Computational Light Transport
Computational Photography
Inverse problems

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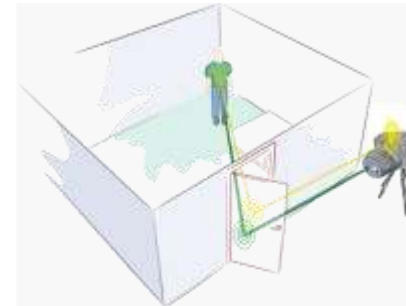
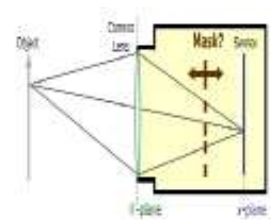
Inverse Problems

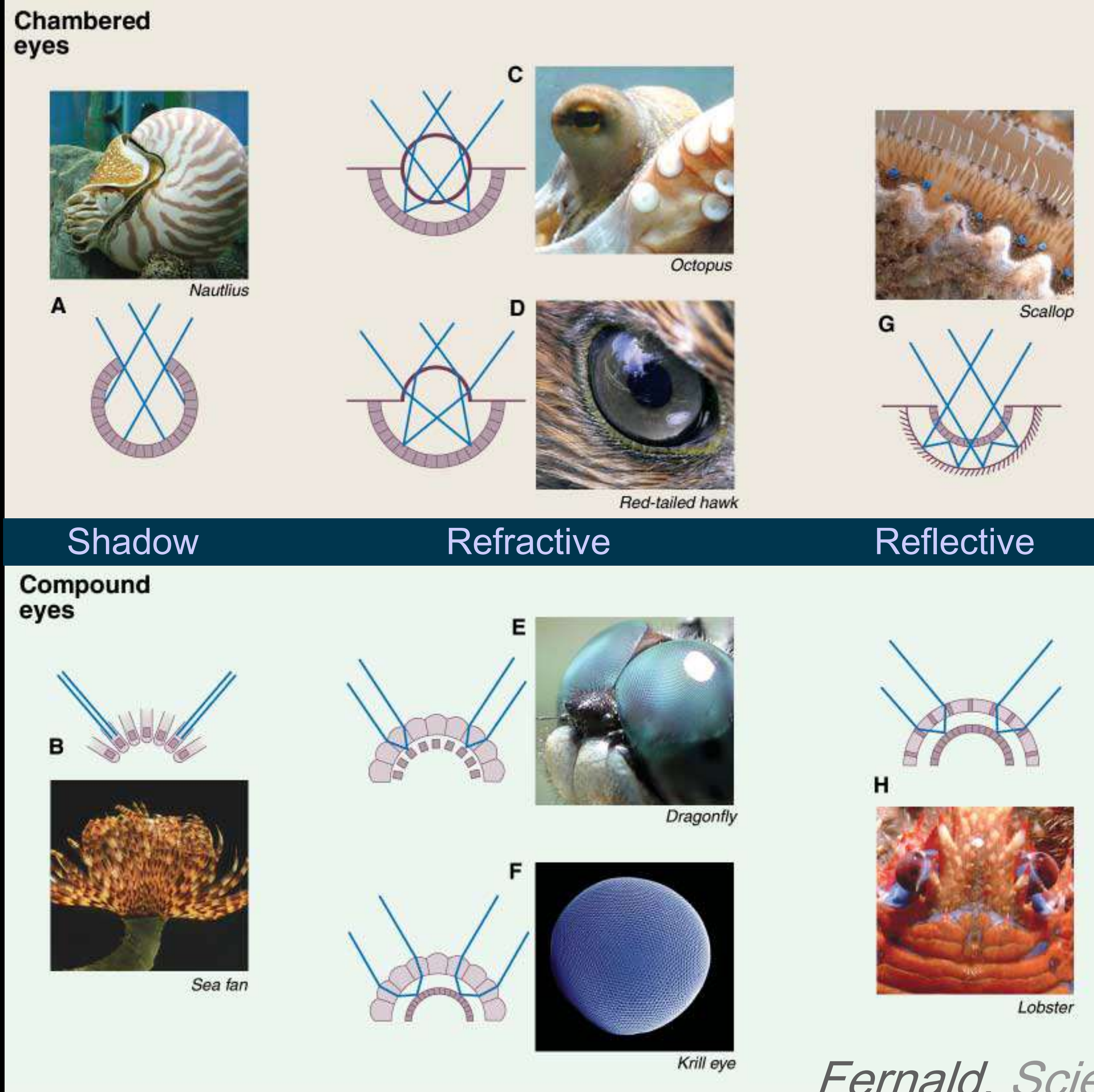


- Co-design of Optics and Computation
  - Photons not just pixels
  - Mid-level cues
- Computational Photography
  - Coded Exposure
  - Compressive Sensing for High Speed Events
    - Limits of CS for general imaging

- Computational Light Transport
  - Looking Around Corners, trillion fps
  - Lightfields:
    - Compressive Campture
    - 3D Displays and Holograms

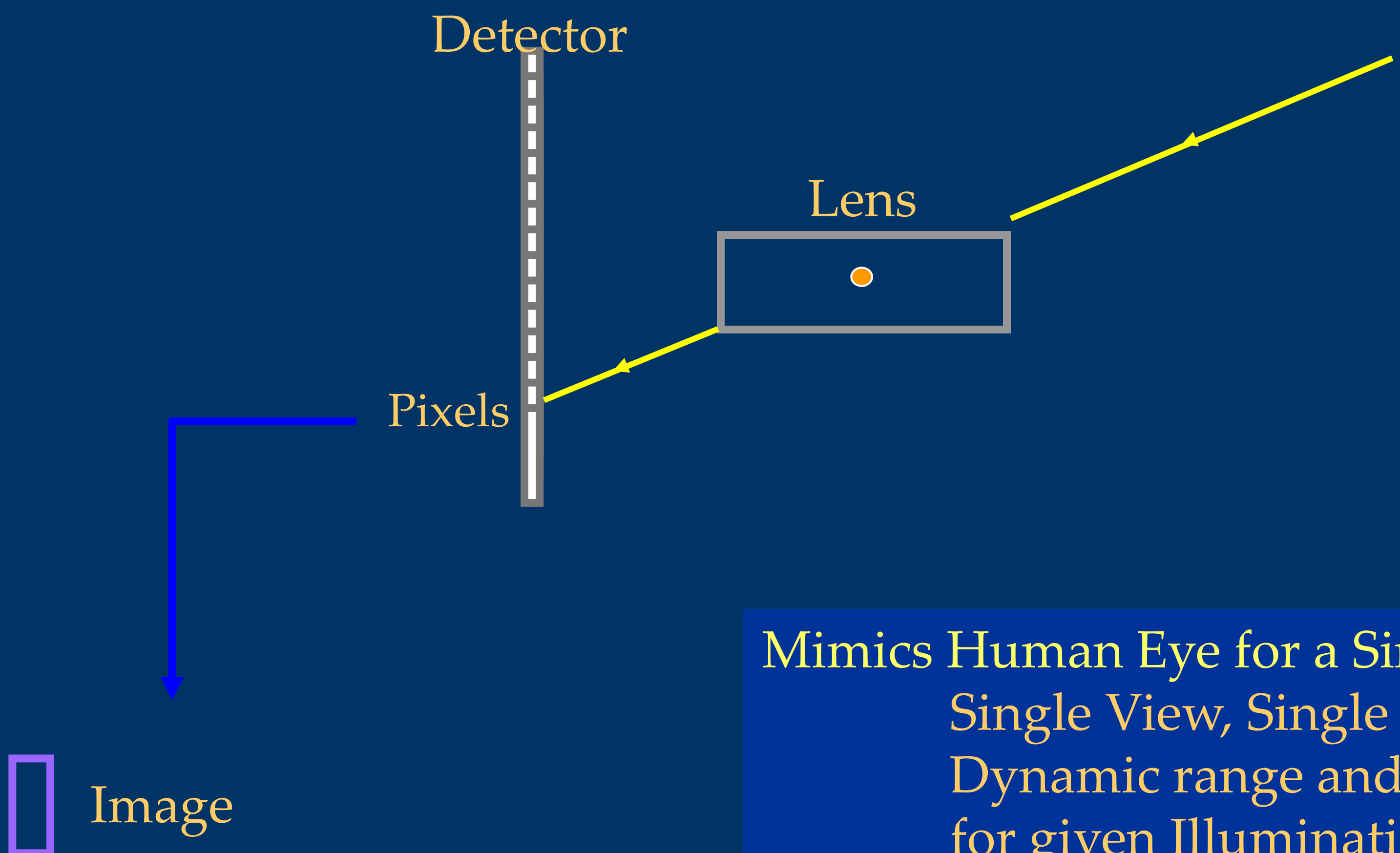


Tools for Visual Computing



Fernald, Science [Sept 2006]

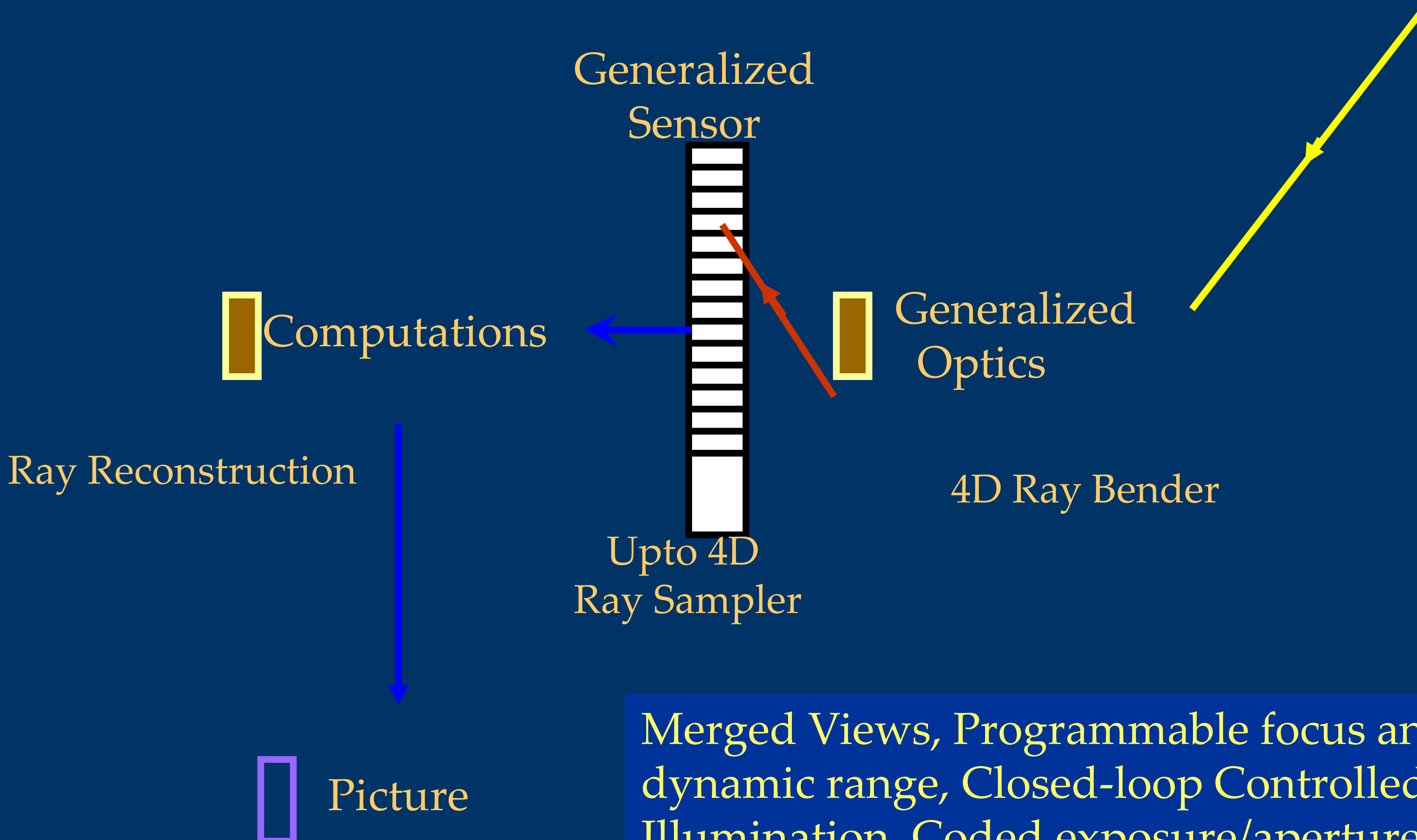
Traditional Photography



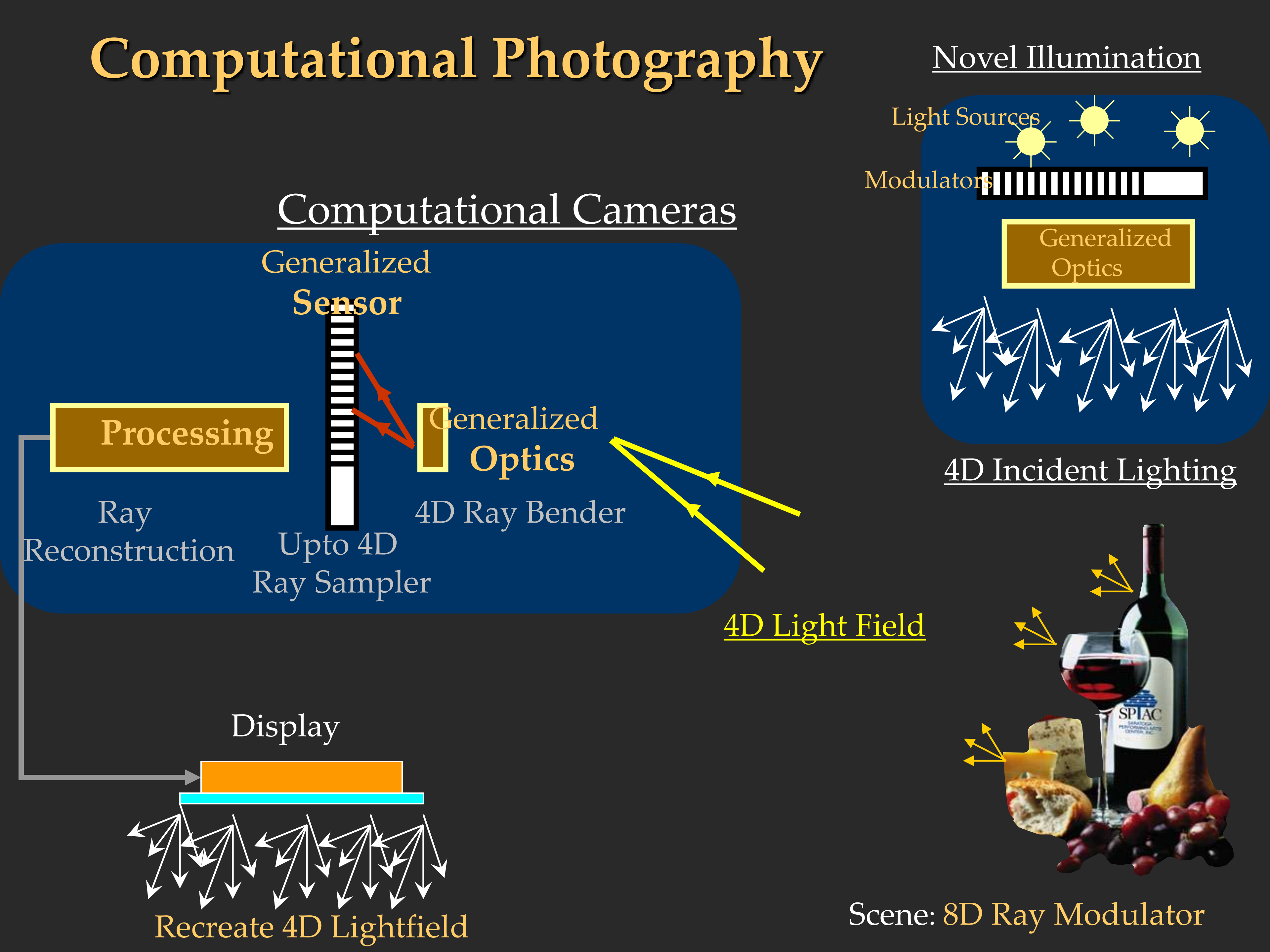
Mimics Human Eye for a Single Snapshot:
Single View, Single Instant, Fixed Dynamic range and Depth of field for given Illumination in a Static world

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
SPAC
Display
Recreate 4D Lightfield
Scene: 8D Ray Modulator

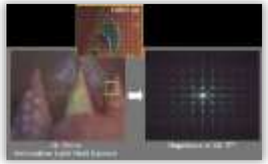
Camera Culture

Creating new ways to capture and share visual information

MIT Media Lab
Ramesh Raskar
http://cameraculture.info
Facebook.com/cameraculture

Computational Photography

1.Light-Field Camera
A new camera design exploiting the fundamental dictionary of light-fields for a single-capture capture of light-fields with full-resolution refocusing effects.



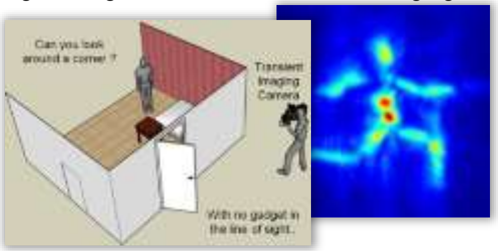
2. Color Primaries
A new camera design with switchable color filter arrays for optimal color fidelity and picture quality on scene geometry, color and illumination.

3. Flutter-Shutter
A camera that codes the exposure time with a binary pseudo-sequence to de-convolve and remove motion blur in textured backgrounds and partial occluders.

4. Compressive Capture
We analyze the gamut of visual signals from low-dimensional images to light-fields and propose non-adaptive projections for efficient sparsity exploiting reconstruction.

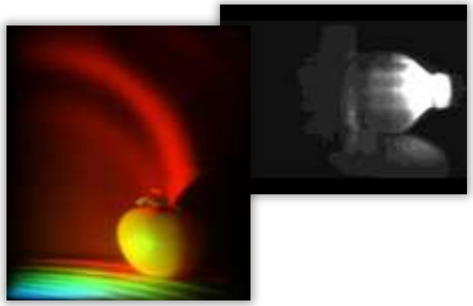
Femtosecond Imaging

1. **Looking around corners**
Using short laser pulses and fast detector, 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.



2. **Reflectance Recovery**
We demonstrate a new technique that allows a camera to rapidly acquire reflectance properties of objects 'in the wild' from a single viewpoint, over relatively long distances and without encircling equipment.

3. **Trillion Frames per Second Imaging**
A camera fast enough to capture light pulses moving through objects. We can use such a camera to understand reflectance, absorption and scattering properties of materials.

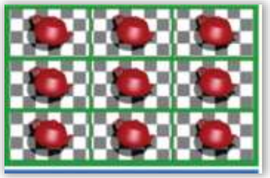


3D Displays

1. **Tensor Display**
A family of compressive light field displays comprising all architectures employing a stack of time-multiplexed, light-attenuating layers illuminated by uniform or directional backlighting

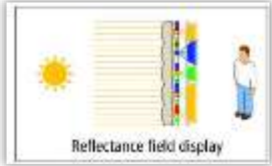
2. **Layered 3D**
Tomographic techniques for image synthesis on displays composed of compact volumes of light-attenuating material. Such volumetric attenuators recreate a 4D light field or high-contrast 2D image when illuminated by a uniform backlight.

3. **Glasses-free 3D HDTV**
Light field displays with increased brightness and refresh rate by stacking a pair of modified LCD panels, exploiting rank and constraint of 3D displays



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

5. **Living Windows 6D Display**
A completely passive display



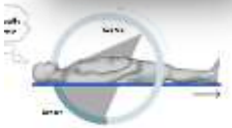
Health & Wellness

1. **Retinal Imaging**
   With simplified optics and cleaver illumination we visualize images of the retina in a standalone device easily operated by the end user.

2. **NETRA/CATRA**
   Low-cost cell-phone attachments that measures eye-glass prescription and cataract information from the eye.

3. **Cellphone Microscopy**
   A platform for computational microscopy and remote healthcare

4. **High-speed Tomography**
   A compact, fast CAT scan machine using no mechanical moving parts or synchronization.

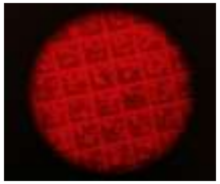


5. **Shield Fields**
   3D reconstruction of objects from a single shot photo using spatial heterodyning.

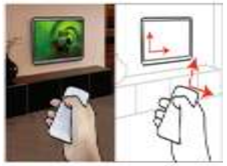
6. **Second Skin**
   Using 3D motion tracking with real-time vibrotactile feedback aids the correct of movement and position errors to improve motor learning.

Human Computer Interaction

1. **Bokode**
   Low-cost, passive optical design so that bar codes can be shrunk to fewer than 3mm and read by ordinary cameras several meters away.



2. **Specklesense**
   Set of motion-sensing configurations based on laser speckle sensing . The underlying principles allow interactions to be fast, precise, extremely compact, and low cost.



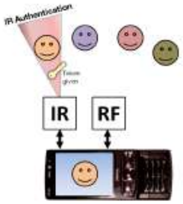
3. **Sound Around**
   Soundaround is a multi-viewer interactive audio system, designed to be integrated into multi-view displays presenting localized audio/video channels with no need for glasses or headphones.

Visual Social Computing

1. **Photocloud**
   A near real-time system for interactively exploring a collectively captured moment without explicit 3D reconstruction.

2. **Vision Blocks**
   On-demand, in-browser, customizable, computer-vision application-building platform for the masses. Without any prior programming experience, users can create and share computer vision applications.

3. **Lenschat**
   LensChat allows users to share mutual photos with friends or borrow the perspective and abilities of many cameras.



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Cameraculture.info

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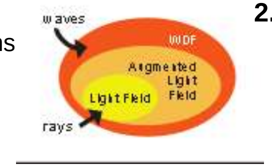
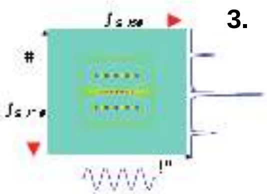
Light Propagation Theory and Fourier Optics

1. **Augmented Light Fields**
   Expands light field representations to describe phase and diffraction effects by using the Wigner Distribution Function



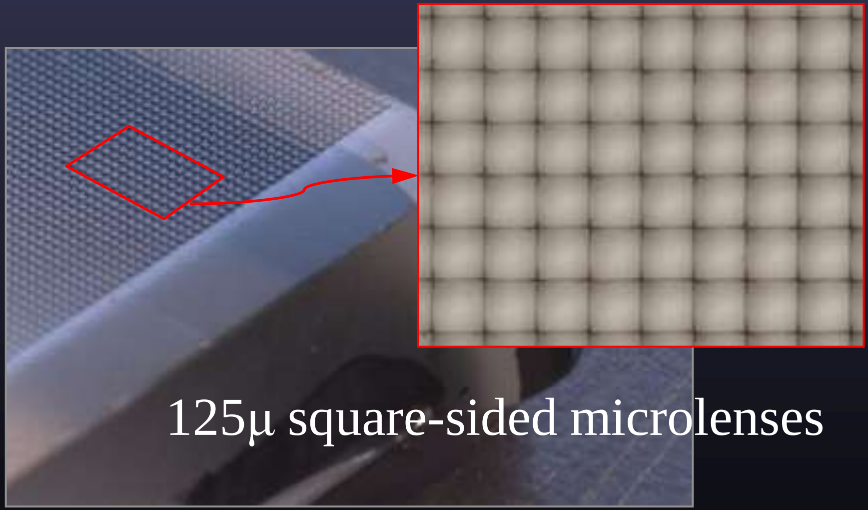
2. **Hologram v Parallax Barrier**
   Defines connections between parallax barrier displays and holographic displays by analyzing their operations and limitations in phase space



3. **Ray–Based Diffraction Model**
   Simplified capture of diffraction model for computer graphics applications.

Post-Doctorial Researchers: Doug Lanman, Gordon Wetzstein, Alex Olwal, Christopher Barsi
Research Assistants: Matthew Hirsch, Otkrist Gupta, Nikhil Naik, Jason Boggess, Everett Lawson, Aydın Arpa, Kshitij Marwah
Visiting Researchers & Students: Di Wu, Daryl Lim

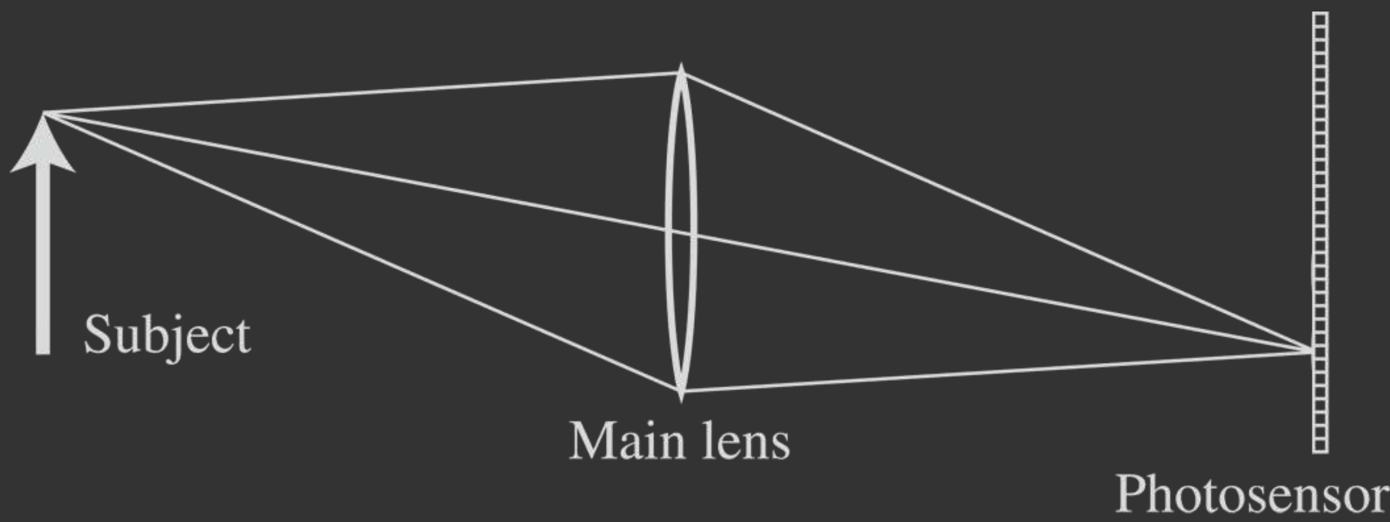
Digital Refocusing using Light Field Camera



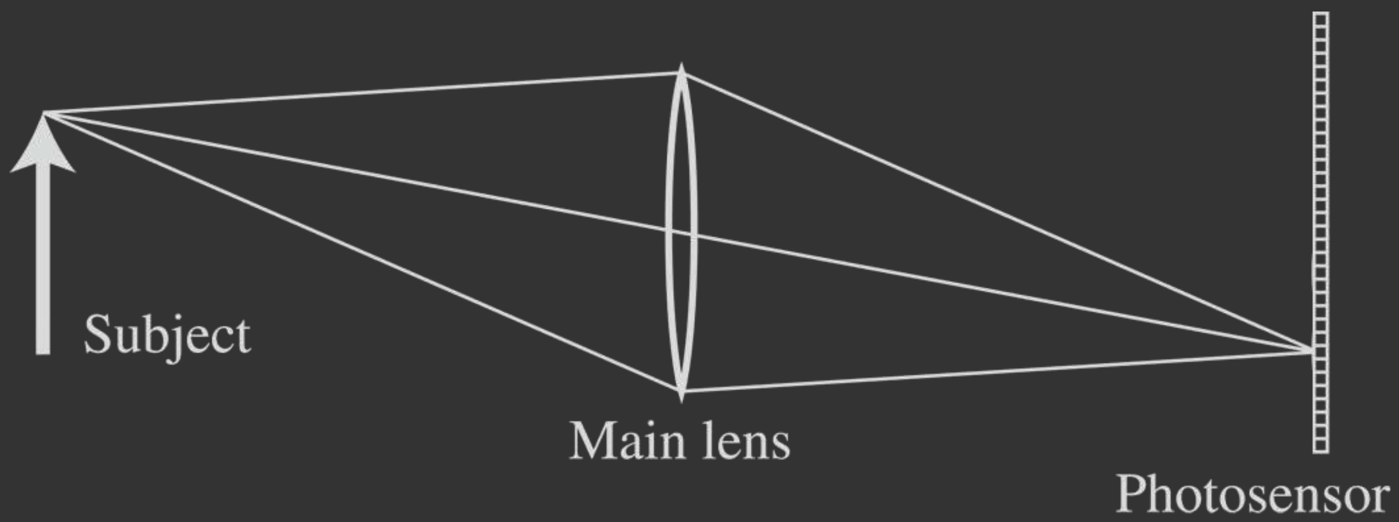
125μ square-sided microlenses

[Ng et al 2005]

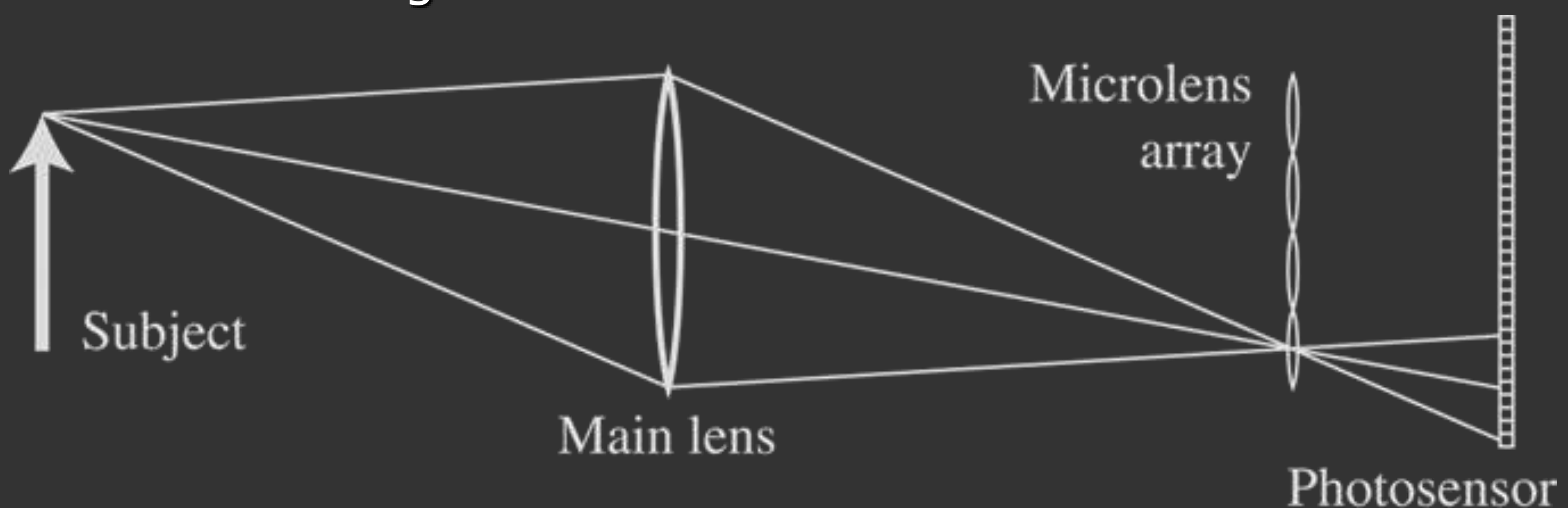
Light Field Inside a Camera



Light Field Inside a Camera

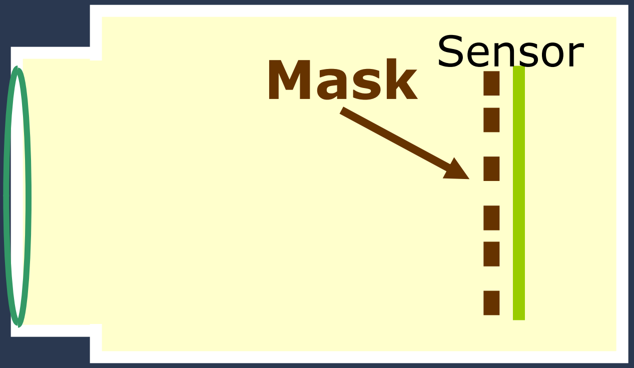


Lenslet-based Light Field camera



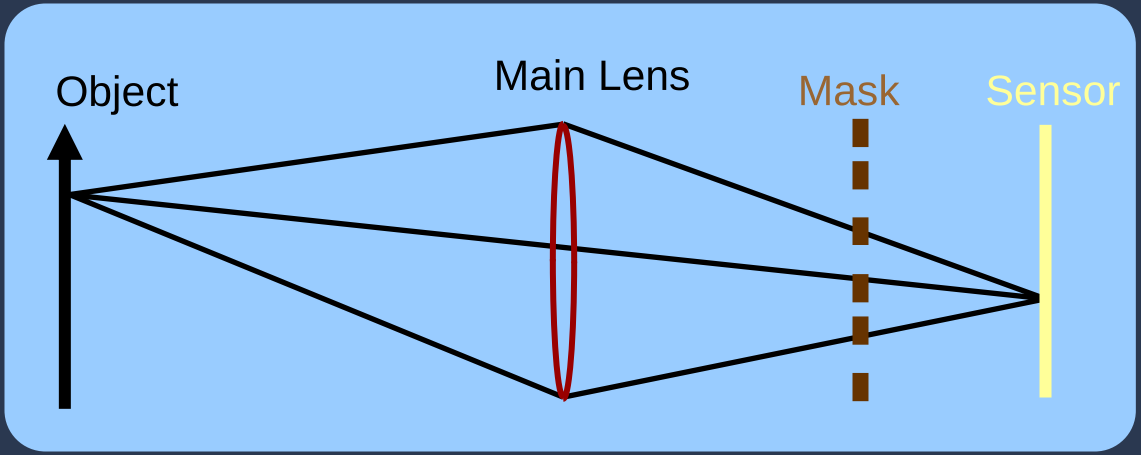
[Adelson and Wang, 1992, Ng et al. 2005]

Mask based Light Field Camera

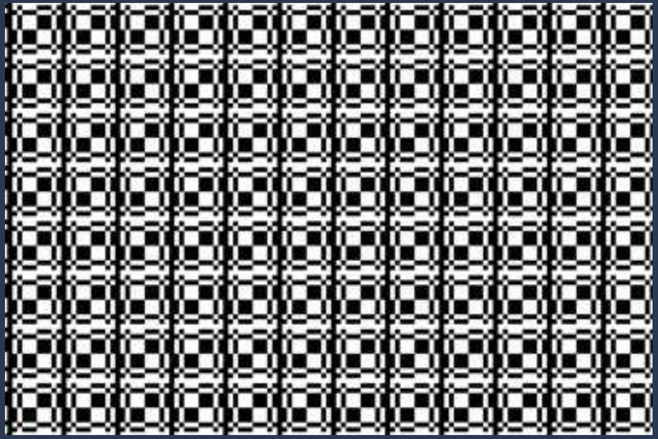


[Veeraraghavan, Raskar, Agrawal, Tumblin, Mohan, Siggraph 2007]

Spatial Heterodyning with Masks

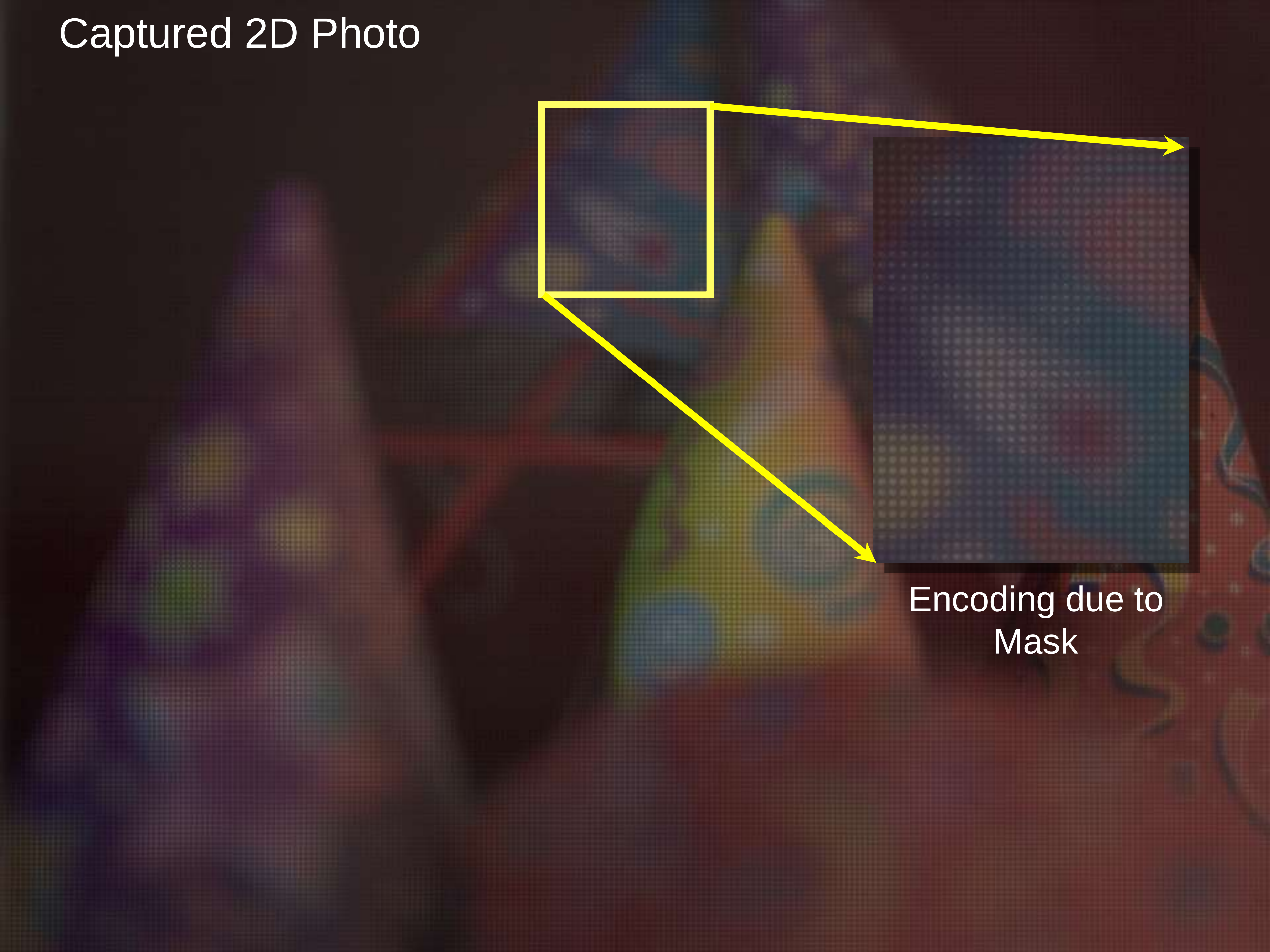


- Mask == Light Field Modulator
- Intensity of ray gets multiplied by Mask
- Convolution in Frequency domain
- **Lightfield without additional lenslets**



Wavefront Analysis for ANY wavelength

Oh, Raskar, Barbastathis 2009: Augmented Light Field

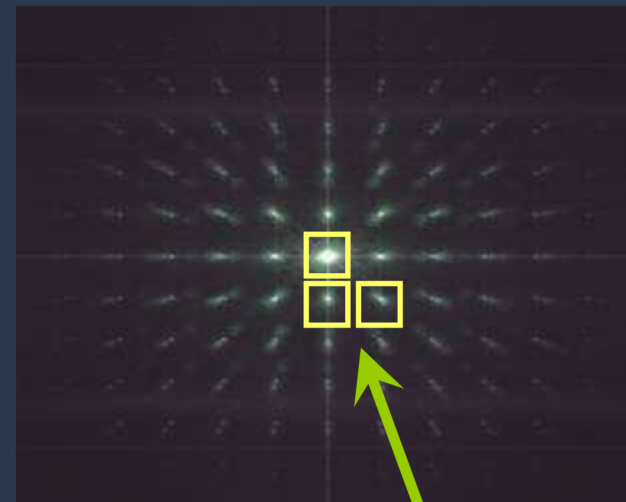

Captured 2D Photo
Encoding due to Mask

Mask-based 4D Light Field

2D Sensor Photo, 1800*1800

2D FFT

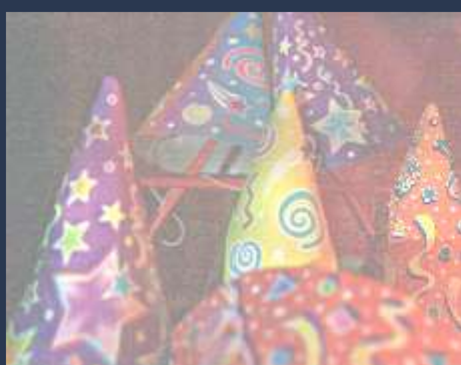
2D Fourier Transform, 1800*1800



9*9=81 spectral copies

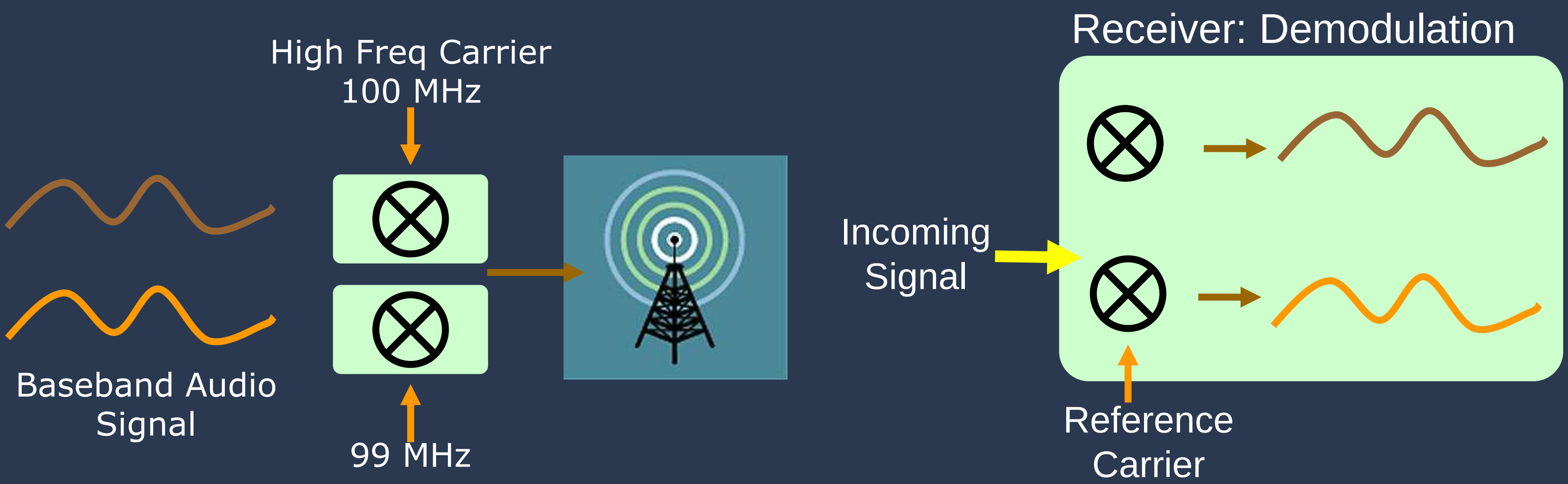
Rearrange 2D tiles into 4D planes
200*200*9*9

4D IFFT

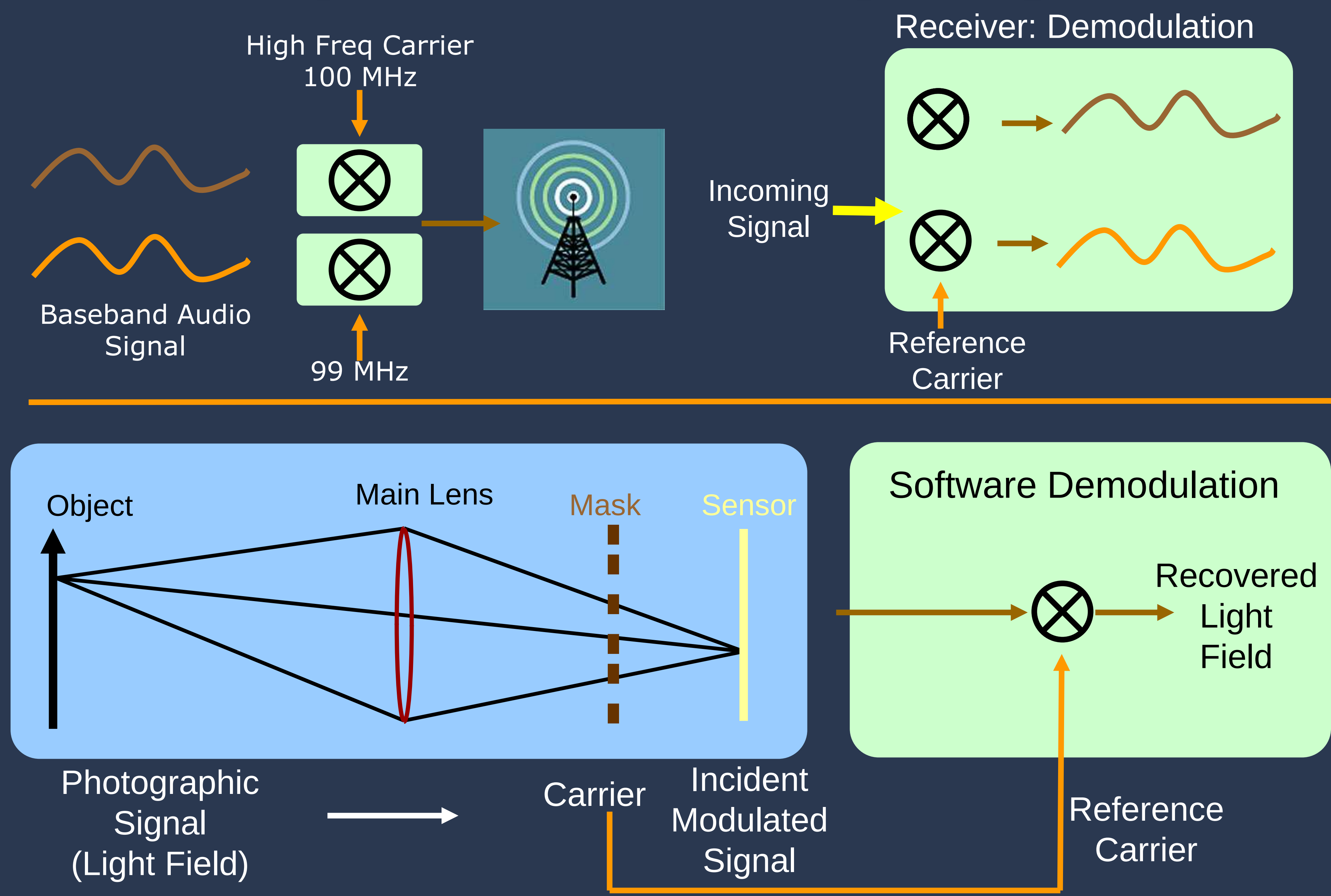


4D Light Field → Depth
200*200*9*9

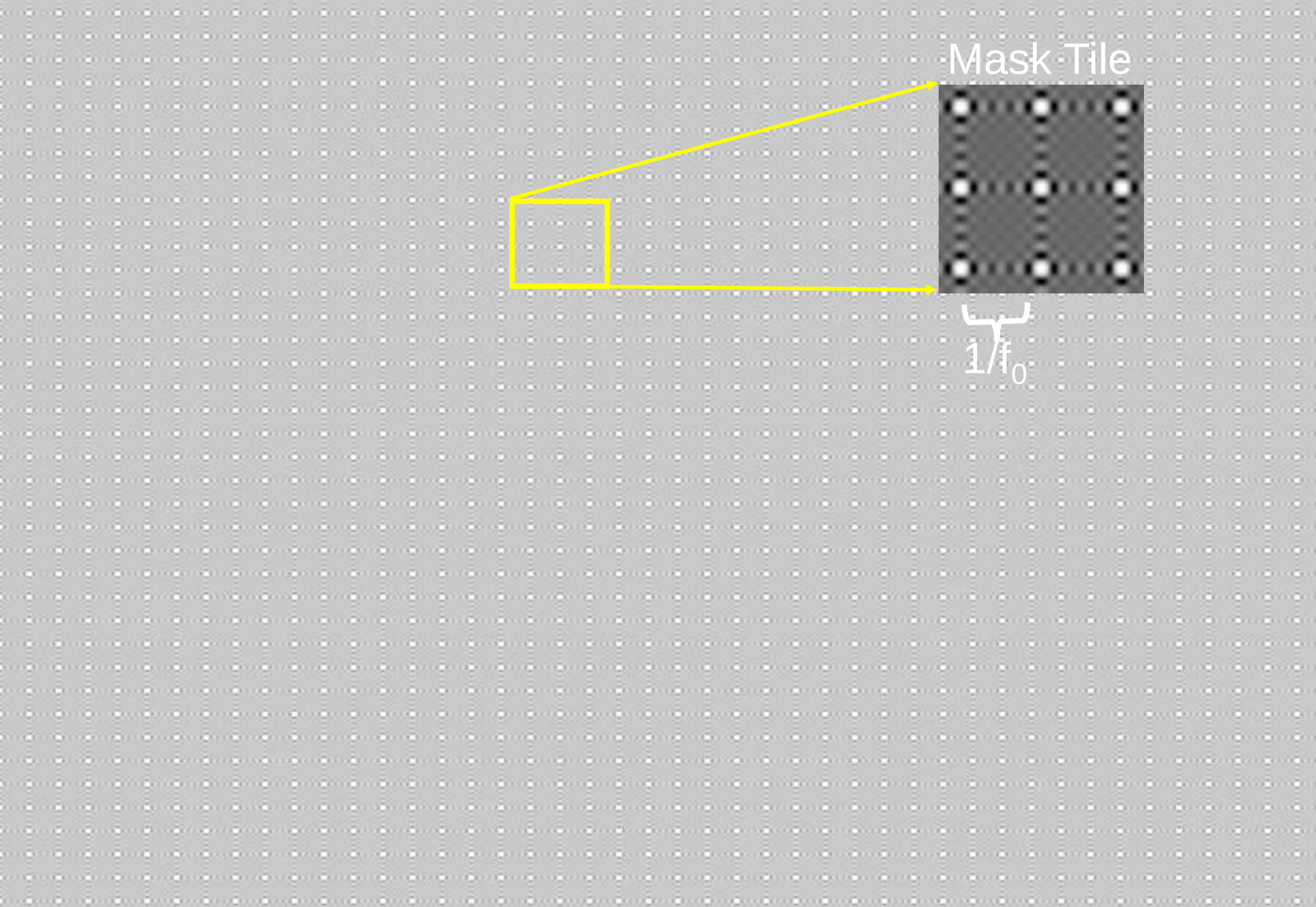
Radio Frequency Heterodyning

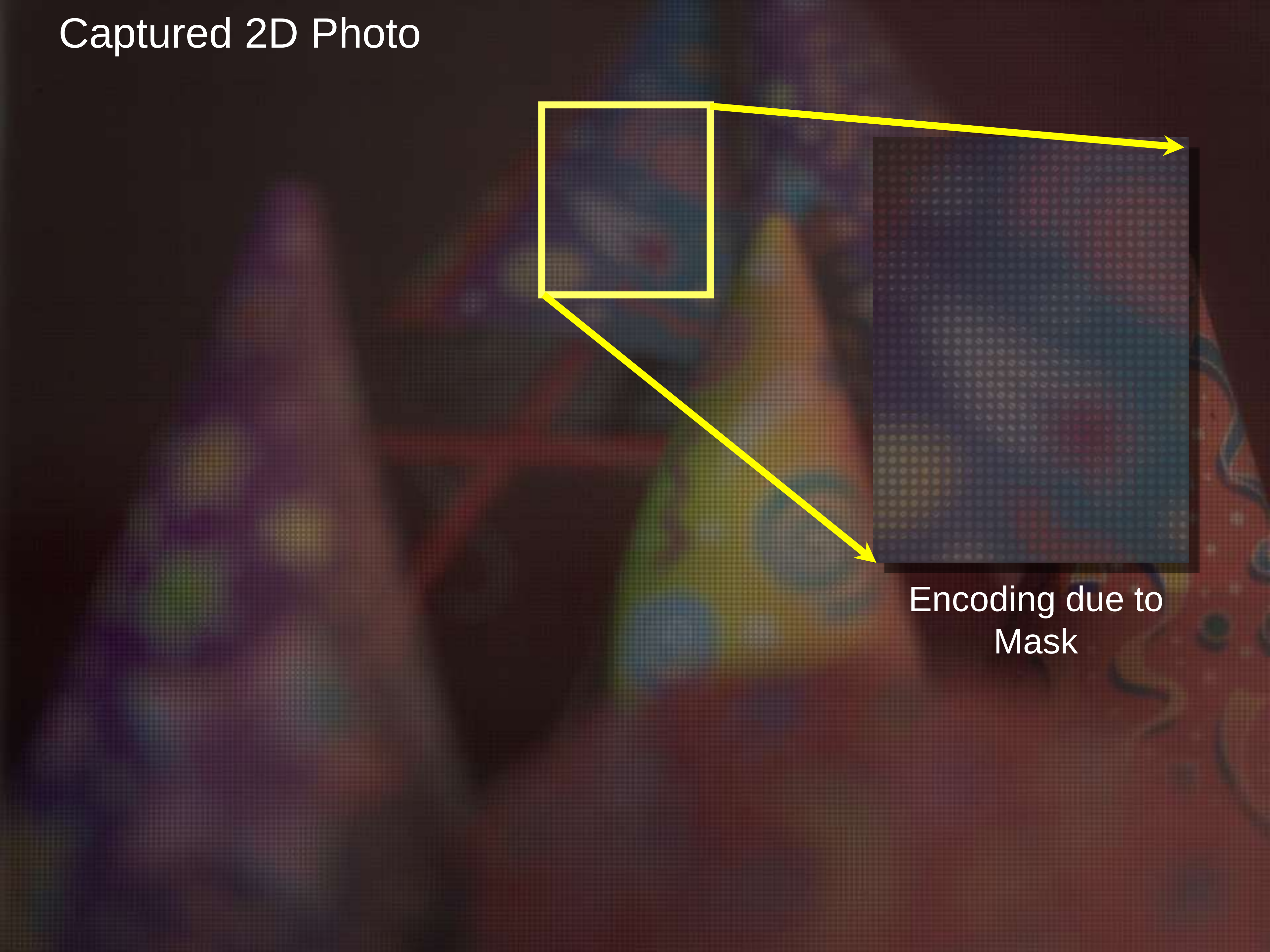


Optical Heterodyning



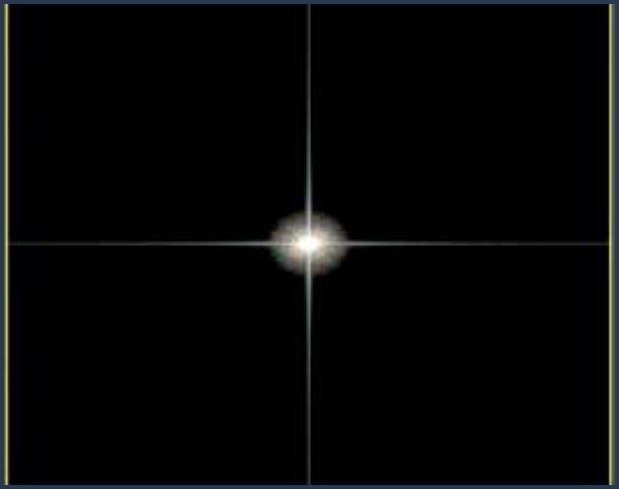
Cosine Mask Used




Captured 2D Photo
Encoding due to Mask

Traditional Camera Photo

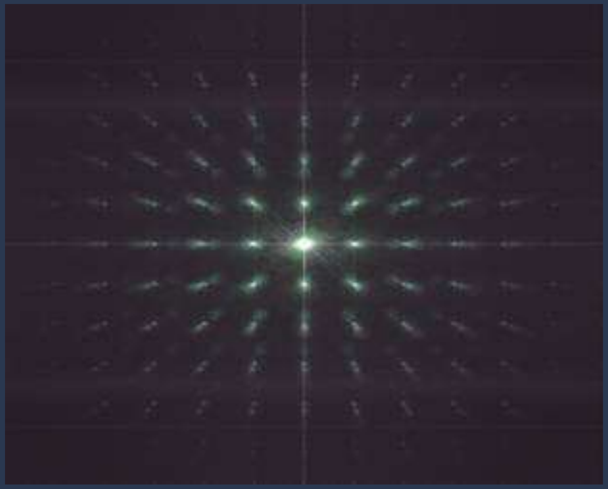
2D
FFT



Magnitude of 2D FFT

Heterodyne Camera Photo

2D
FFT



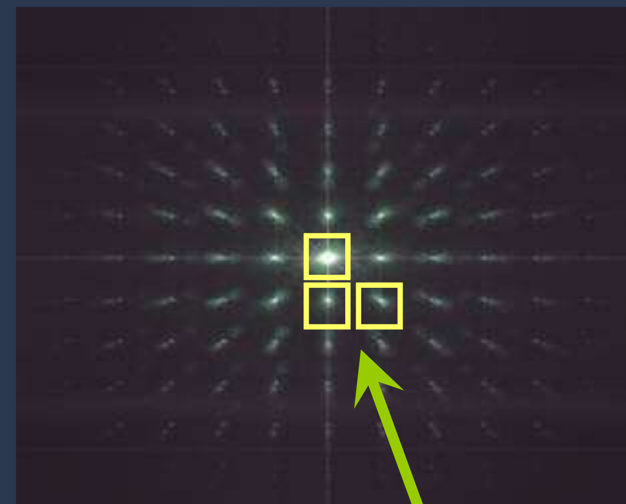
Magnitude of 2D FFT

Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D 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

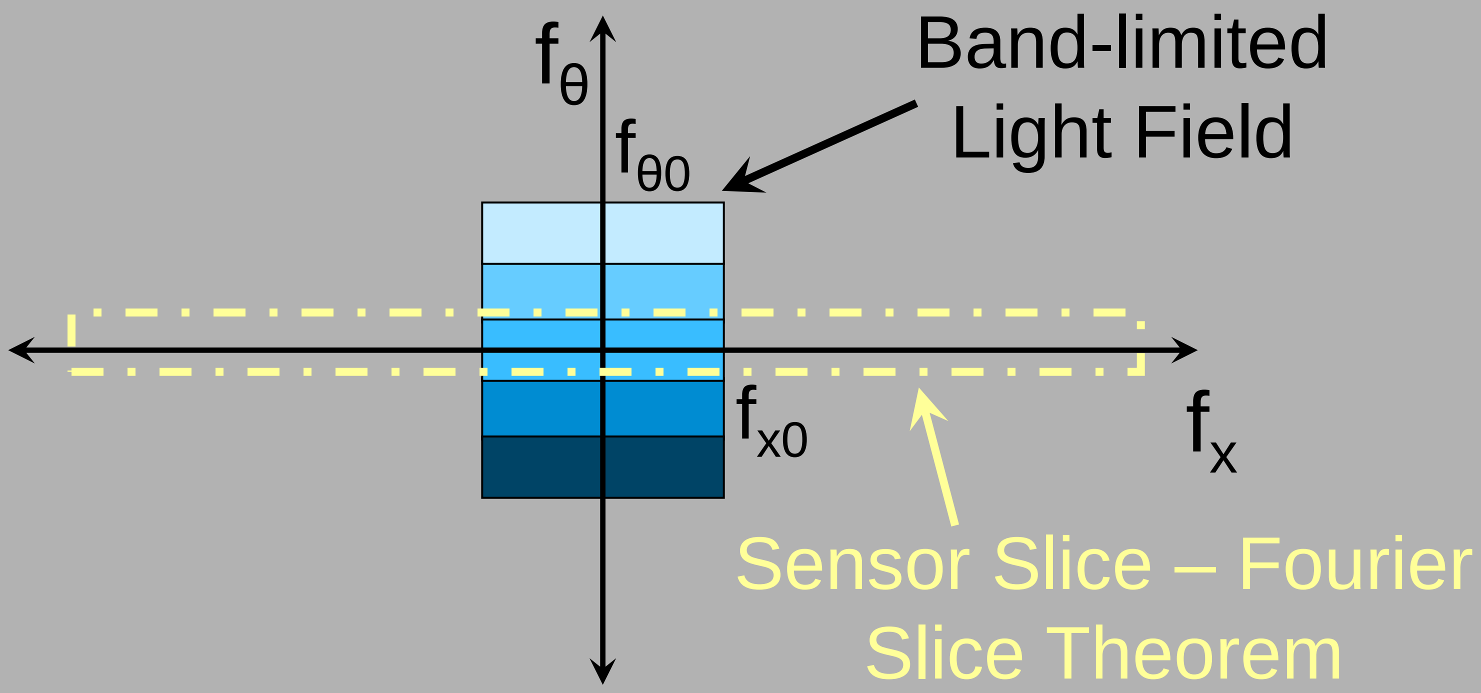
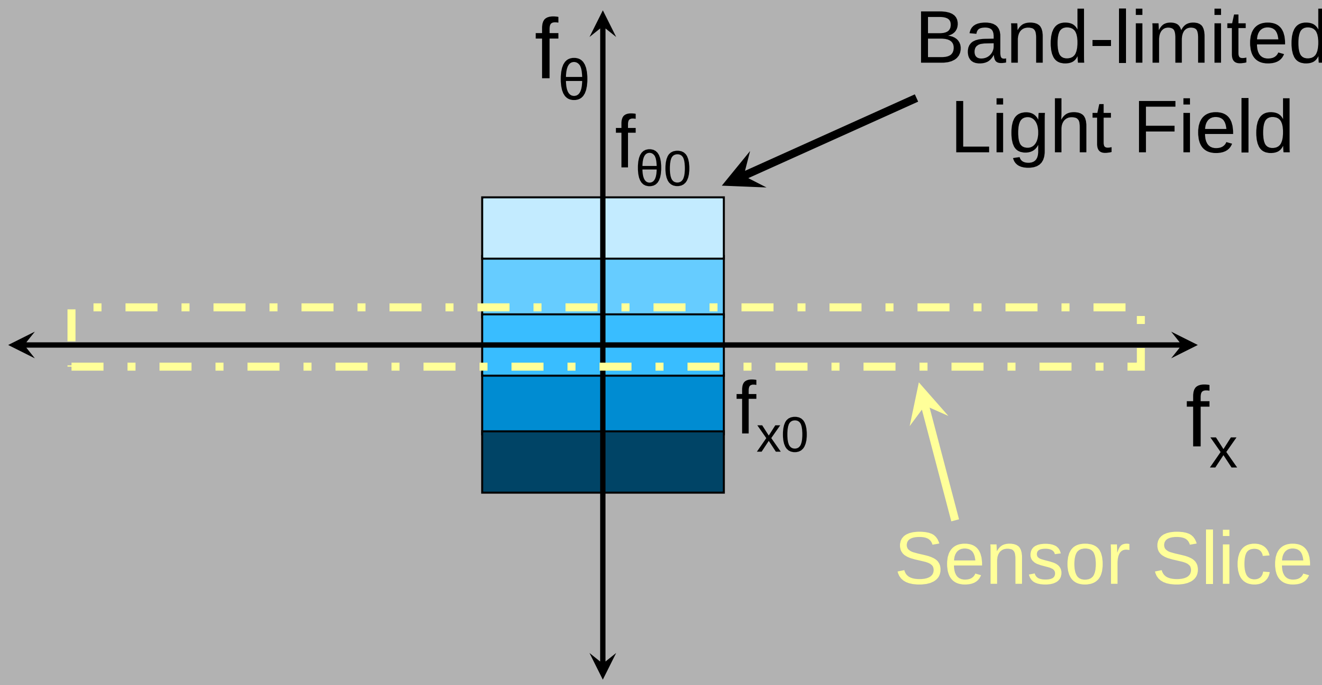


Photo = Slice of Light Field in Fourier Domain

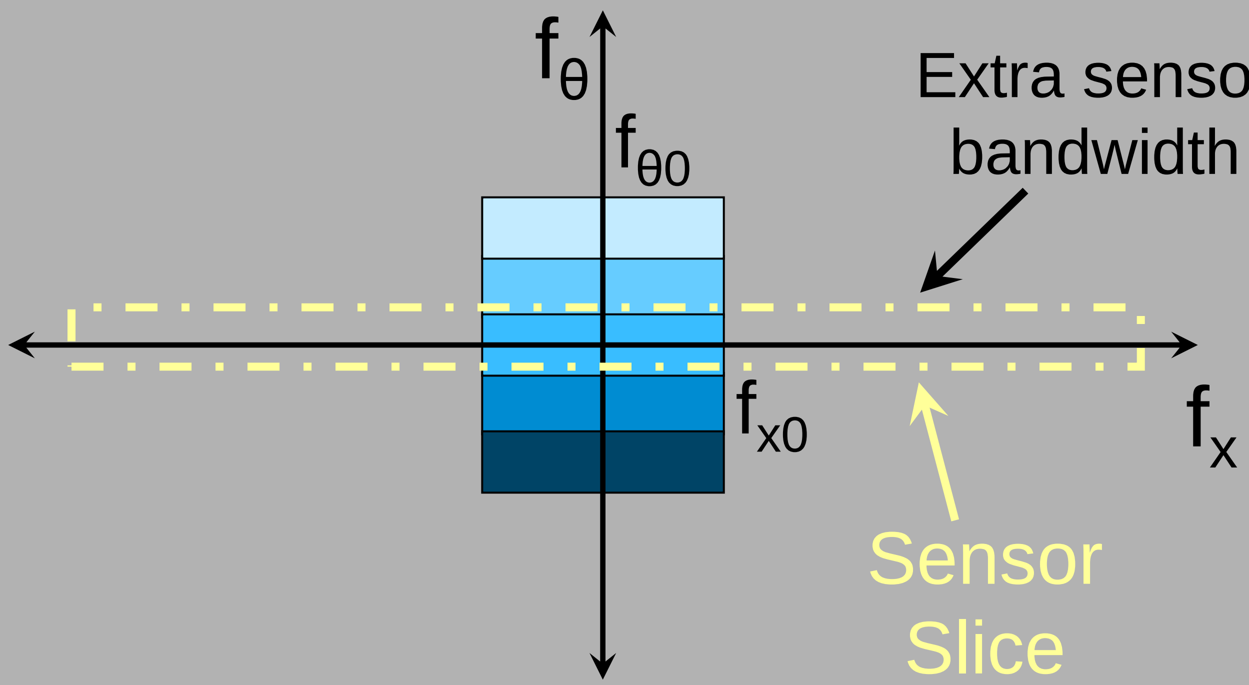
[Ren Ng, SIGGRAPH 2005]

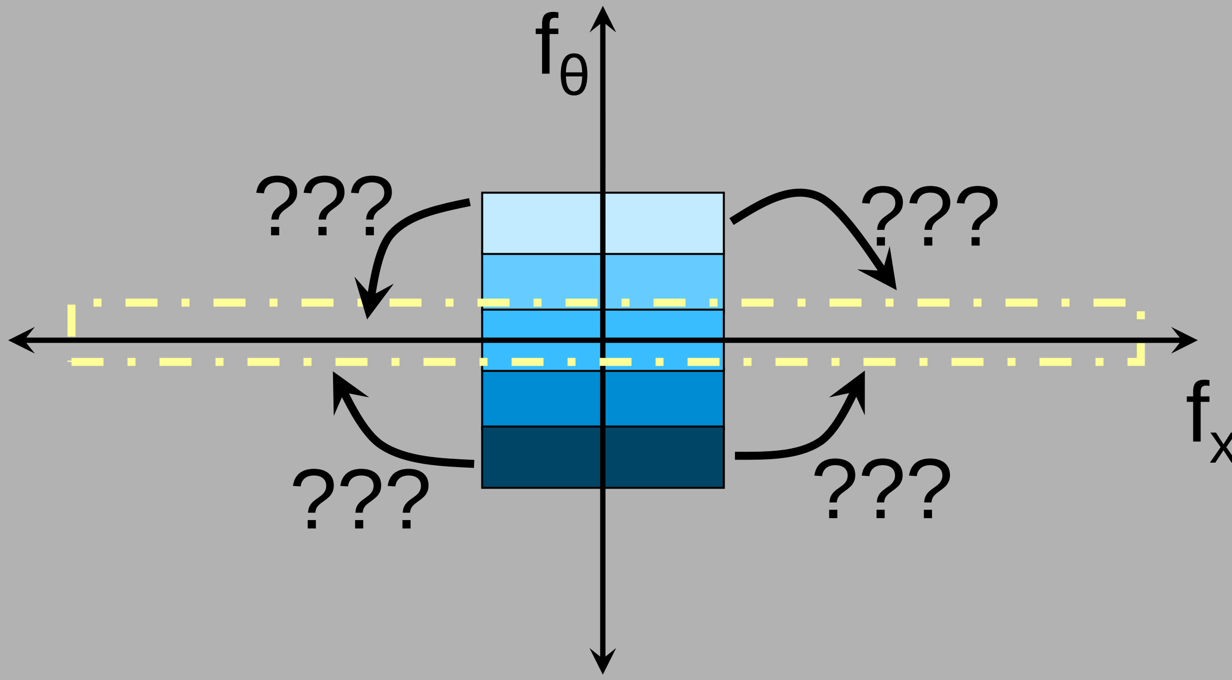
How to Capture 2D Light Field with 1D Sensor ?



Fourier Light Field Space

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

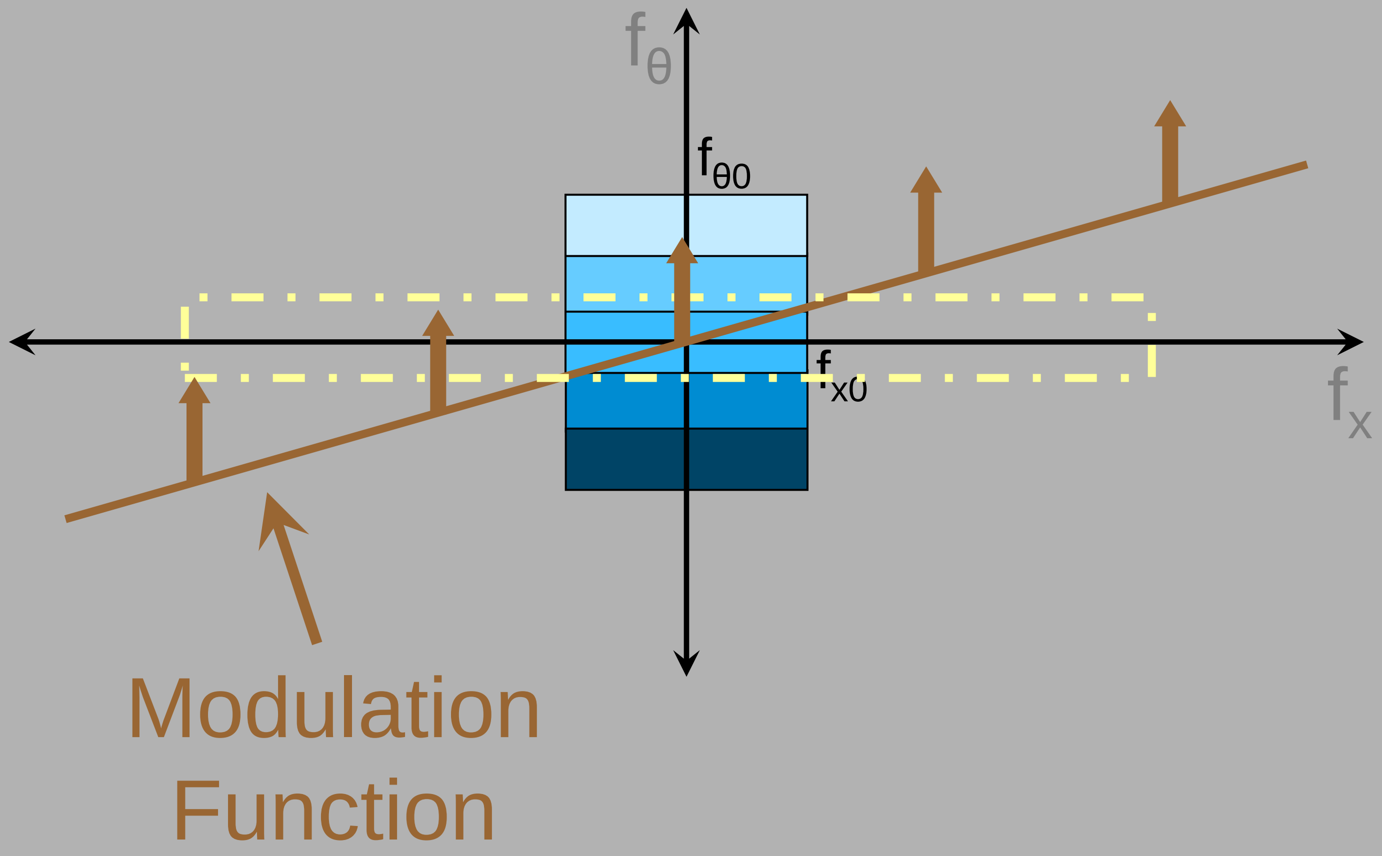




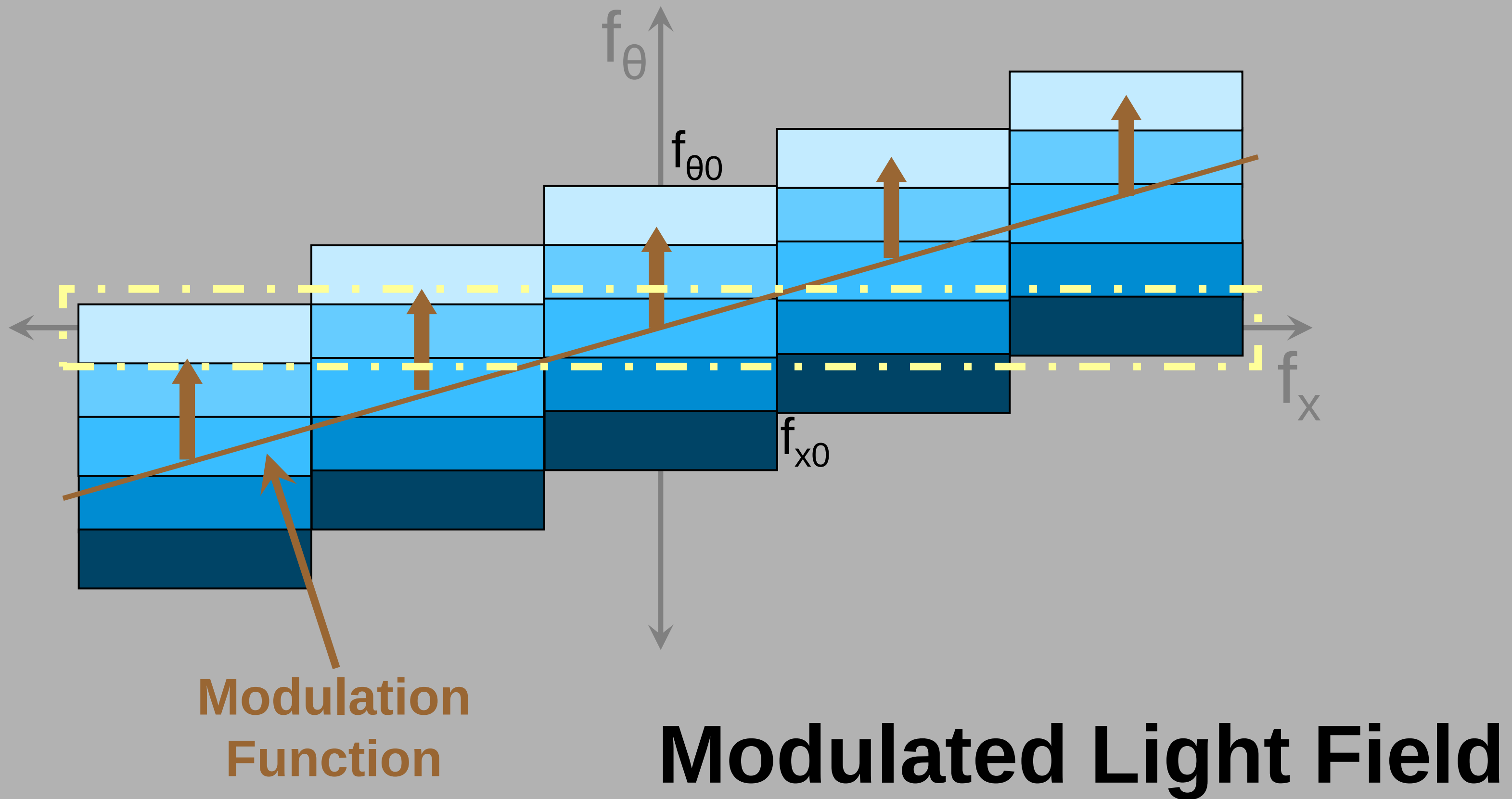
f_θ
???
???
???
???
f_x

Solution: Modulation Theorem

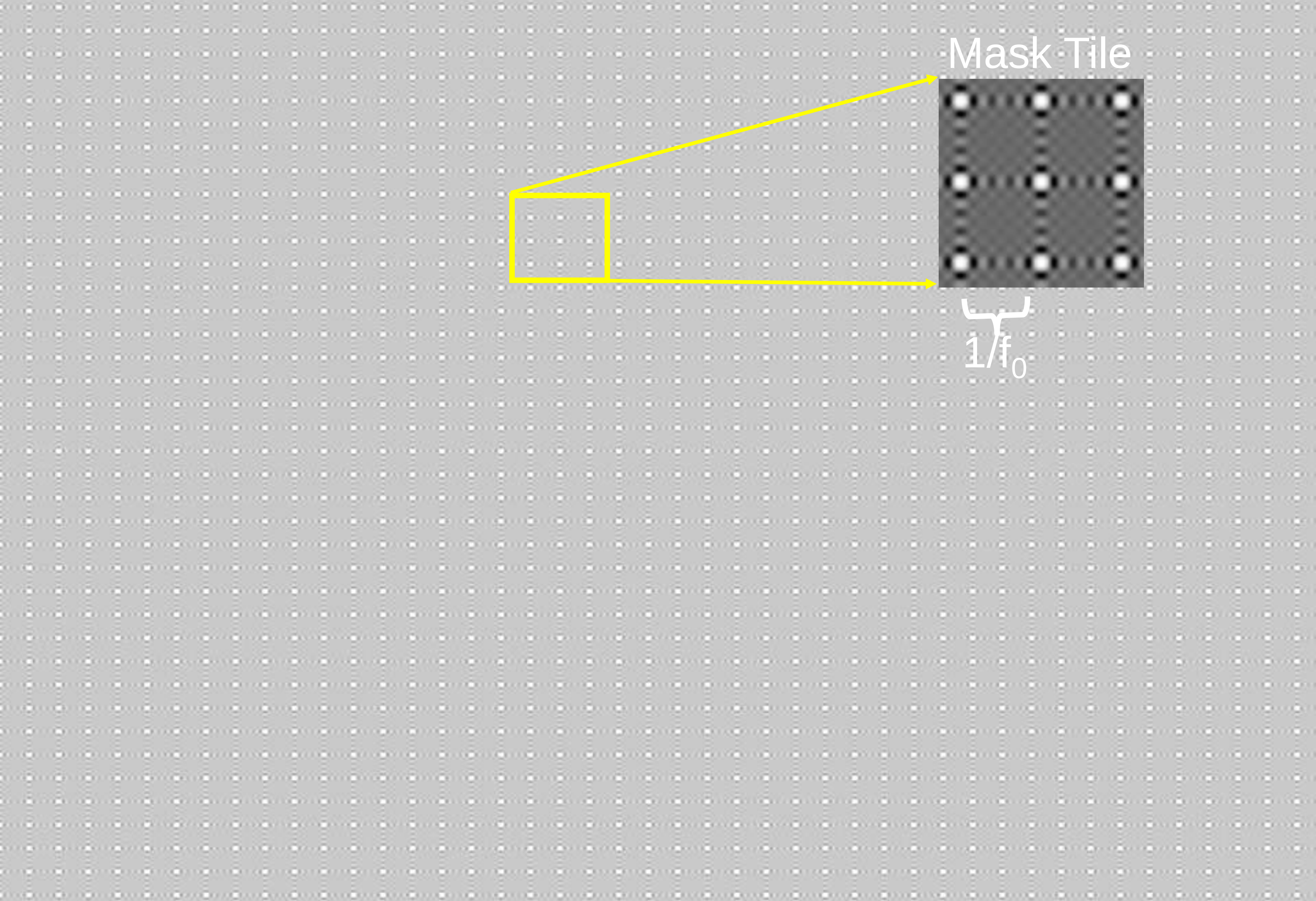
Make spectral copies of 2D light field



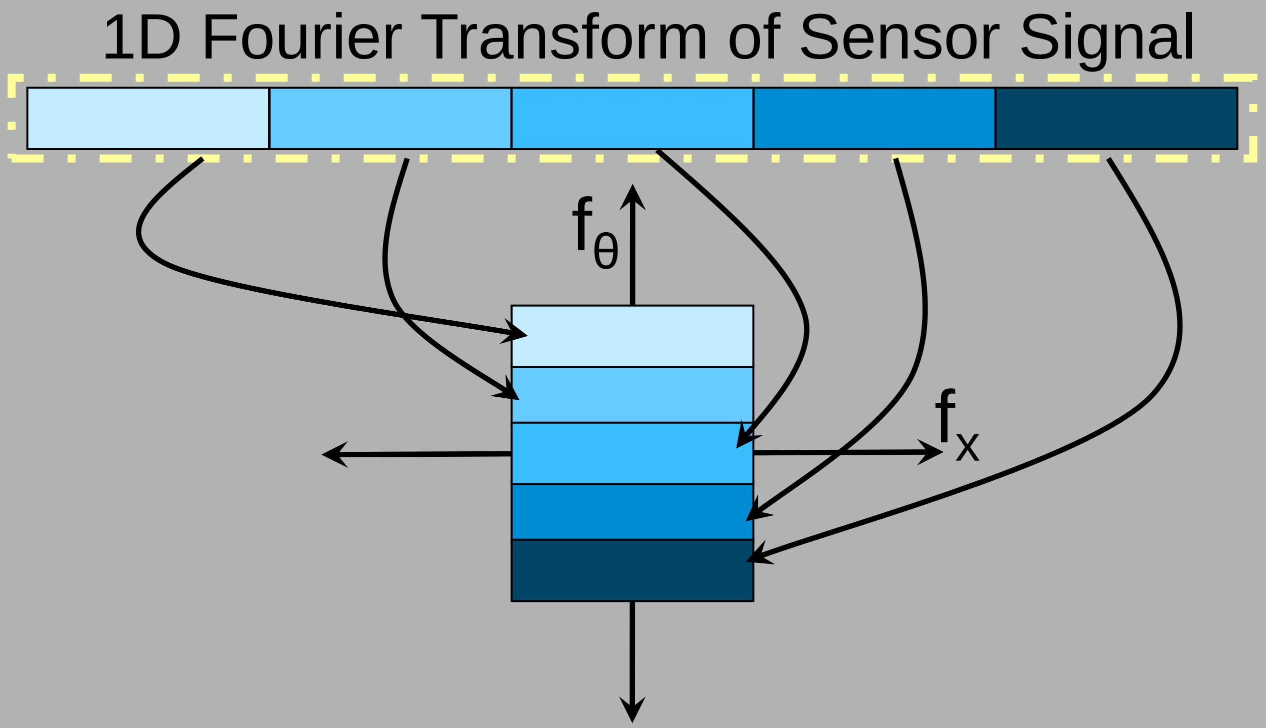
Sensor Slice captures entire Light Field



Cosine Mask Used



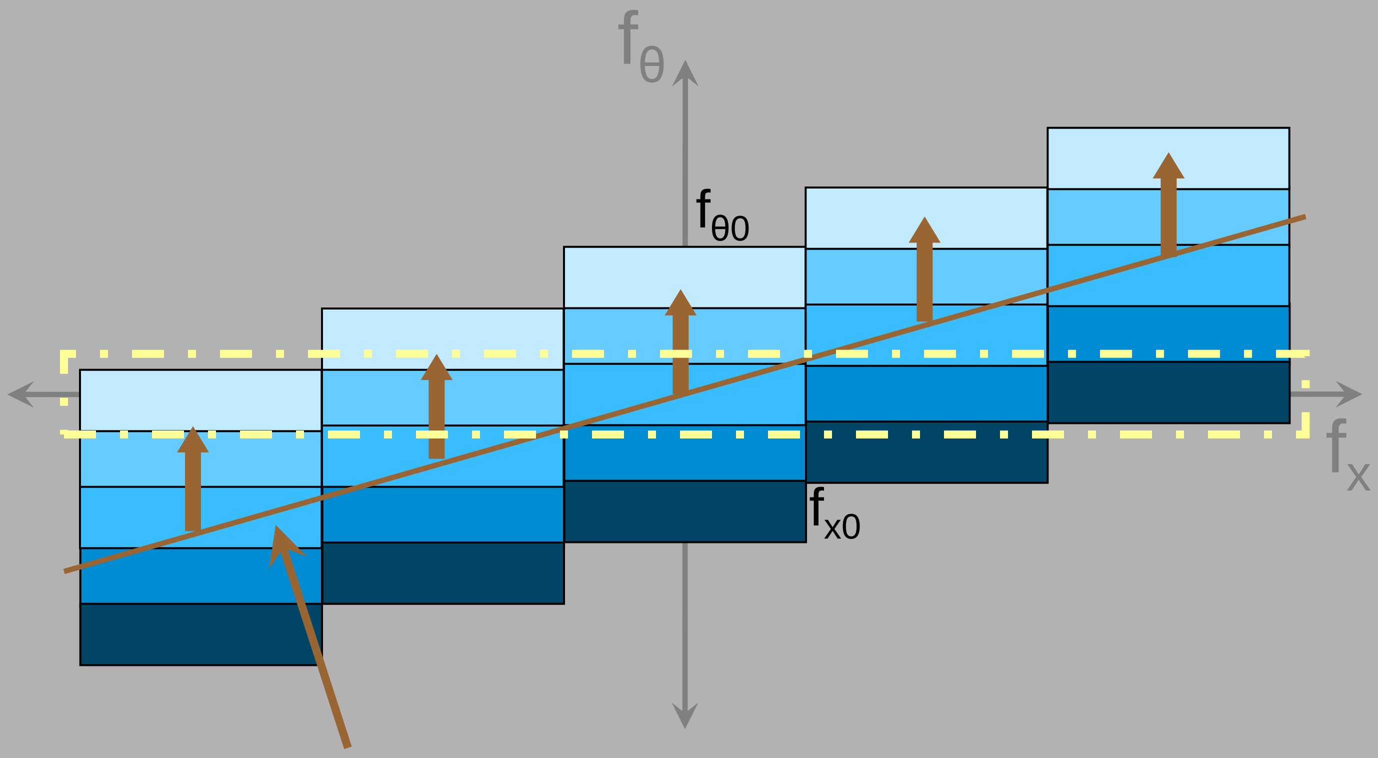
Demodulation to recover Light Field



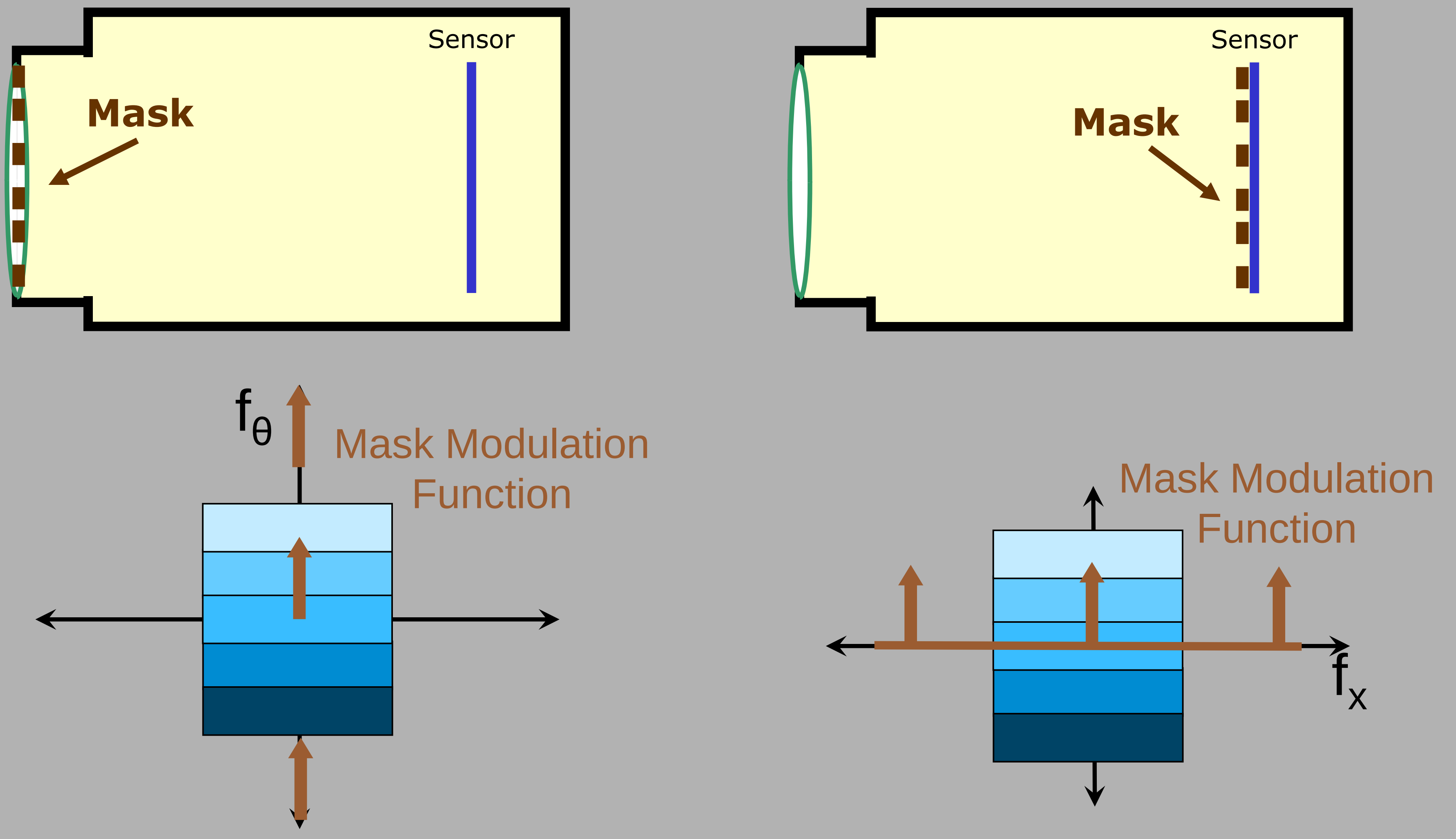
Reshape 1D Fourier Transform into 2D

Modulation Function == Sum of Impulses

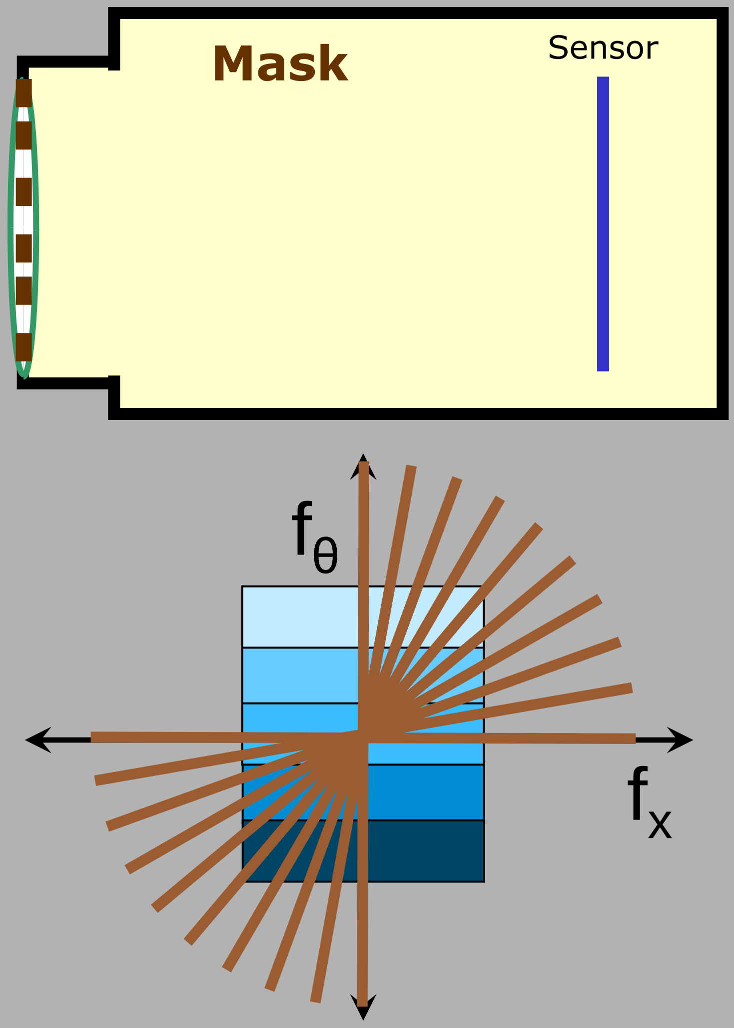
Physical Mask = Sum of Cosines



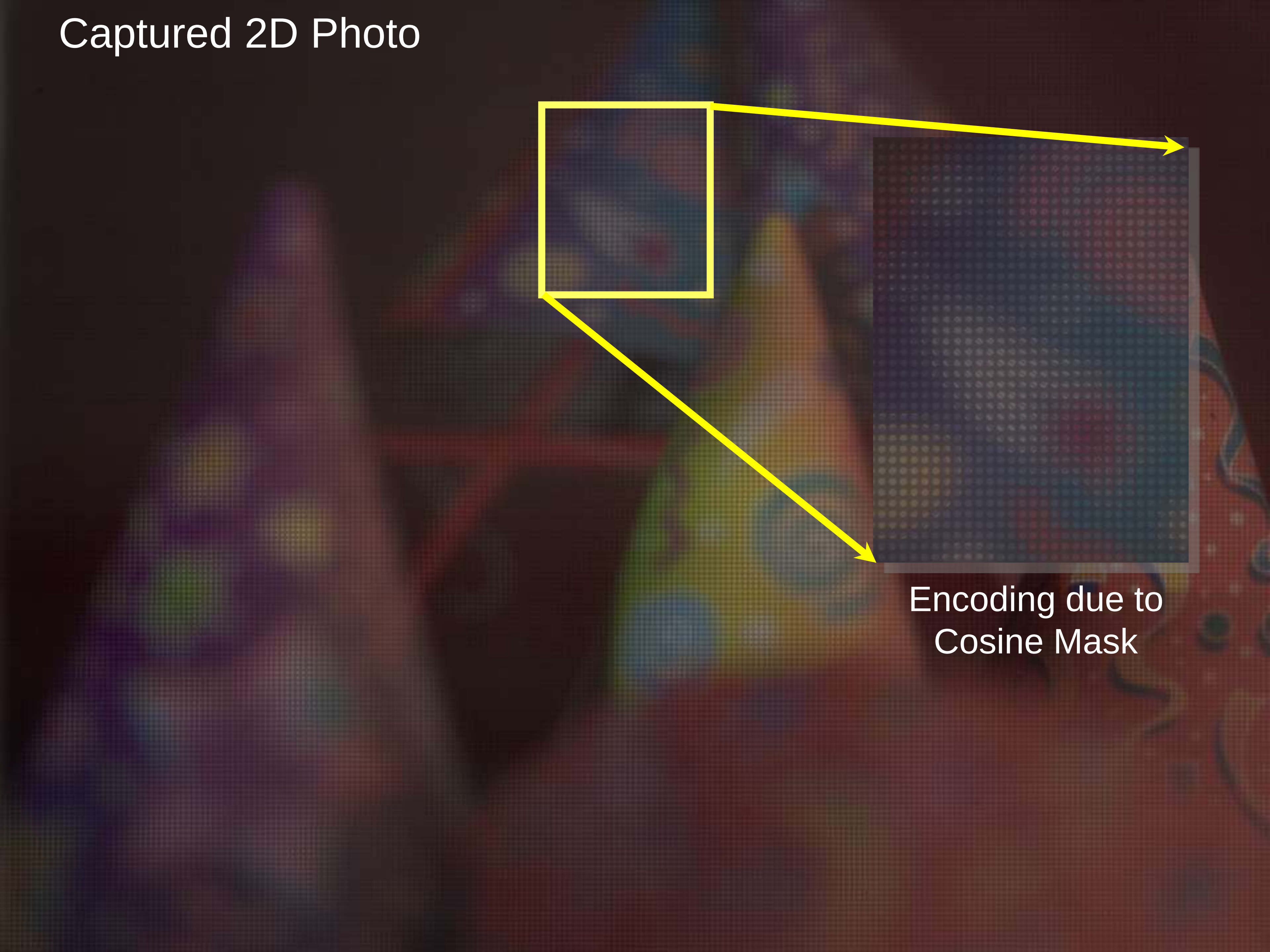
Where to place the Mask?



Where to place the Mask?



Mask
Modulation
Function

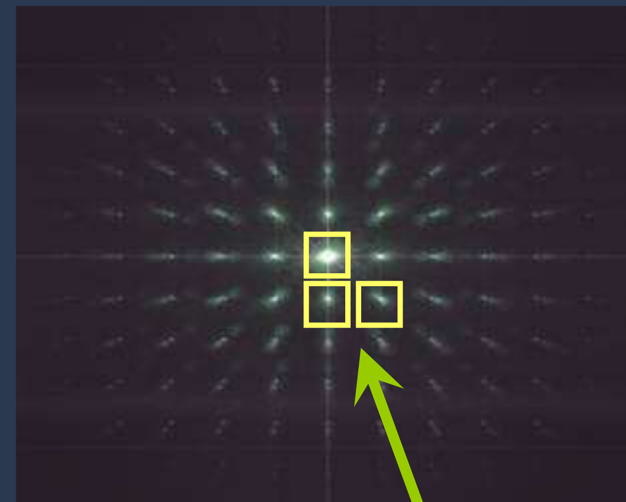

Captured 2D Photo
Encoding due to Cosine Mask

Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D FFT

2D Fourier Transform



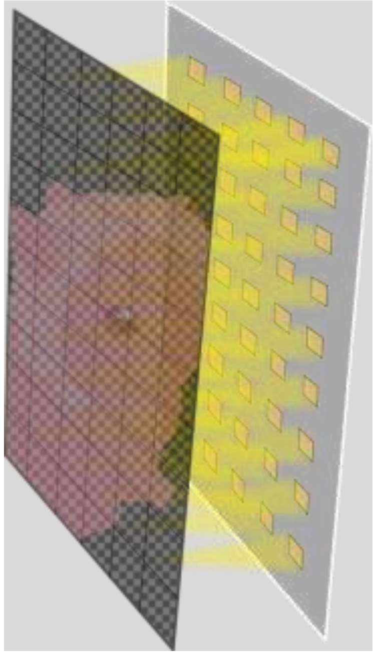
9*9=81 spectral copies

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

4D IFFT

4D Light Field
200*200*9*9

BiDi Screen: Thin LCD for touch+hover

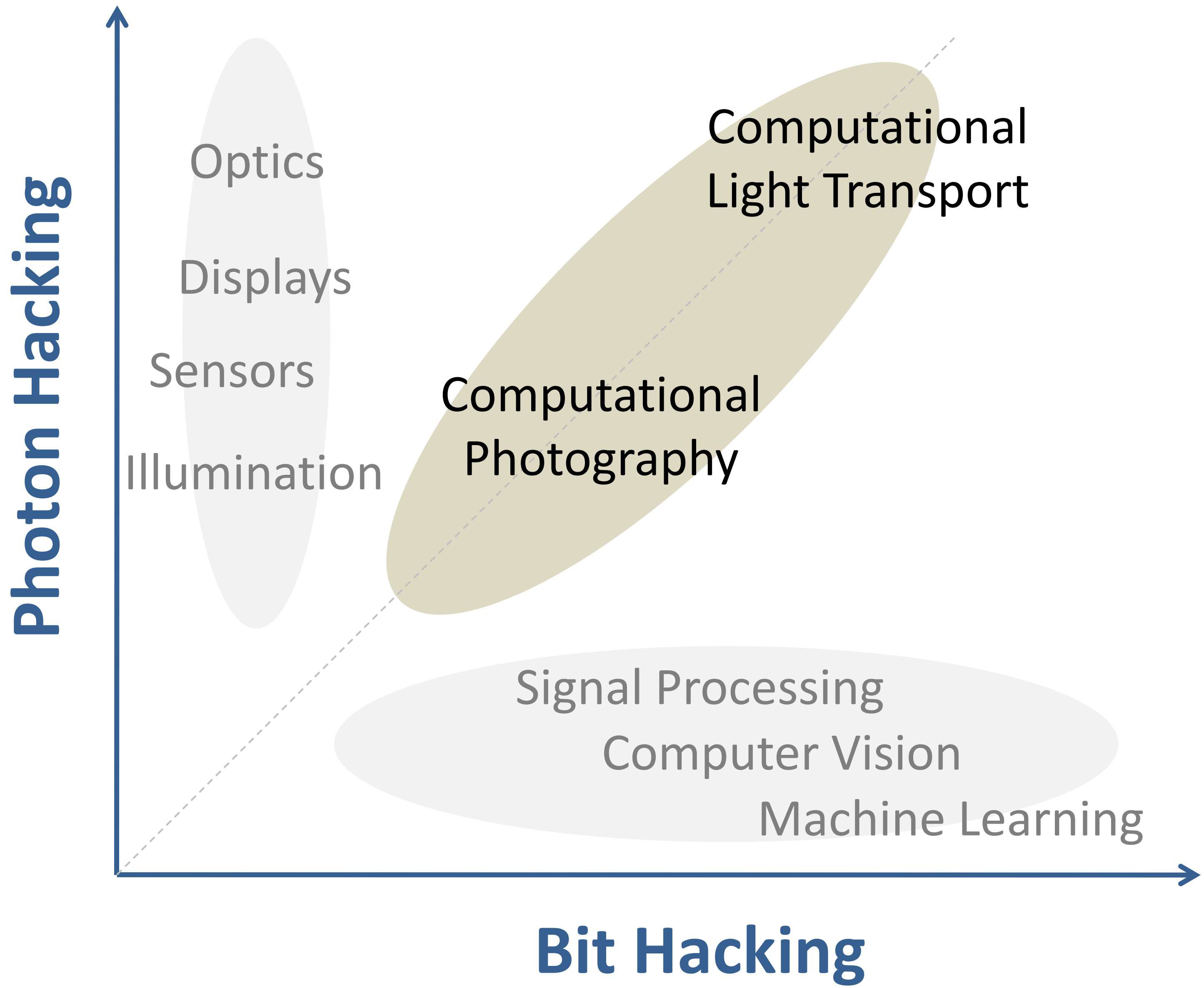


Sensing Depth from Light Sensing LCD
By creating Array of Virtual Cameras in LCD

Hirsch, Lanman, Holtzman, Raskar   Siggraph Asia 2009

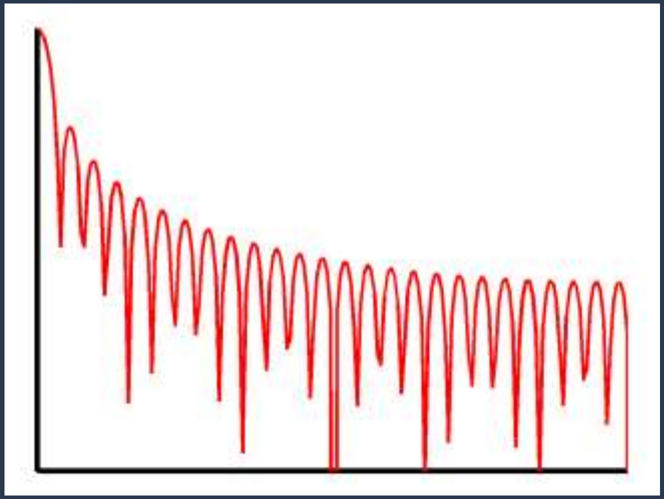
BiDi Screen: Multi-touch + Hover 3D interface
LCD = Large Lensless Camera

Co-designing Optical and Digital Processing

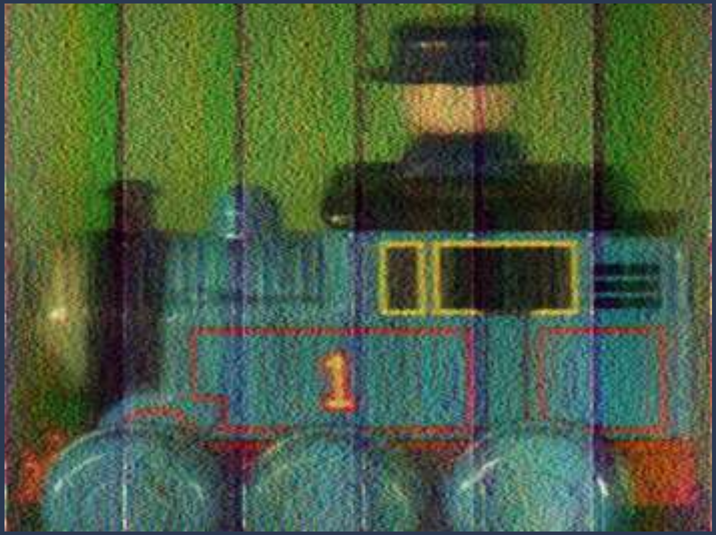


Motion Blur in Low Light

Traditional



Blurred Photo

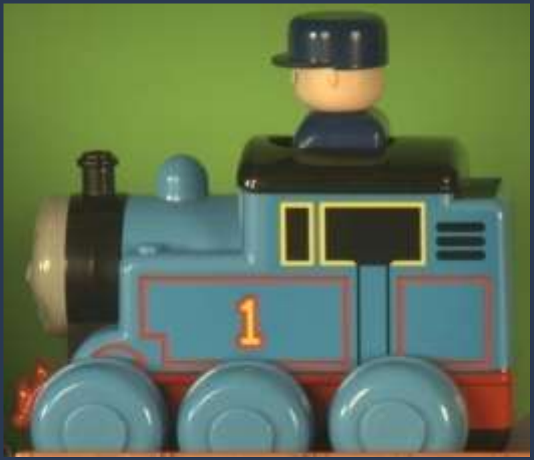


Deblurred Image

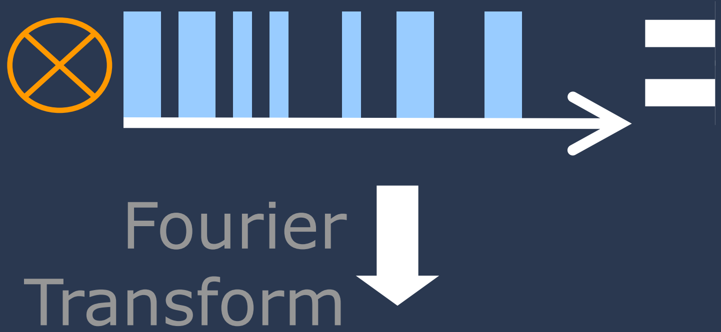
Fluttered Shutter Camera

Raskar, Agrawal, Tumblin Siggraph2006

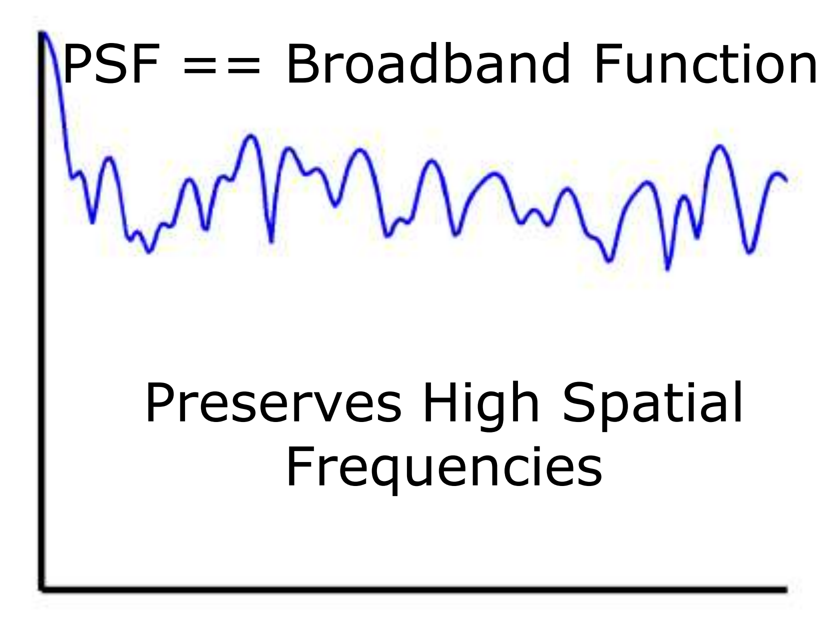
Ferroelectric shutter in front of the lens is turned opaque or transparent in a rapid binary sequence



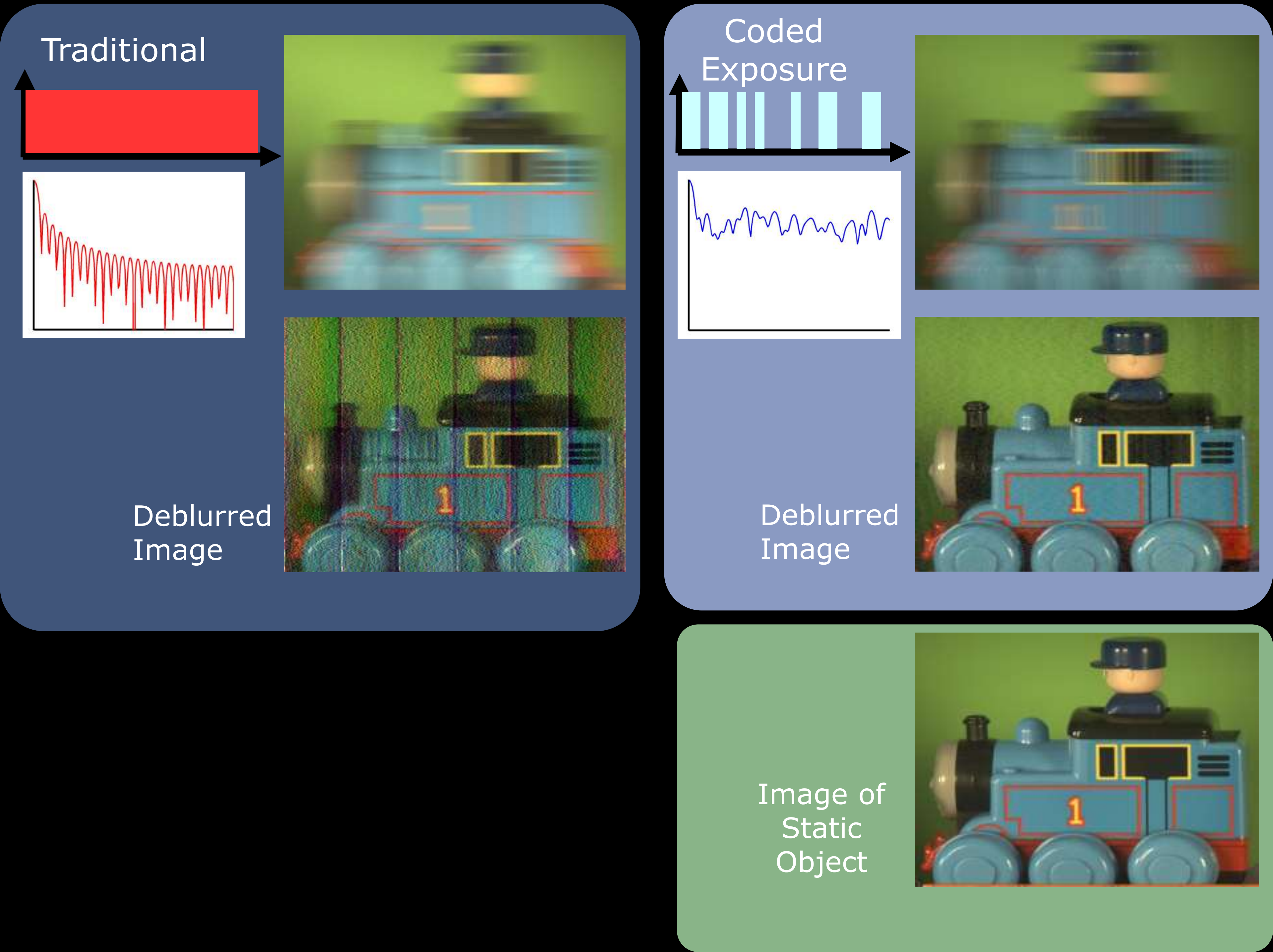
Sharp
Photo



Blurred
Photo

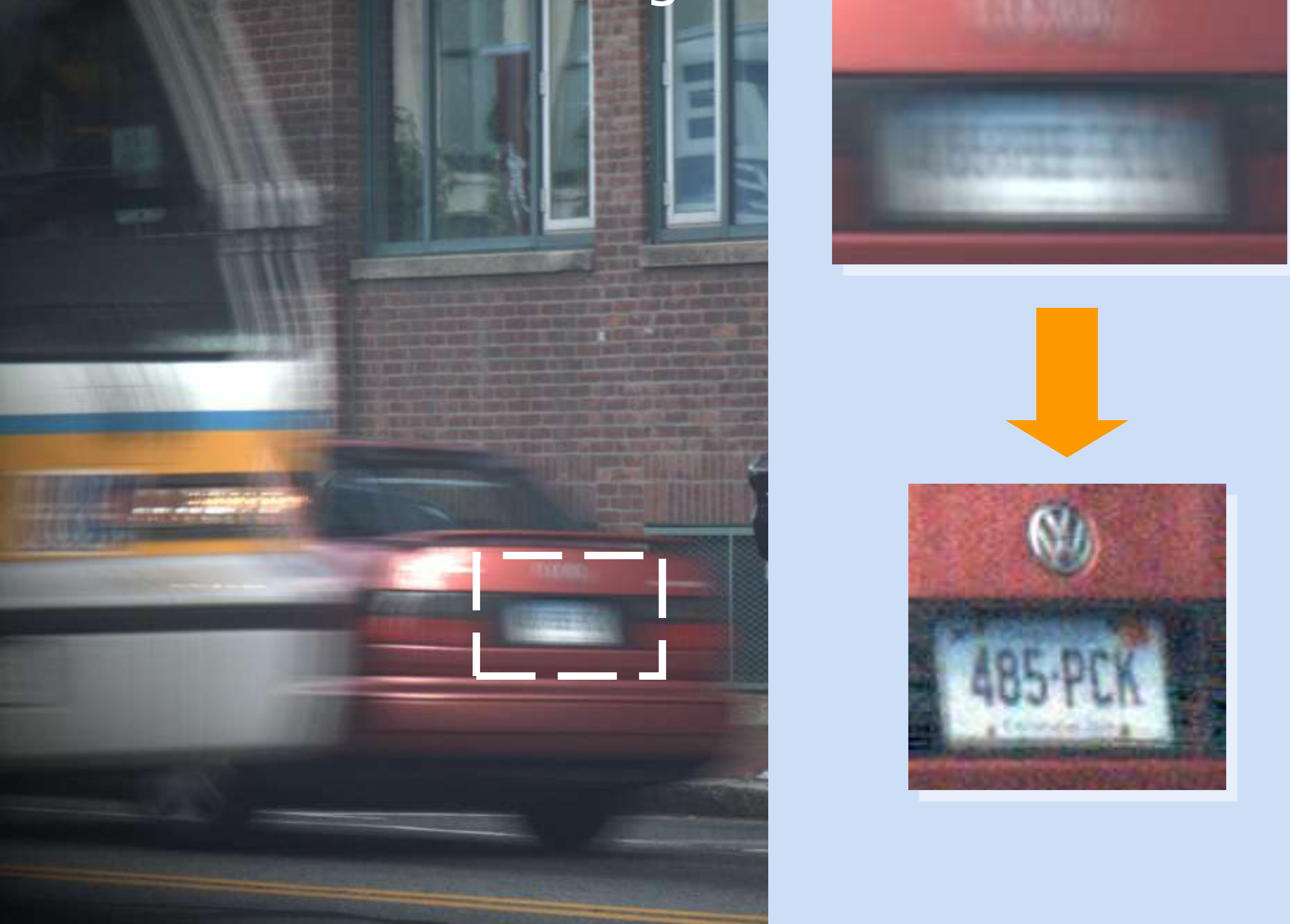


Flutter Shutter: Shutter is OPEN and CLOSED



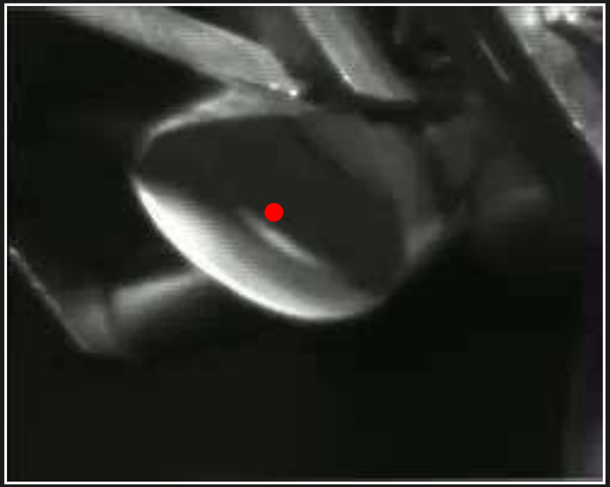
Traditional
Coded Exposure
Deblurred Image
Deblurred Image
Image of Static Object

Motion Blur in Low Light



Fast periodic phenomena

Bottling line



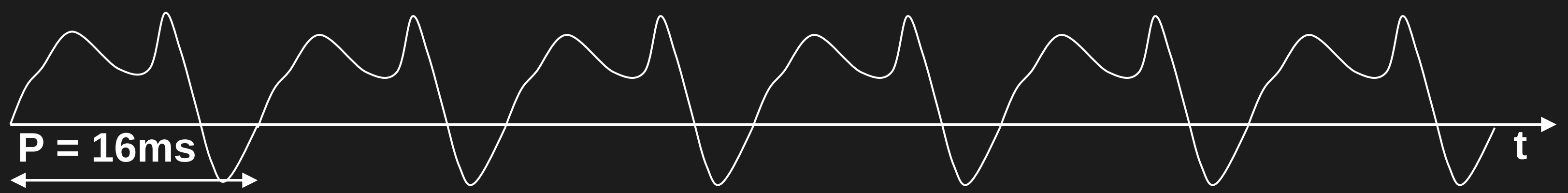
500 fps hi-speed camera

Vocal folds flapping at 40.4 Hz

4000 fps hi-speed camera

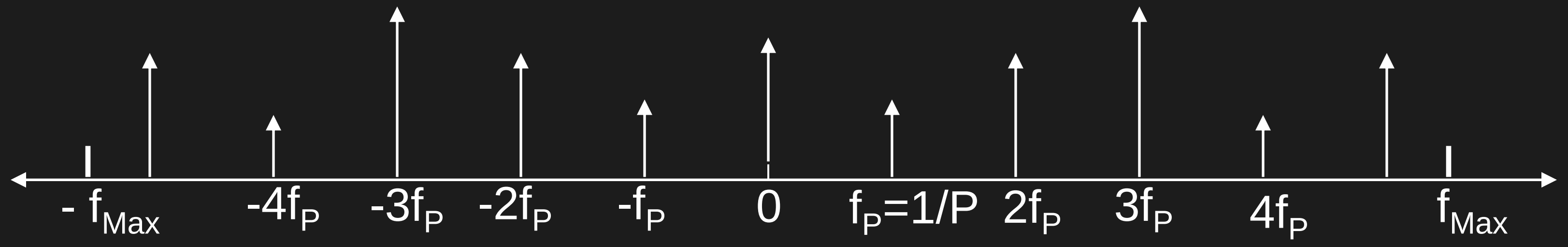
Periodic signals

Periodic signal x(t) with period P



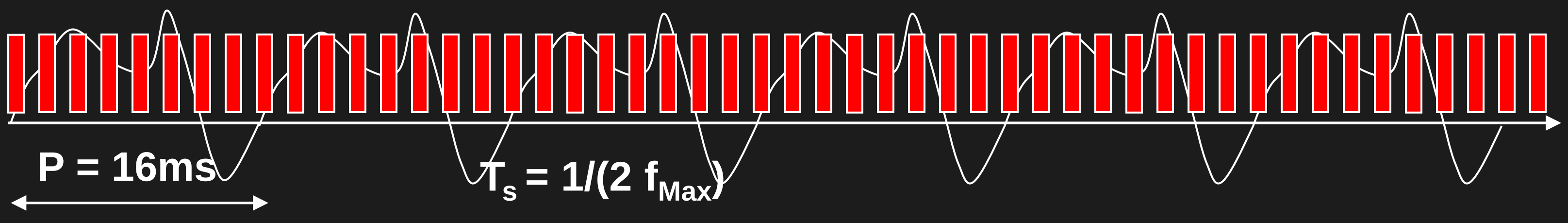
Periodic signal with period P and band-limited to f_{Max} = 500 Hz.

Fourier transform is non-zero only at multiples of f_P=1/P ~ 63Hz.



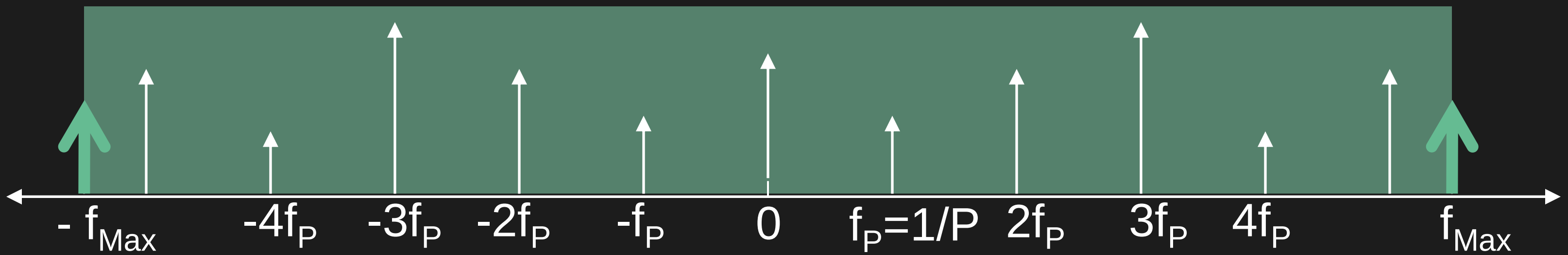
High speed camera

Nyquist Sampling of x(t)



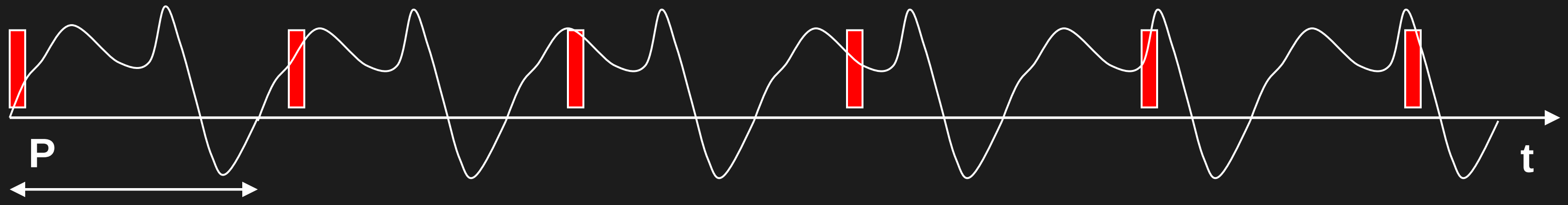
Periodic signal has regularly spaced, sparse Fourier coefficients.

Is it necessary to use a high-speed video camera? Why waste bandwidth?



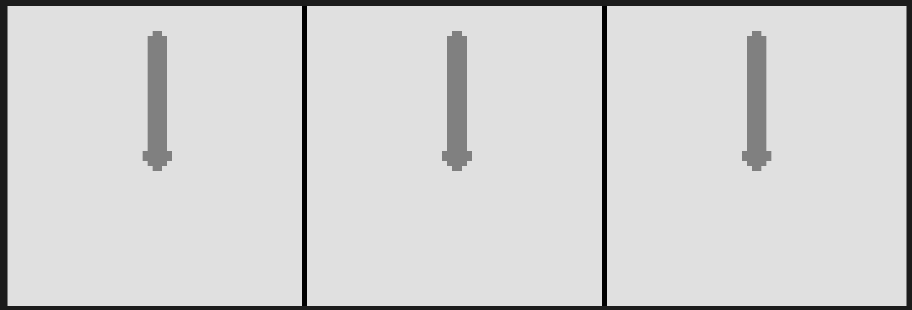
Traditional Strobing

Use low frame-rate camera and generate beat frequencies.



Low exposure to avoid blurring. Low light throughput.

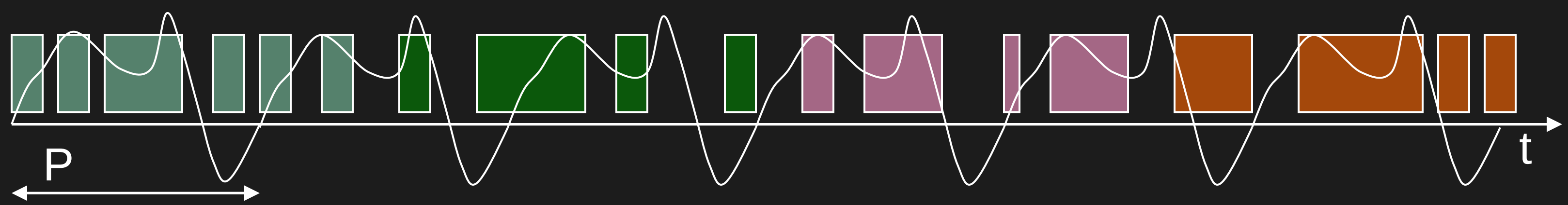
Period known apriori.



Strobing animation credit Wikipedia

Random Projections Per Frame of Camera using Coded Strobing Photography

In every exposure duration **observe different linear combinations** of the periodic signal.



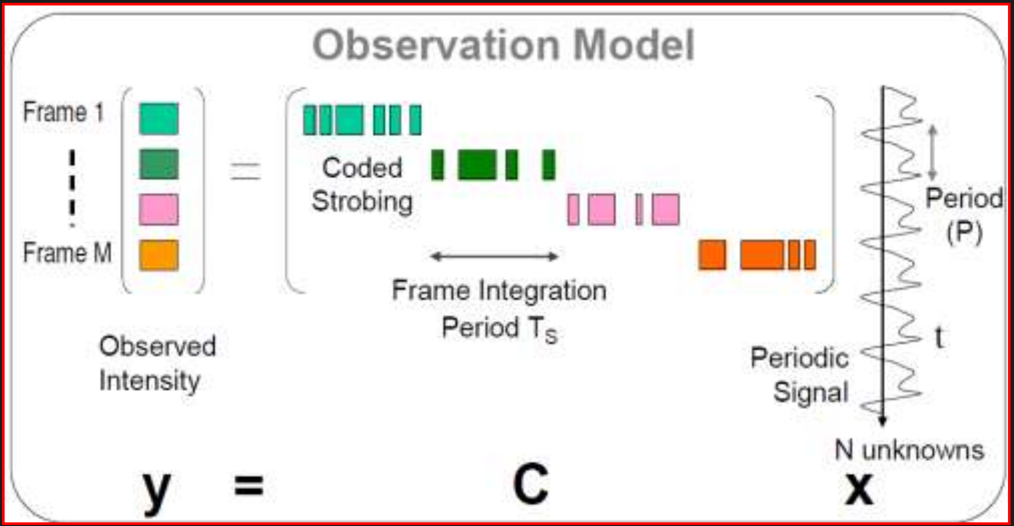
Advantage of the design

- Exposure coding **independent of the frequency**

- On an average, **light throughput is 50%**

Coded Strobing Photography. Reddy, D., Veeraraghavan, A., Raskar, R. IEEE PAMI 2011

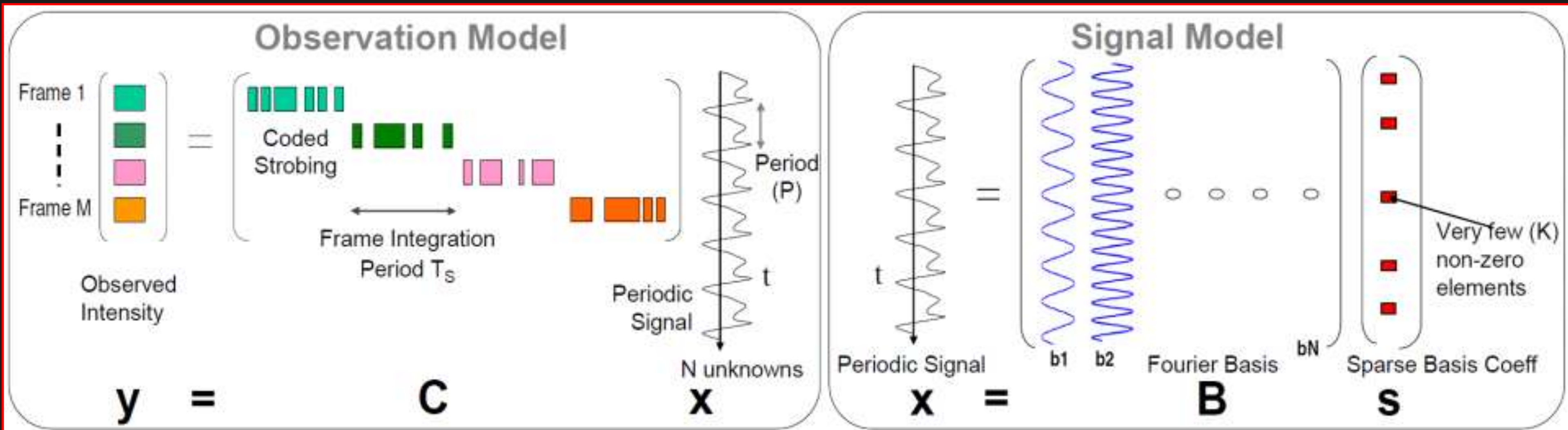
Observation Model



y at 25fps

x at 2000fps

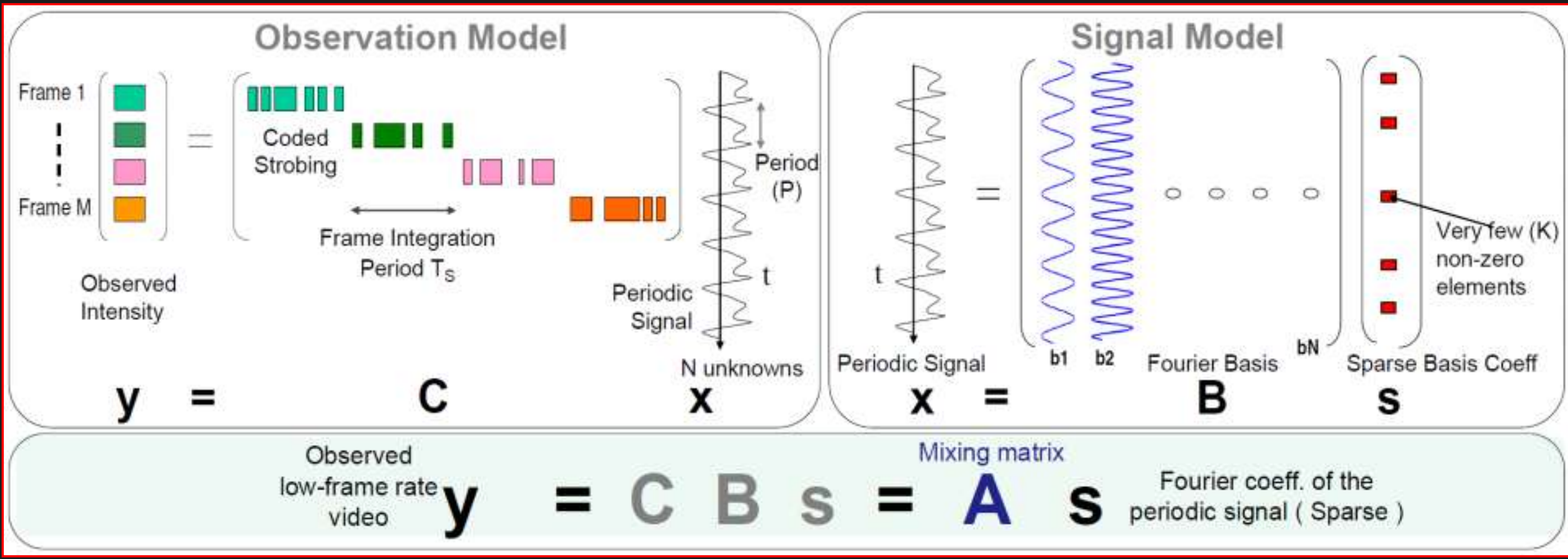
Signal Model



y at 25fps

x at 2000fps

Signal & Observation Model



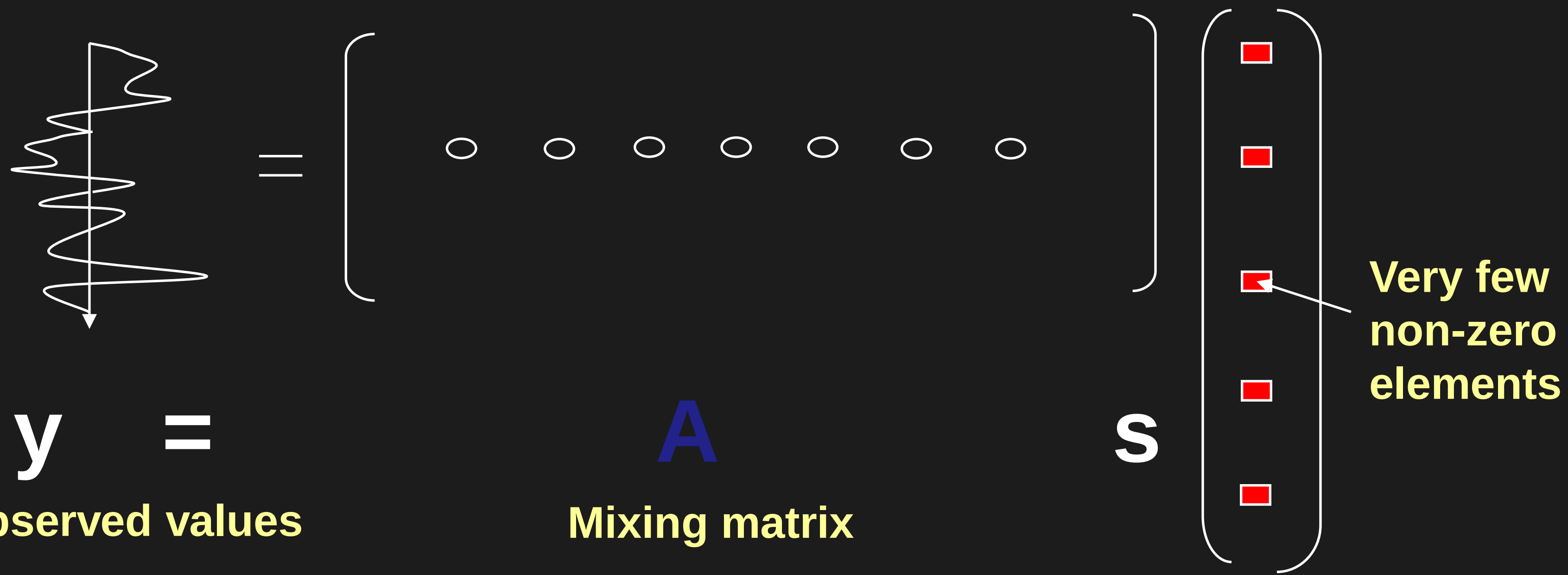
y at 25fps

x at 2000fps

A is M x N, M<<N

N / M = 2000 / 25 = 80

Recovery: Sparsity



Observed values

Mixing matrix

Structured Sparse Coefficients

Basis Pursuit De-noising

$$\min \|s\|_1 \quad s.t. \quad \|y - As\| \leq \varepsilon$$

Simulation on hi-speed toothbrush

25fps normal camera

25fps coded strobing camera

Reconstructed frames

2000fps hi-speed camera

~100X speedup

Rotating mill tool

Mill tool rotating at 50Hz

Reconstructed Video at 2000fps

Normal Video: 25fps

Coded Strobing Video: 25fps

Blur increases as rotational velocity increases

rotating at 100Hz

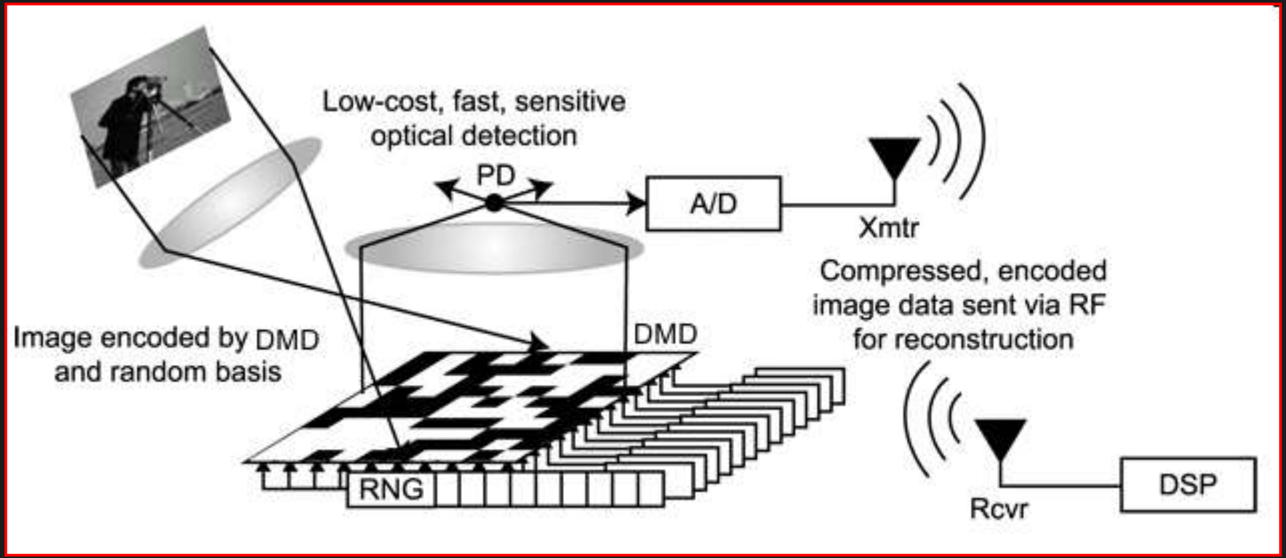
rotating at 150Hz

rotating at 200Hz

increasing blur

Compressive Sensing for Images .. A good idea?

Single Pixel Camera



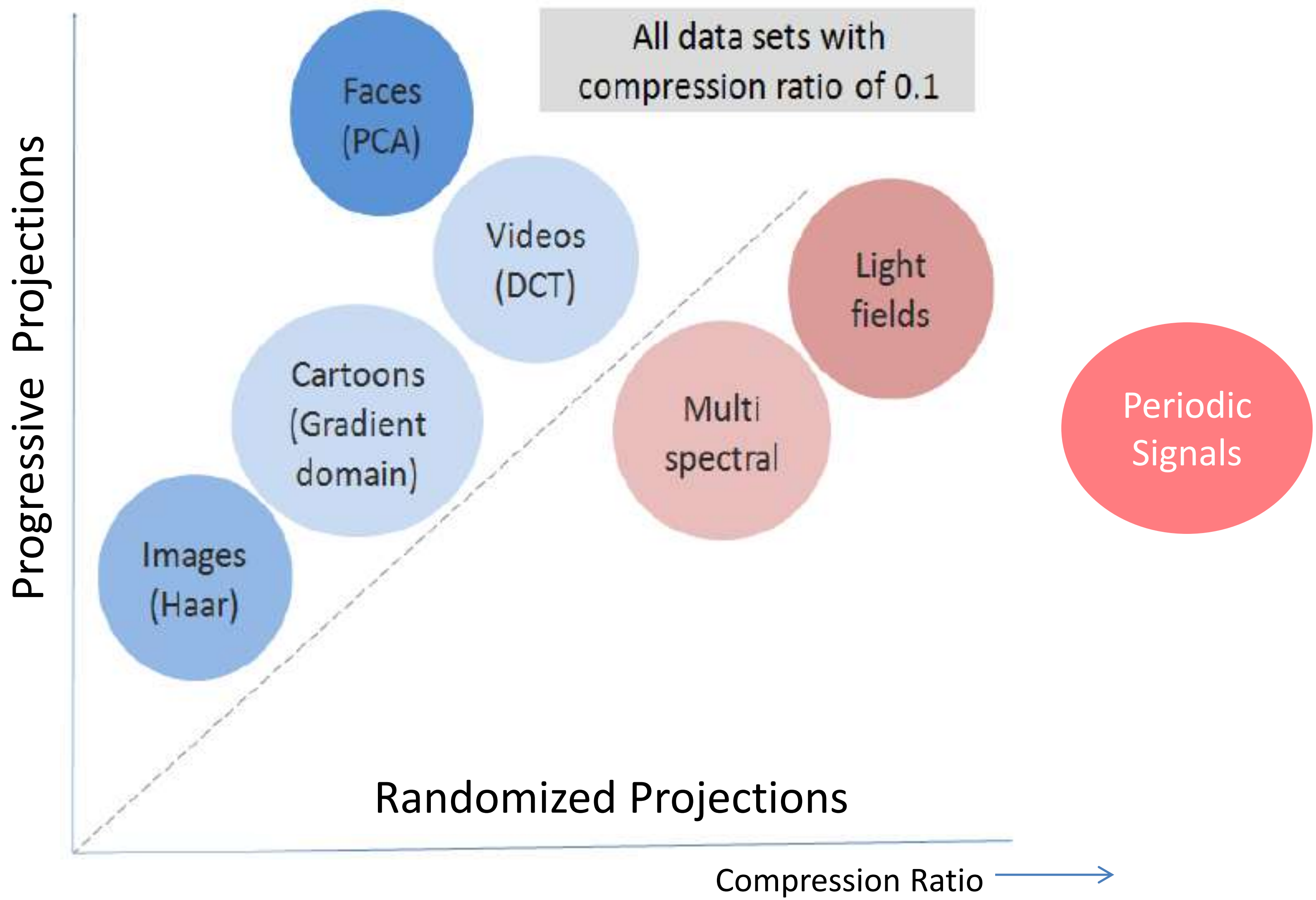
$$y = \Phi x \quad , \quad \Phi_{M \times N} \text{ where } M < N$$

image

compressive image

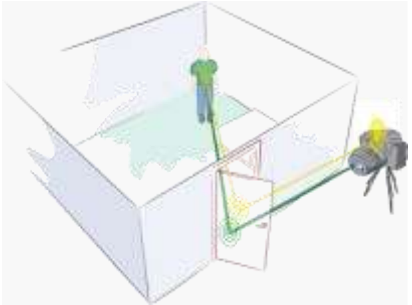
measurement matrix

Is Randomized Projection-based Capture apt for Natural Images ?

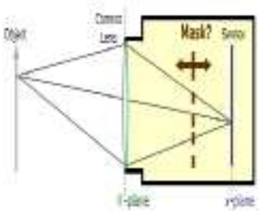


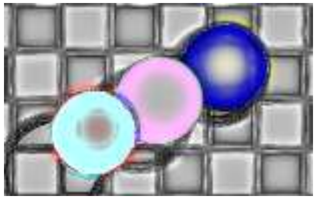
[Pandharkar, Veeraraghavan, Raskar 2009]

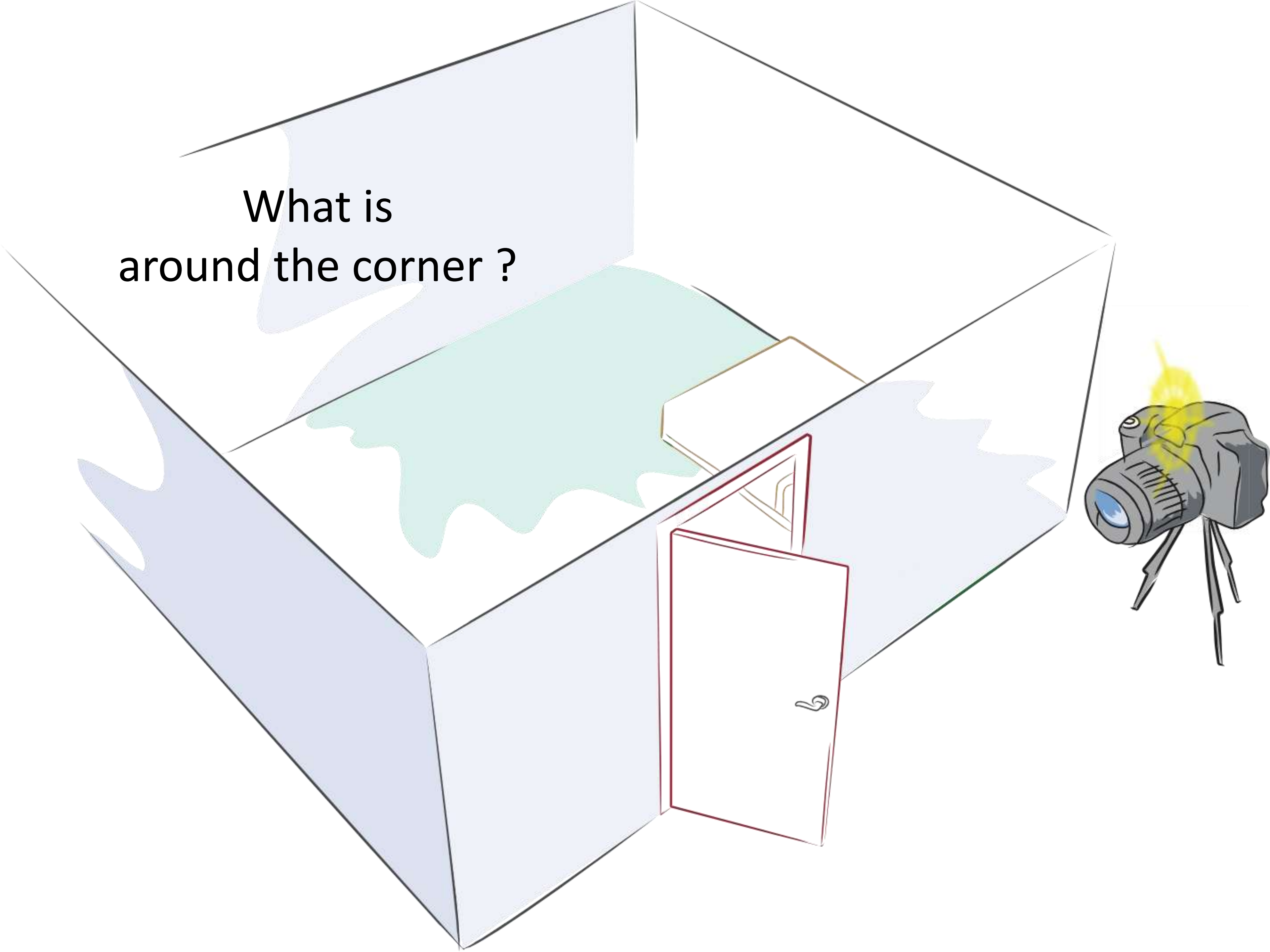
Inverse Problems



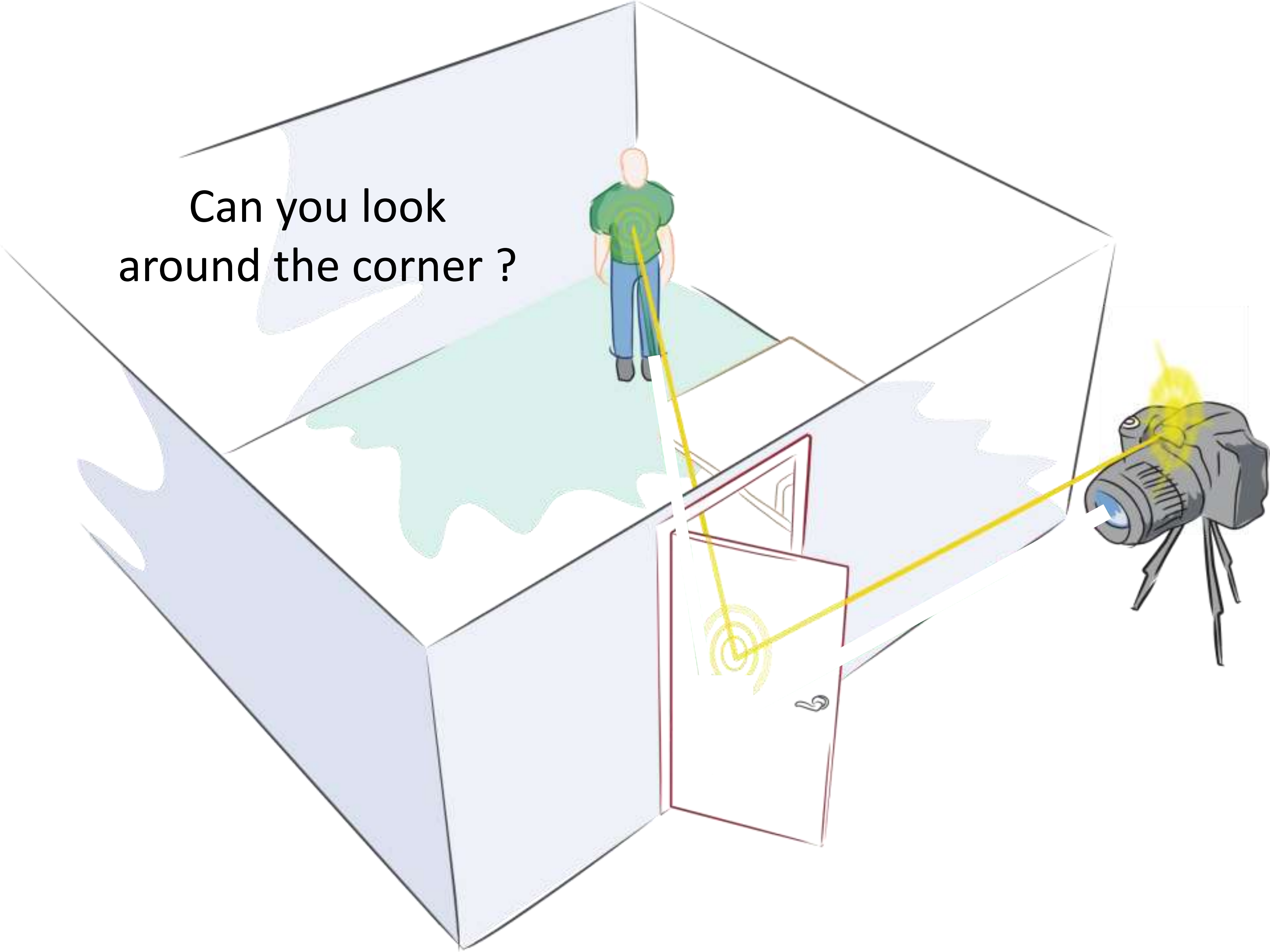
- Co-design of Optics and Computation
  - Photons not just pixels
  - Mid-level cues
- Computational Photography
  - Coded Exposure
  - Compressive Sensing for High Speed Events
    - Limits of CS for general imaging
- Computational Light Transport
  - Looking Around Corners, trillion fps
  - Lightfields:
    - Compressive Campture
    - 3D Displays and Holograms

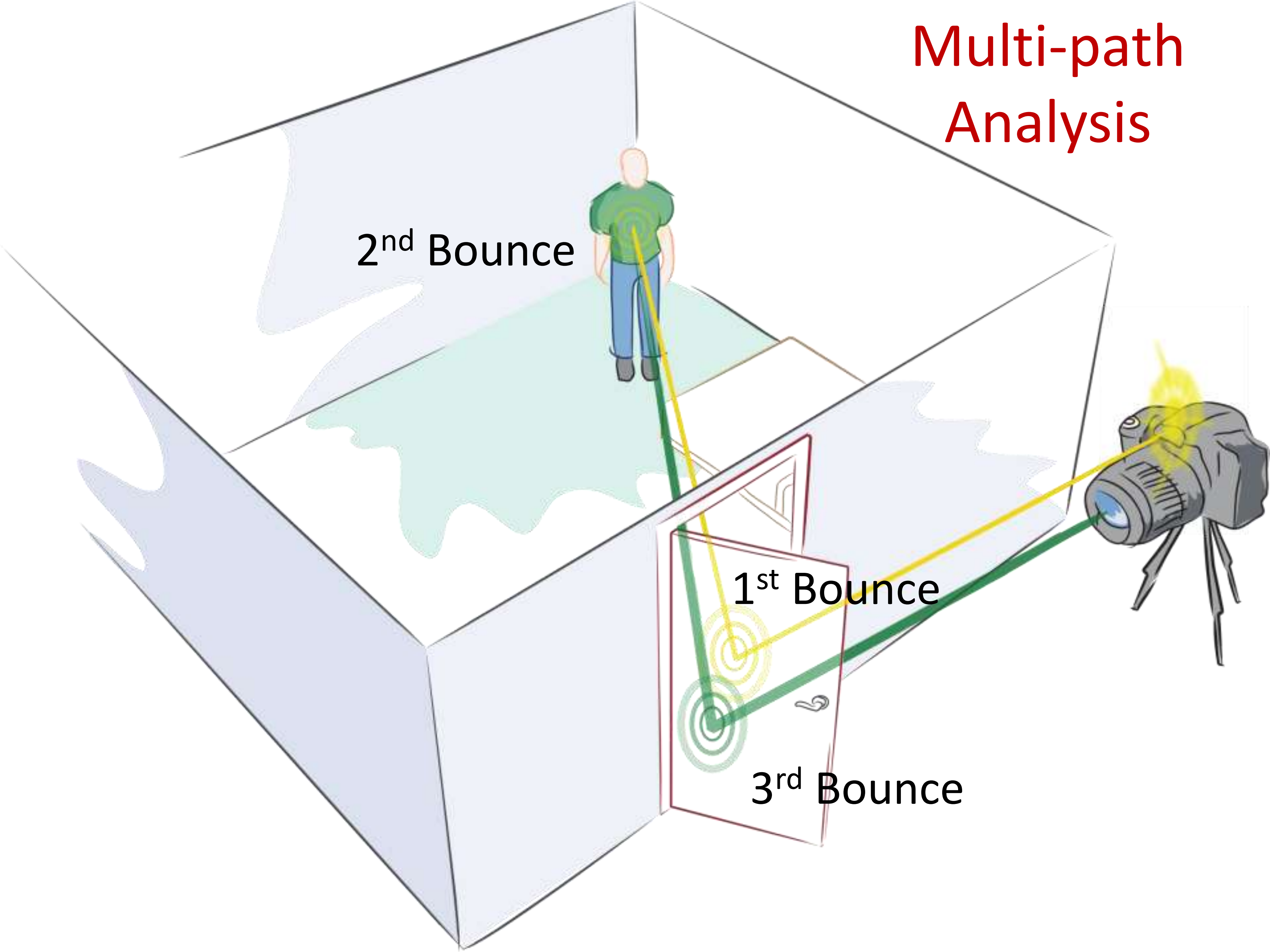





What is
around the corner ?

Can you look
around the corner ?

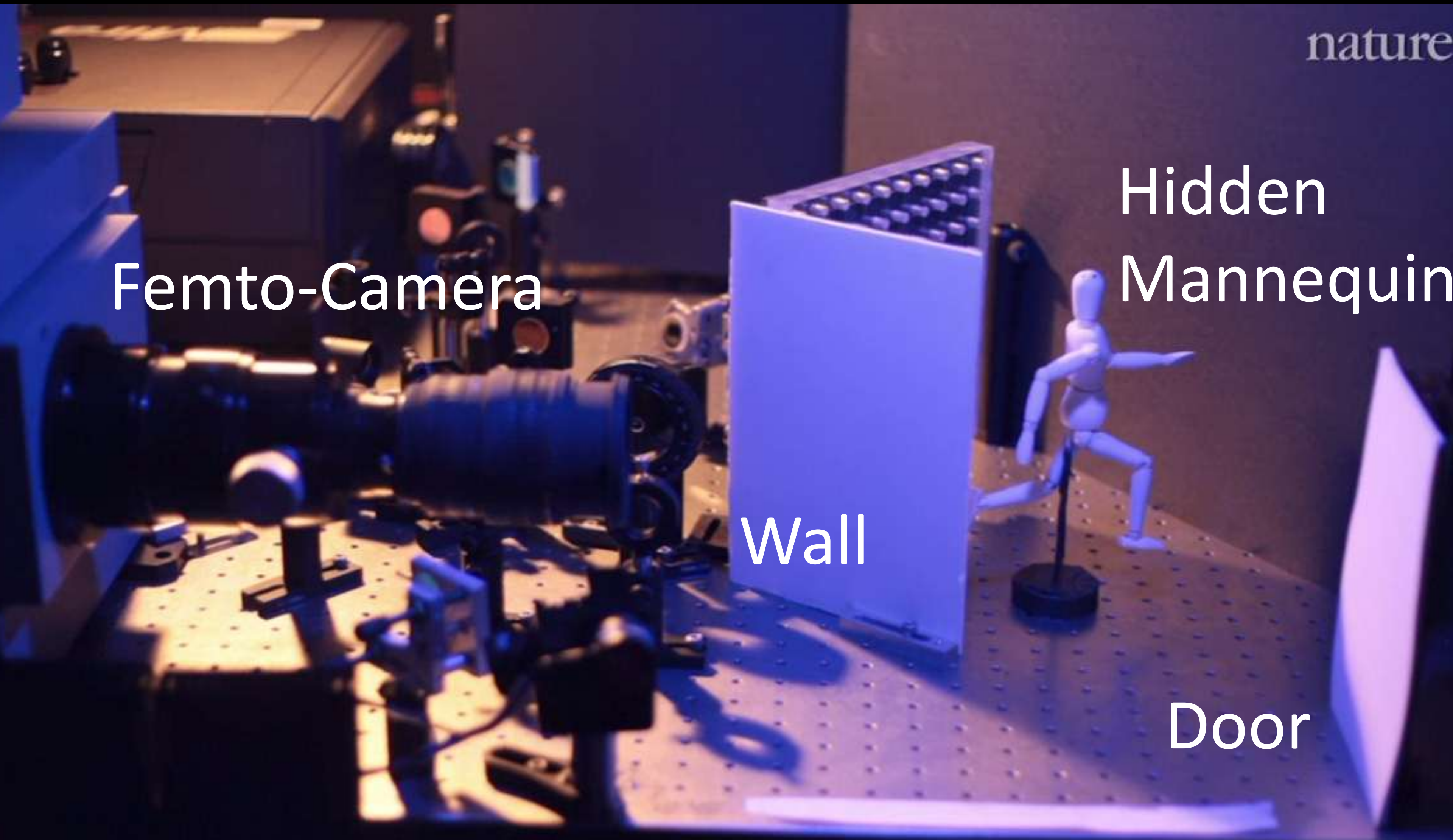




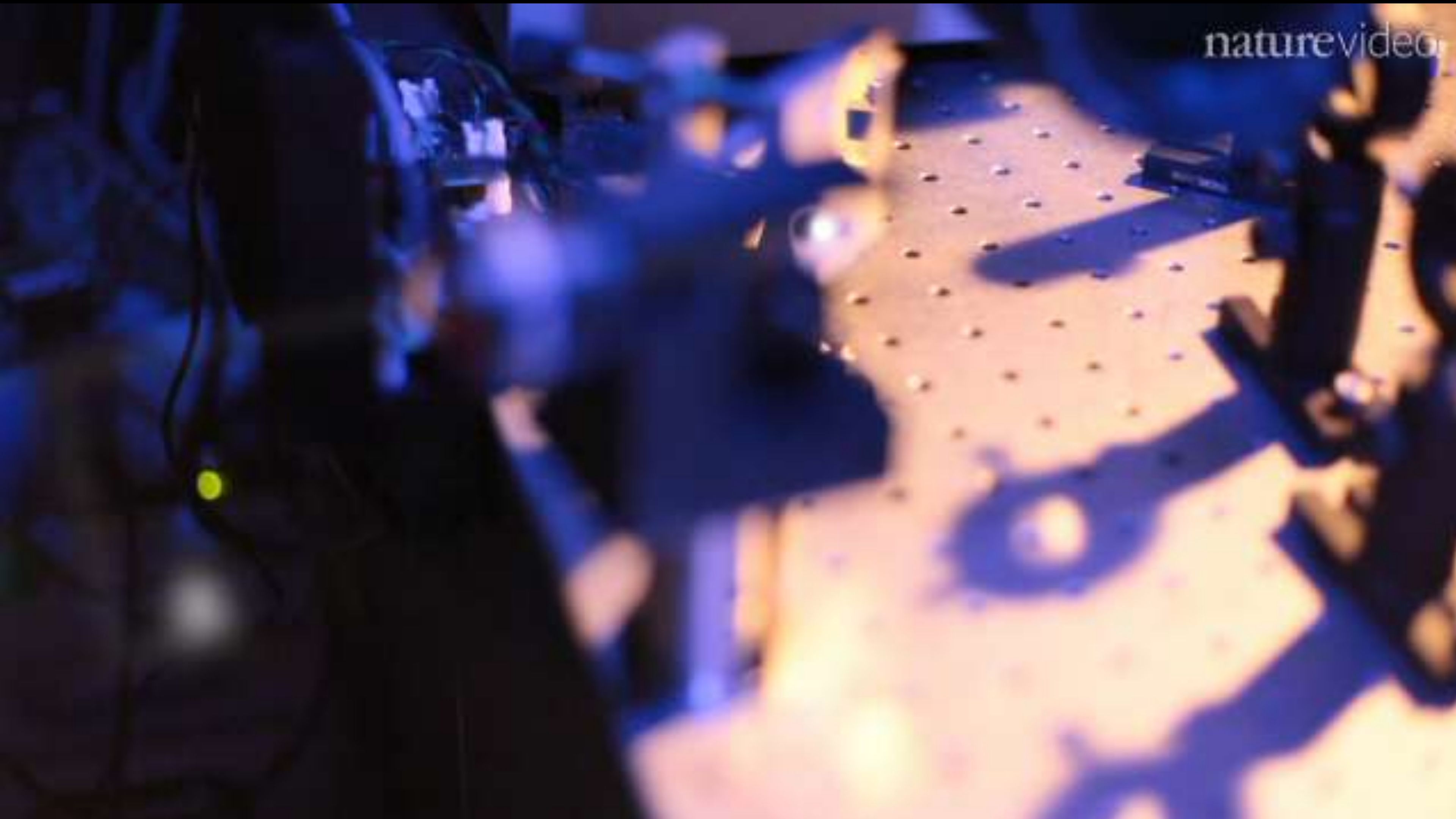
Multi-path Analysis
2nd Bounce
1st Bounce
3rd Bounce

Light in Slow Motion ..

10 Billion x Slow

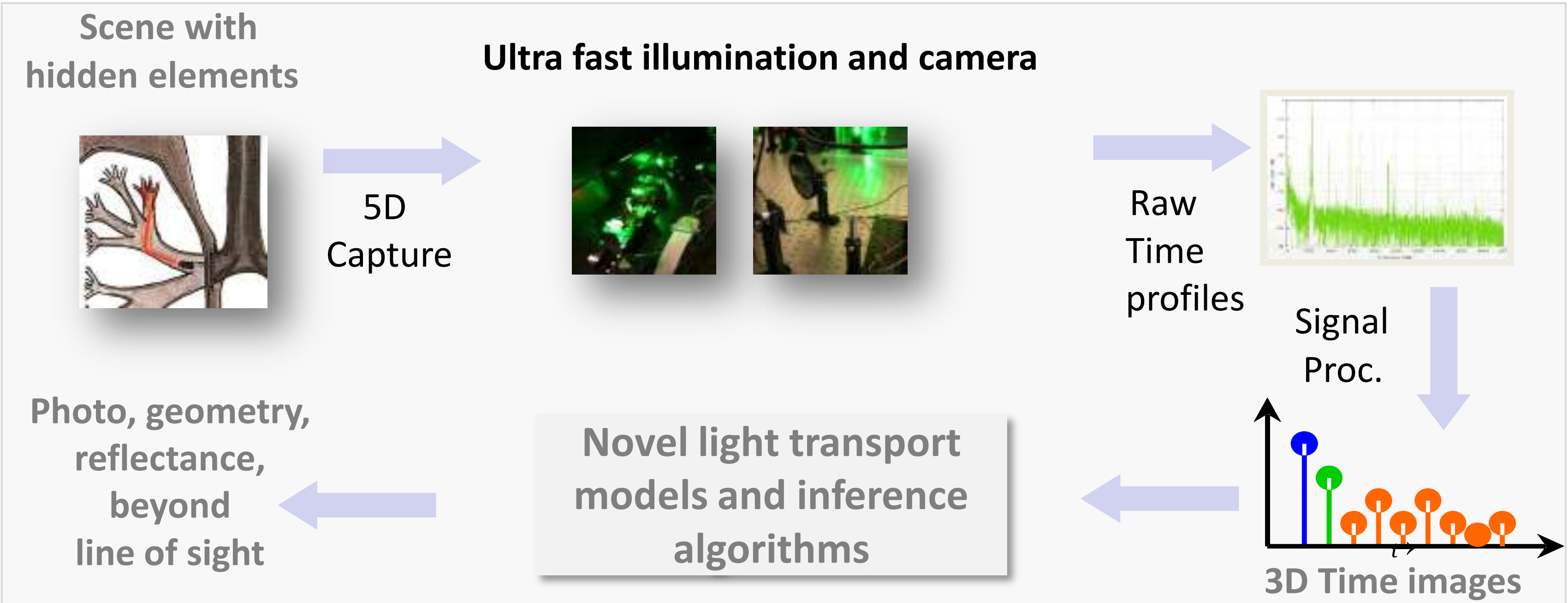


Velten et al, Nature Communications 2012


naturevideo

Femto Photography

Time Resolved Multi-path Imaging



Tasks: Non-line of sight, Motion estimation, Material sensing, Volumetric

Inversion: Sparsity, Rank, Bounded Approx, Scene Priors, Transforms

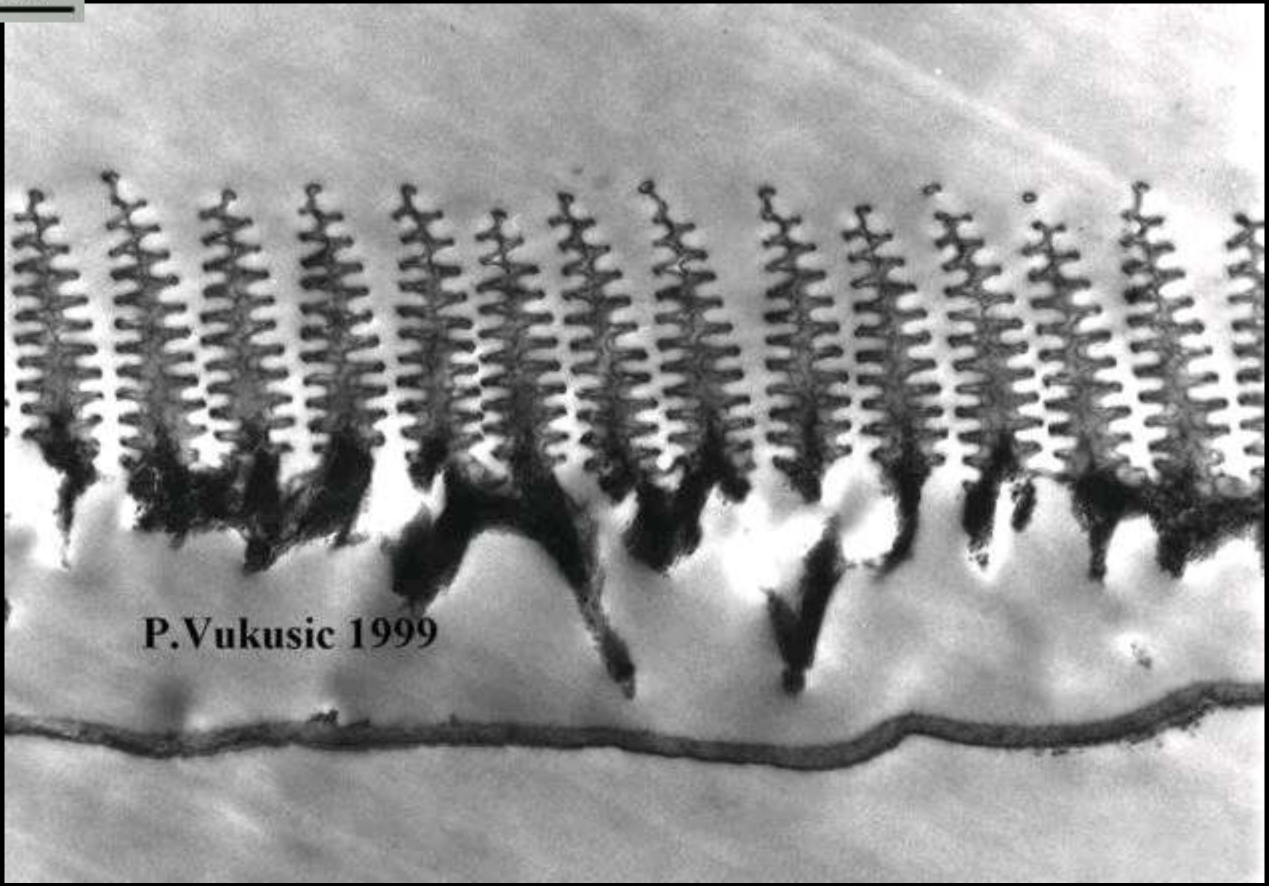
Signal Processing: Compressive, SNR, Bandwidth, Noise models

Illumination: Coding space/time/wavelength, Semicondctr lasers, nonlinear optics

FormFactors: Endoscopy, OCT, Bench-top, Room size, Outdoors

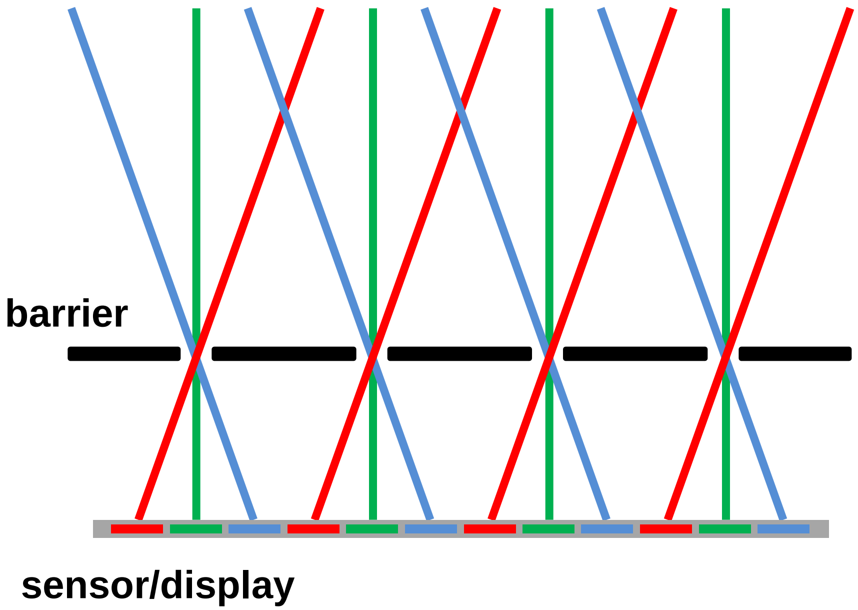
Applications: ComputerVision, MedicalImaging, Biochemistry, Rescue/Planning, IndustrialInspection, Robotics, Spectroscopy
Art/Education

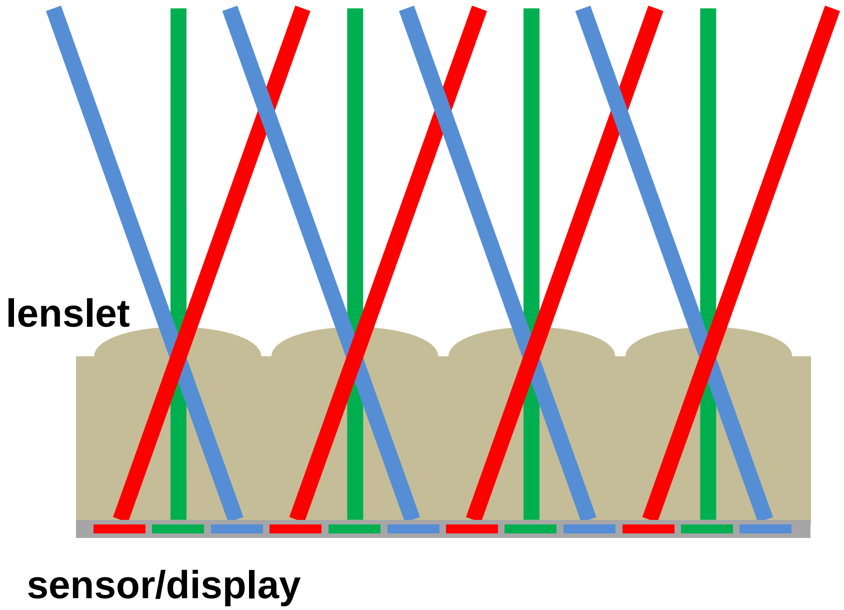
Collaborations Welcome/ Apply for internships

View Dependent Appearance and Iridescent color
Cross section through a single M. rhetenor scale

Two Layer Displays

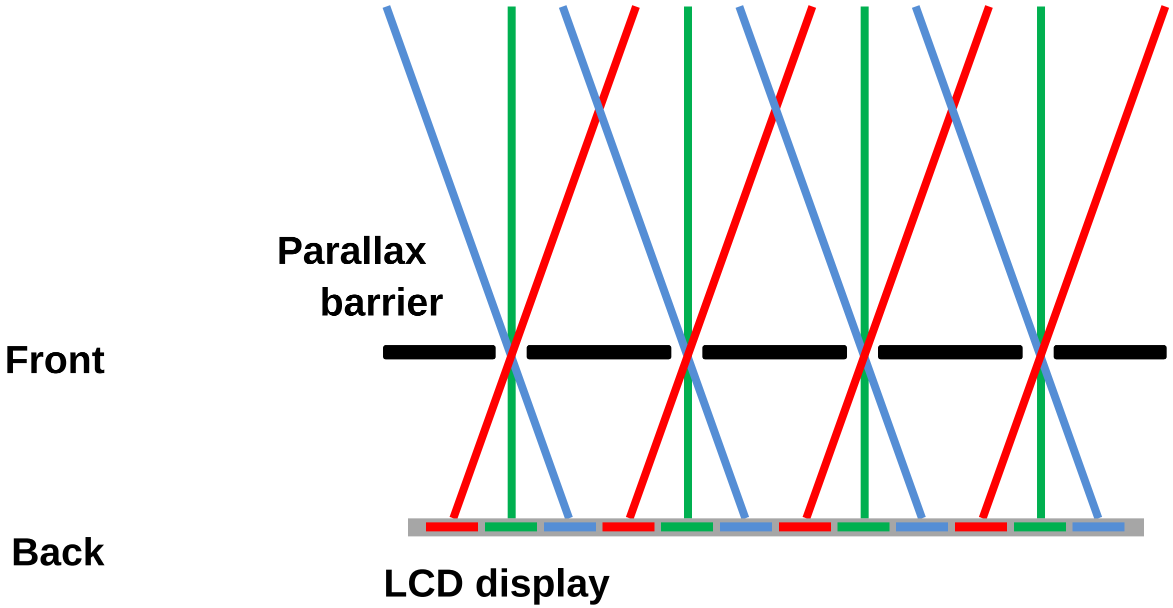




PB = dim displays
Lenslets = fixed spatial and angular resolution

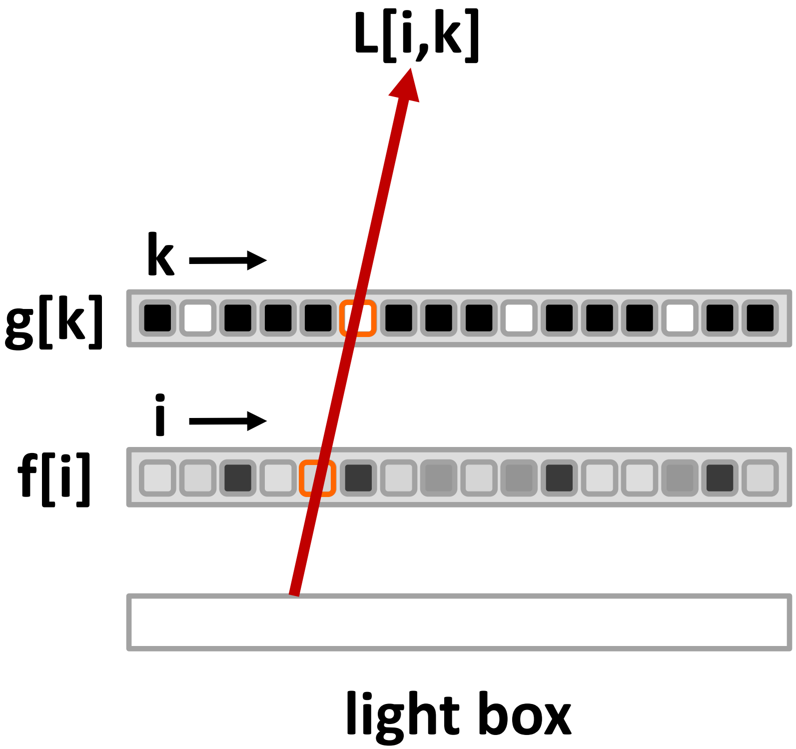
Dynamic Masks = Brighter, High spatial resolution

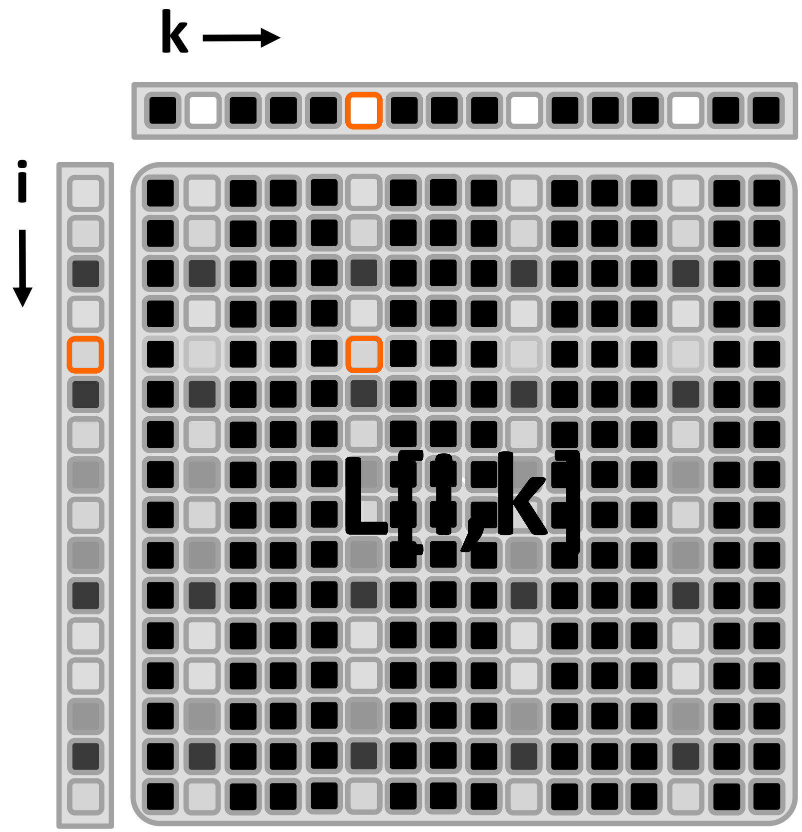
Limitations of 3D Display



Lanman, Hirsch, Kim, Raskar   Siggraph Asia 2010

Light Field Analysis of Barriers

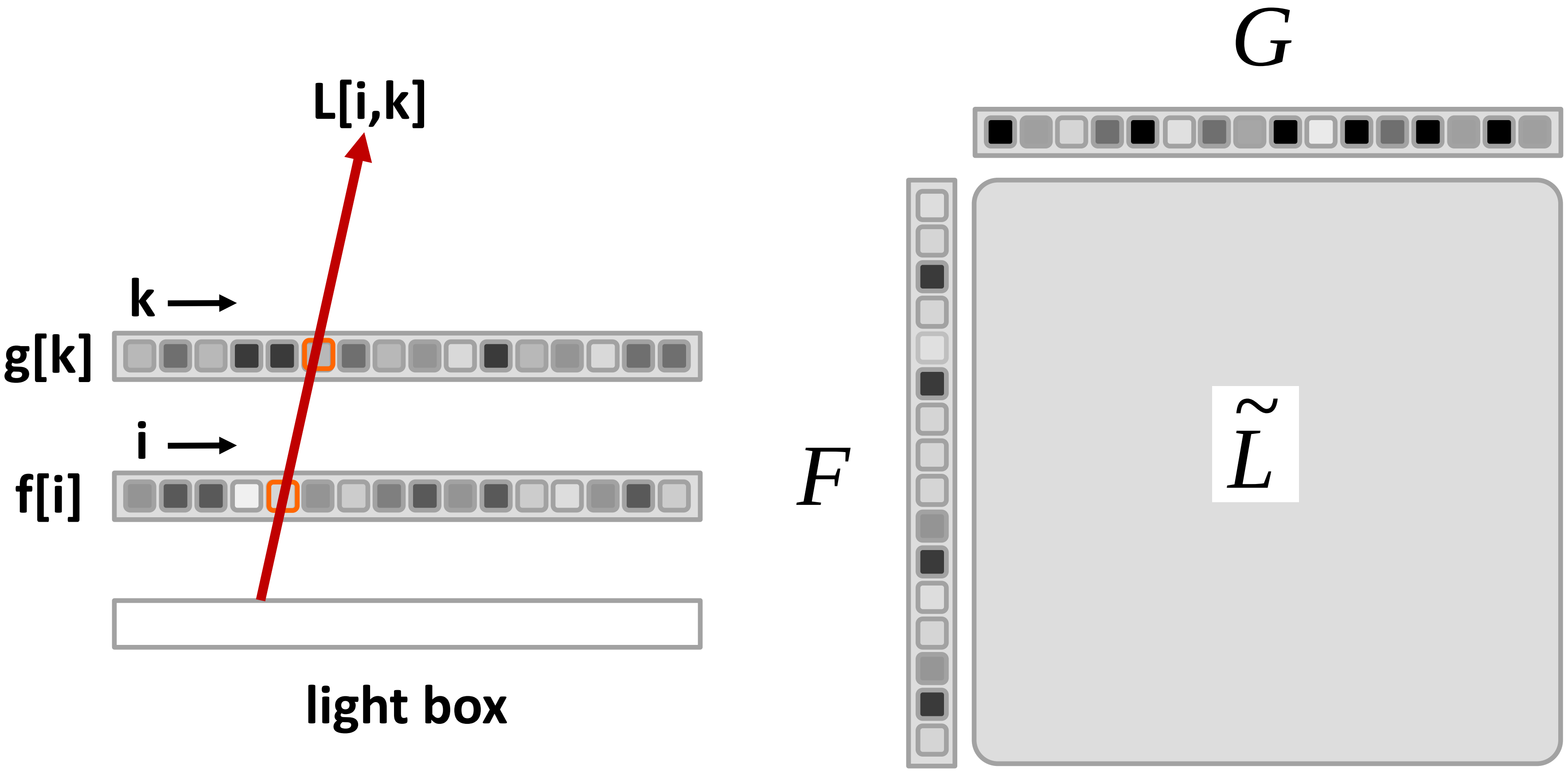




$$L[i,k] = f[i] \cdot g[k]$$

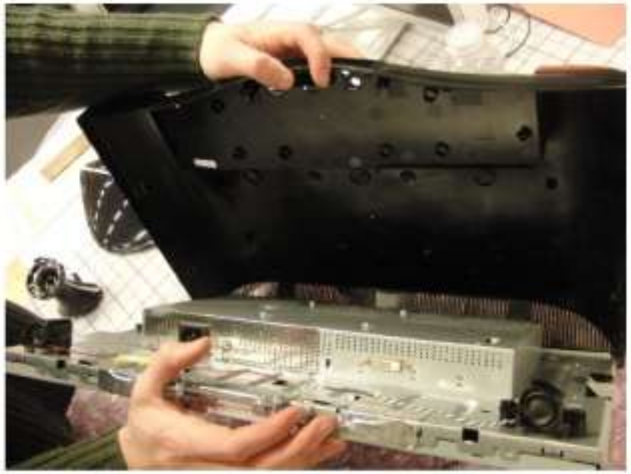
$$L = f \otimes g$$

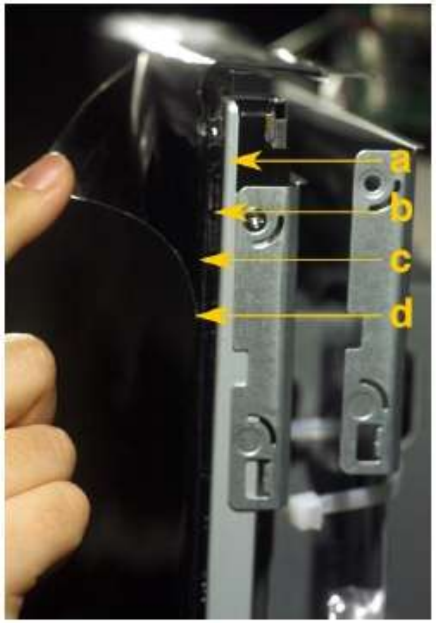
Content-Adaptive Parallax Barriers



$$\tilde{L} = FG$$

Implementation

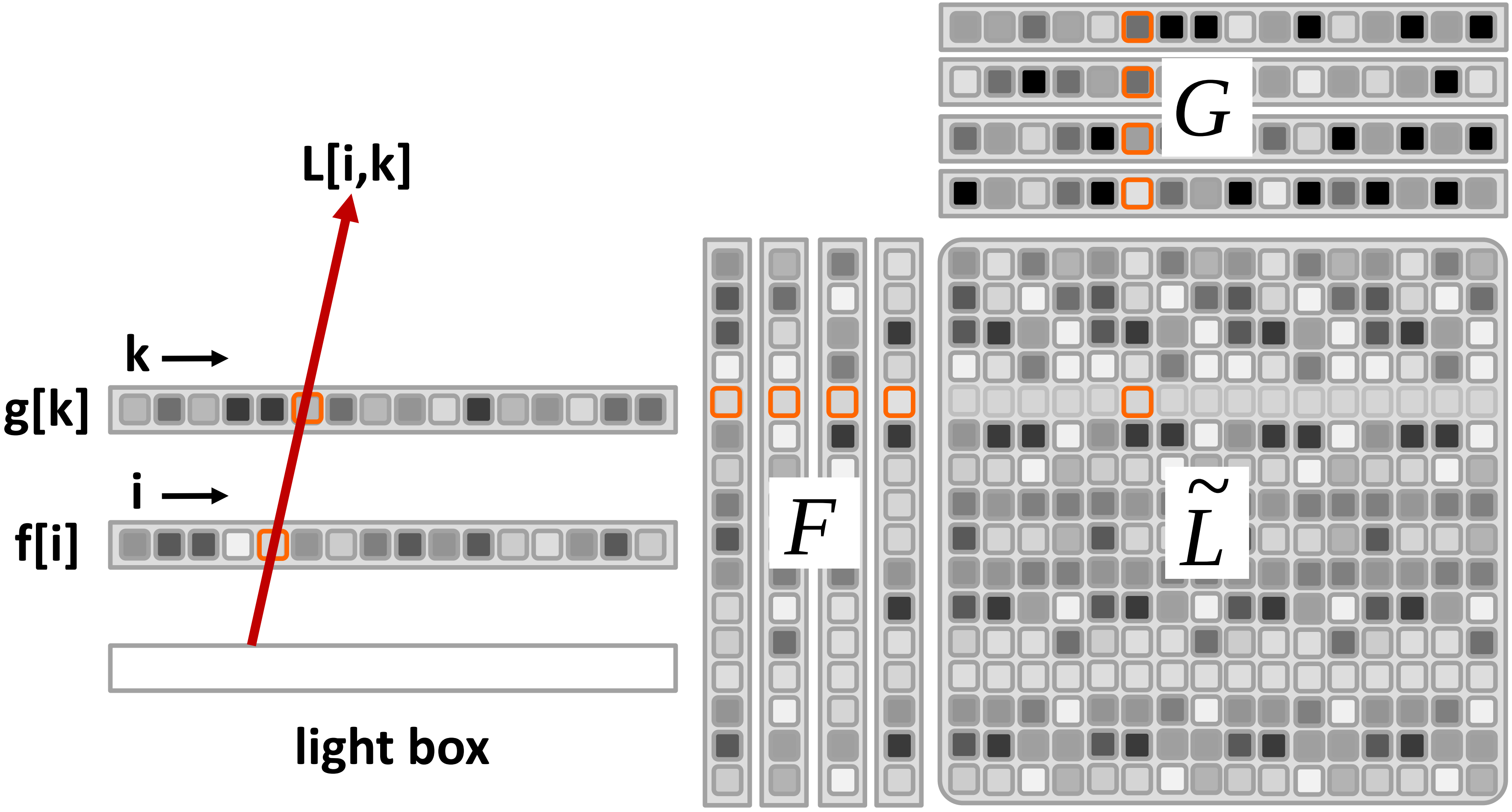




Components

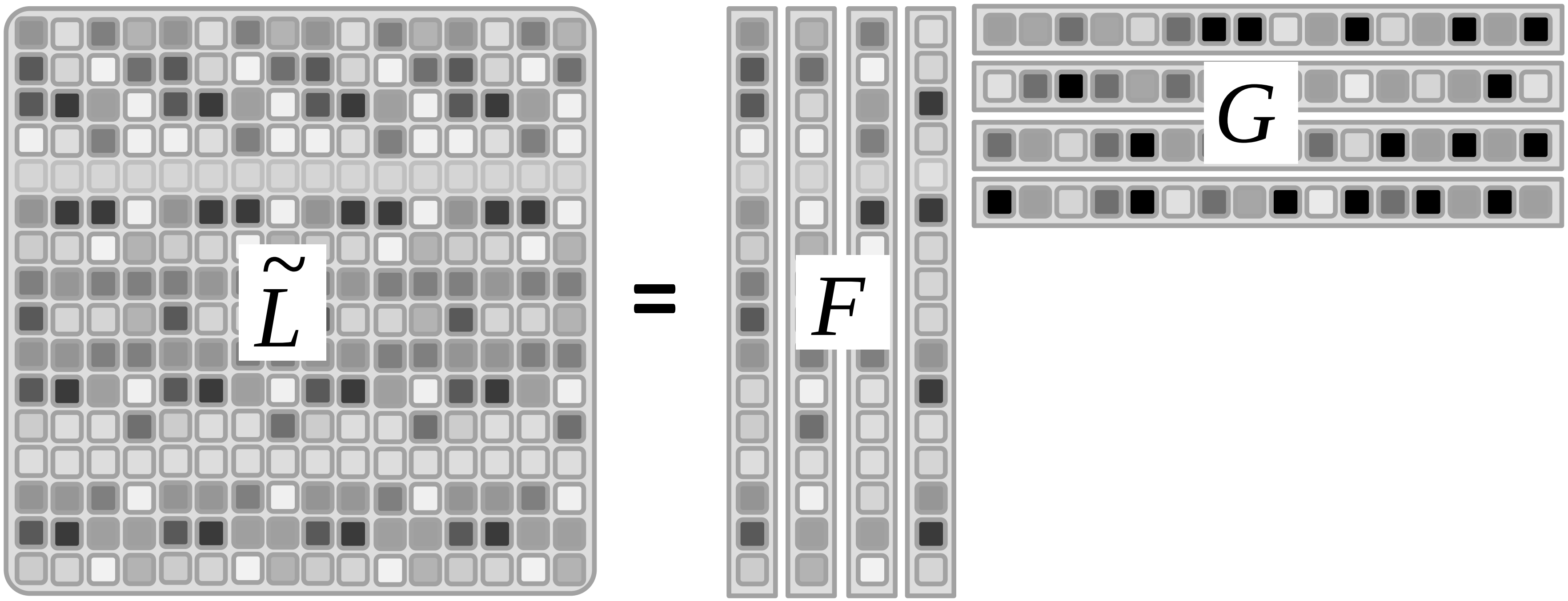
- 22 inch ViewSonic FuHzion VX2265wm LCD [1680 × 1050 @ 120 fps]

Content-Adaptive Parallax Barriers



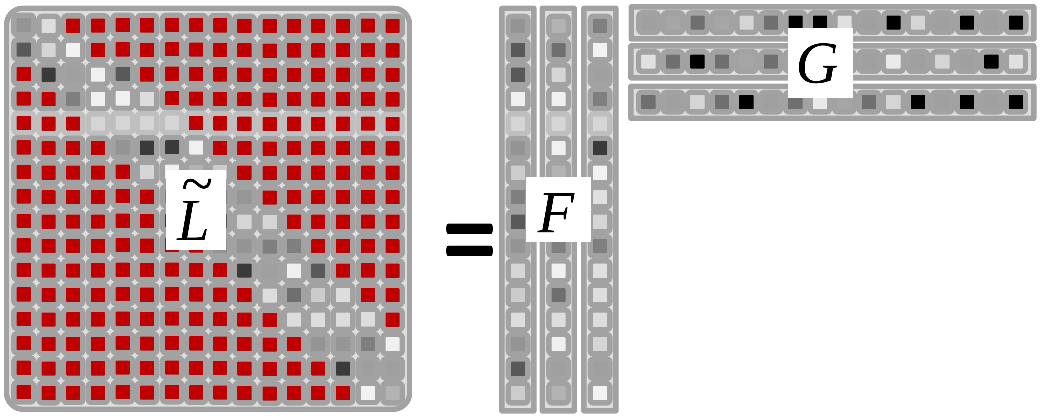
$$\tilde{L} = FG$$

Content-Adaptive Parallax Barriers

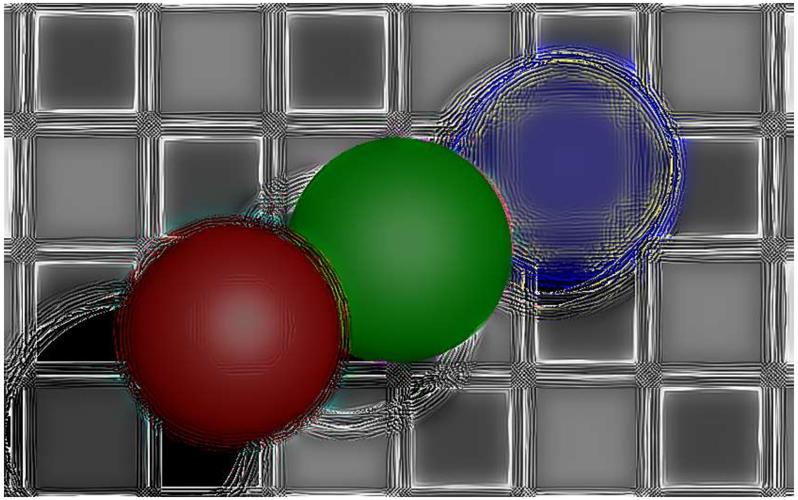


$$\underset{F,G}{\arg\min}\ \frac{1}{2}\left\| L - FG \right\|^2, \text{ for } F, G \geq 0$$

Rank-Constrained Displays and LF Adaptation



$$\underset{F,G}{\arg\min}\ \frac{1}{2}\left\|L - FG\right\|_W^2, \text{ for } F, G \geq 0$$



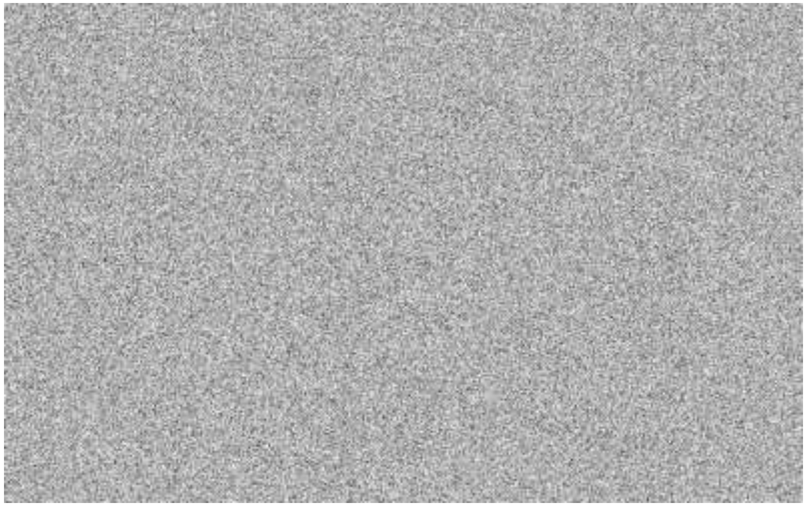
Content-Adaptive Parallax Barriers

All dual layer display = *rank-1 constraint*

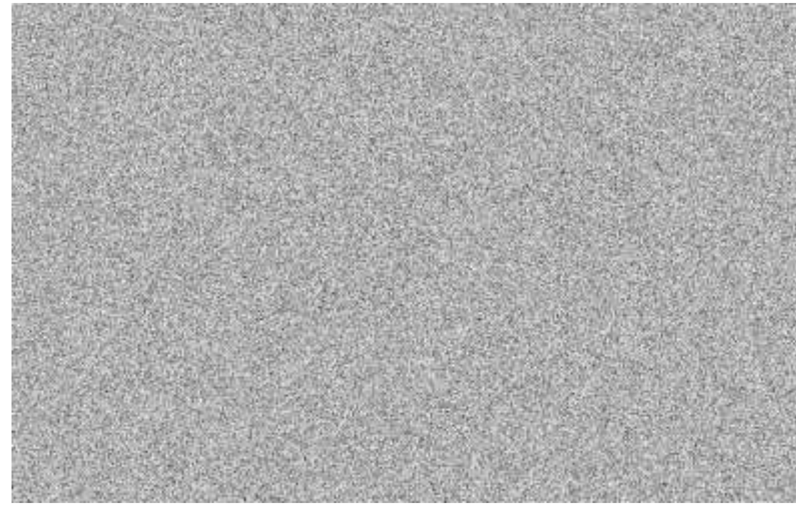
Light field display is a *matrix approximation problem*

Exploit *content-adaptive parallax barriers*

Optimization: Iteration 1



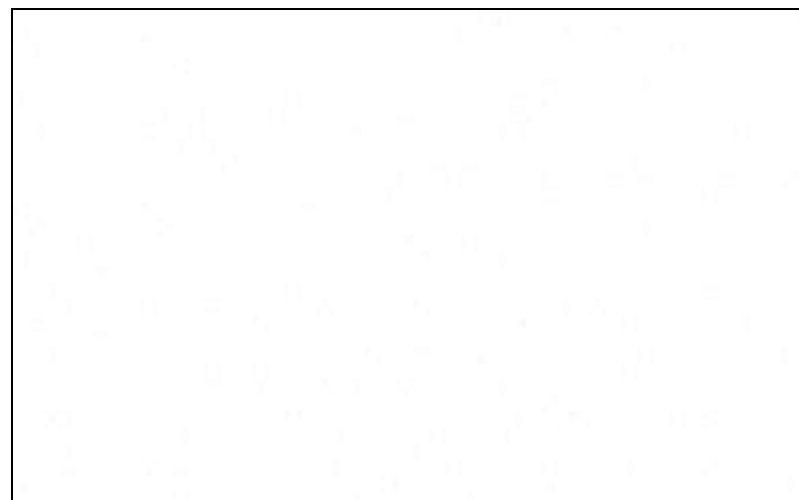
rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

$$F \leftarrow F \circ \frac{[(W \circ L)G^t]}{[(W \circ (FG))G^t]}$$

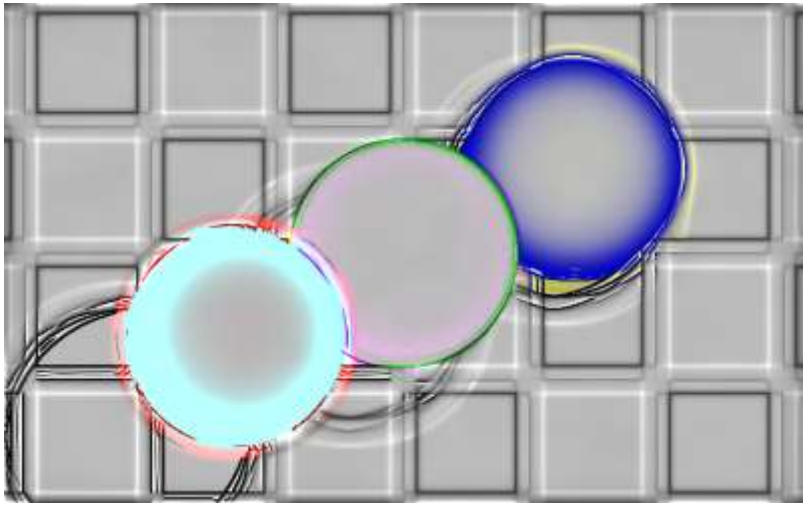
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



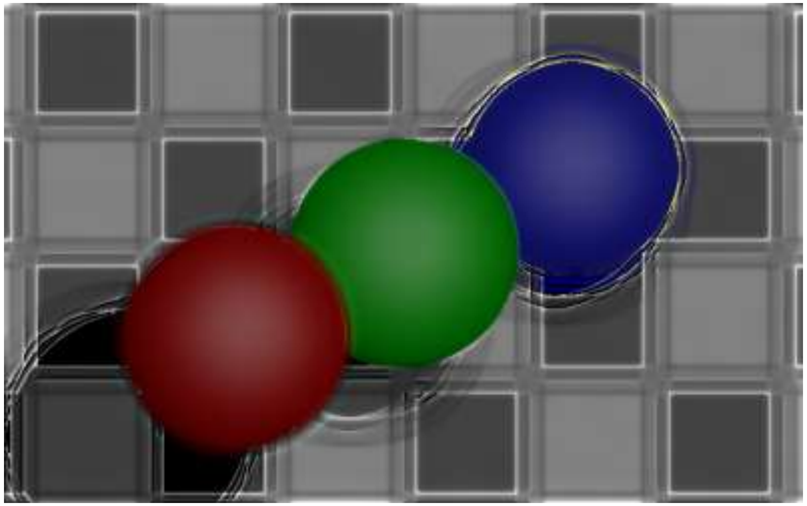
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

Optimization: Iteration 10



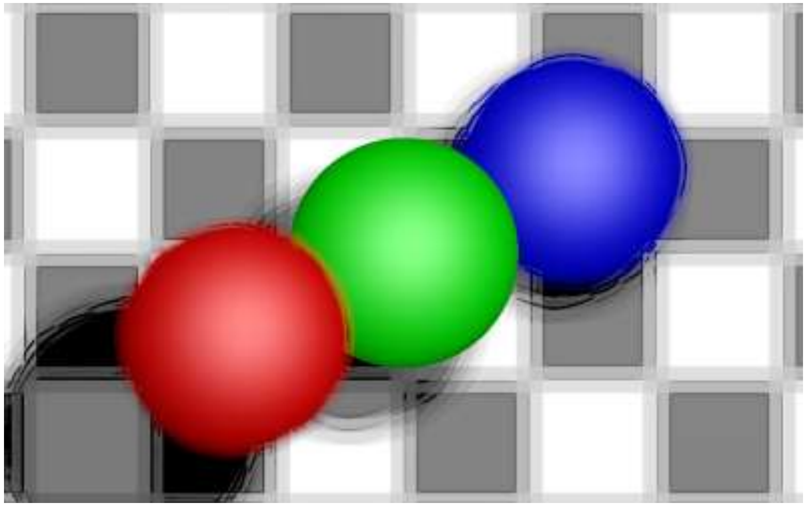
rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

$$F \leftarrow F \circ \frac{[(W \circ L)G^t]}{[(W \circ (FG))G^t]}$$

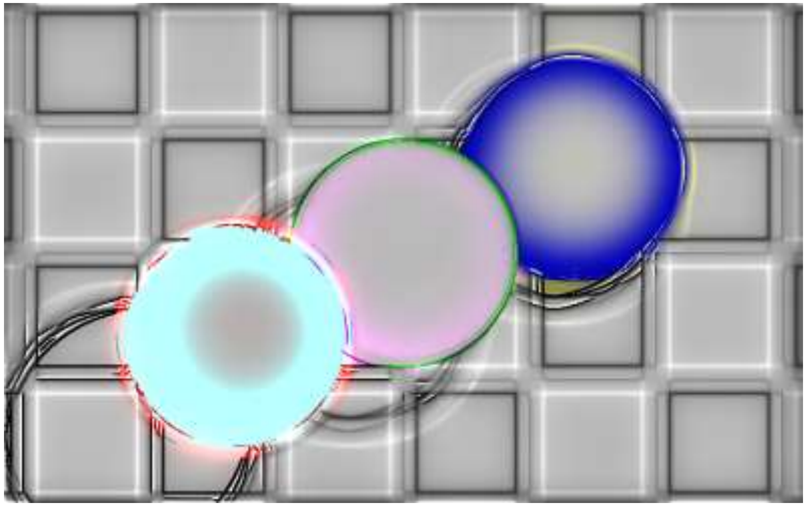
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



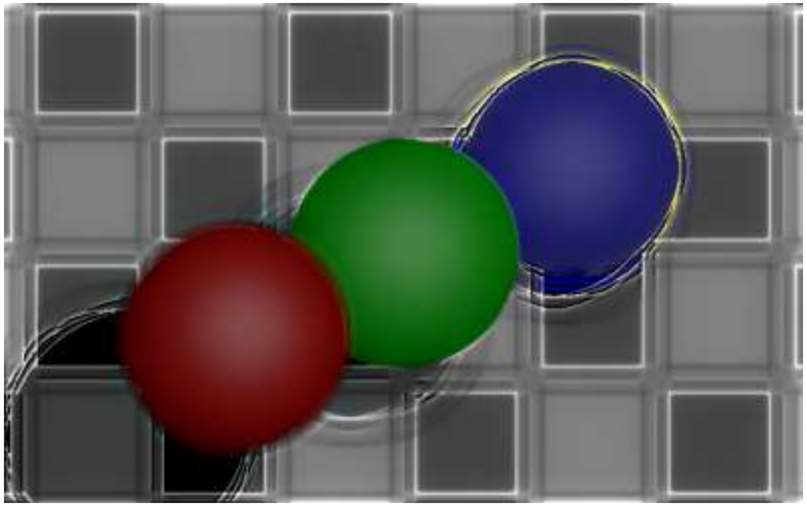
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

Optimization: Iteration 20



rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

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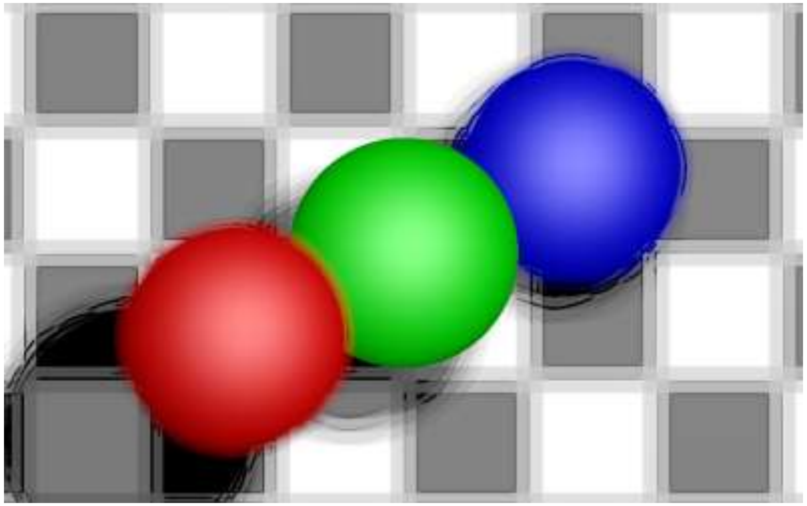
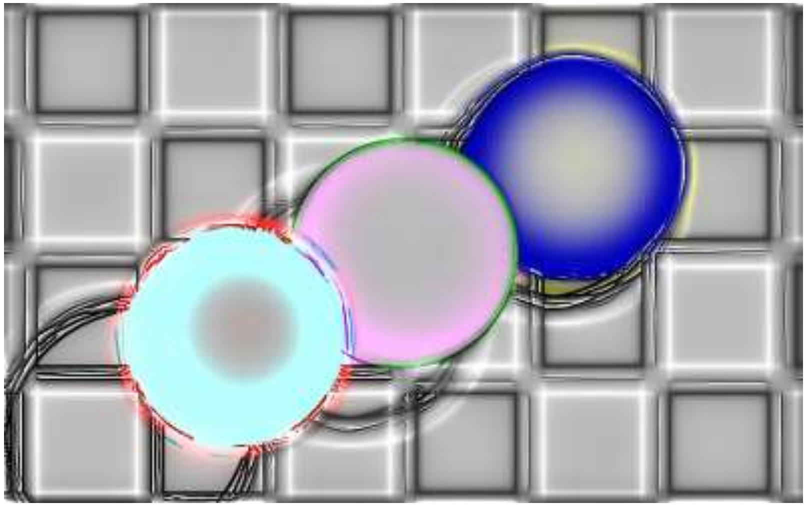
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



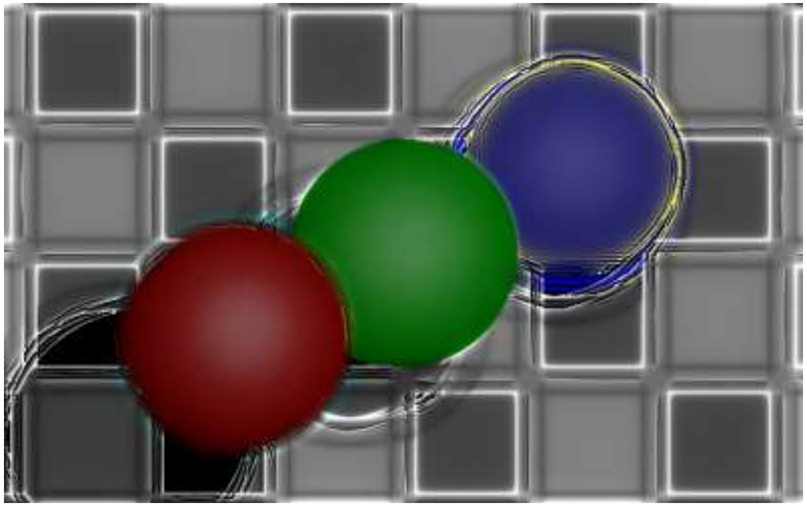
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

Optimization: Iteration 30



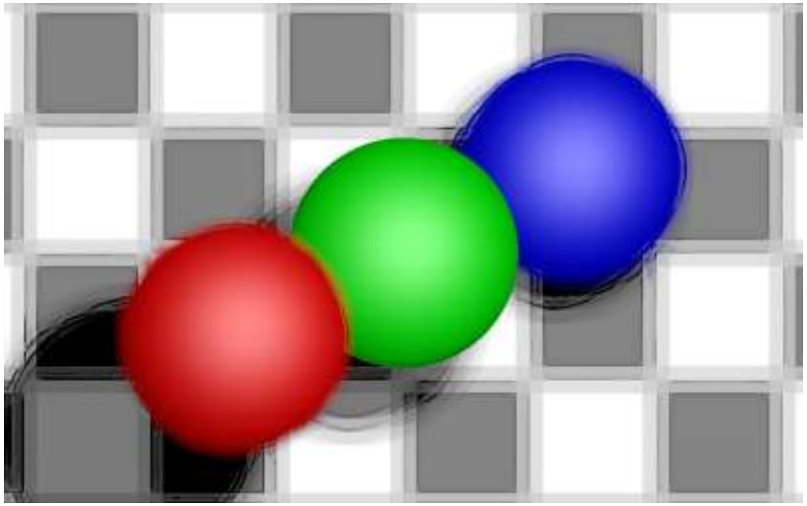
rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

$$F \leftarrow F \circ \frac{[(W \circ L)G^t]}{[(W \circ (FG))G^t]}$$

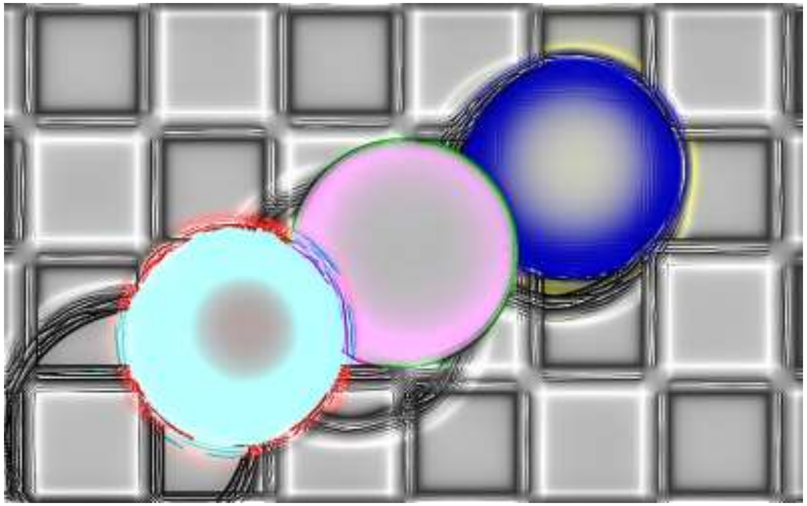
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



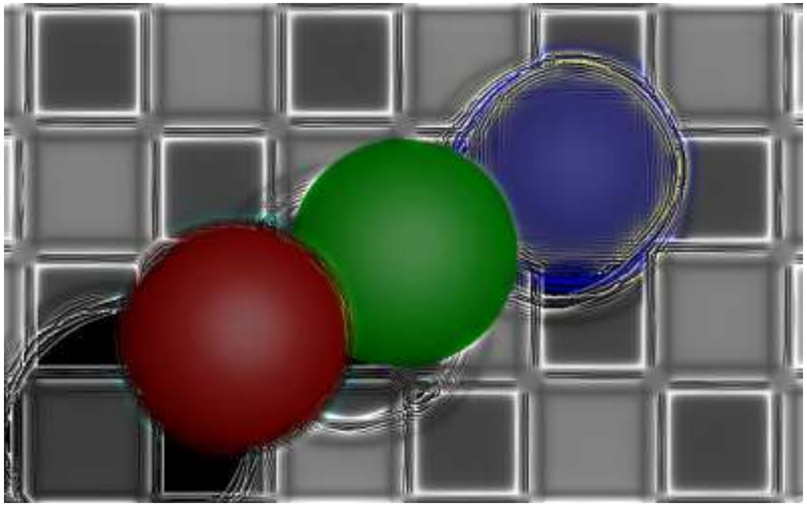
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

Optimization: Iteration 40



rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

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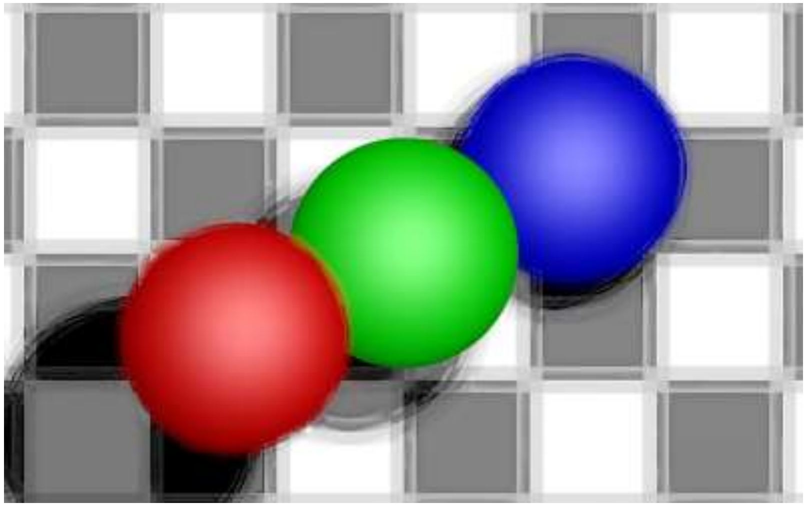
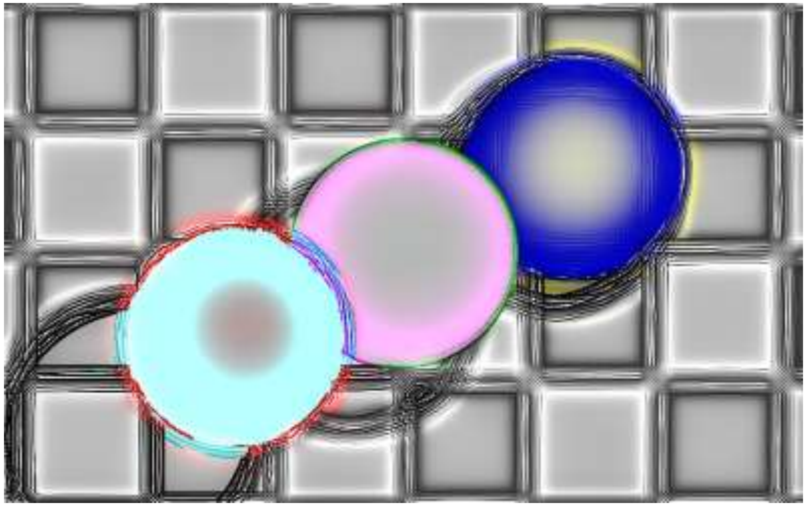
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



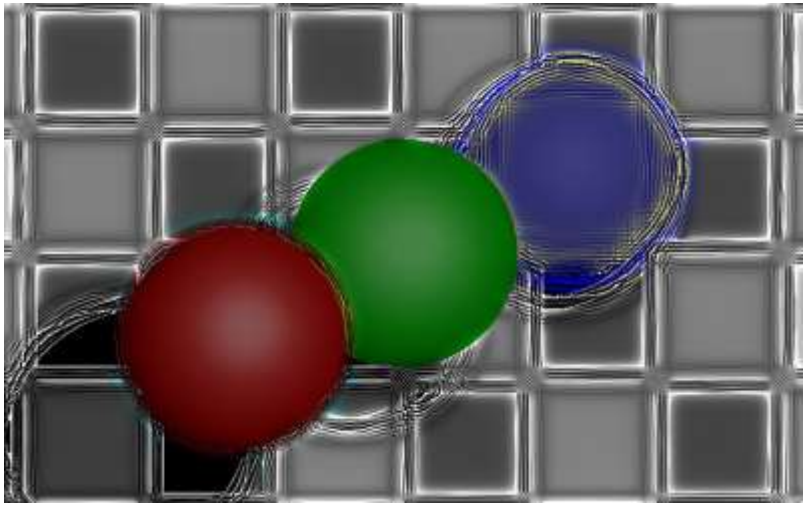
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

Optimization: Iteration 50



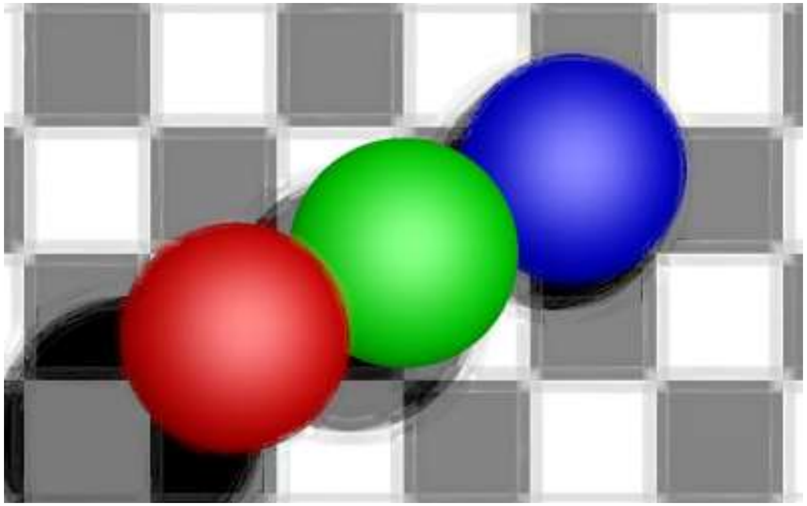
rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

$$F \leftarrow F \circ \frac{[(W \circ L)G^t]}{[(W \circ (FG))G^t]}$$

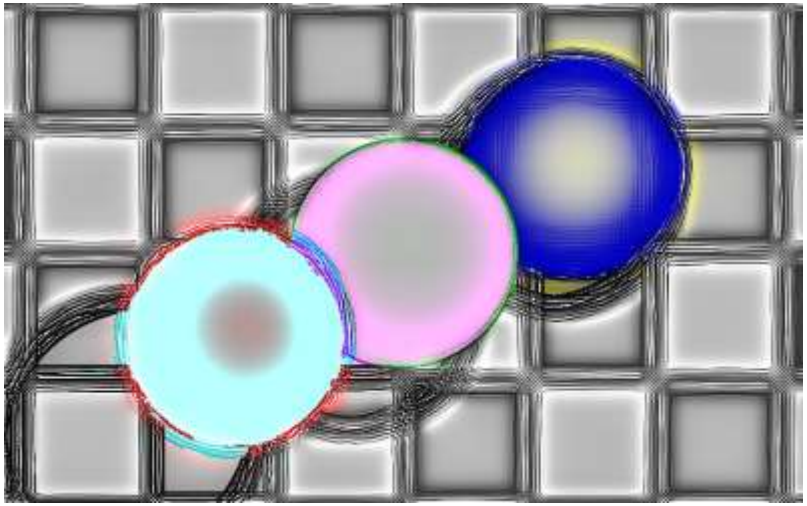
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



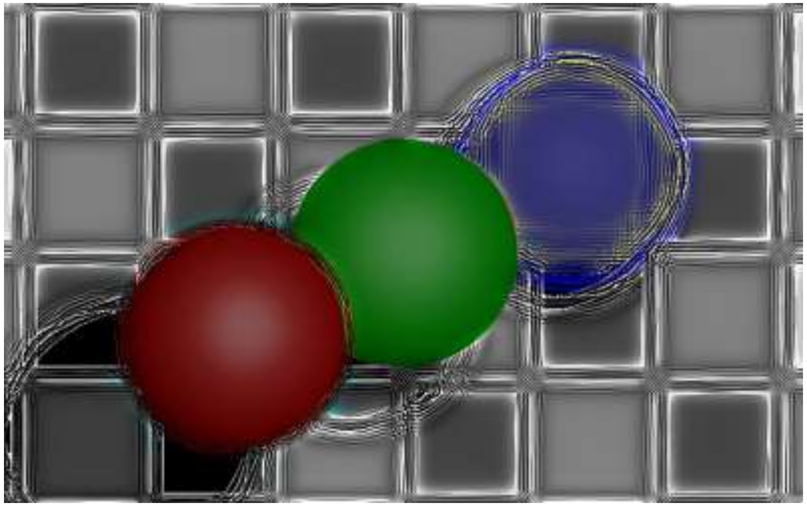
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

Optimization: Iteration 60



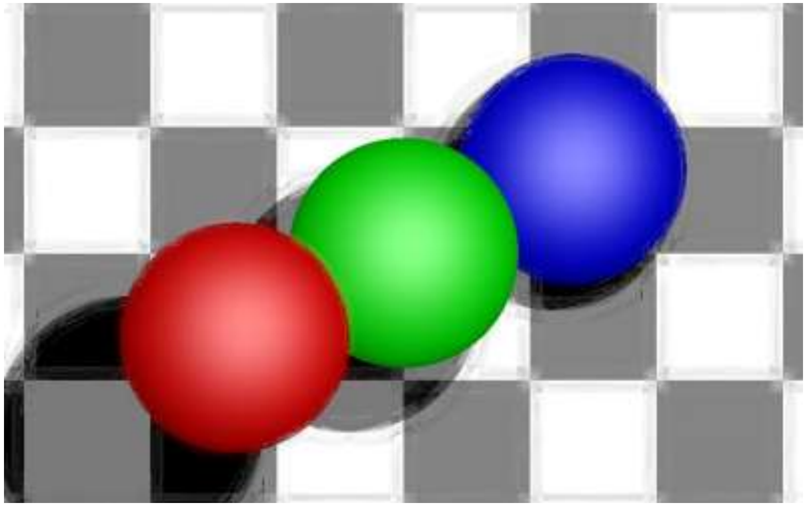
rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

$$F \leftarrow F \circ \frac{[(W \circ L)G^t]}{[(W \circ (FG))G^t]}$$

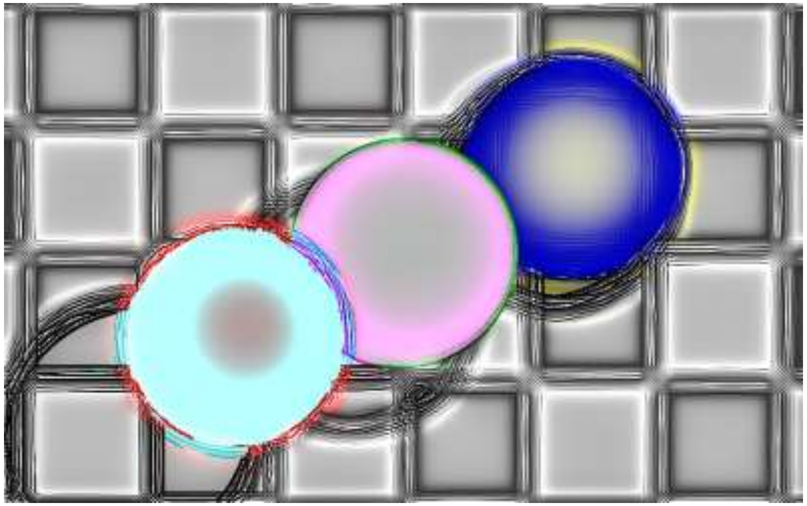
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



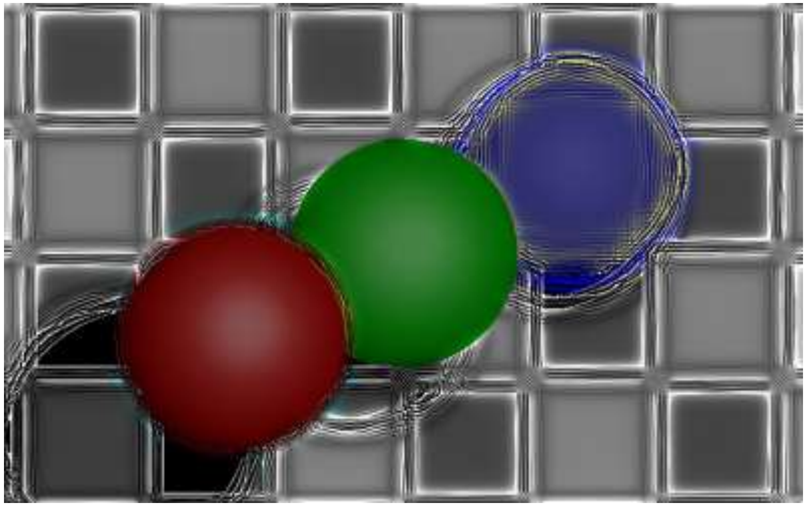
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

Optimization: Iteration 70



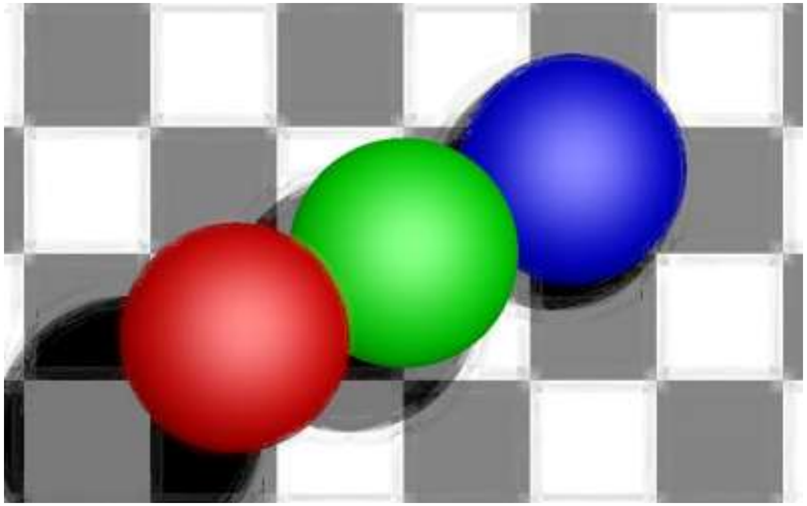
rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

$$F \leftarrow F \circ \frac{[(W \circ L)G^t]}{[(W \circ (FG))G^t]}$$

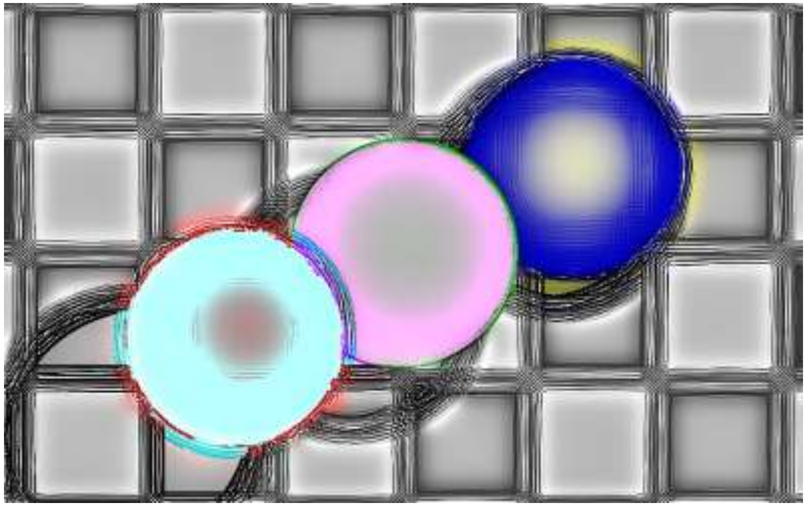
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



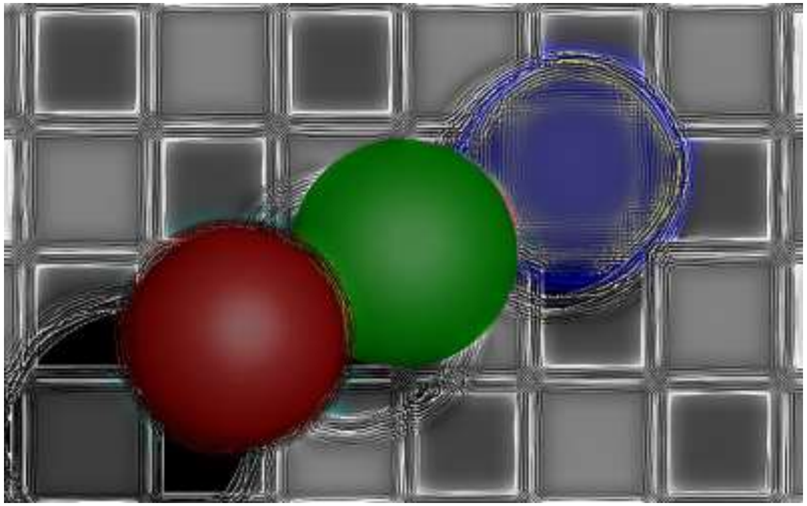
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

Optimization: Iteration 80



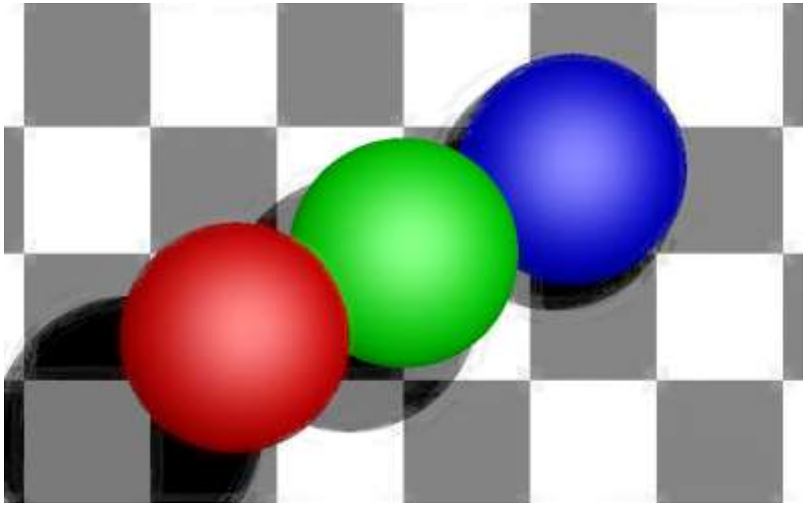
rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

$$F \leftarrow F \circ \frac{[(W \circ L)G^t]}{[(W \circ (FG))G^t]}$$

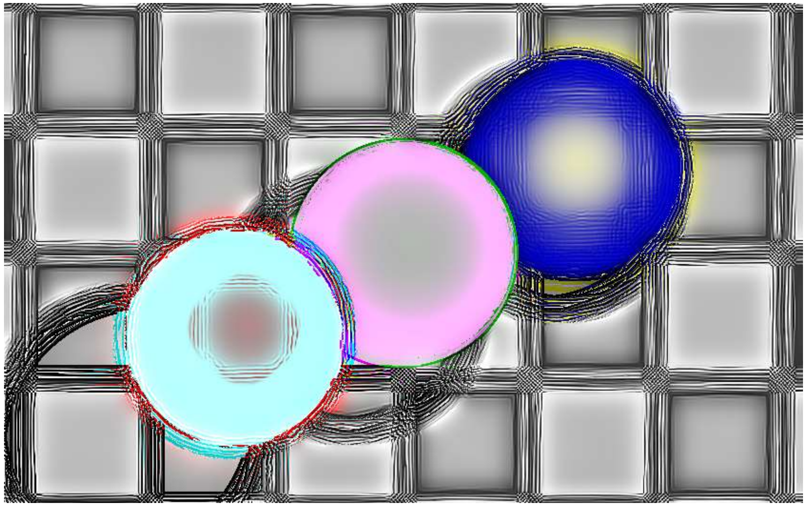
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



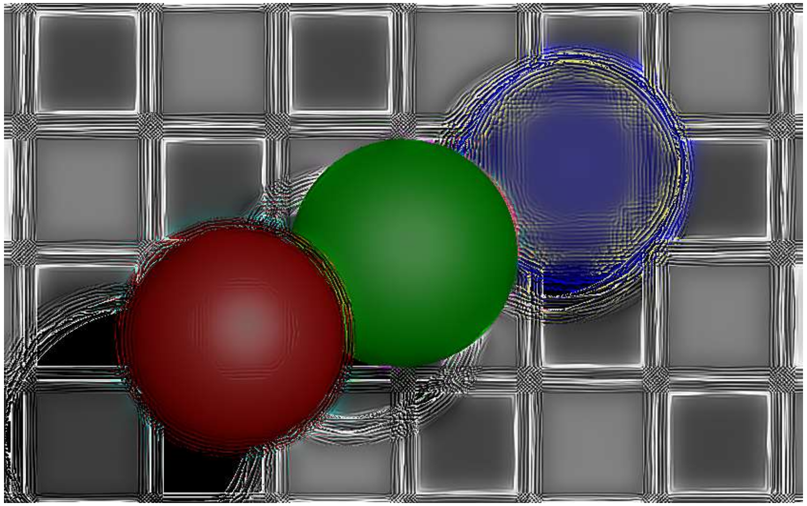
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

Optimization: Iteration 90



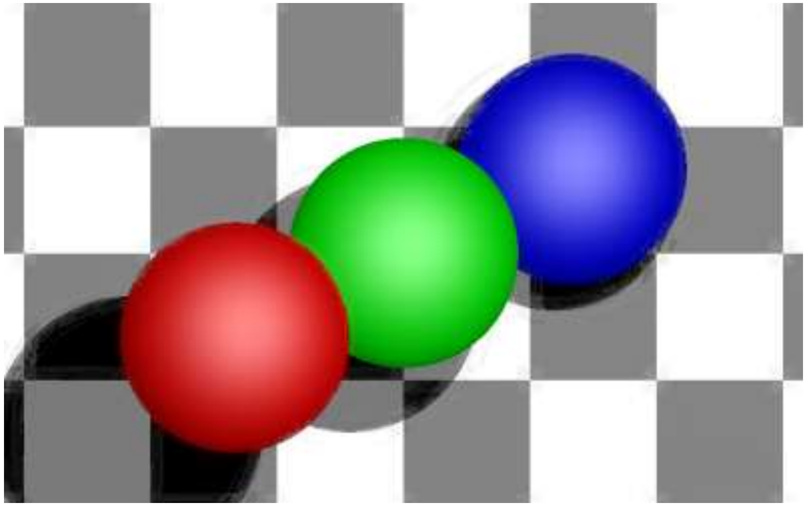
rear mask: $f_1[i,j]$



front mask: $g_1[k,l]$

$$F \leftarrow F \circ \frac{[(W \circ L)G^t]}{[(W \circ (FG))G^t]}$$

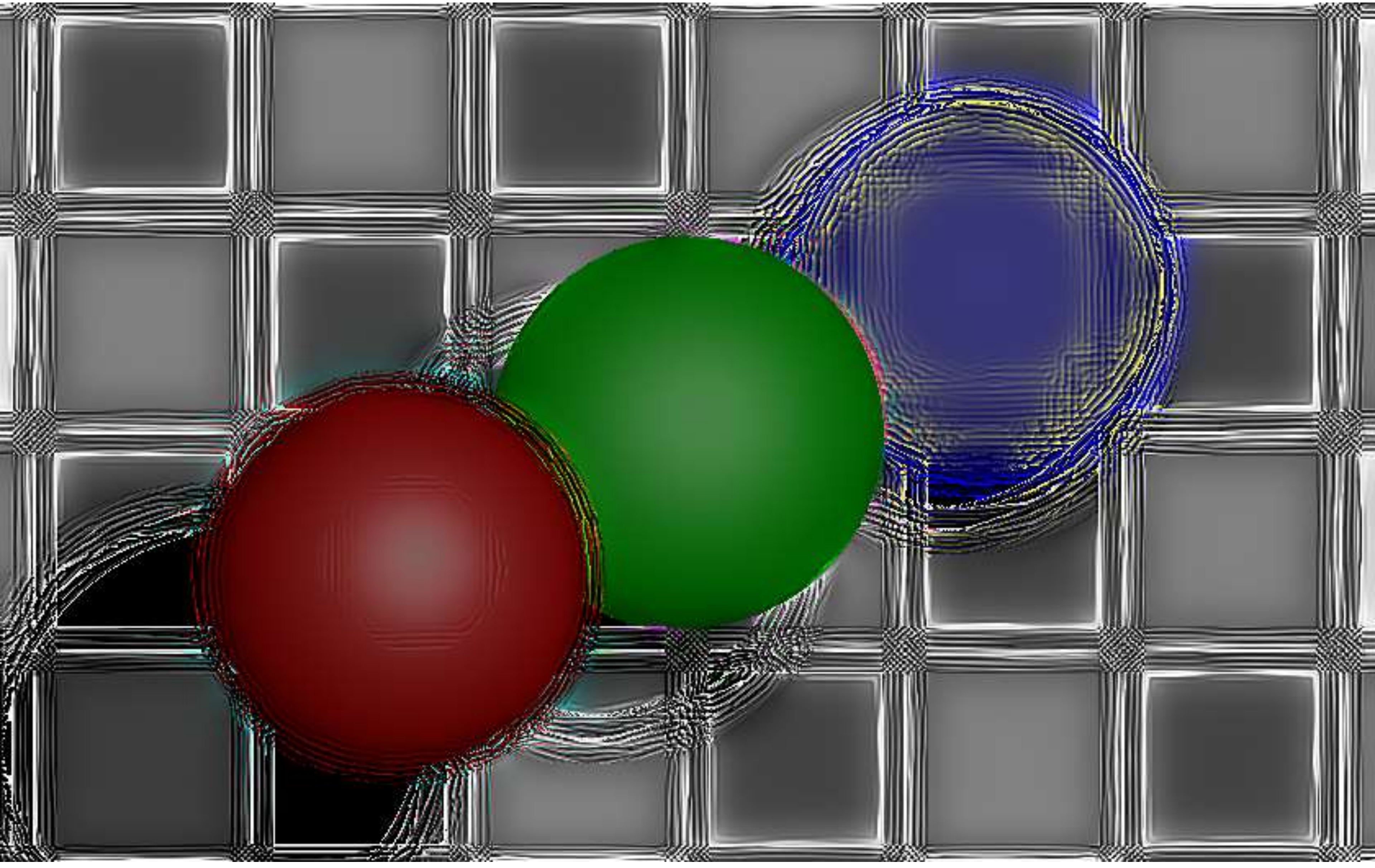
$$G \leftarrow G \circ \frac{[F^t(W \circ L)]}{[F^t(W \circ (FG))]}$$



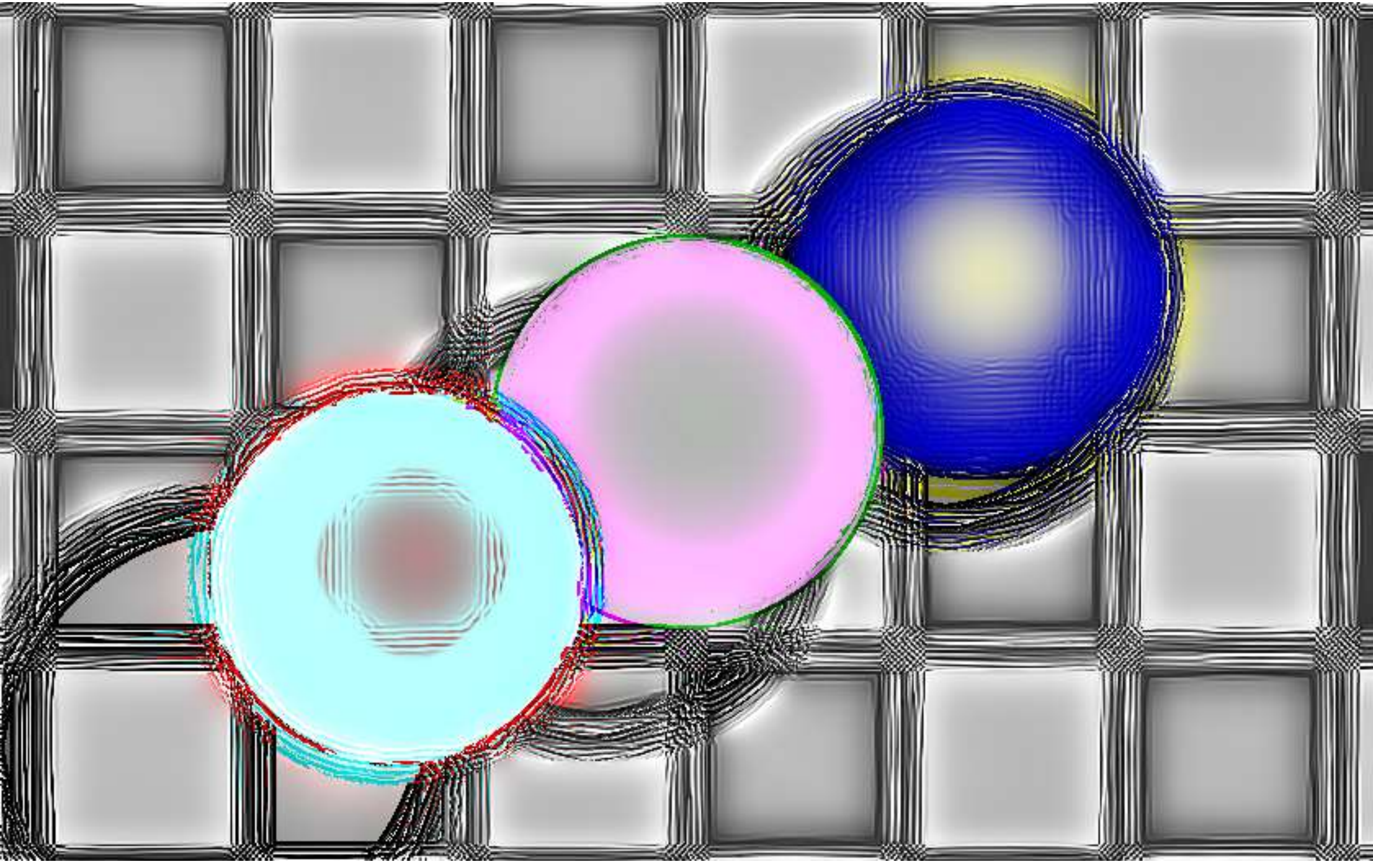
reconstruction (central view)

Daniel Lee and Sebastian Seung. Non-negative Matrix Factorization. 1999.
Vincent Blondel *et al*. Weighted Non-negative Matrix Factorization. 2008.

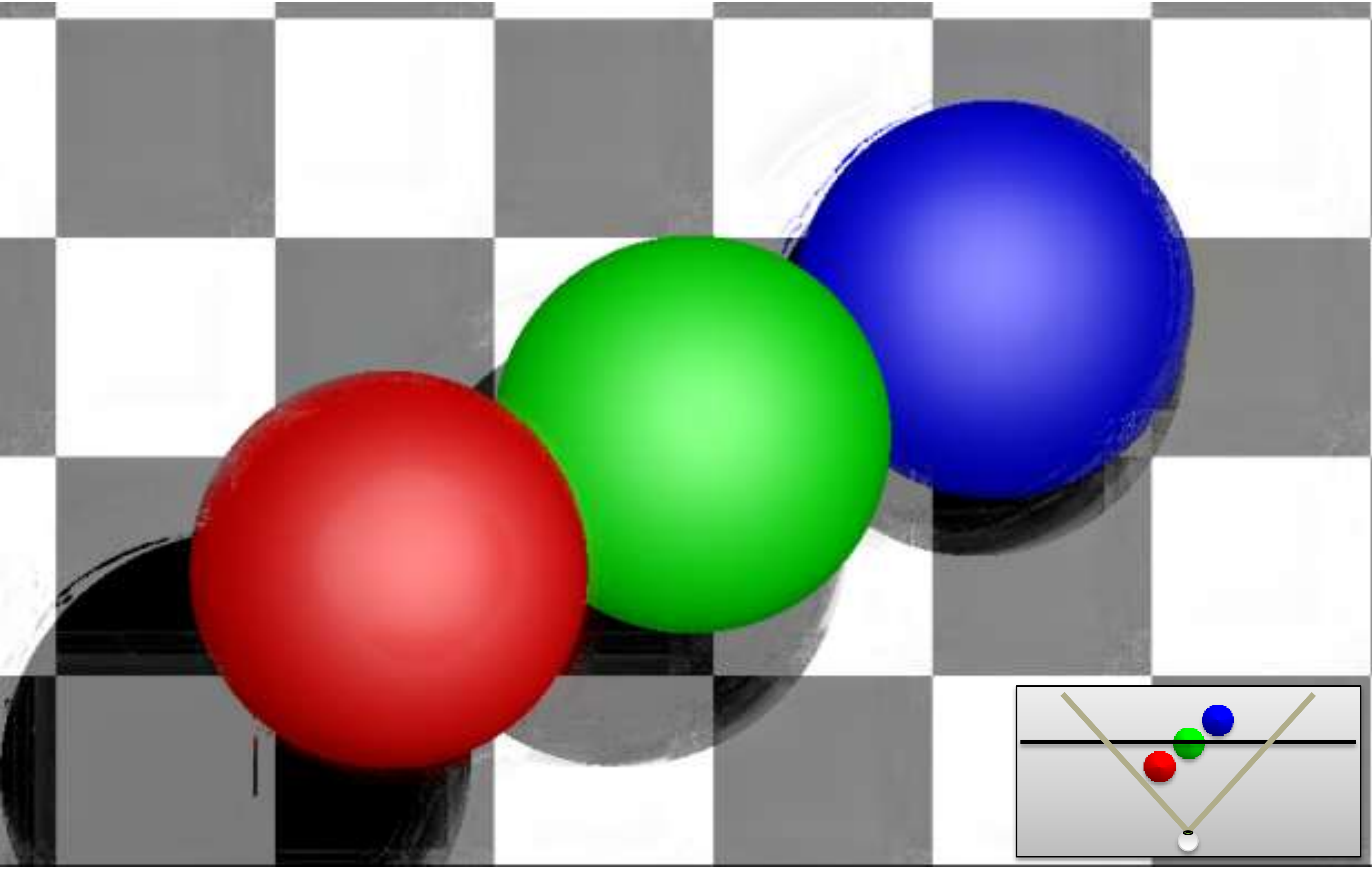
Content-Adaptive Front Mask (1 of 9)



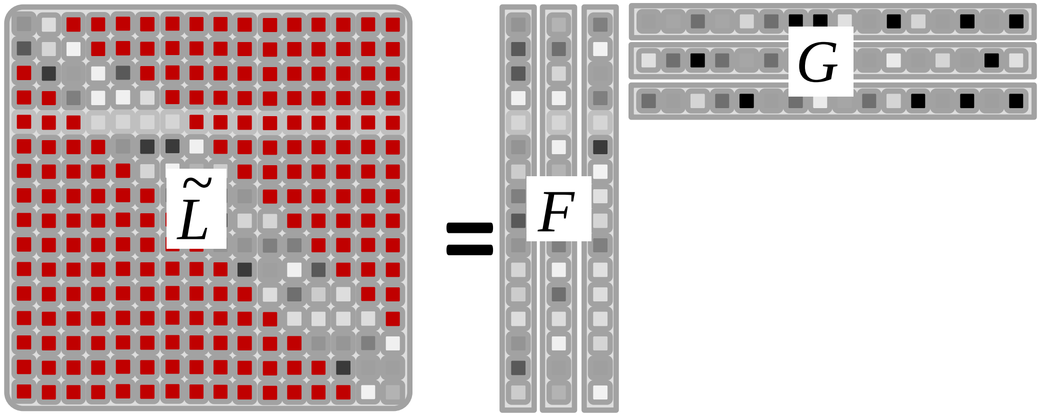
Content-Adaptive Rear Mask (1 of 9)



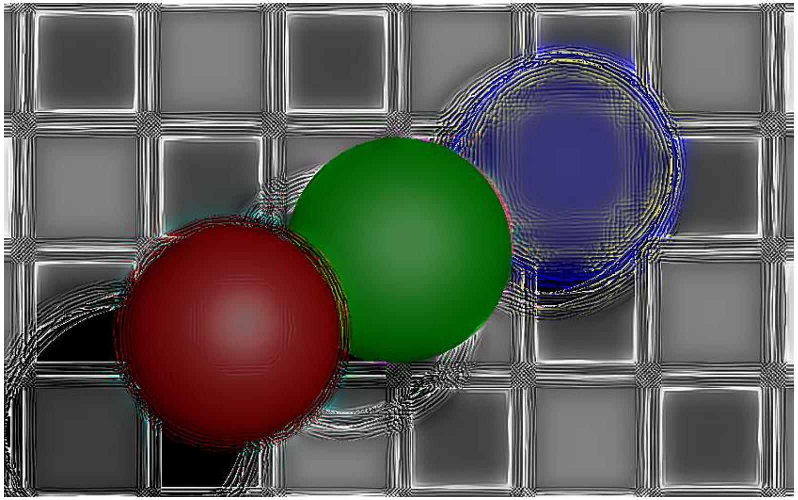
Emitted 4D Light Field



Conclusion



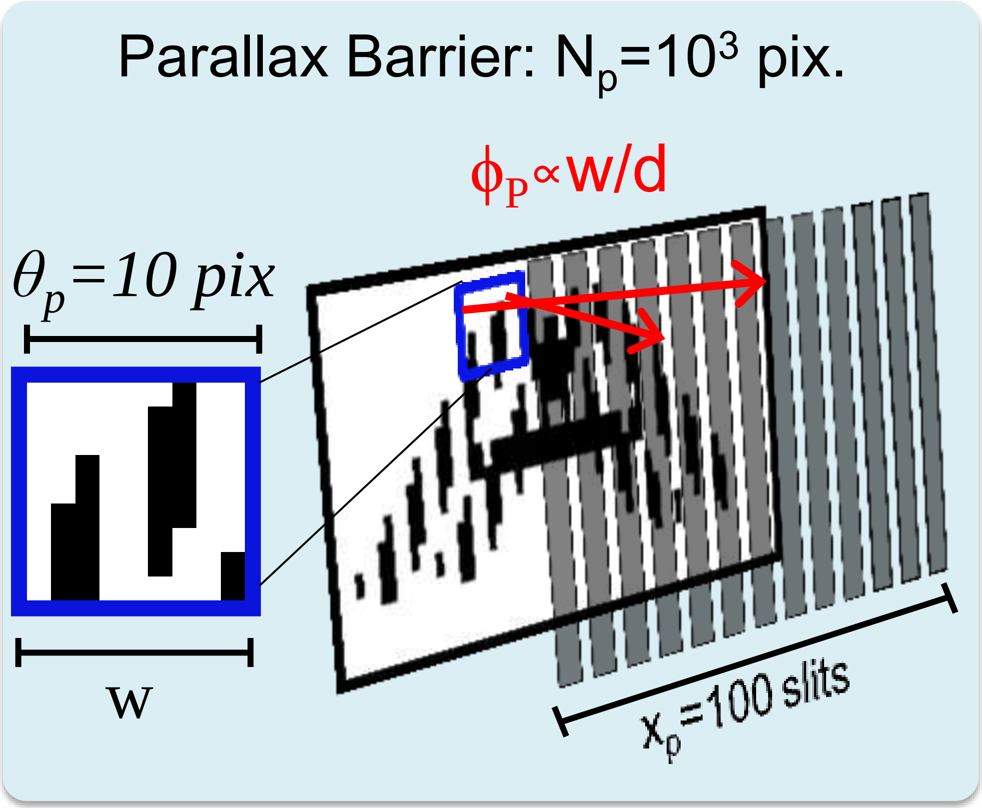
$$\arg\min_{F,G} \frac{1}{2}\left\| L - FG \right\|_W^2, \text{ for } F, G \geq 0$$

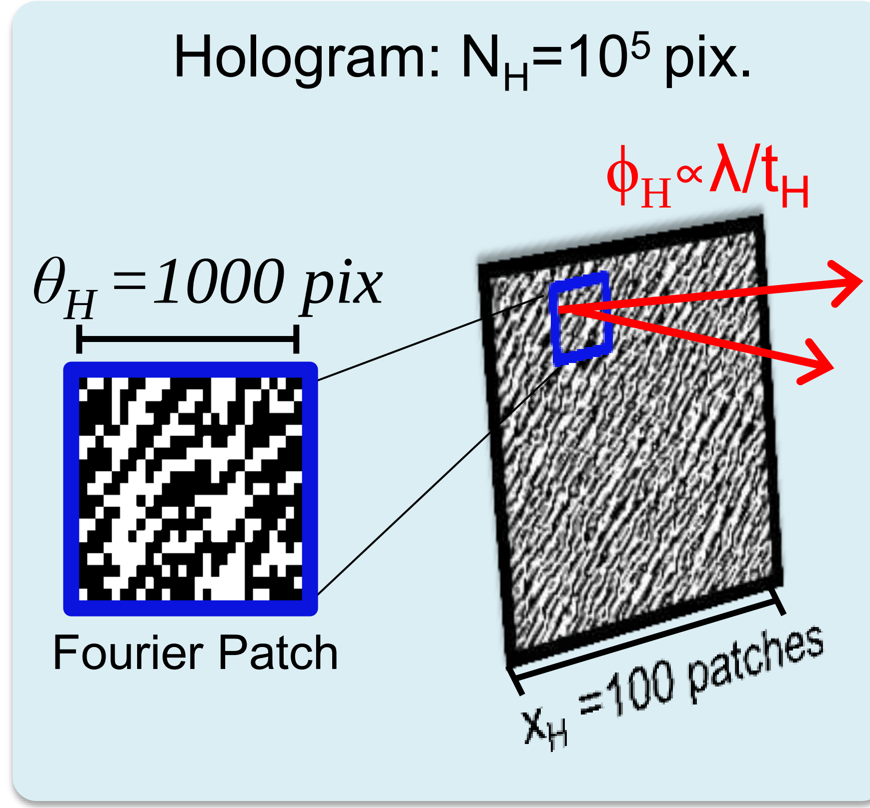


Content-Adaptive Parallax Barriers

- Described a *rank constraint* for all dual-layer displays
  - With a fixed pair of masks, emitted light field is rank-*1*
- Achieved higher-rank approximation using temporal multiplexing
  - With *T* time-multiplexed masks, emitted light field is rank-*T*
  - Constructed a prototype using off-the-shelf panels
- Demonstrated light field display is a *matrix approximation problem*
- Introduced *content-adaptive parallax barriers*
  - Applied weighted NMF to optimize weighted Euclidean distance to target

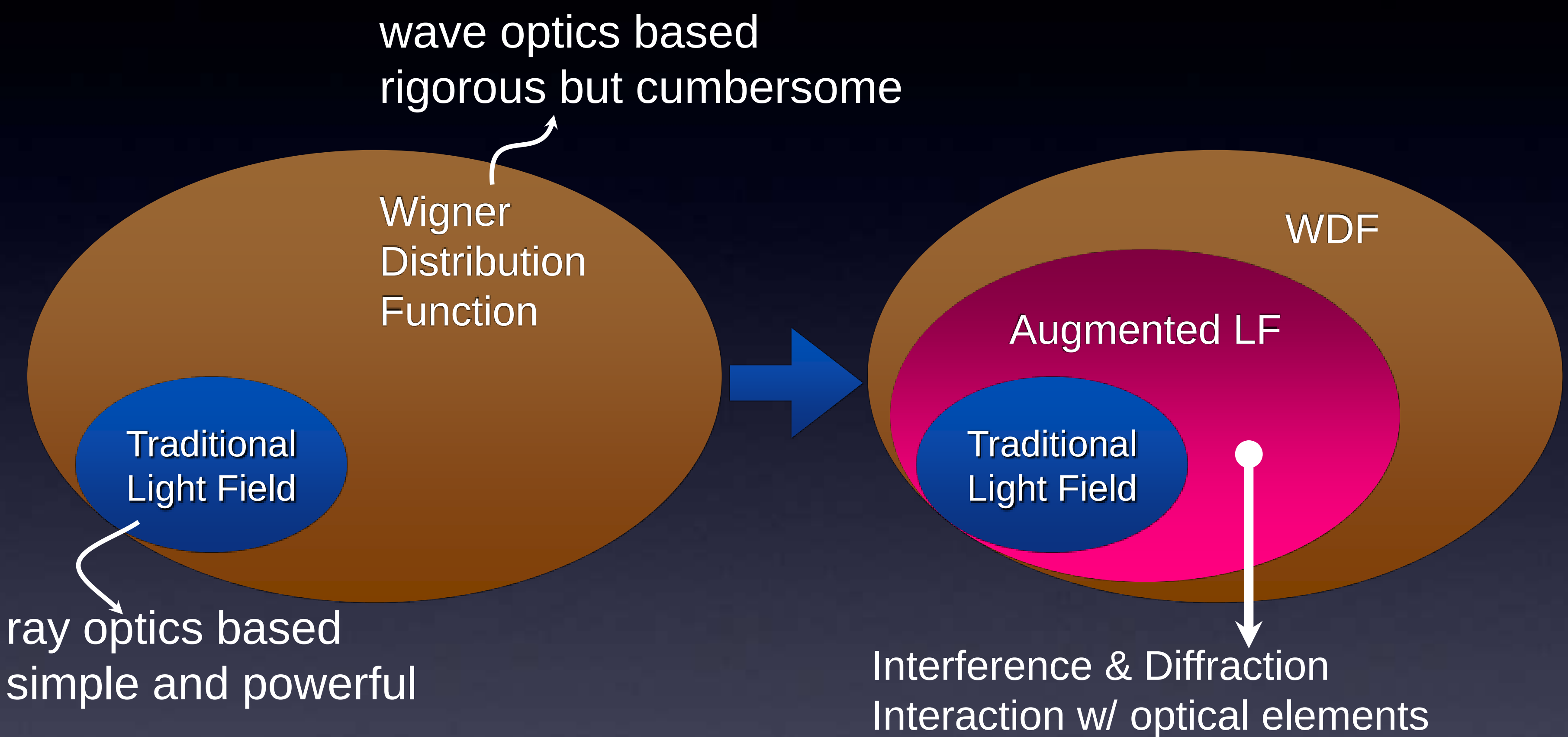
Adaptation increases brightness and refresh rate of dual-stacked LCDs





Horstmeyer, Oh, Cuypers, Barbastathis, Raskar, 2009

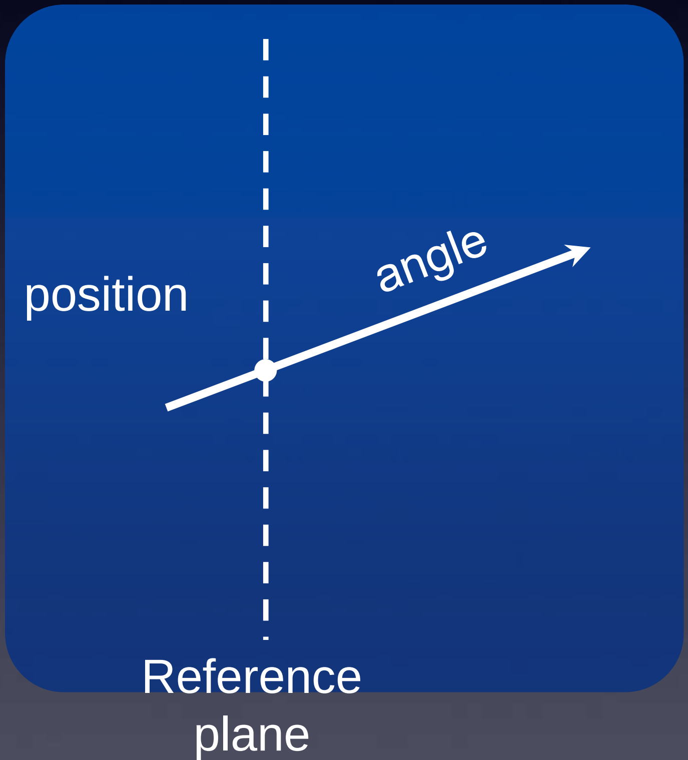
Augmented Light Field

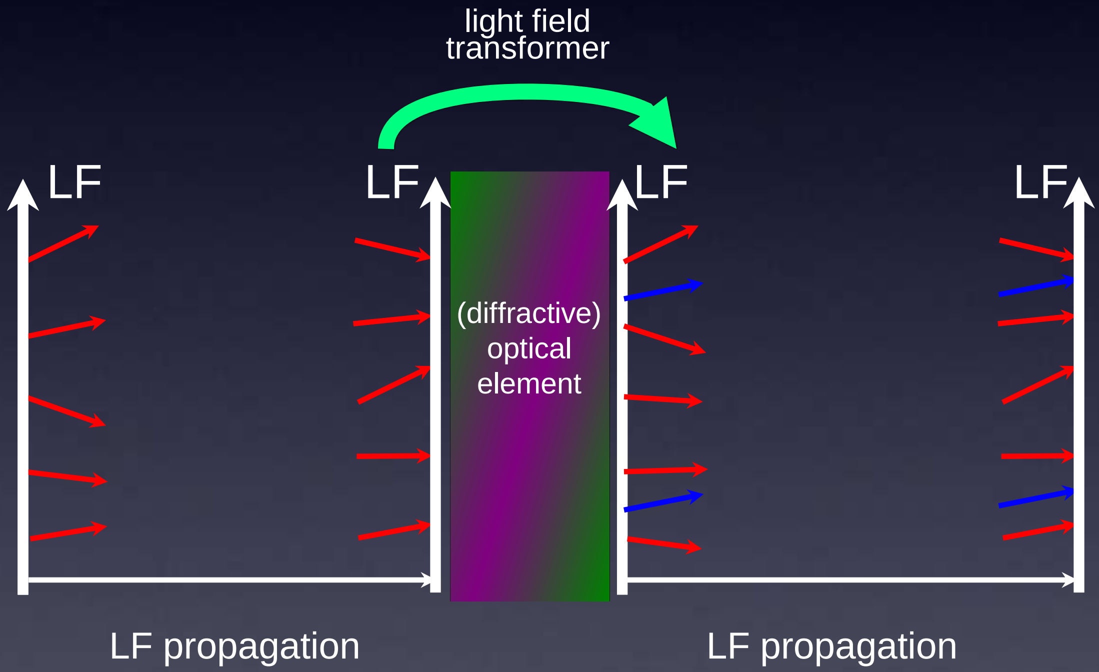


Oh, Raskar, Barbastathis 2009: Augmented Light Field

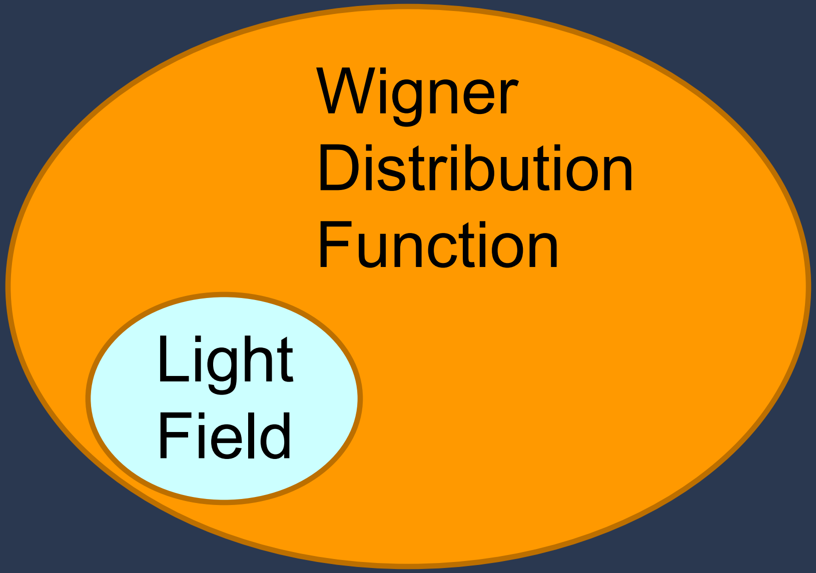
Light Fields

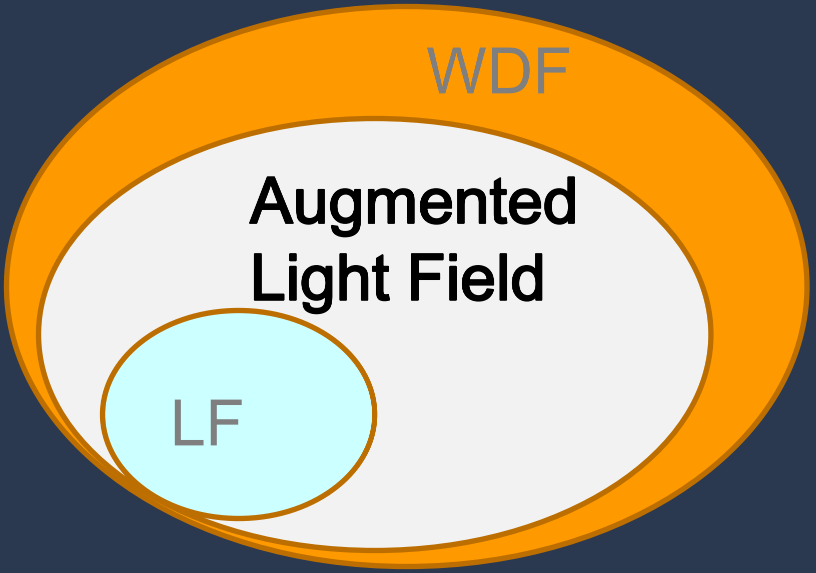
Goal: Representing propagation, interaction and image formation of light using purely position and angle parameters





Augmented Lightfield for Wave Optics Effects





LF < WDF

Lacks phase properties
Ignores diffraction, interferrence

Radiance = Positive

ALF ~ WDF

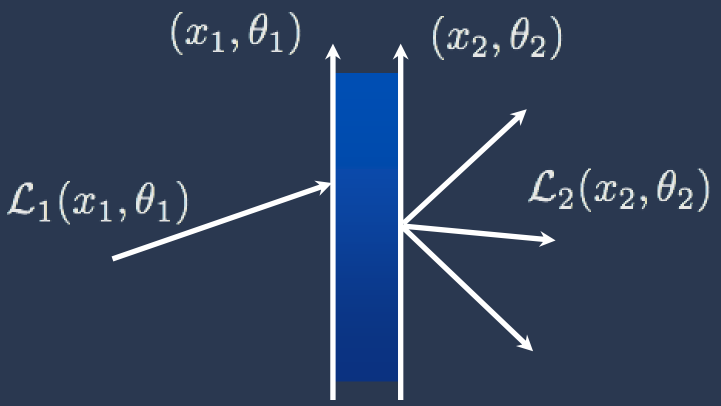
Supports coherent/incoherent

Radiance = Positive/Negative

Virtual light sources

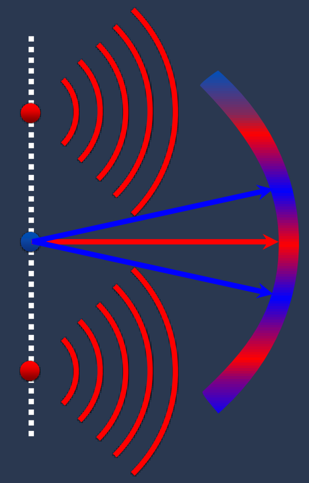
Free-space propagation

Light field transformer



Virtual light projector

Possibly negative radiance

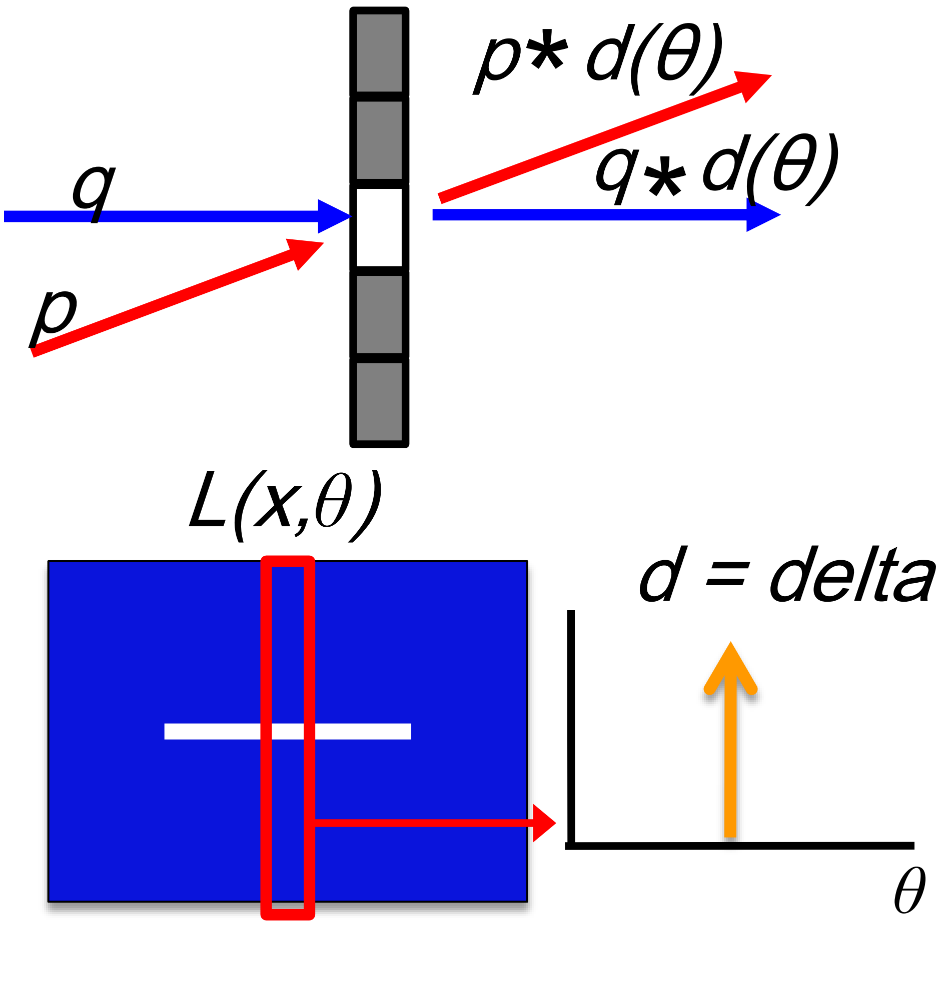


Lightfield vs Hologram Displays

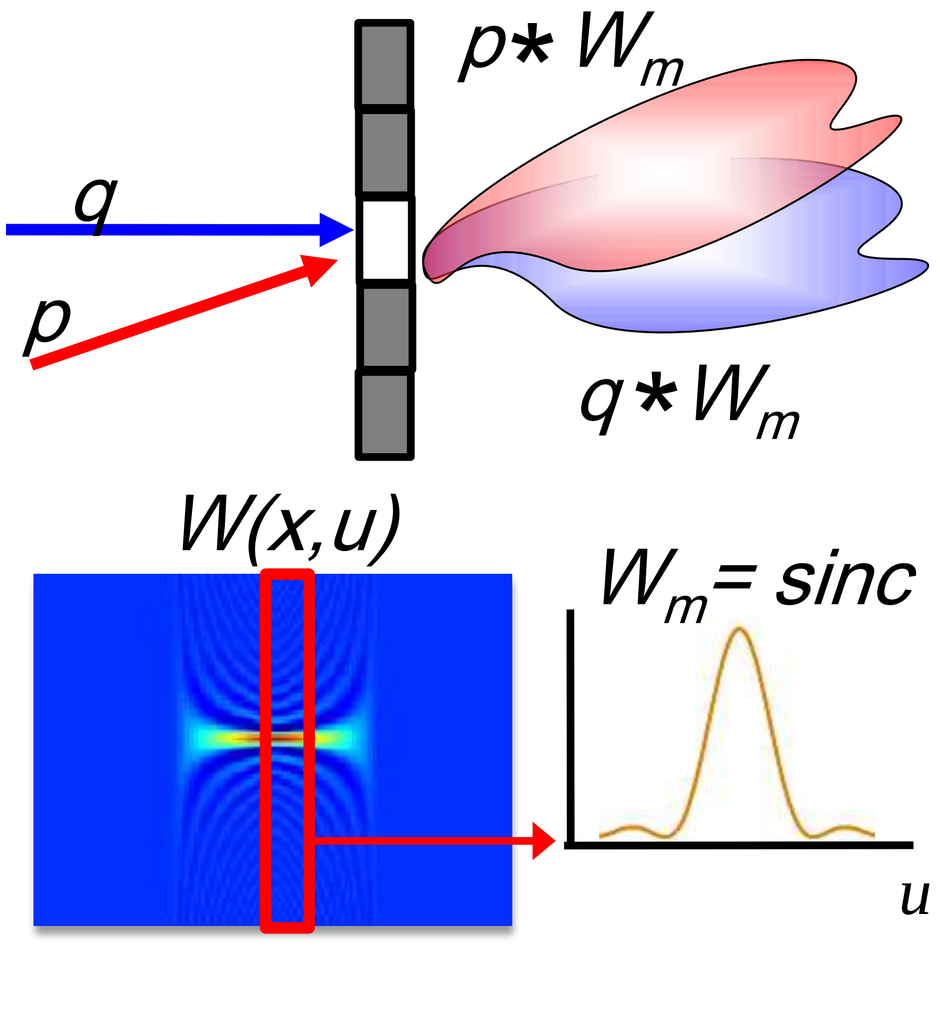
Is hologram just another ray-based light field?
Can a hologram create any intensity distribution in 3D?
Why hologram creates a 'wavefront' but PB does not?
Why hologram creates automatic accommodation cues?
What is the effective resolution of HG vs PB?

Zooming into the Light Field

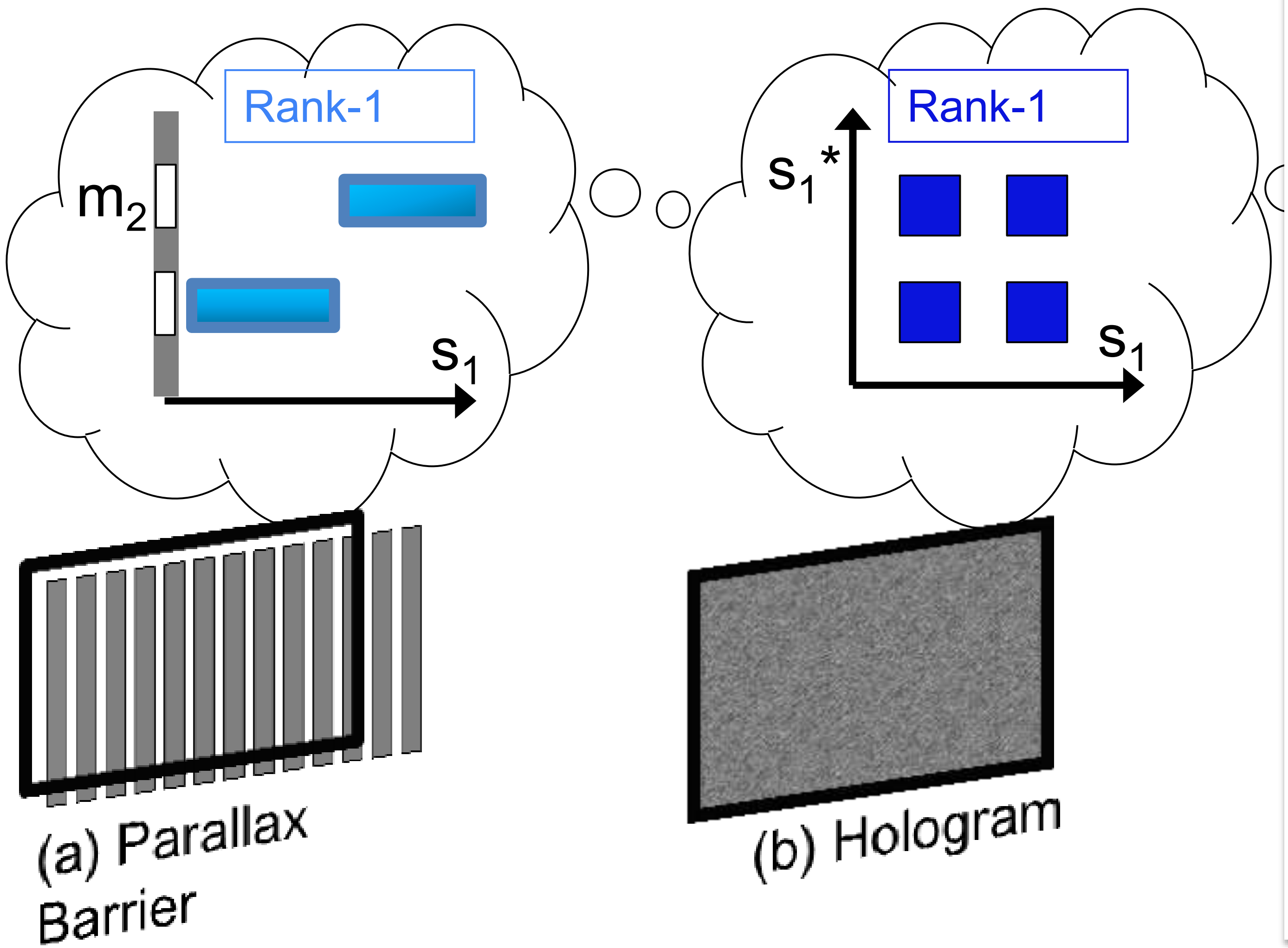
Rays: No Bending

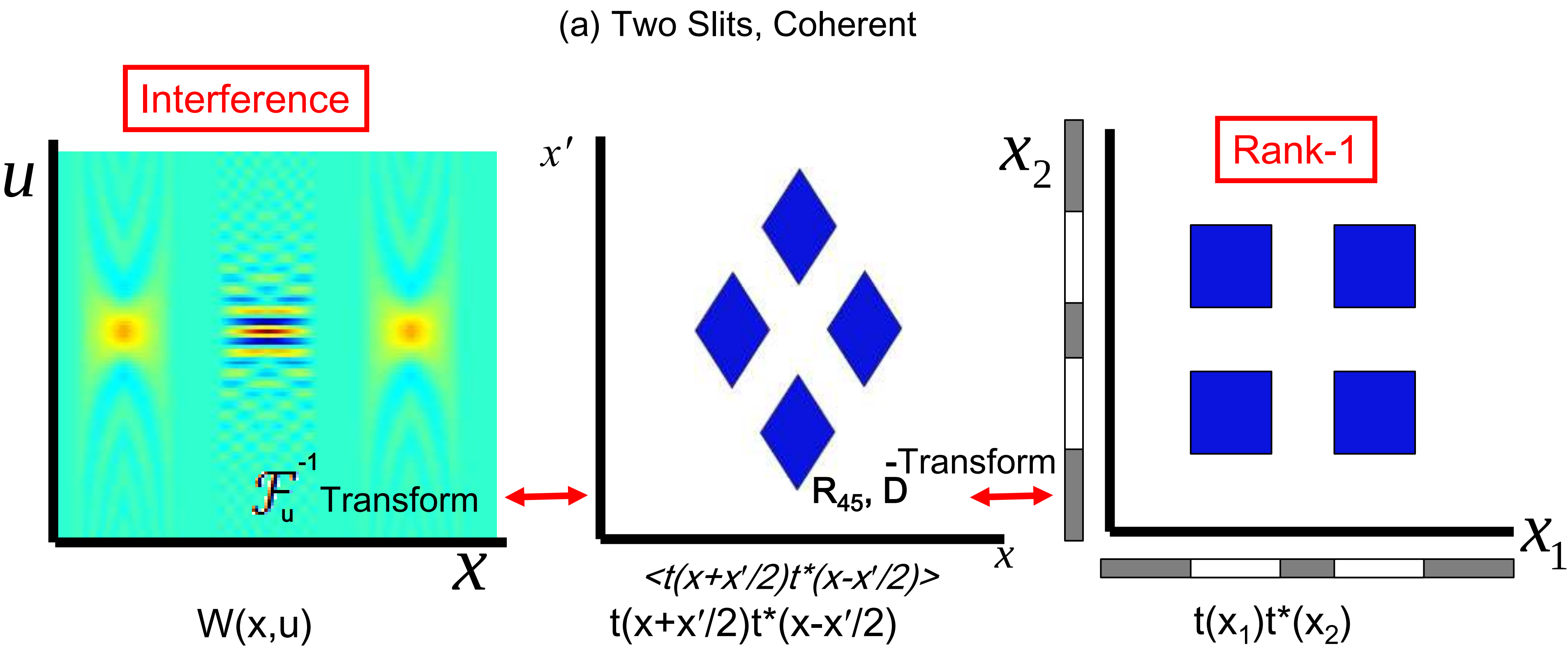


1 Fresnel HG Patch

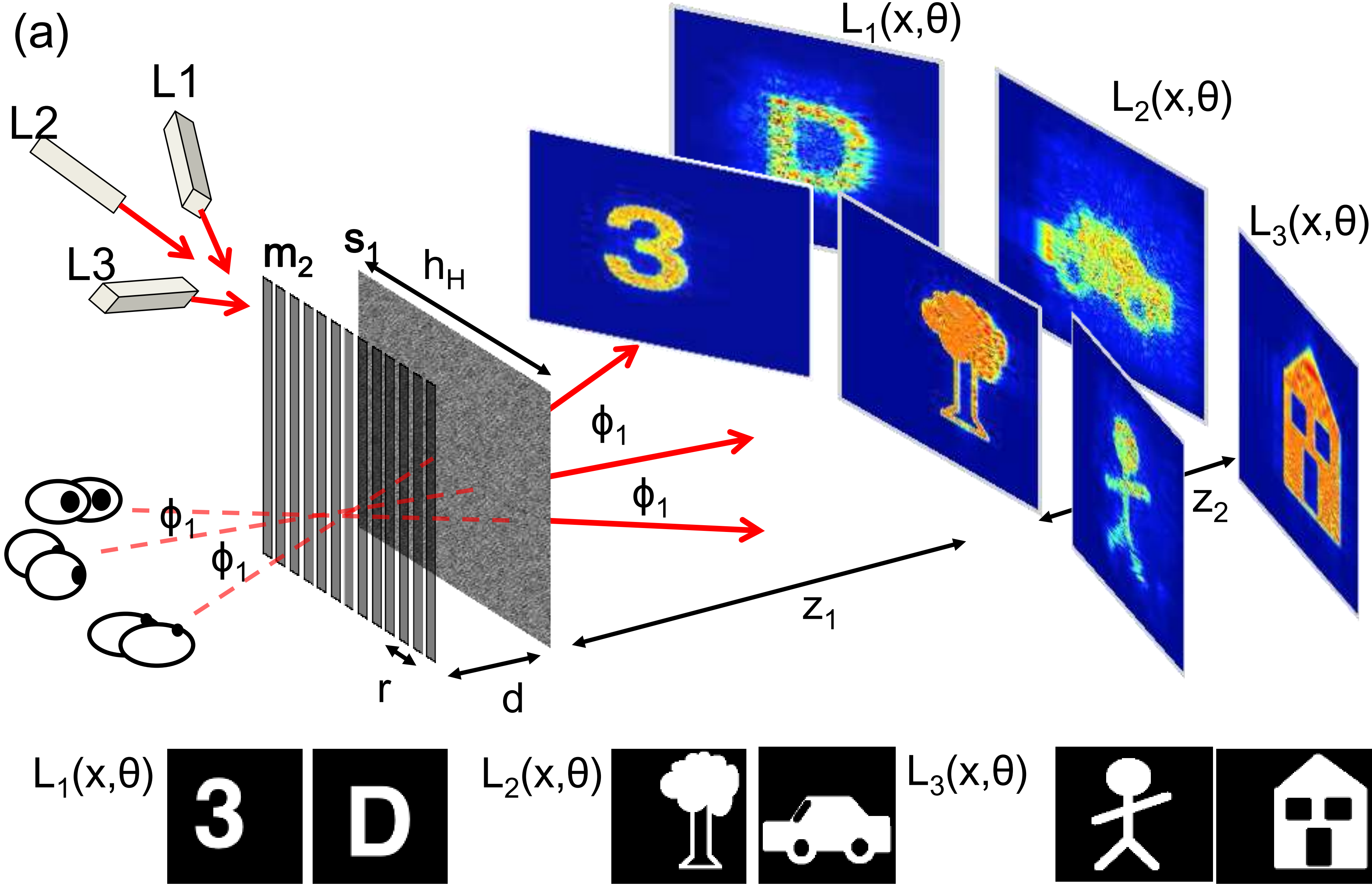


Algebraic Rank Constraint





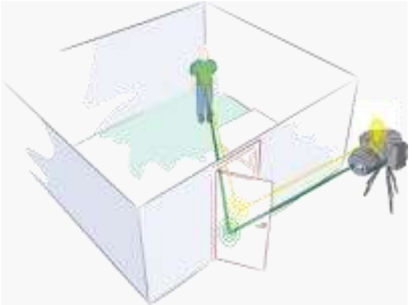
(a) Two Slits, Coherent
Interference
u
x
$\mathcal{F}_u^{-1}$ Transform
W(x,u)
x′
x
R45, D -Transform
<t(x+x′/2)t*(x-x′/2)>
t(x+x′/2)t*(x-x′/2)
Rank-1
x2
x1
t(x1)t*(x2)



(a)
L1
L2
L3
m_2
s_1
h_H
ϕ_1
ϕ_1
ϕ_1
ϕ_1
r
d
z_1
z_2
$L_1(x,\theta)$
$L_2(x,\theta)$
$L_3(x,\theta)$
3
D
$L_1(x,\theta)$
$L_2(x,\theta)$
$L_3(x,\theta)$
3
D

Is hologram just another ray-based light field?
Can a hologram create any intensity distribution in 3D?
Why hologram creates a ‘wavefront’ but PB does not?
Why hologram creates automatic accommodation cues?
What is the effective resolution of HG vs PB?

Inverse Problems



- Co-design of Optics and Computation
  - Photons not just pixels
  - Mid-level cues
- Computational Photography
  - Coded Exposure
  - Compressive Sensing for High Speed Events
    - Limits of CS for general imaging

- Computational Light Transport
  - Looking Around Corners, trillion fps
  - Lightfields:
    - Compressive Campture
    - 3D Displays and Holograms