Additional Cost = $0



How to handle focus blur?

Coded Exposure (Flutter Shutter)

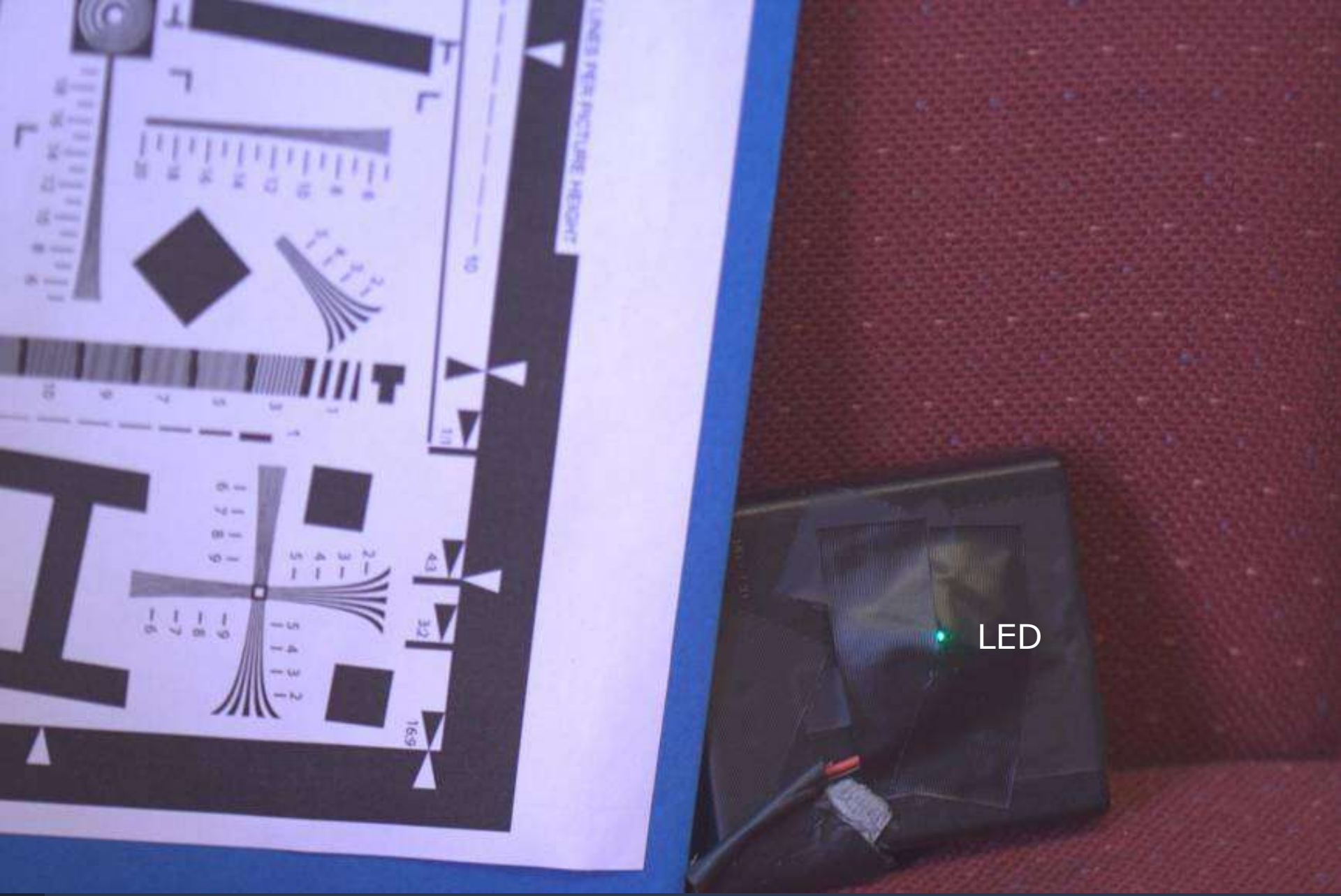
Raskar, Agrawal, Tumblin
SIGGRAPH 2006

Temporal 1-D broadband code:
Motion Deblurring

Coded Aperture

with Veeraraghavan, Raskar, Tumblin, & Mohan,
SIGGRAPH 2007

Spatial 2-D broadband code:
Focus Deblurring



In Focus Photo

Out of Focus Photo: Open Aperture

Out of Focus Photo: Coded Aperture

Blurred Photos

Open Aperture

Coded Aperture, 7 * 7 Mask

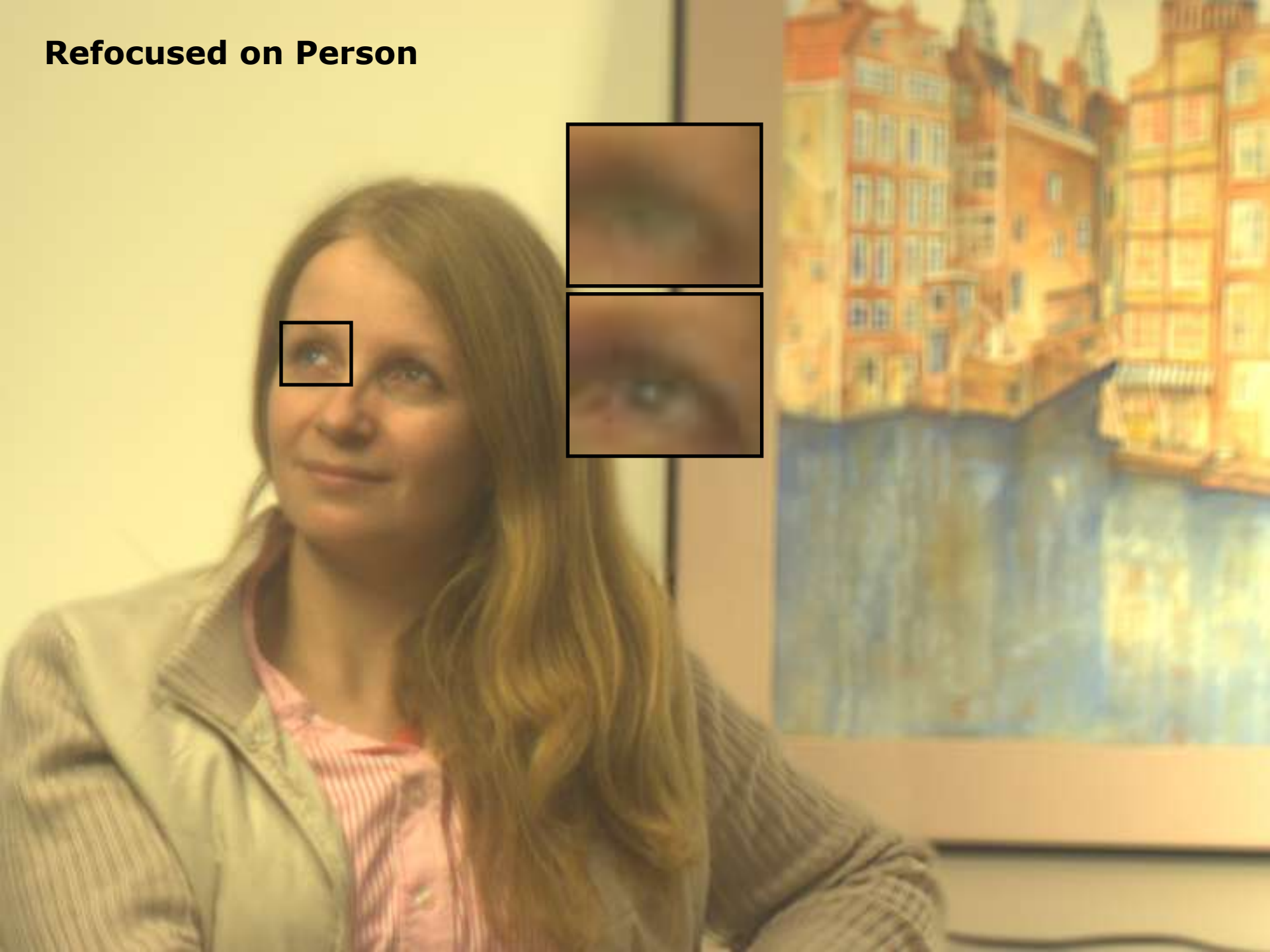
Deblurred Photos

Open Aperture

Coded Aperture, 7 * 7 Mask

Captured Blurred
Photo

Refocused on Person



Beal.
Beal.

Coded Imaging

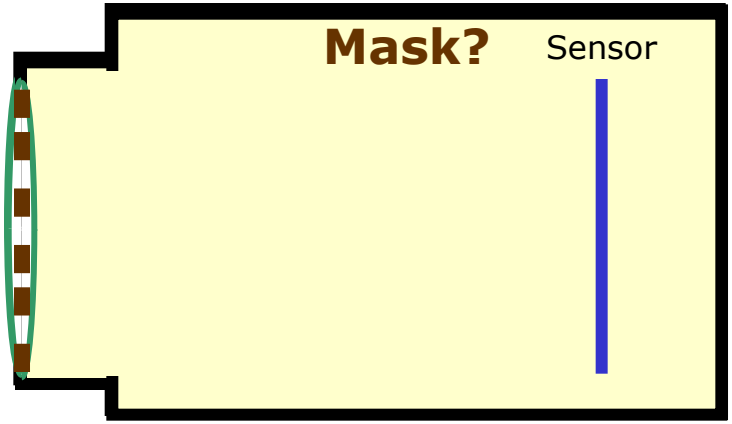
Blocking Light == More Information

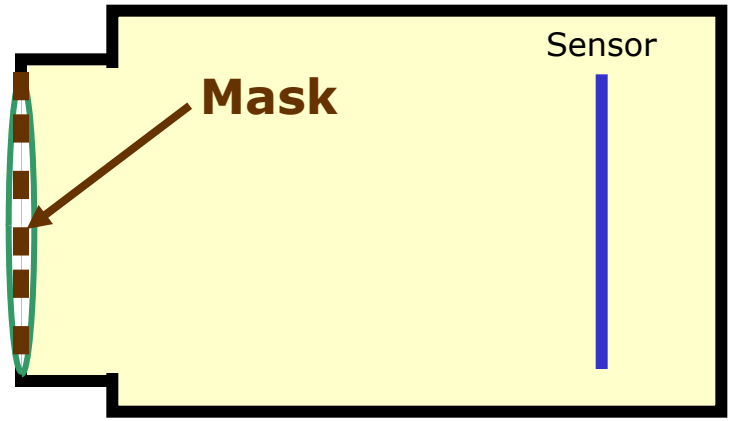
Coded Exposure
Coding in Time

Coded Aperture
Coding in Space

Computational Cameras

Camera	Coding/Modulation Dimension
Flutter Shutter	Time (Exposure)
Coded Aperture	Space
Light Field Camera	Space and Angle





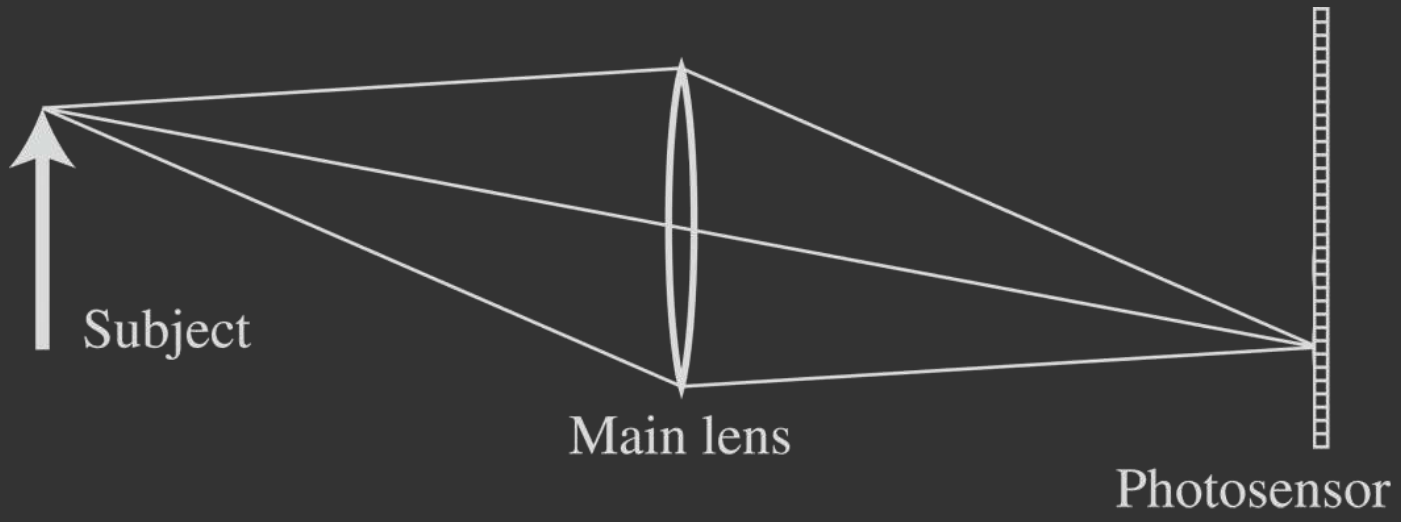
Full Resolution Digital Refocusing:

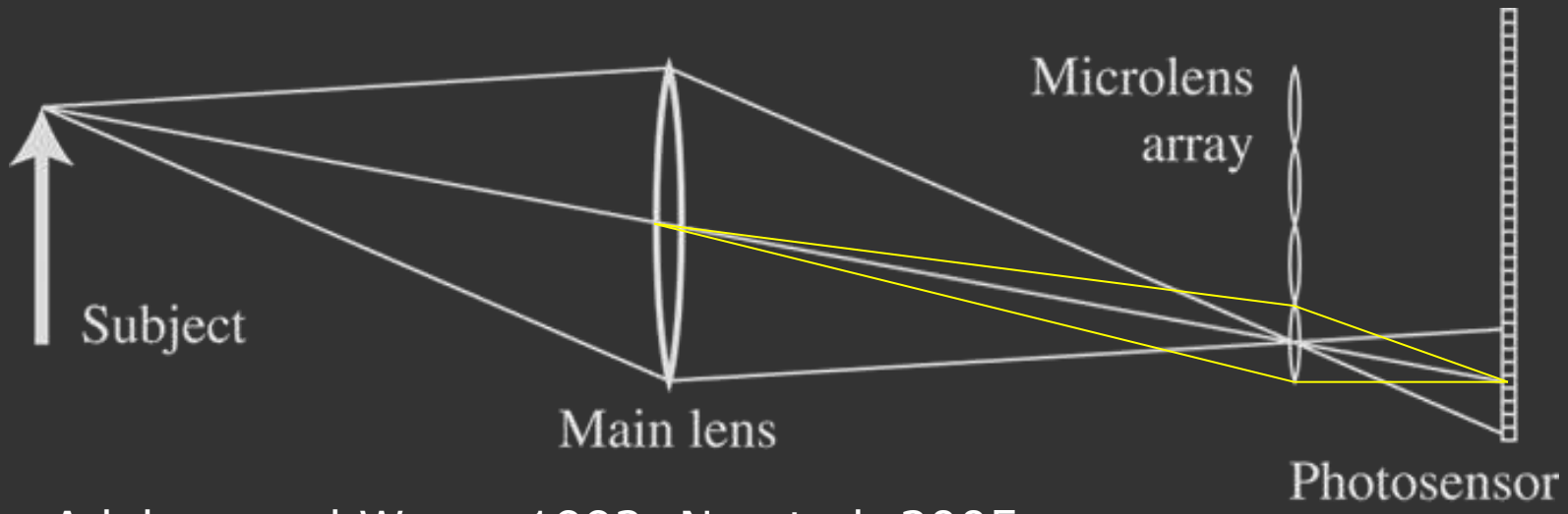
Coded Aperture Camera

4D Light Field from 2D Photo:

Heterodyne Light Field Camera

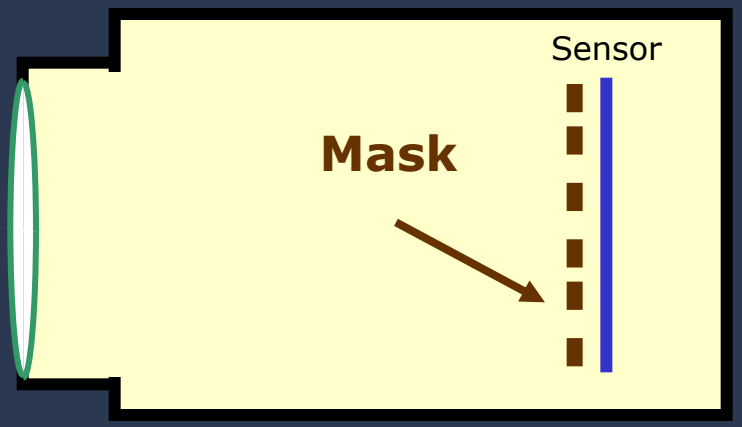
Lytro: Lenslet-based Light Field camera





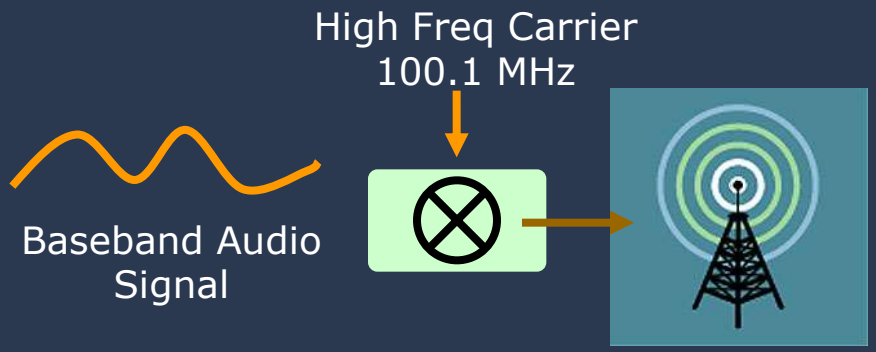
Adelson and Wang, 1992, Ng et al. 2005

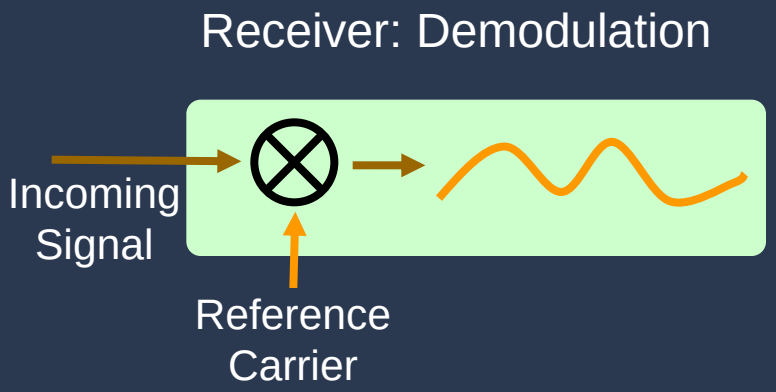
Mask based Light Field Camera (SIGGRAPH 2007)

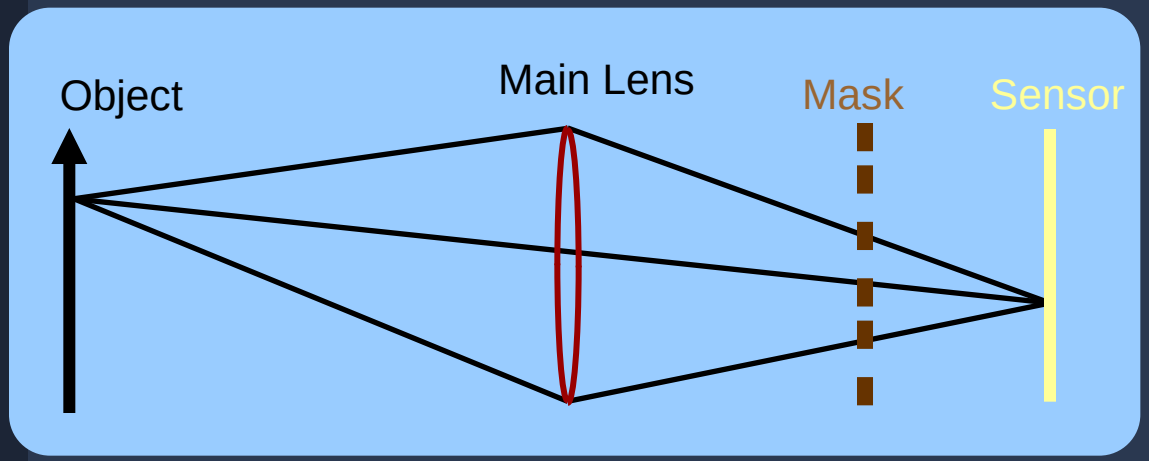


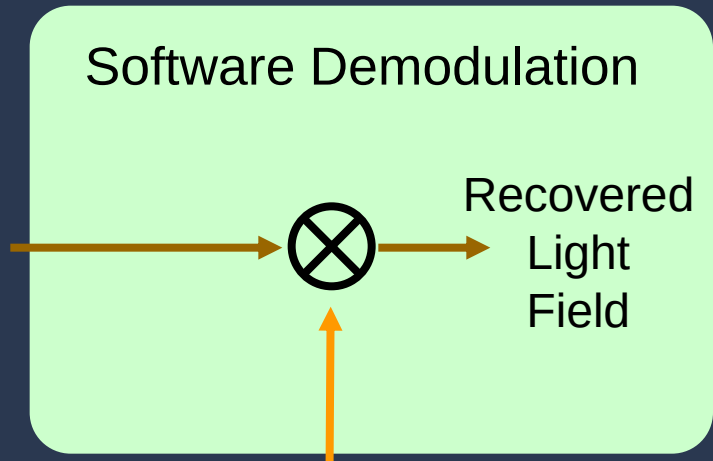
- Sum of Cosines Mask
- Pinhole Array Mask
- Tiled Broadband Mask

Optical Heterodyning









Photographic Signal (Light Field)

Carrier

Incident Modulated Signal

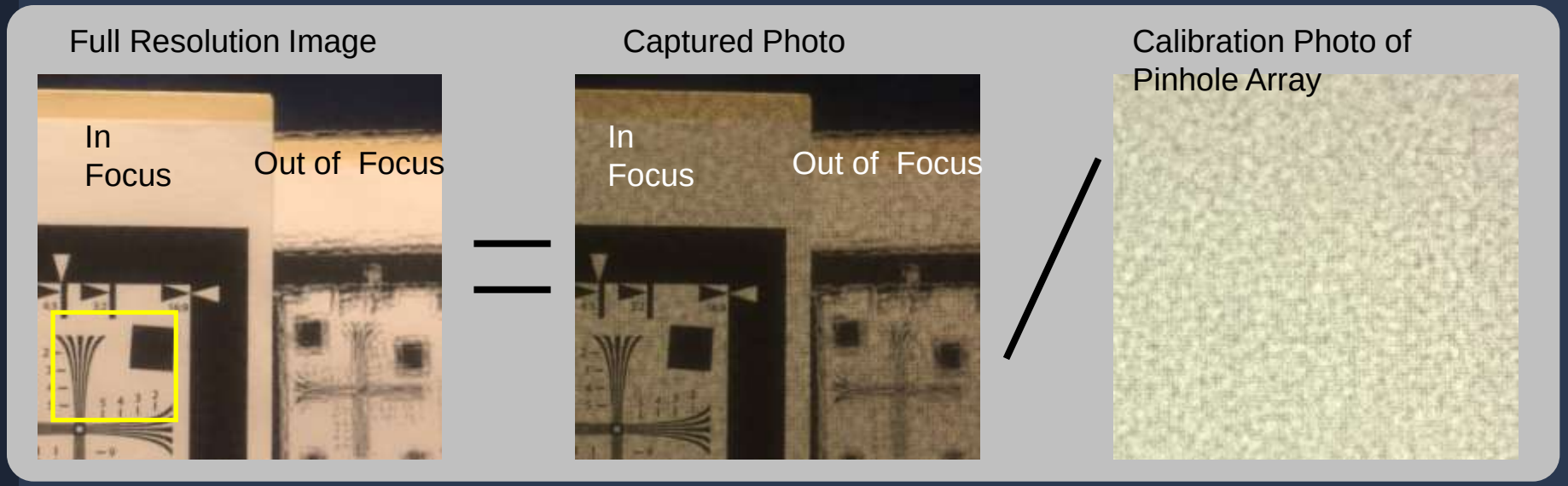
Reference Carrier

Captured Light Field

Digital Refocusing

Recovering Full Resolution 2D Image

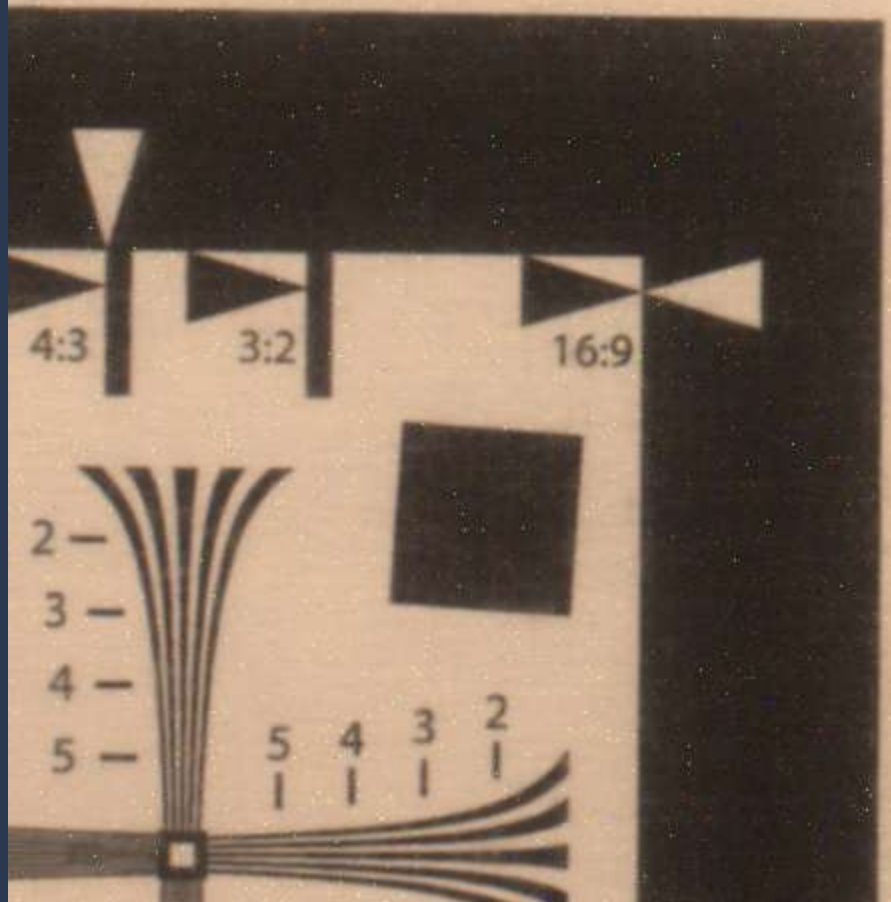
- For in-focus scene
- Inserting Mask == Spatially Varying Image Attenuation
- Compensate using calibration image



Recovered Image

In Focus

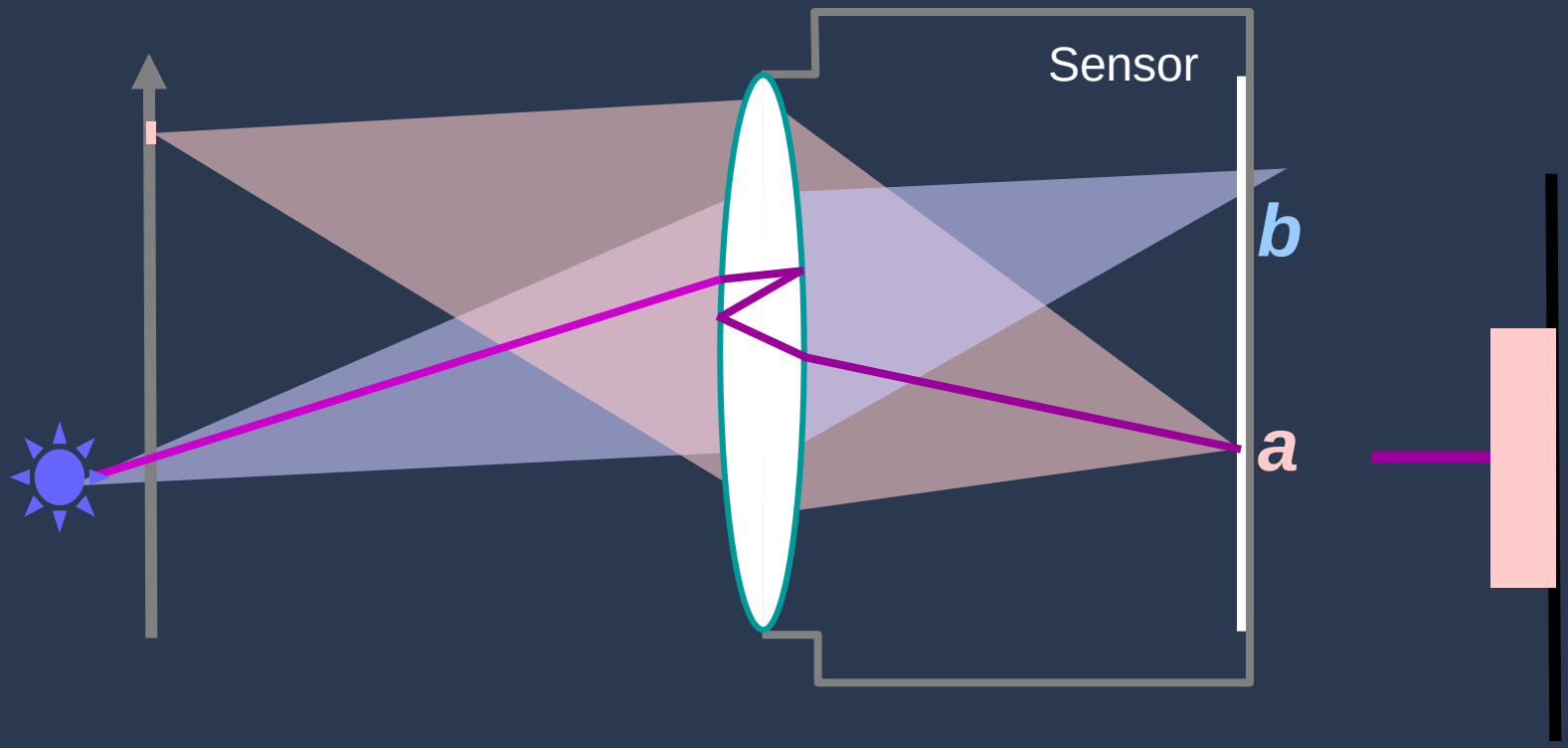
Out of Focus



Lens Glare Reduction using Light Field

Effects of Glare on Image

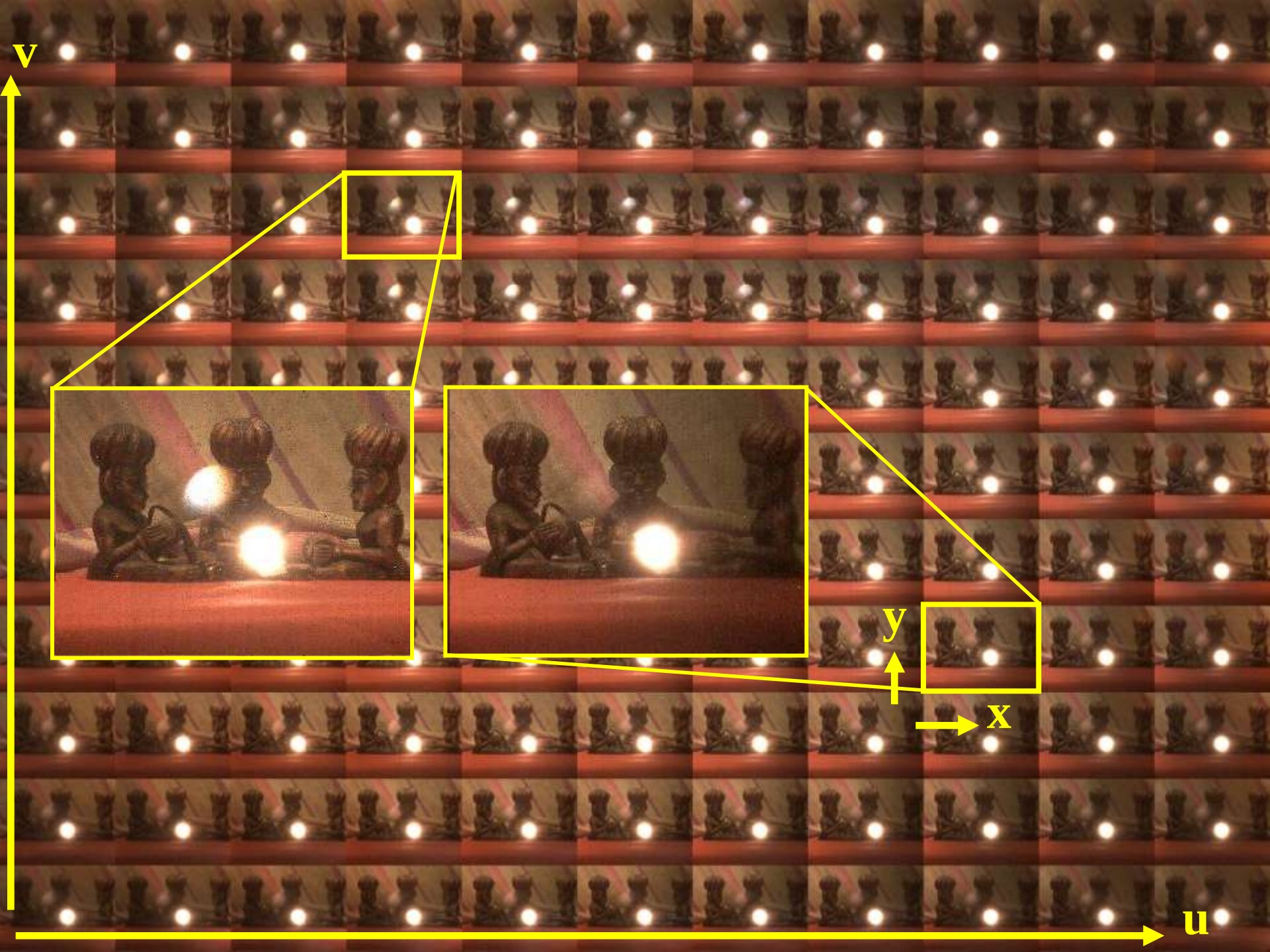
- Hard to model, Low Frequency in 2D
- But reflection glare is outlier in 4D ray-space



Lens Inter-reflections

Angular Variation at pixel ***a***

Captured Photo: LED On


v
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Sequence of Sub-Aperture Views

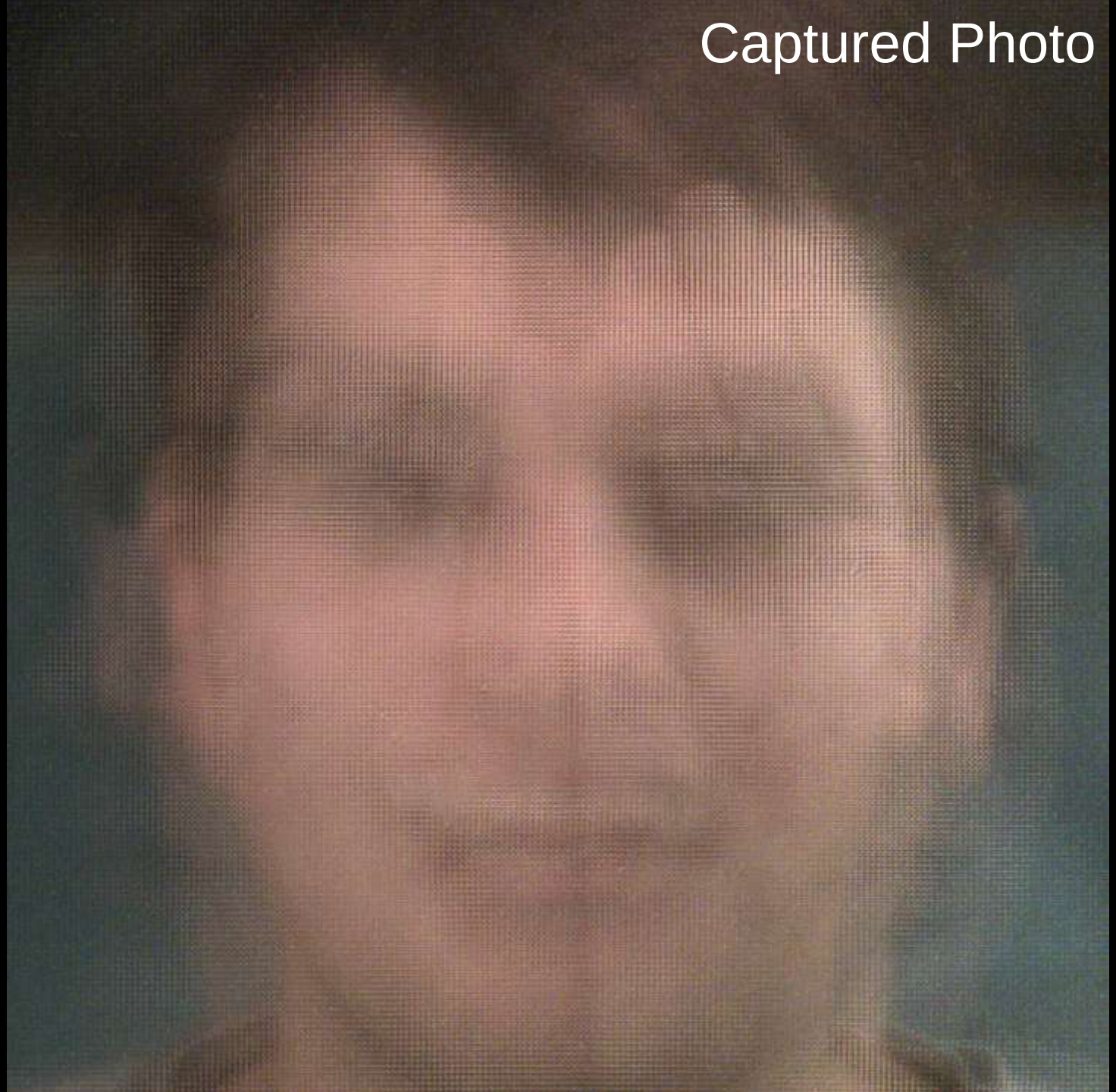
Traditional Camera Photo

Glare Reduced Photo

SHOES
SHOES

Computational Cameras

Camera	Coding/Modulation Dimension
Flutter Shutter	Time (Exposure)
Coded Aperture	Space
Light Field Camera	Space and Angle
Reinterpretable Camera	Space, Time, Angle


Captured Photo

Video from Single-Shot (Temporal Frames)

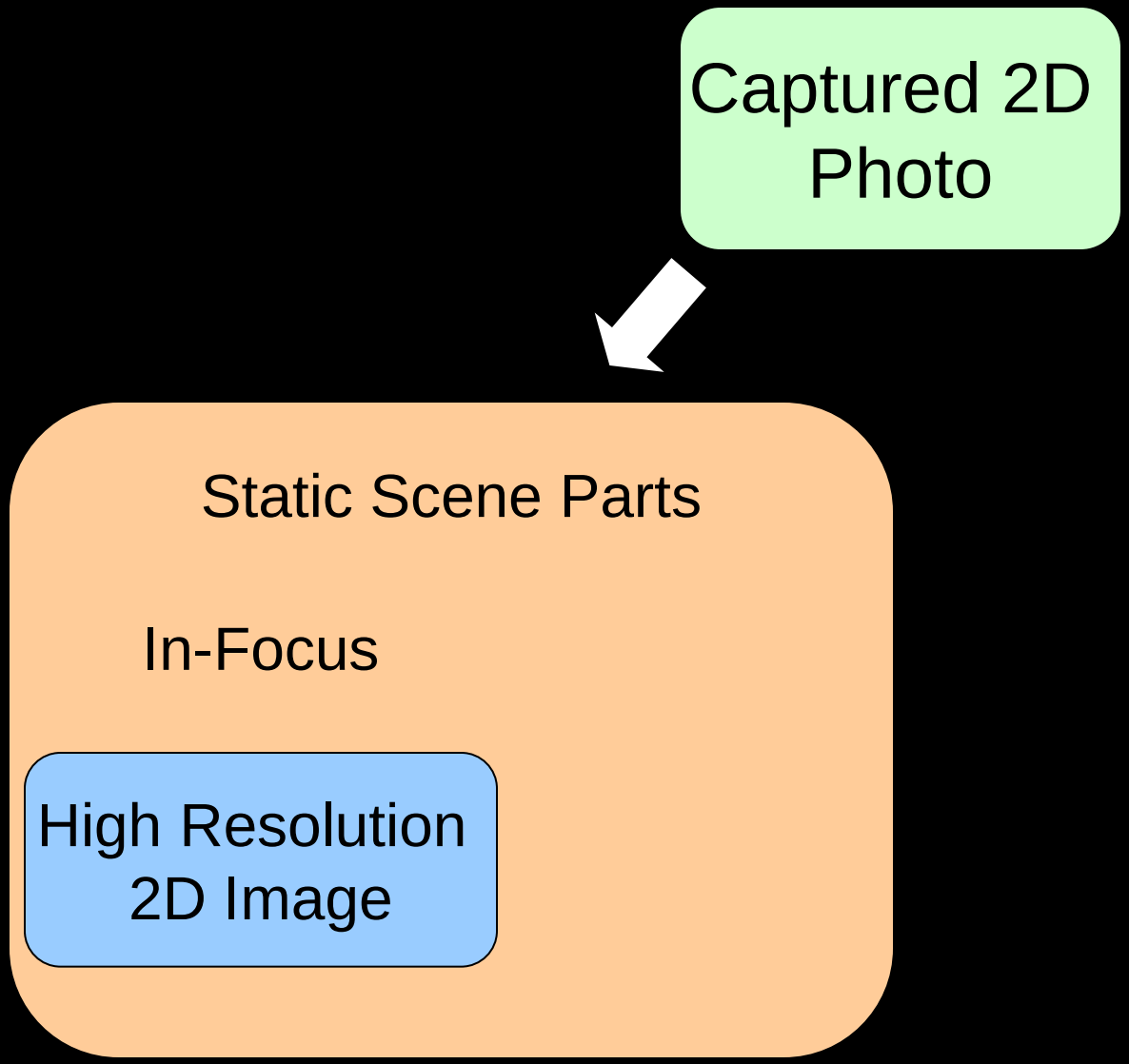
Captured Photo

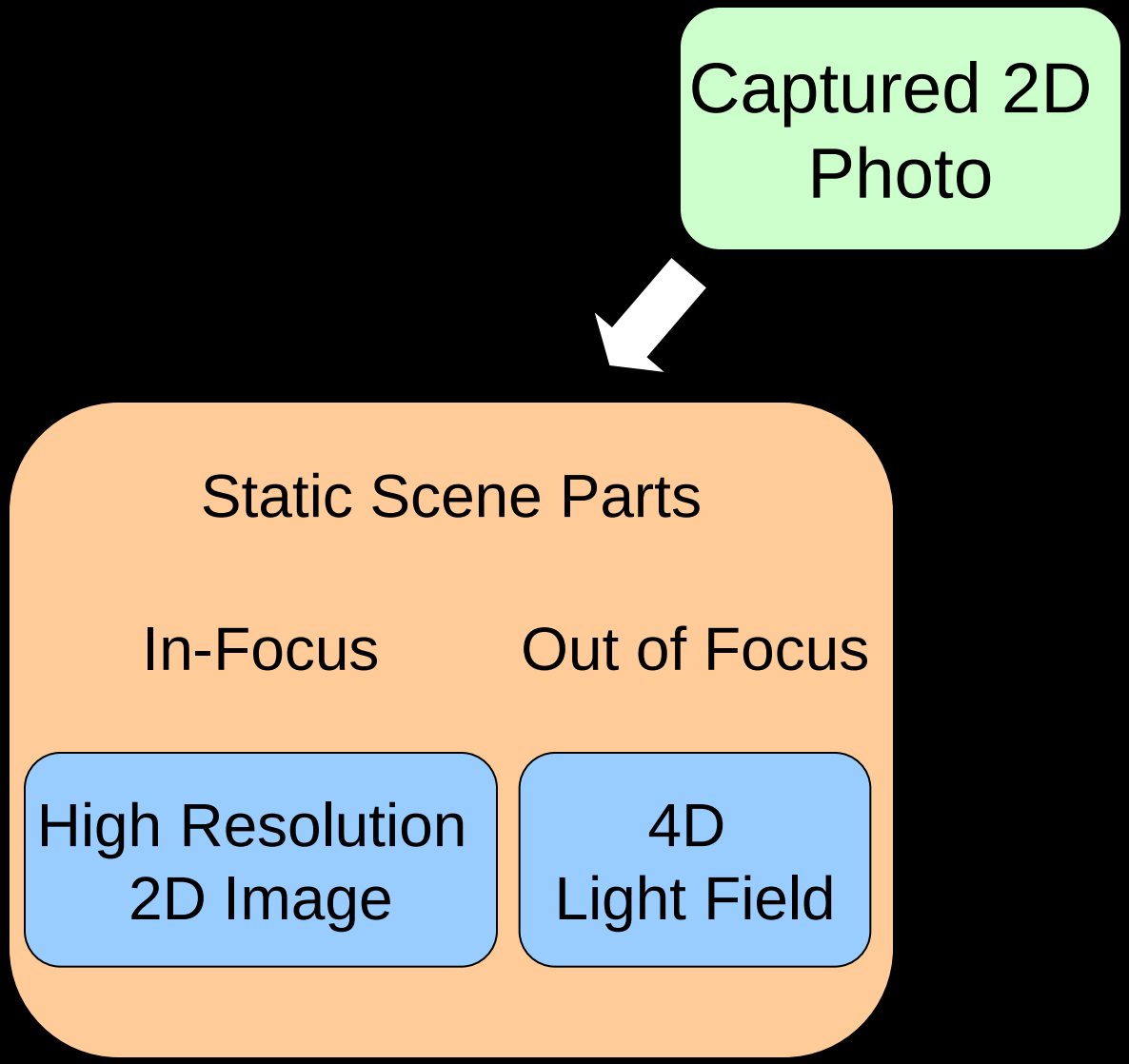
Rotating Doll in Focus

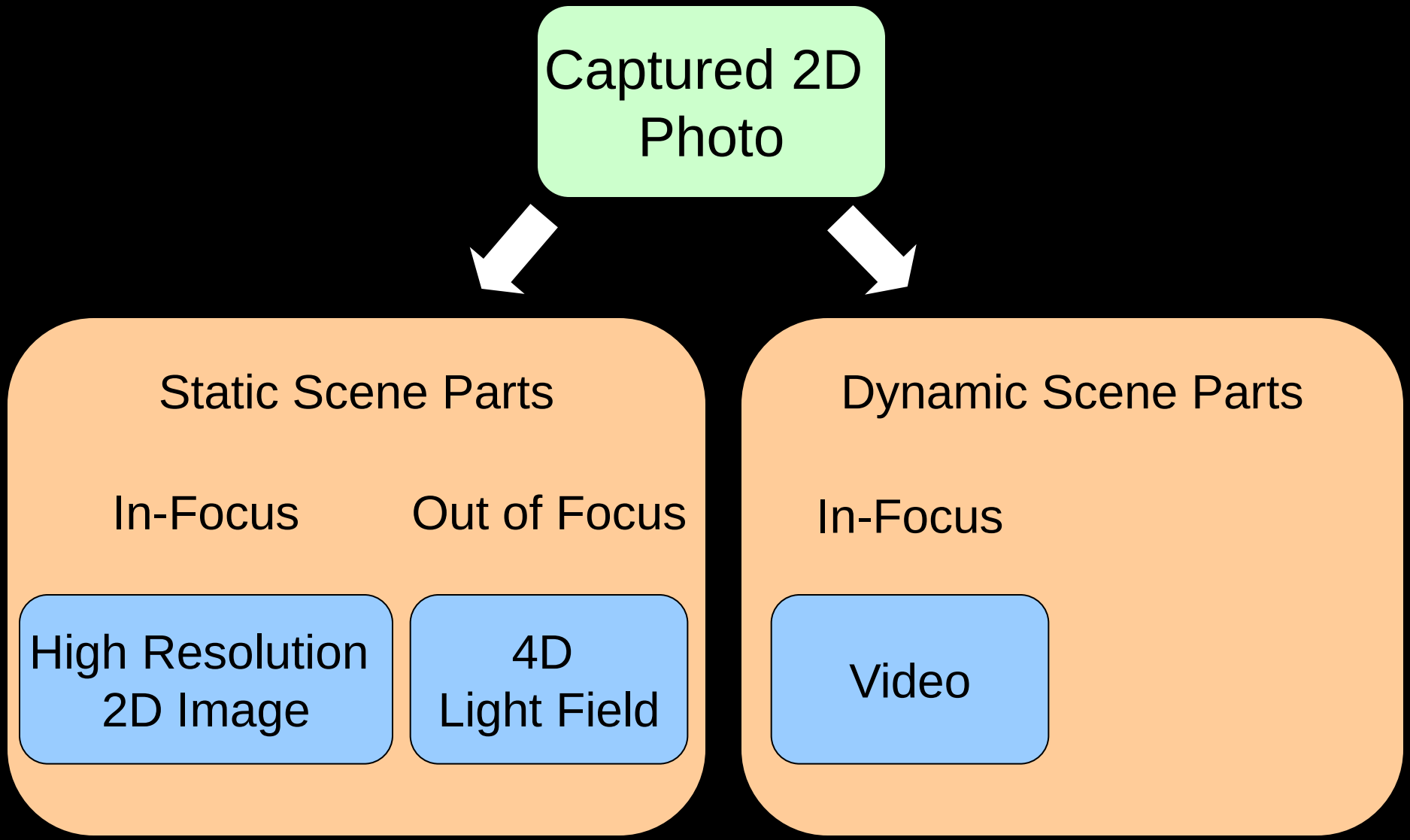
Reinterpretable Camera

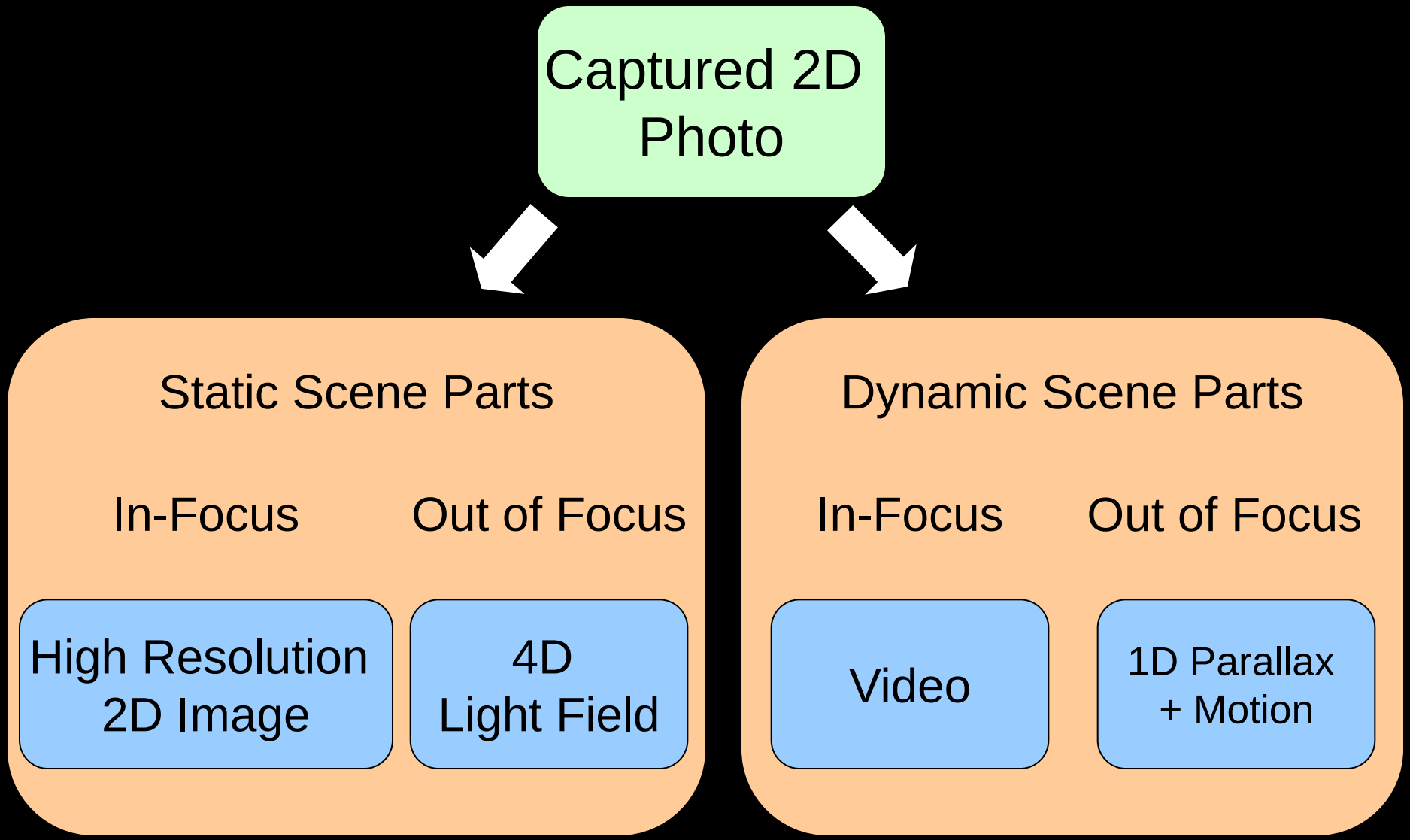
- Resolution tradeoff for Conventional Imaging
  - Fixed before capture
    - video camera, lightfield camera
  - Scene independent
- Resolution tradeoff for Reinterpretable Camera
  - Variable in post-capture
  - Scene dependent
  - Different for different parts of the scene/captured photo

Captured 2D Photo

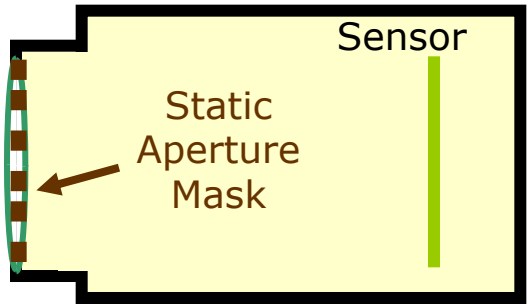

Captured 2D Photo
Static Scene Parts
In-Focus
High Resolution 2D Image


Captured 2D Photo
Static Scene Parts
In-Focus
Out of Focus
High Resolution 2D Image
4D Light Field


Captured 2D Photo
Static Scene Parts
In-Focus
Out of Focus
High Resolution 2D Image
4D Light Field
Dynamic Scene Parts
In-Focus
Video


Captured 2D Photo
Static Scene Parts
In-Focus
Out of Focus
High Resolution 2D Image
4D Light Field
Dynamic Scene Parts
In-Focus
Out of Focus
Video
1D Parallax + Motion

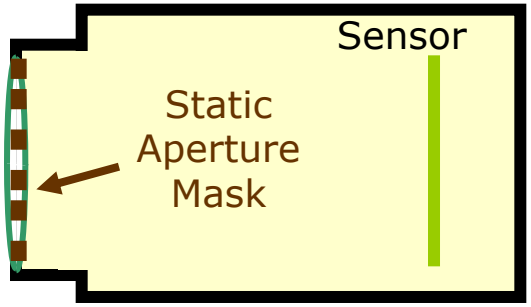
Coded Aperture



SIGGRAPH 2007

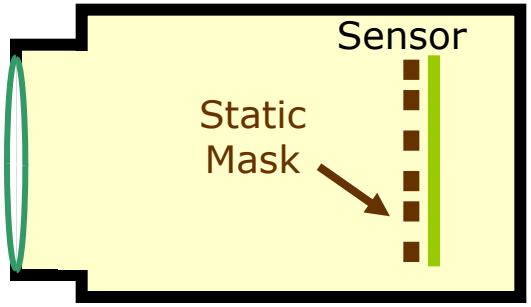
Digital
Refocusing

Coded Aperture



SIGGRAPH 2007

Optical Heterodyning

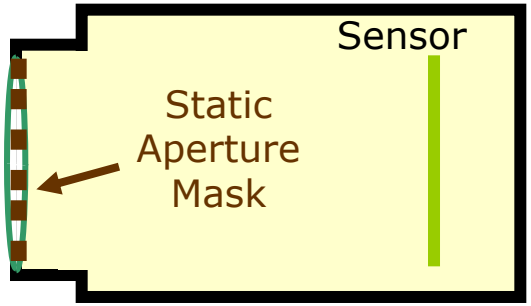


SIGGRAPH 2007

Digital
Refocusing

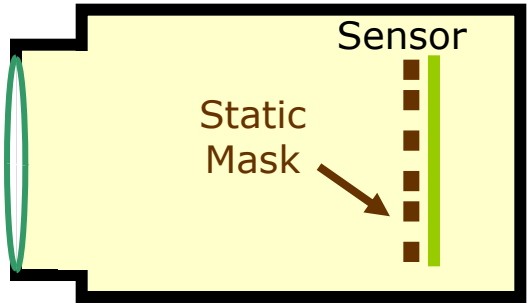
Light Field
Capture

Coded Aperture



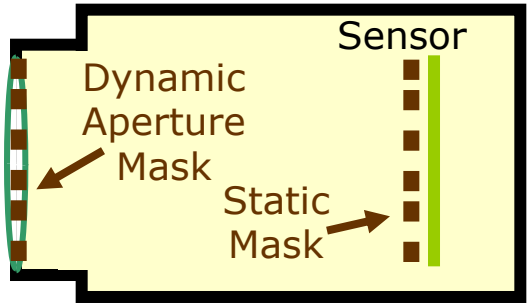
SIGGRAPH 2007

Optical Heterodyning



SIGGRAPH 2007

Reinterpretable Camera



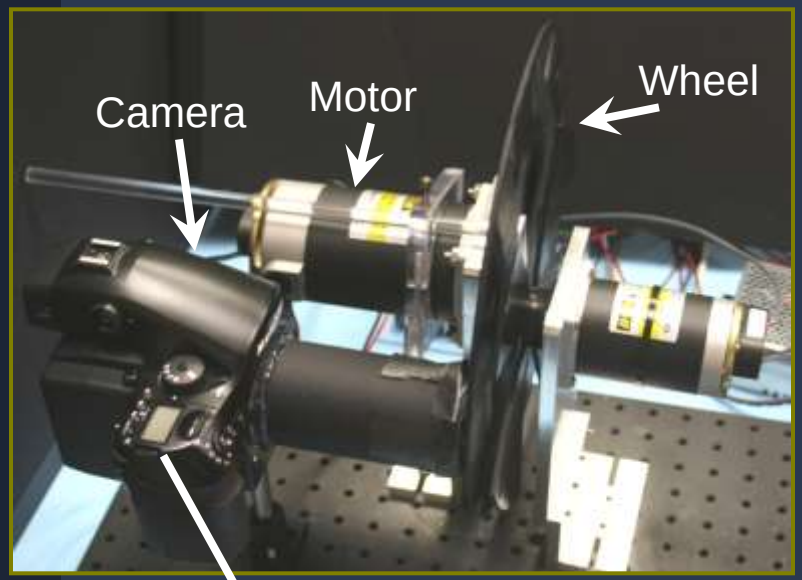
Eurographics 2010

Digital
Refocusing

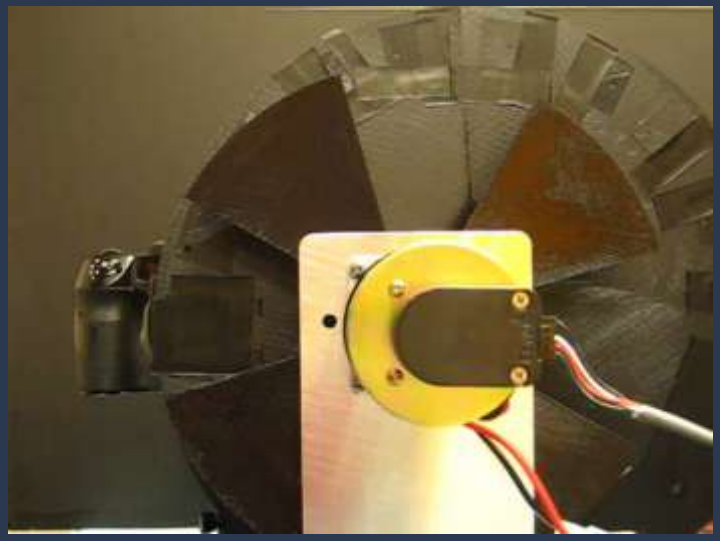
Light Field
Capture

Post-Capture
Resolution Control

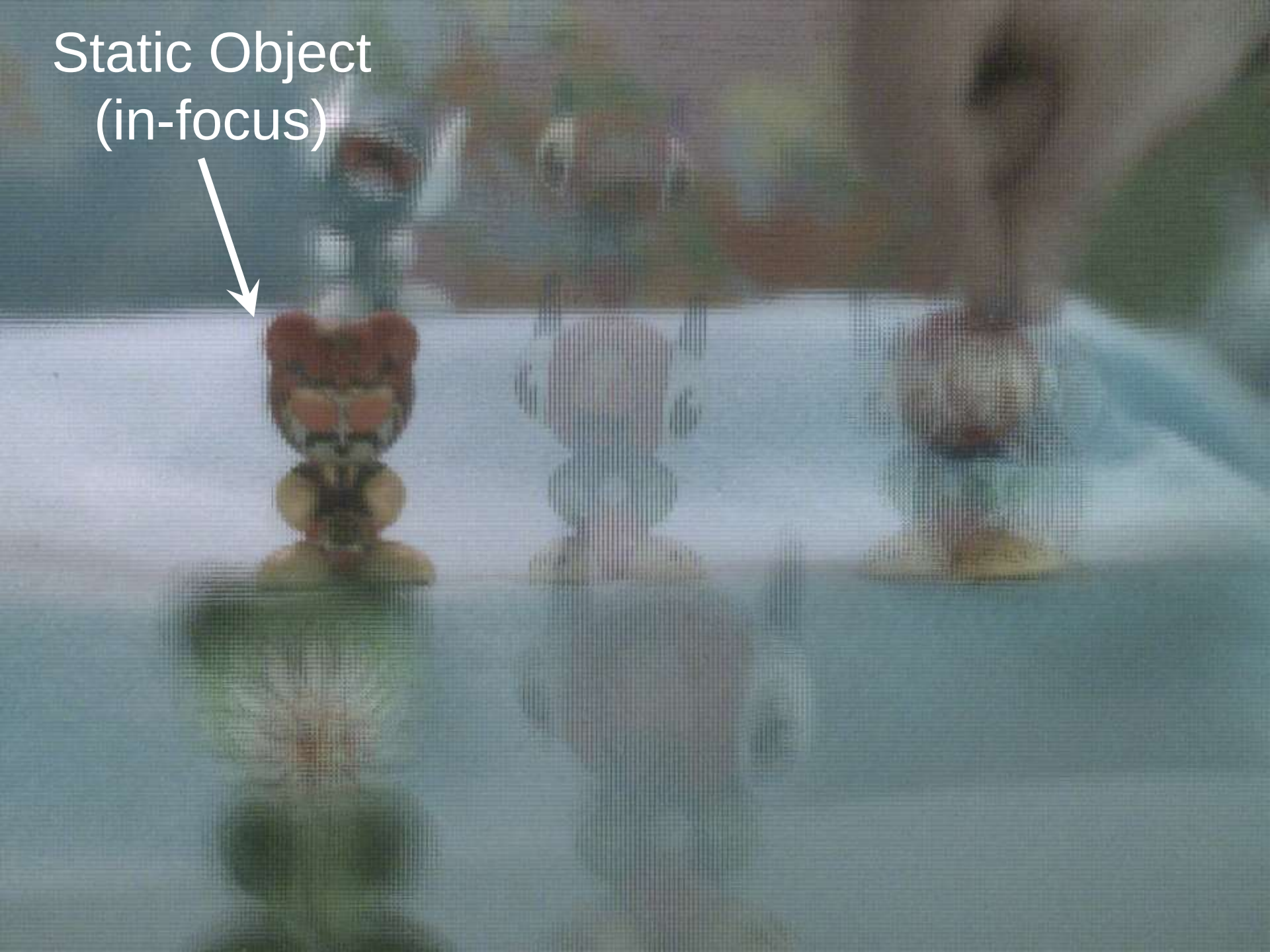
Implementation

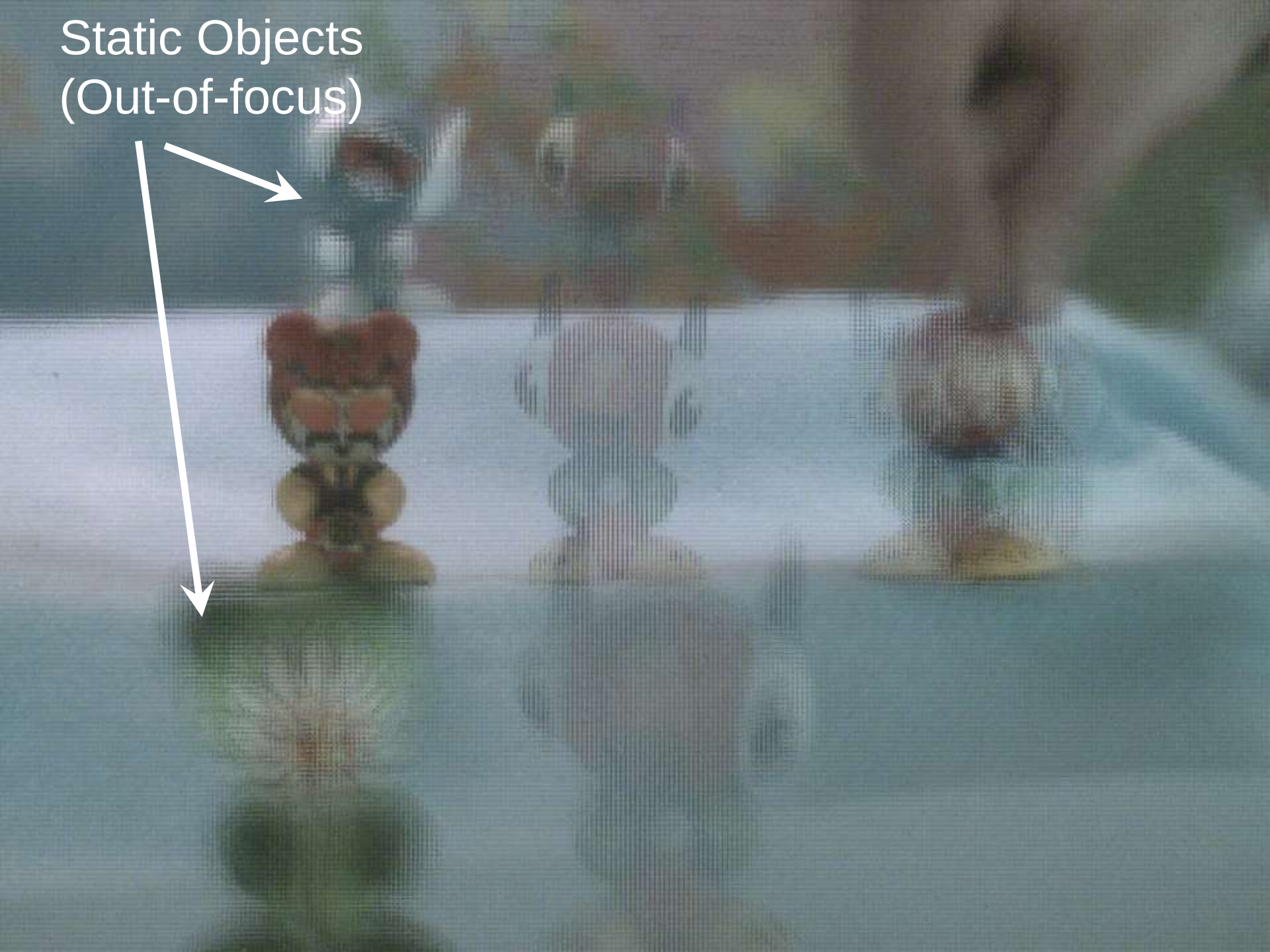


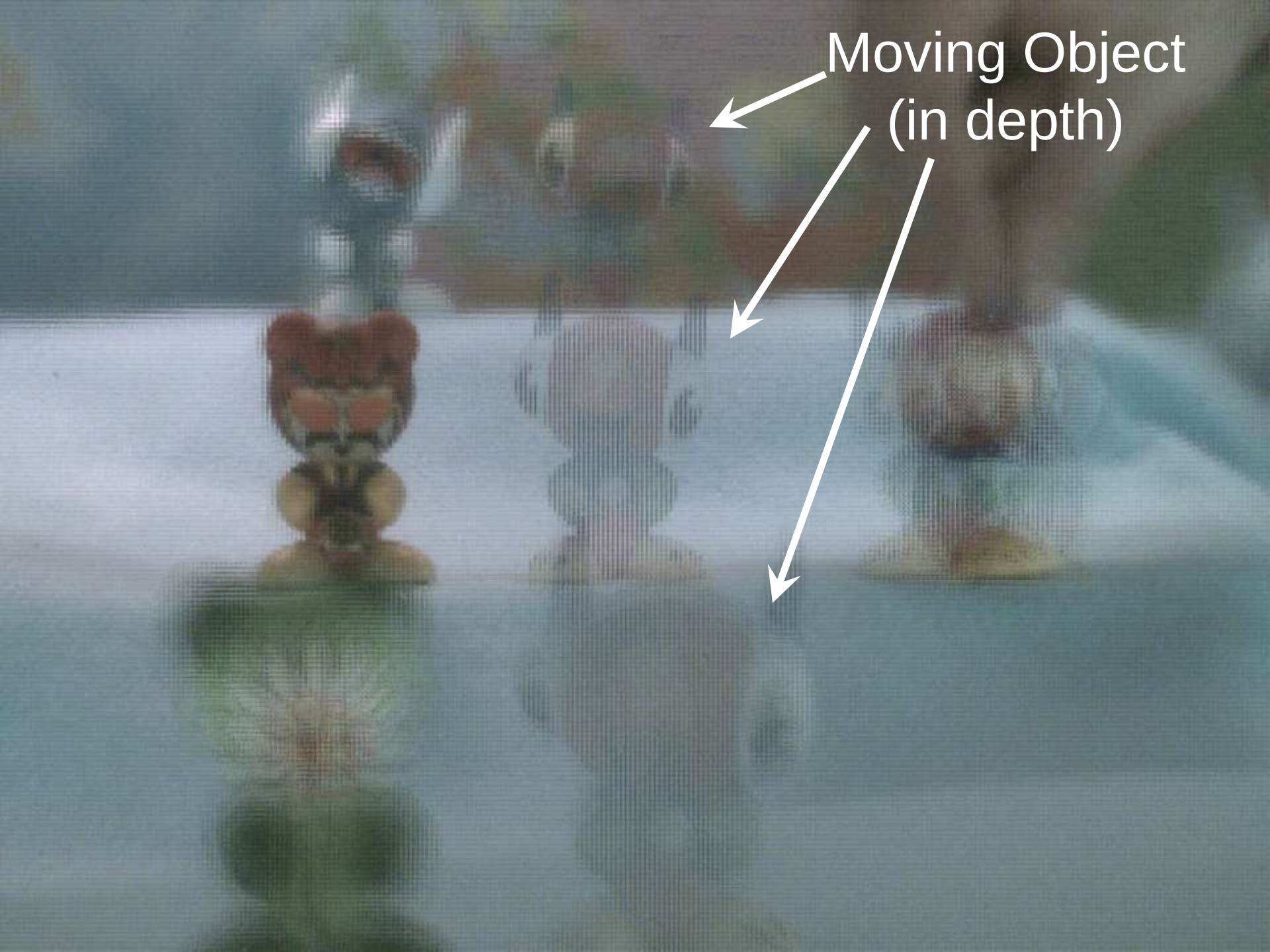
Near-Sensor Mask

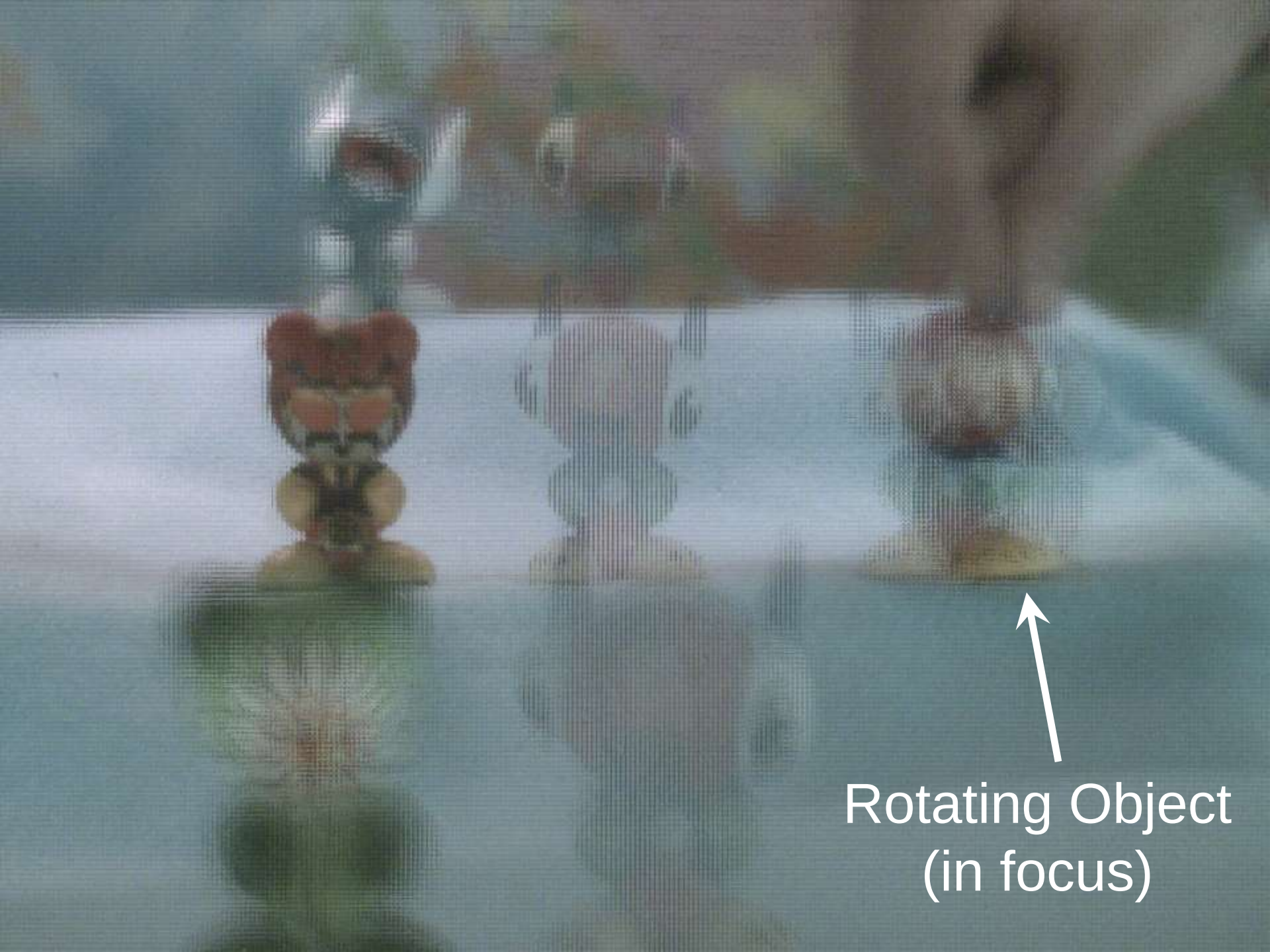


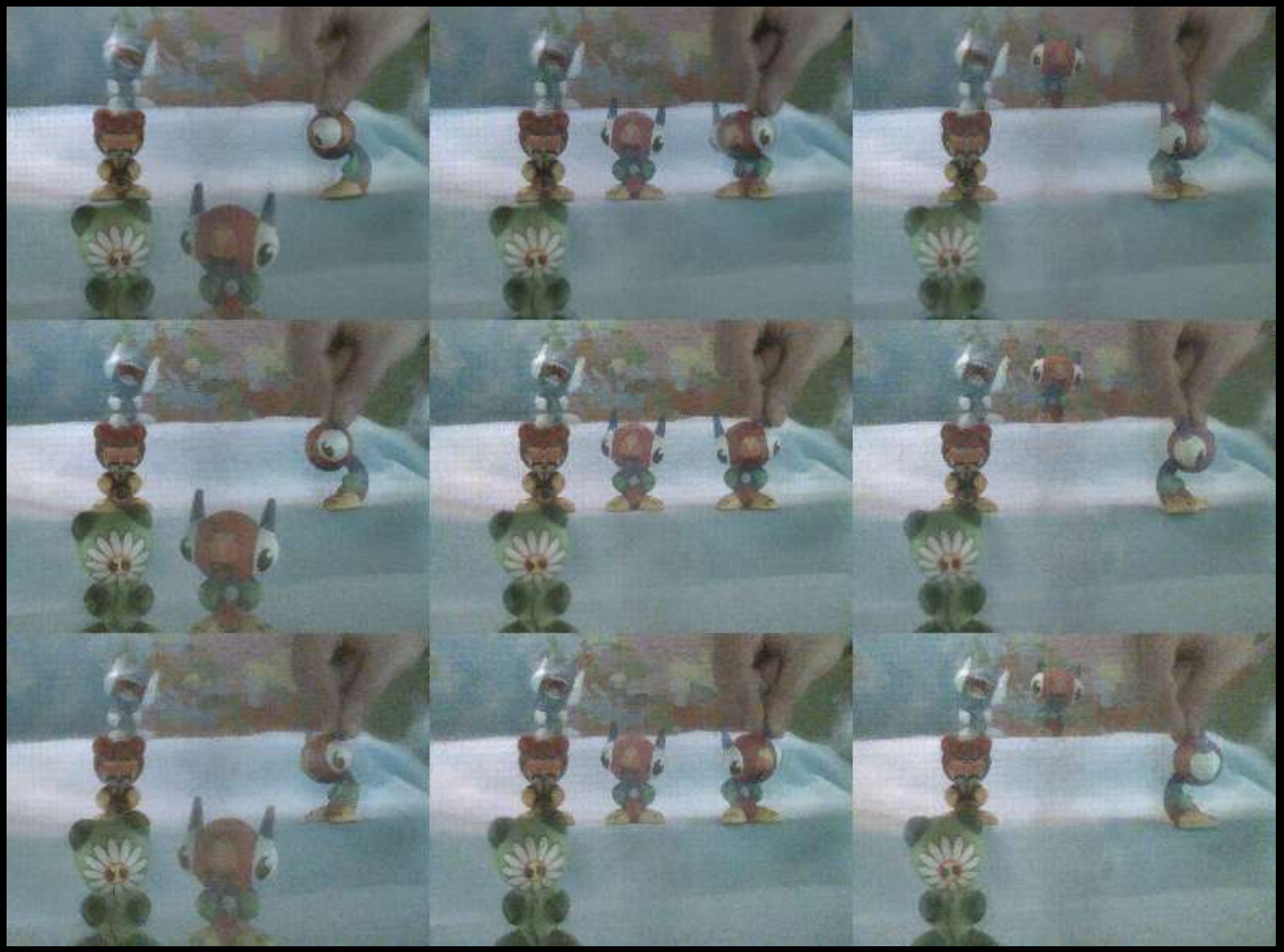
Captured Photo


Static Object
(in-focus)


Static Objects
(Out-of-focus)

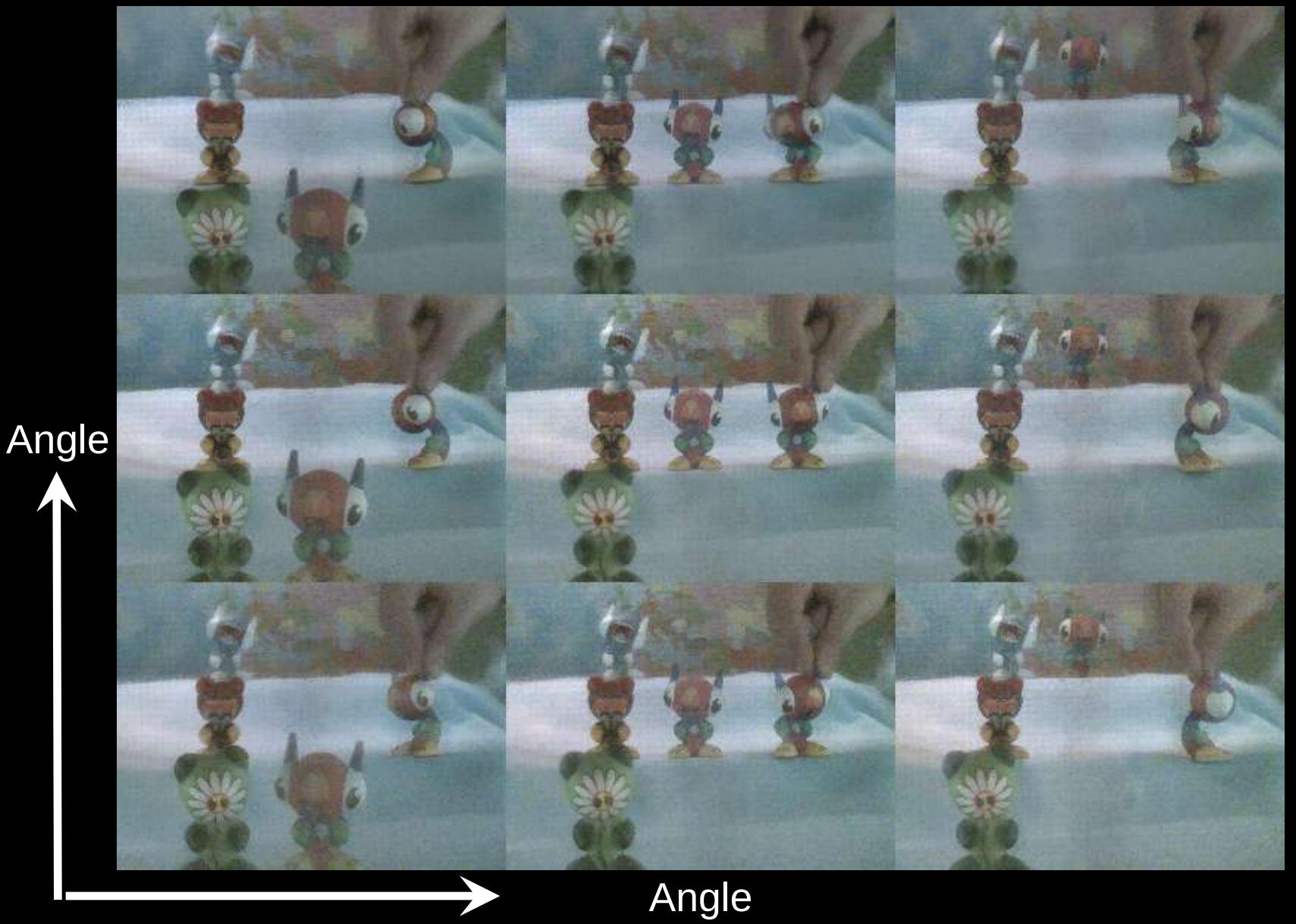

Moving Object
(in depth)


Rotating Object
(in focus)

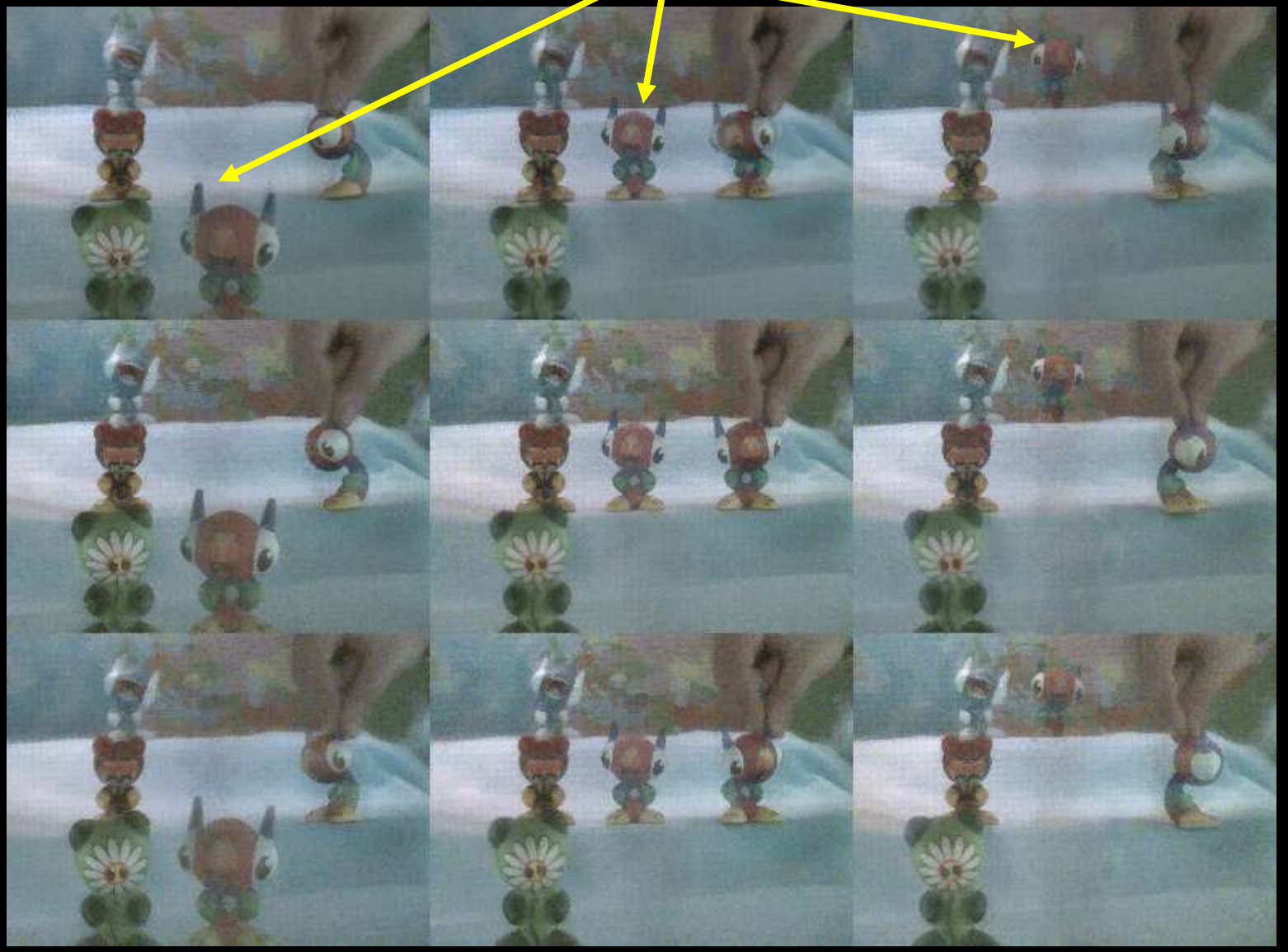


Reconstructed Sub-Aperture Views (3 by 3 Light Field)

For Static Objects



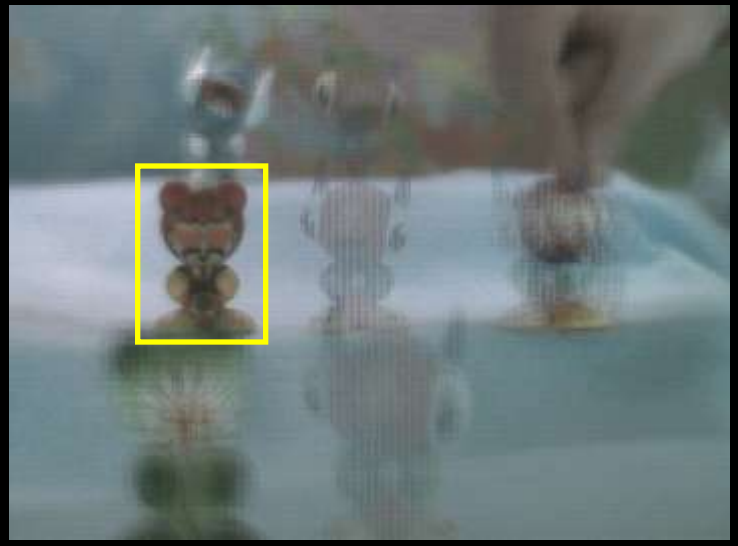
For Moving Toy in Middle



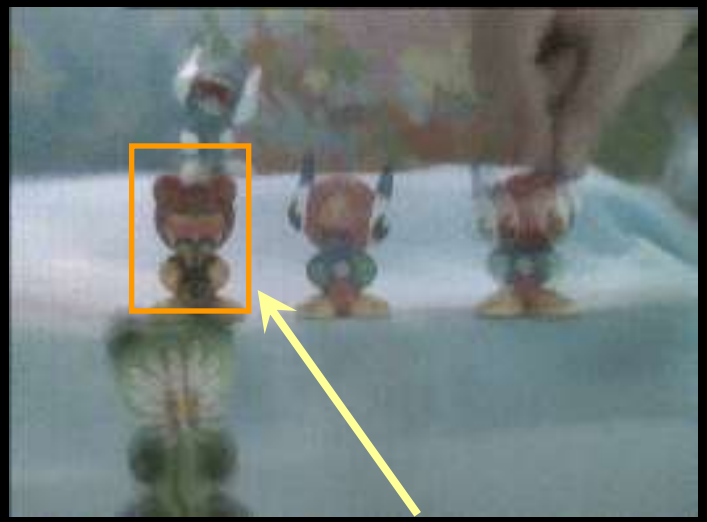
Angle

Time

For Rotating Toy on Right



High Resolution Image



Refocused on Static Toy

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Static Objects

Digital Refocusing on Toy Moving in Depth

Digital Refocusing on Toy Moving in Depth

Digital Refocusing on Toy Moving in Depth

Digital Refocusing on Toy Moving in Depth

Digital Refocusing on Toy Moving in Depth

Digital Refocusing on Toy Moving in Depth

Video for Rotating Toy in-focus

Computational Cameras

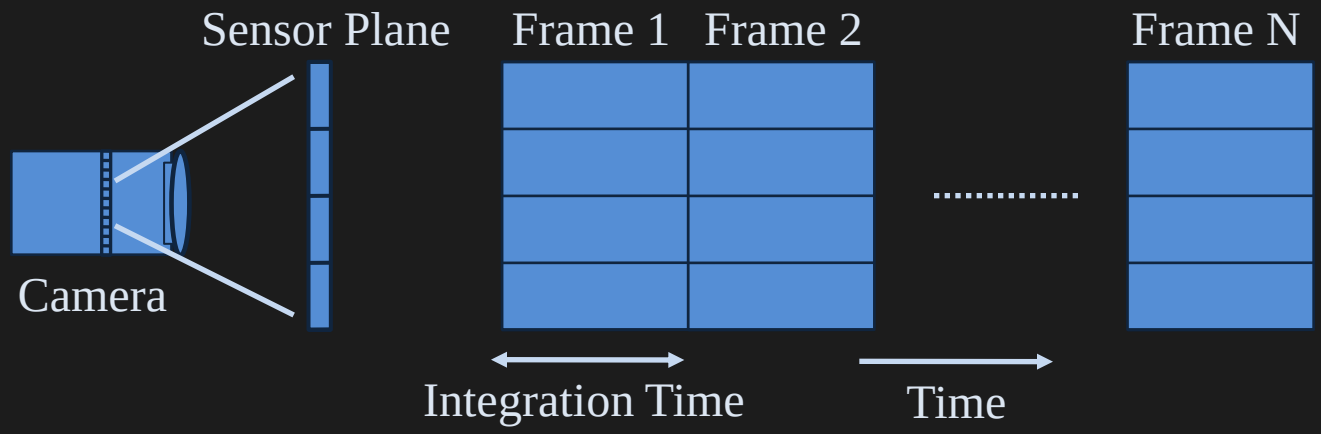
Camera	Coding/Modulation Dimension
Flutter Shutter	Time (Exposure)
Coded Aperture	Space
Light Field Camera	Space and Angle
Reinterpretable Camera	Space, Time, Angle
Flexible Voxels	Space and Time

Flexible Voxels

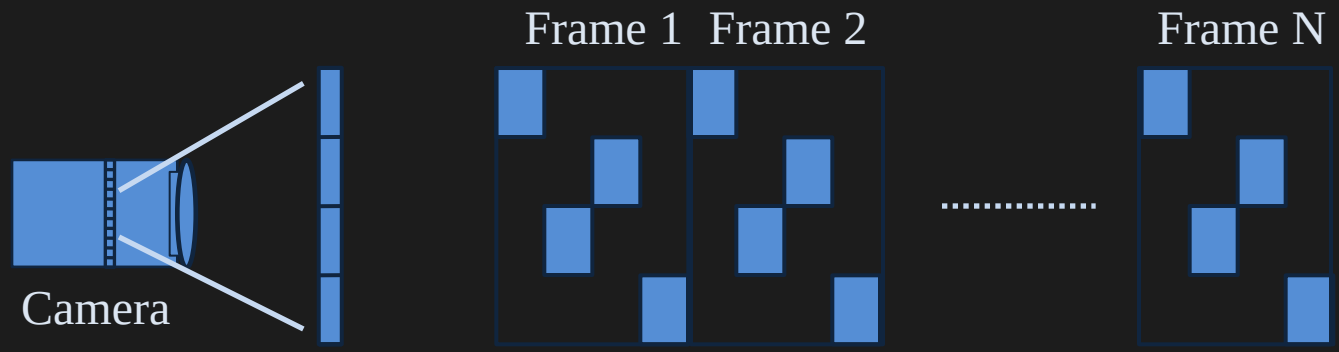
- Similar idea as Reintepretable Camera
  - But for videos
- Traditional Video Camera
  - Spatial/Temporal Resolution is fixed
  - Scene Independent
- Flexible Voxels
  - 'Motion Aware' Video Camera
  - Scene dependent variable resolution

Sampling of the Space-Time Volume

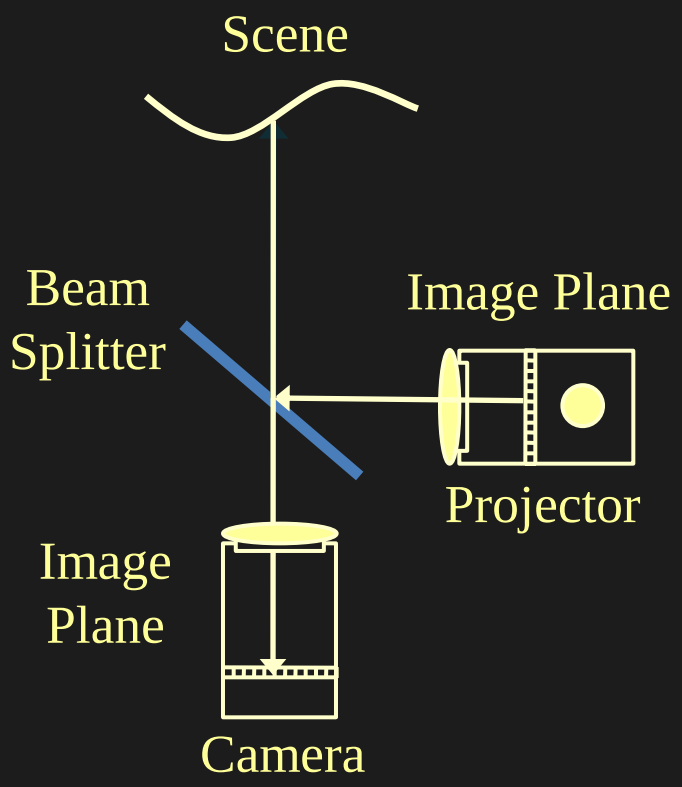
Conventional Sampling Scheme:

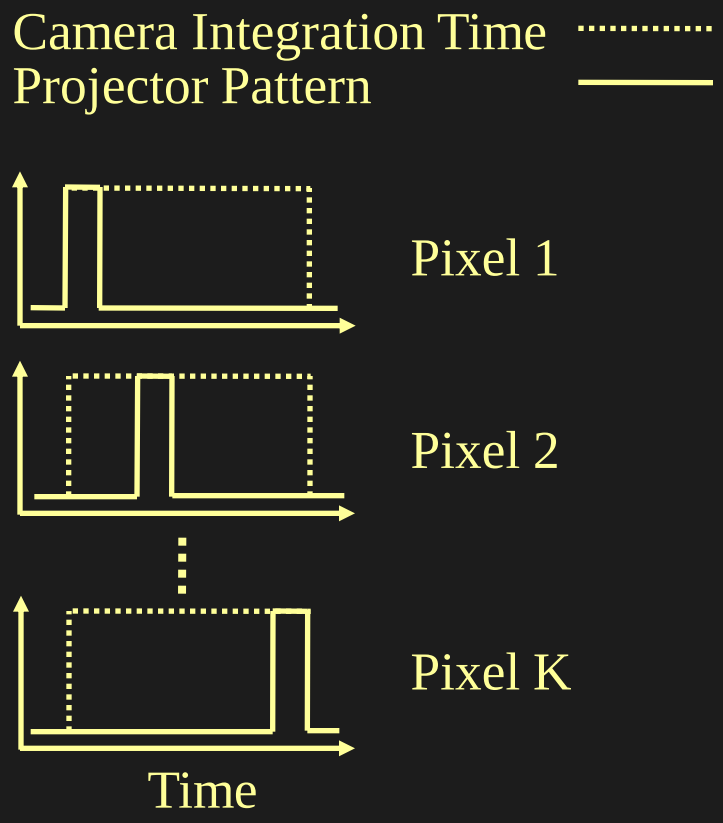


Our Sampling Scheme:



Co-located Projector-Camera Setup



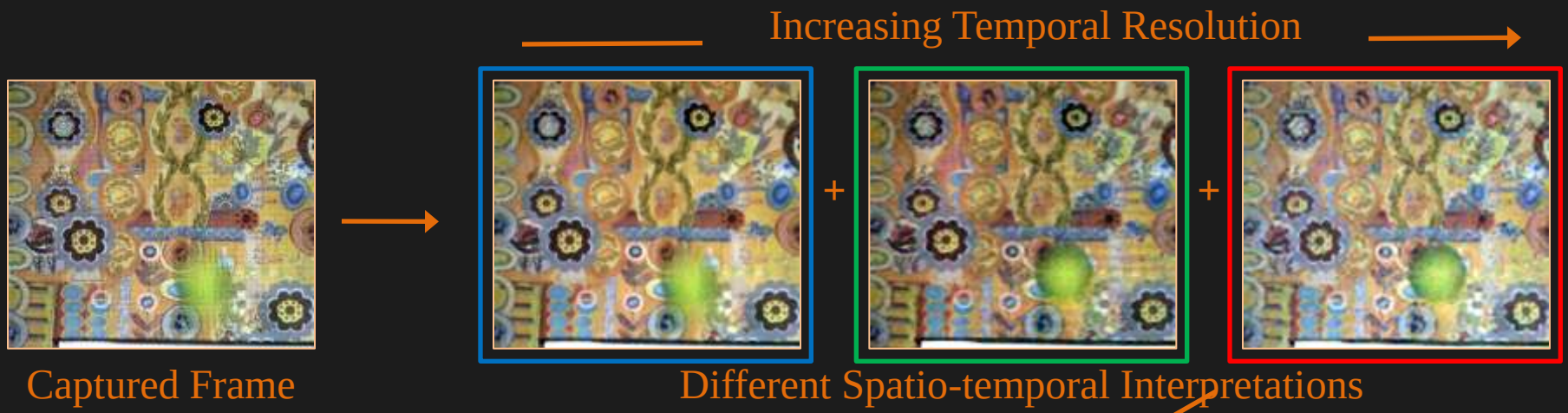


Multiple Balls Bouncing and Colliding (15 FPS)

Large Motion Blur

Close-up

Motion-aware Video



Multiple Balls Bouncing

Input Sequence

Motion-Aware Video

Computational Cameras

Camera	Coding/Modulation Dimension
Flutter Shutter	Time (Exposure)
Coded Aperture	Space
Light Field Camera	Space and Angle
Reinterpretable Camera	Space, Time and Angle
Flexible Voxels	Space and Time

Common Implementation using fast programmable LCD's

Light Fields

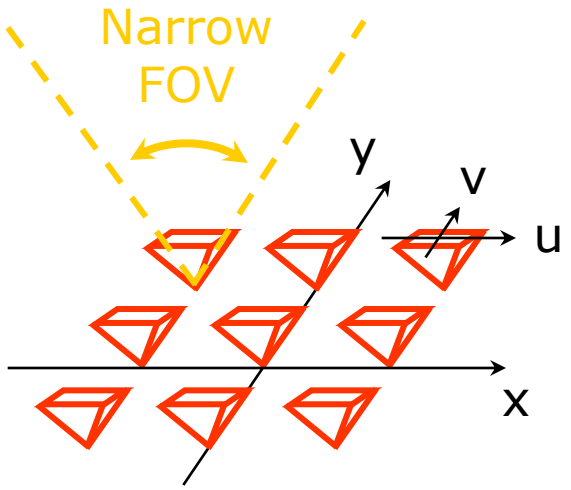
- Camera arrays / Hand-held light field cameras
  - Represented by a set of perspective cameras
  - Typically capture narrow field of view (FOV) light field

[Wilburn et al. 05]

[Ng et al. 05]

[Georgiev et al. 06]

[Veeraraghavan et al. 07]

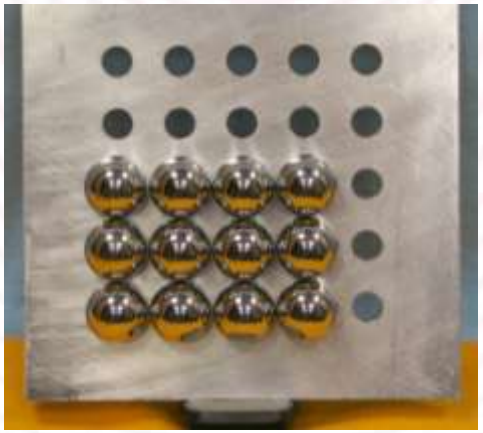


Set of Perspective Cameras

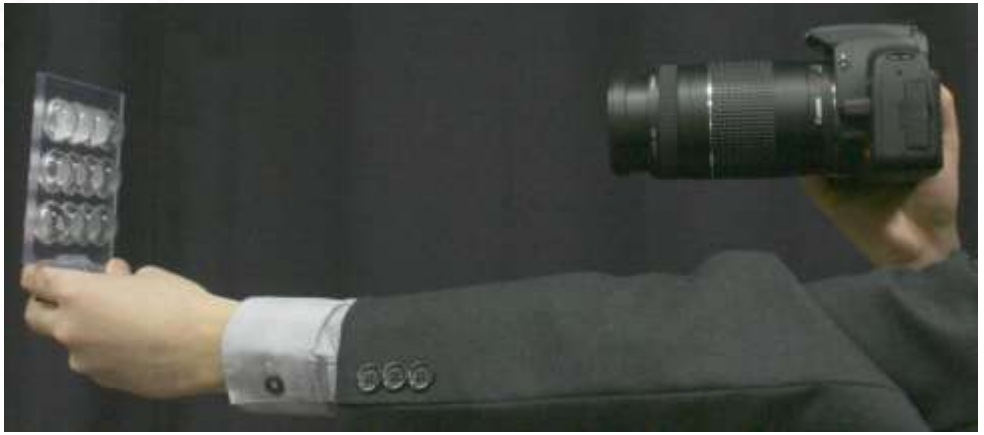
Wide FOV Light Field ?

Normal Wide FOV Images

Wide FOV Light Field !



Spherical Mirror Array



Refractive Sphere Array

Wide FOV Refocusing (150°x150°)

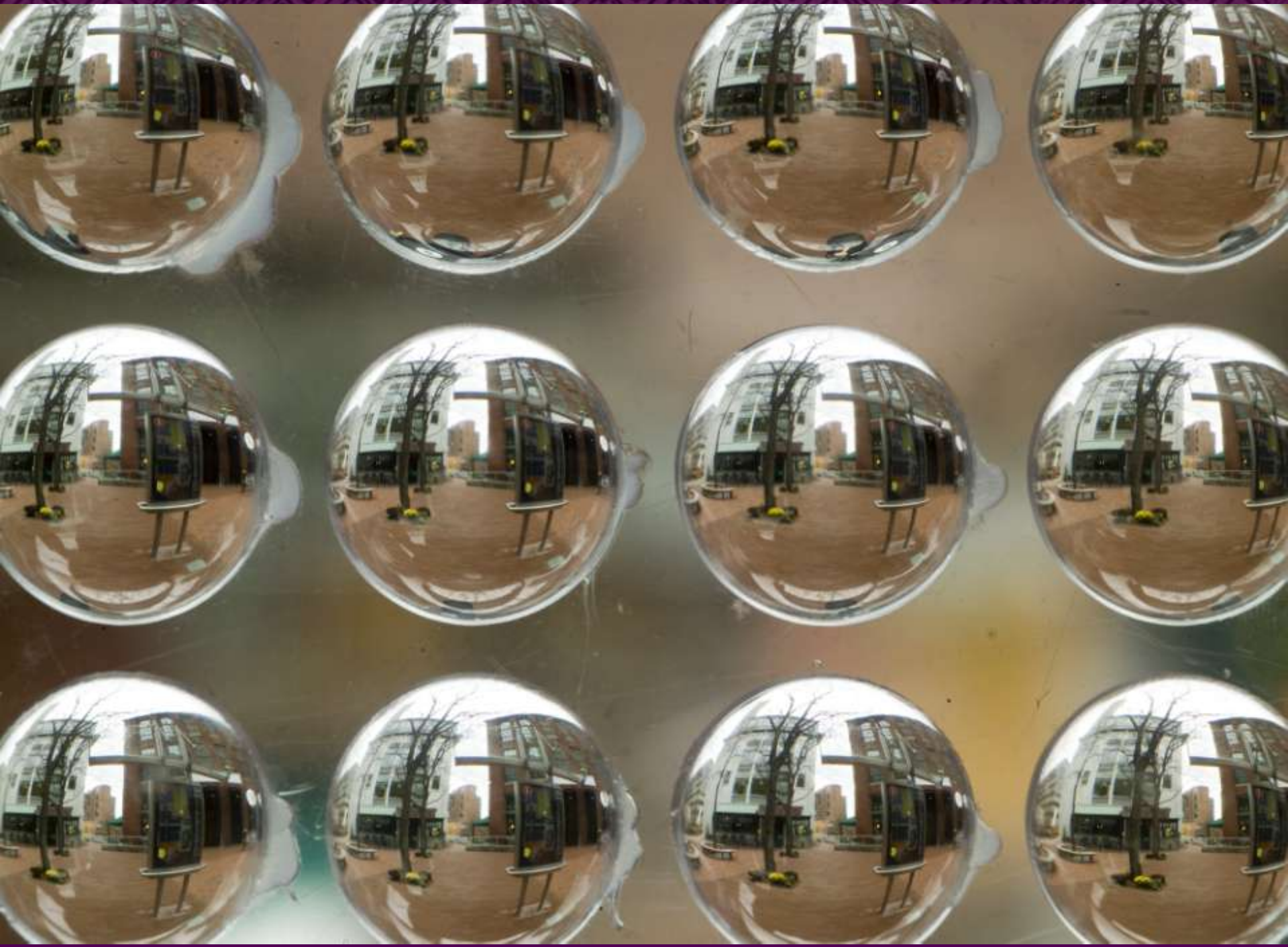
Focus Back

Focus Ball

Focus Person

All-in-Focus

Depth Map



Wide FOV Refocusing (90°x80°)

Focus Back

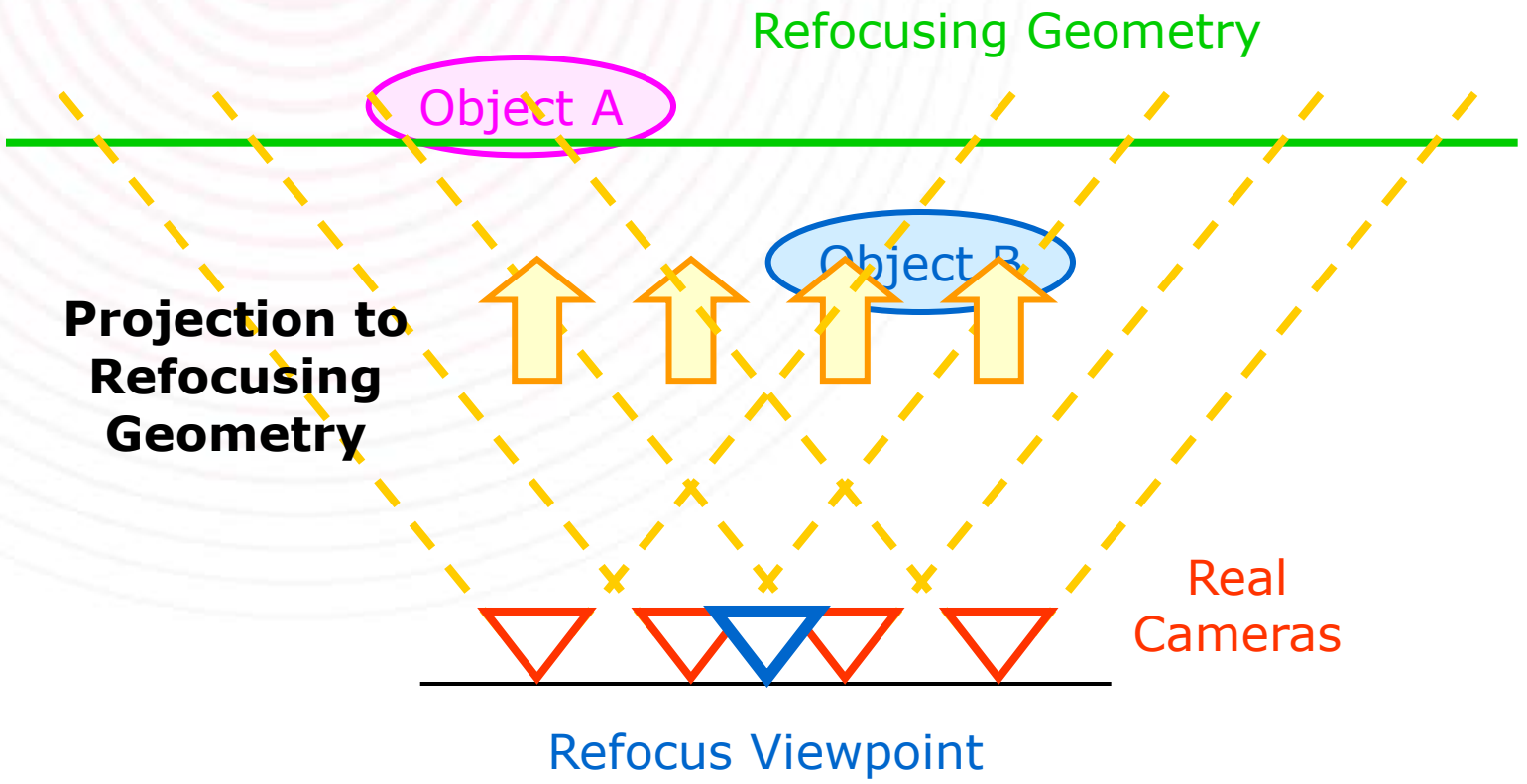
Focus Tree

Focus Board

All-in-Focus

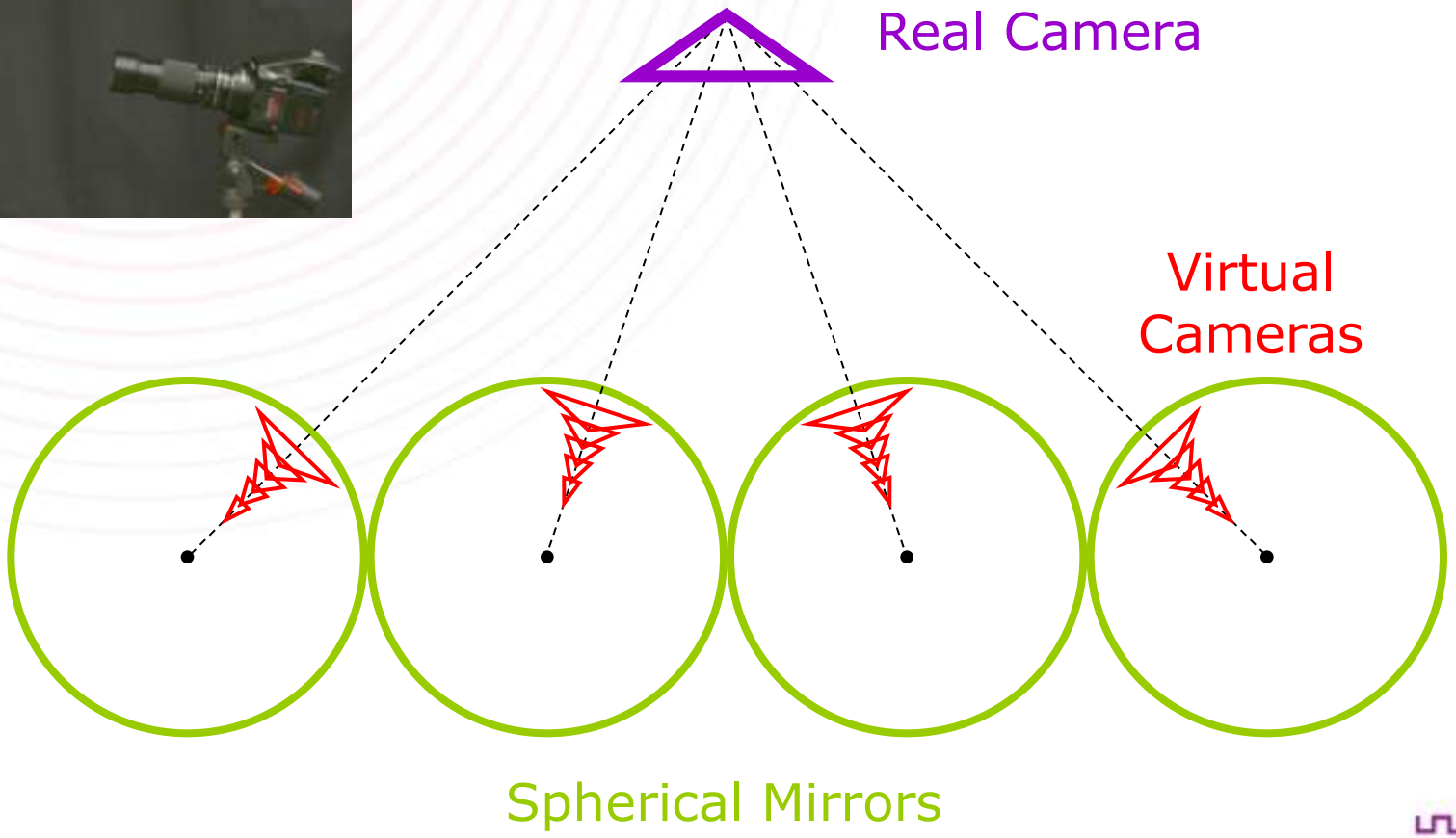
Depth Map

Refocusing in Traditional Light Field

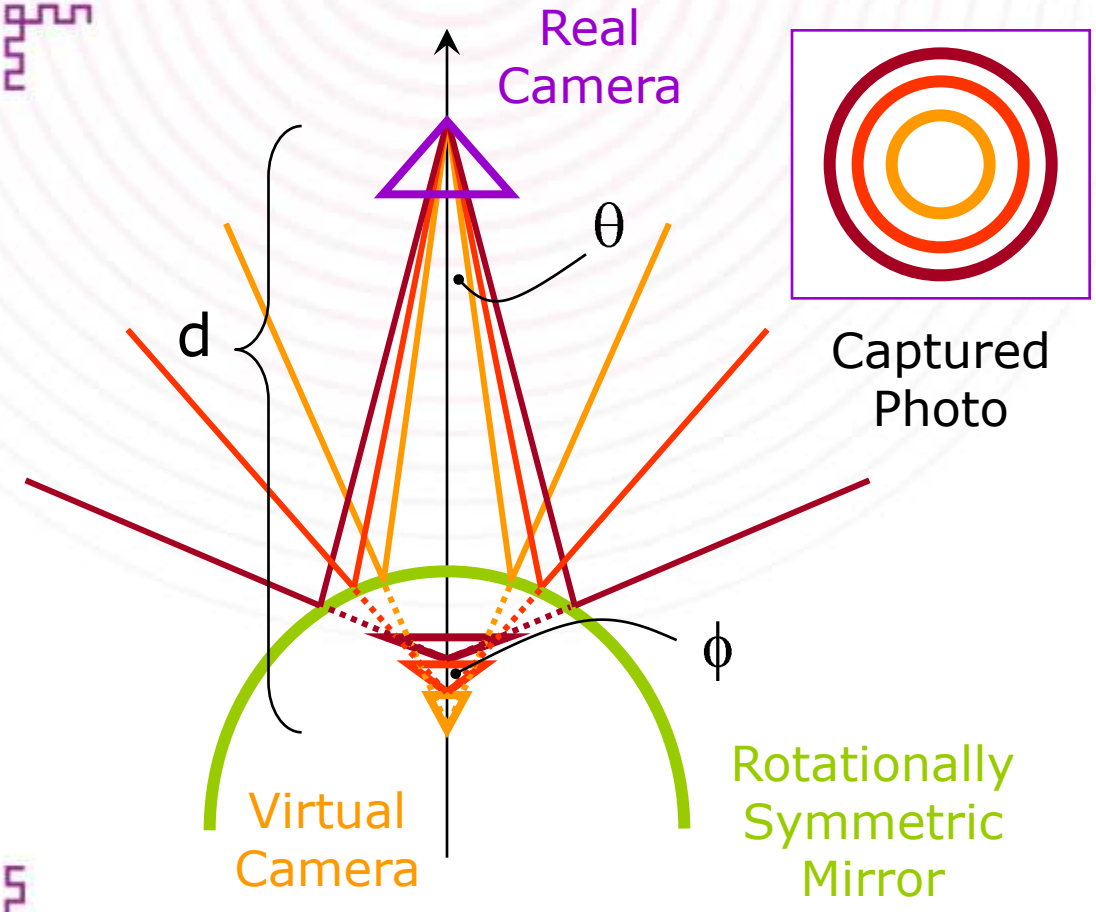


- Efficient operation using projective texture mapping on GPU

Axial-Cone Modeling of Spherical Mirror Array



Axial-Cone Modeling of Rotationally Symmetric Mirror



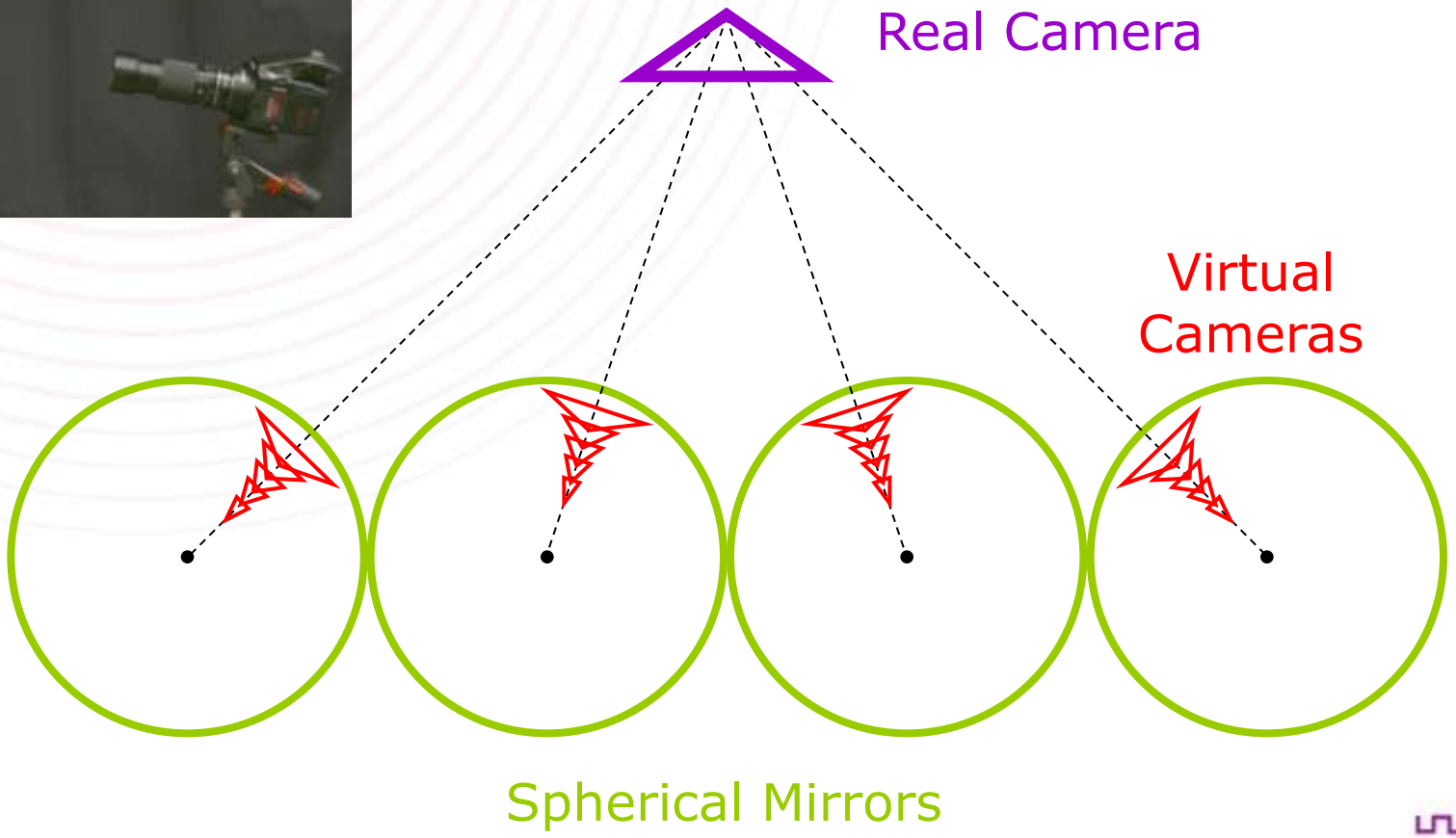
Captured Photo

A cone of rays
in the real camera
(Angle θ)

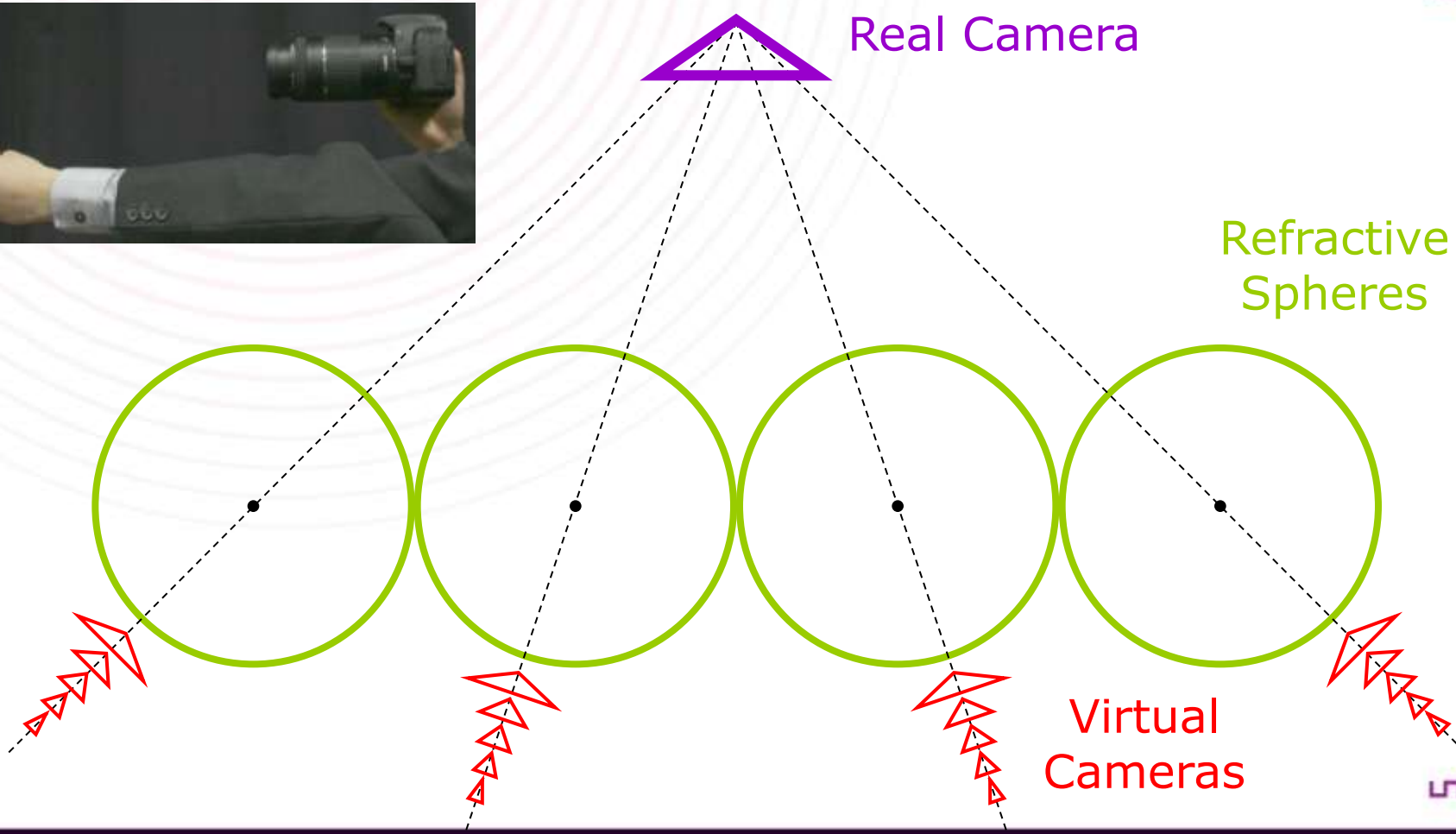
⇕

A cone of rays
in a virtual camera
(Distance d, Angle ϕ)

Axial-Cone Modeling of Spherical Mirror Array



Axial-Cone Modeling of Refractive Sphere Array



Captured Photo

Each Sphere Image

Axial-Cone Modeling

Projection to
Refocusing Geometry

One Light Field View

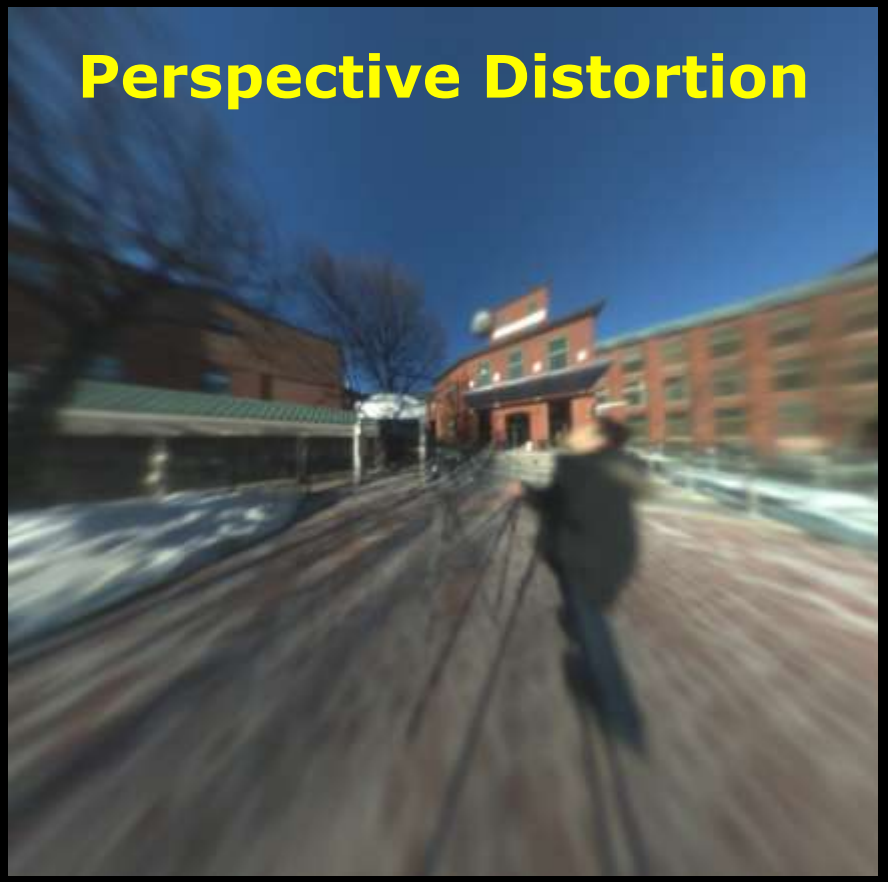
Light Field Views (100°x100°)

Light Field Views (100°x100°)

Refocusing Result (100°x100°)

Rendering using a Single Perspective Camera

FOV: 100°x100°



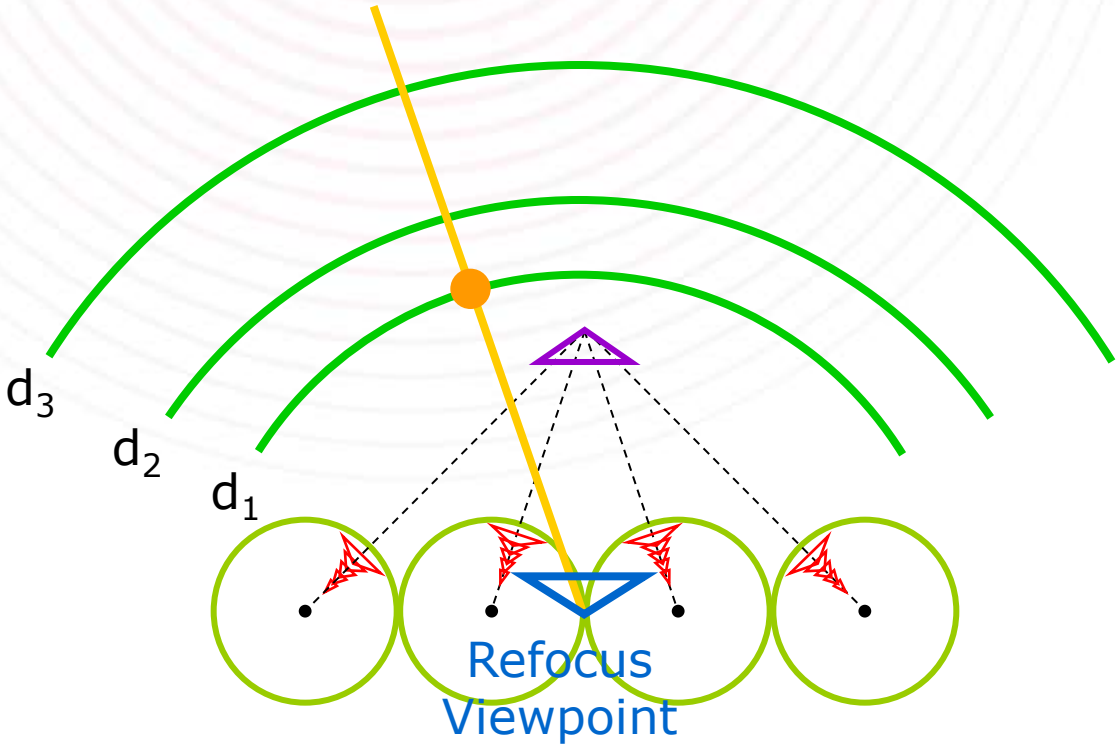
FOV: 150°x150°

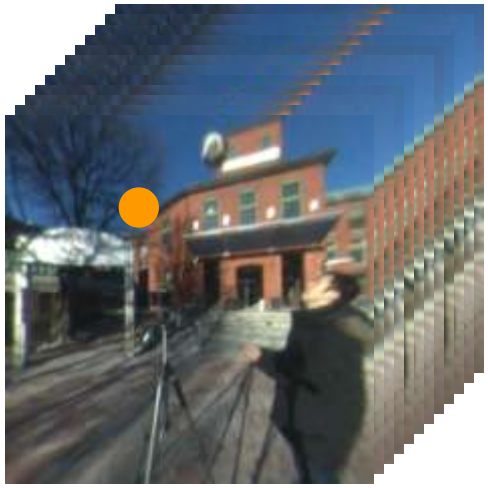
Refocusing Result: Cube Map (150°x150°)

Refocusing Result: Mercator Projection (150°x150°)

Dense Depth Estimation

- Plane sweeping for dense depth estimation

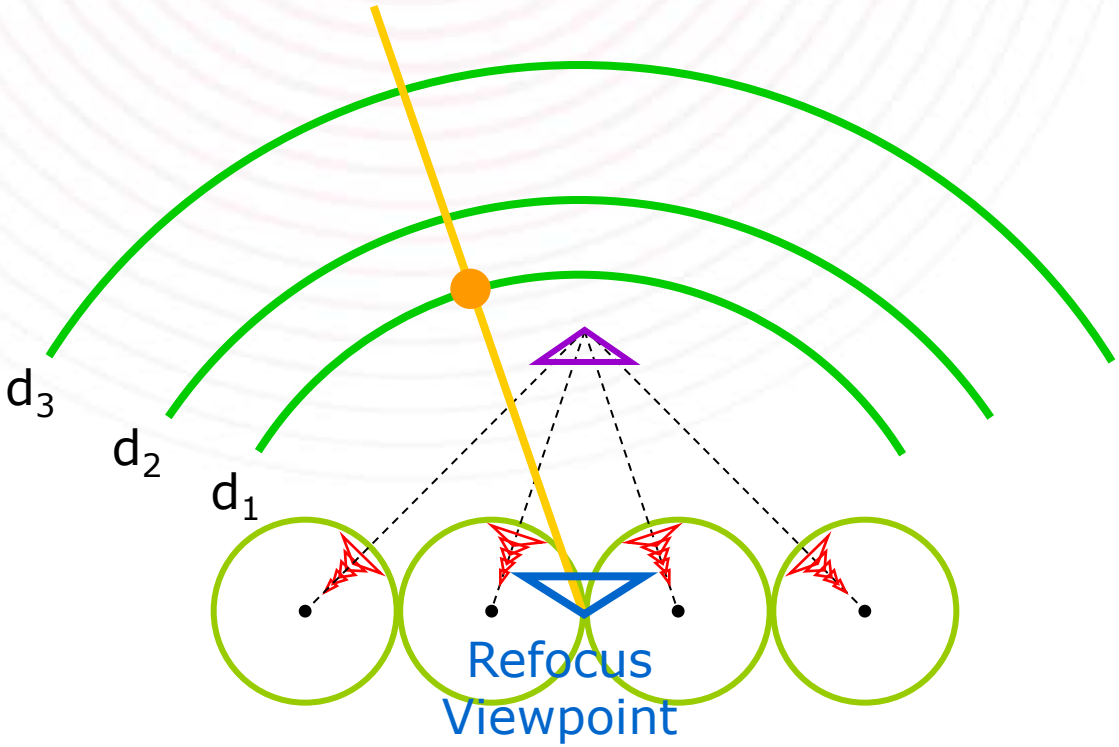


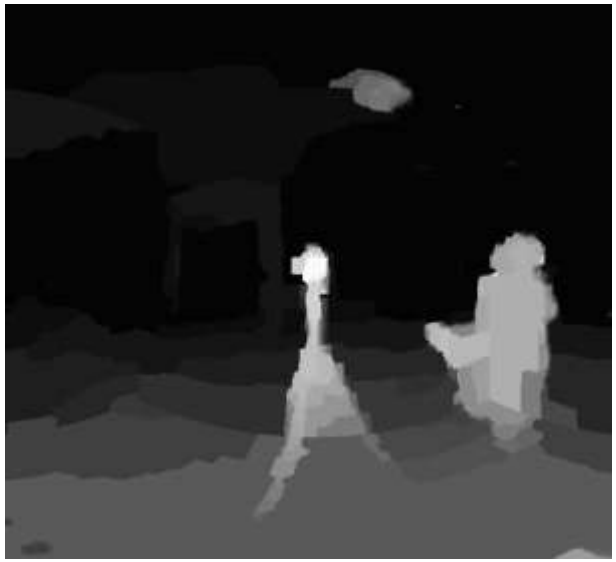


Check color consistency across light field views at each depth layer

Dense Depth Estimation

- Plane sweeping for dense depth estimation

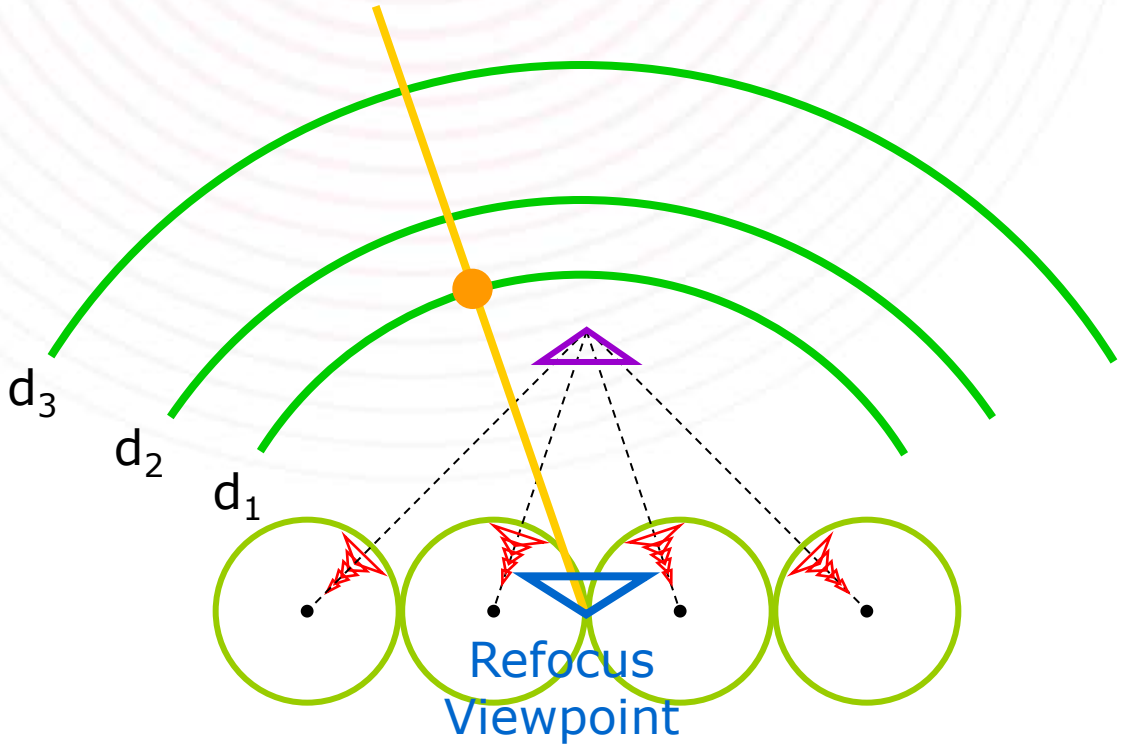




Depth Map

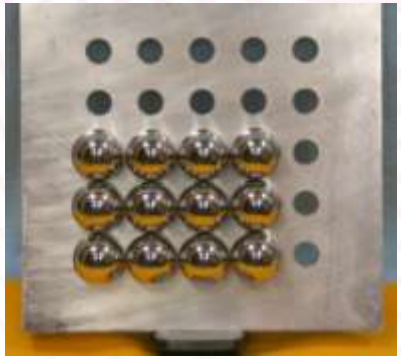
Dense Depth Estimation

- Plane sweeping for dense depth estimation

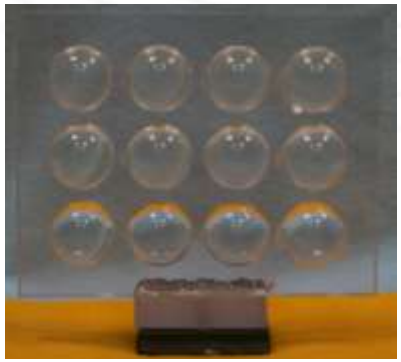


All-in-Focus Rendering

Prototypes



Spherical Mirror Array



Refractive Sphere Array

Advantages

- Single-shot
- Flexible camera placement
- Low cost
- Portable

Array of 1” Refractive Spheres

Refocusing Perspective Projection (90°x80°)

All-in-Focus Perspective Projection (90°x80°)

Depth Map Perspective Projection (90°x80°)

- Light Field Mode?
- Flutter Shutter mode?
- Reinterpretable Mode?

Computational Cameras

- Sensing
  - Per-Pixel Control
  - Wide Angle Light Fields
  - Modulation in other dimensions: wavelength
  - Slicing and Sampling of Plentoptic function
- Reconstruction algorithms
  - Image/video based priors, compressive sensing
  - Statistical properties of plenoptic function

Acknowledgements

- Ramesh Raskar, MIT
- Jack Tumblin, Northerwestern Univ
- Ashok Veeraraghavan, Rice Univ.
- Mohit Gupta, Columbia Univ
- Ankit Mohan, Flutter
- Srinivasa Narasimhan, CMU
- Cyrus Wilson
- Yuichi Taguchi, MERL
- Srikumar Ramalingam, MERL

- MERL, Jay Thornton, Joseph Katz, John Barnwell
- MELCO, Japan

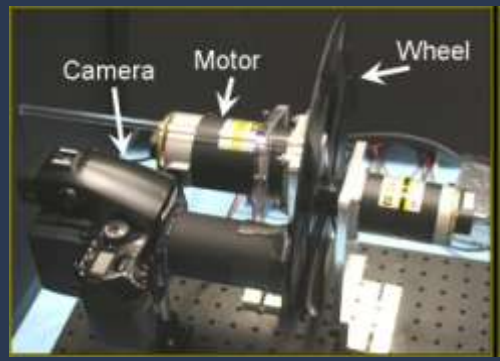
Computational Cameras

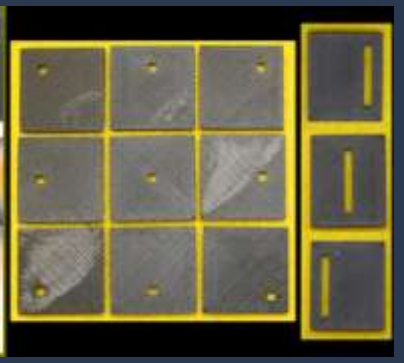
Flutter Shutter Camera

Coded Aperture

Mask based light field camera

Reinterpretable Camera





Wide Angle light field camera

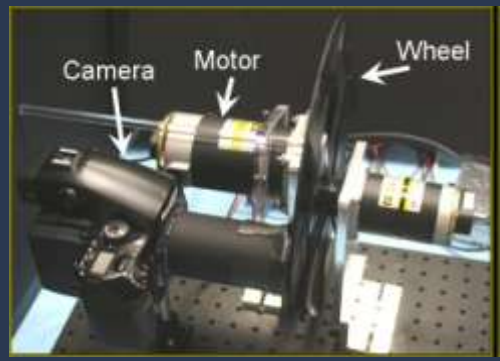
Computational Cameras

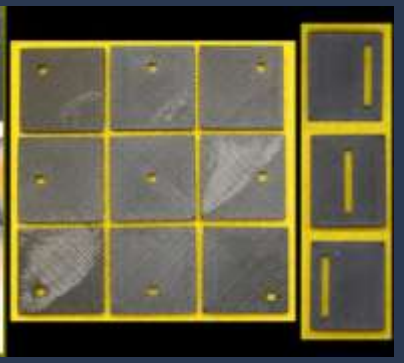
Flutter Shutter Camera

Coded Aperture

Mask based light field camera

Reinterpretable Camera





Wide Angle light field camera