Computational Cameras for Light Field Processing

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Candidacy Exam

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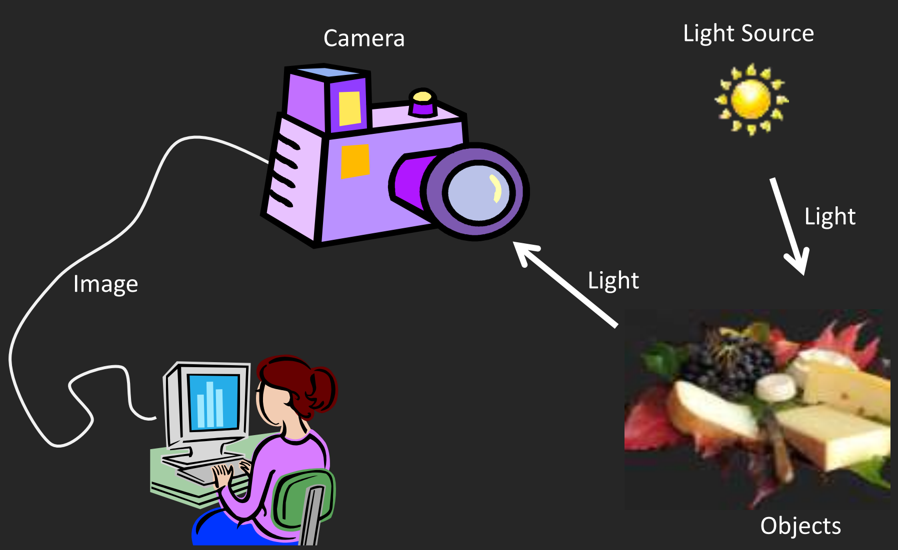
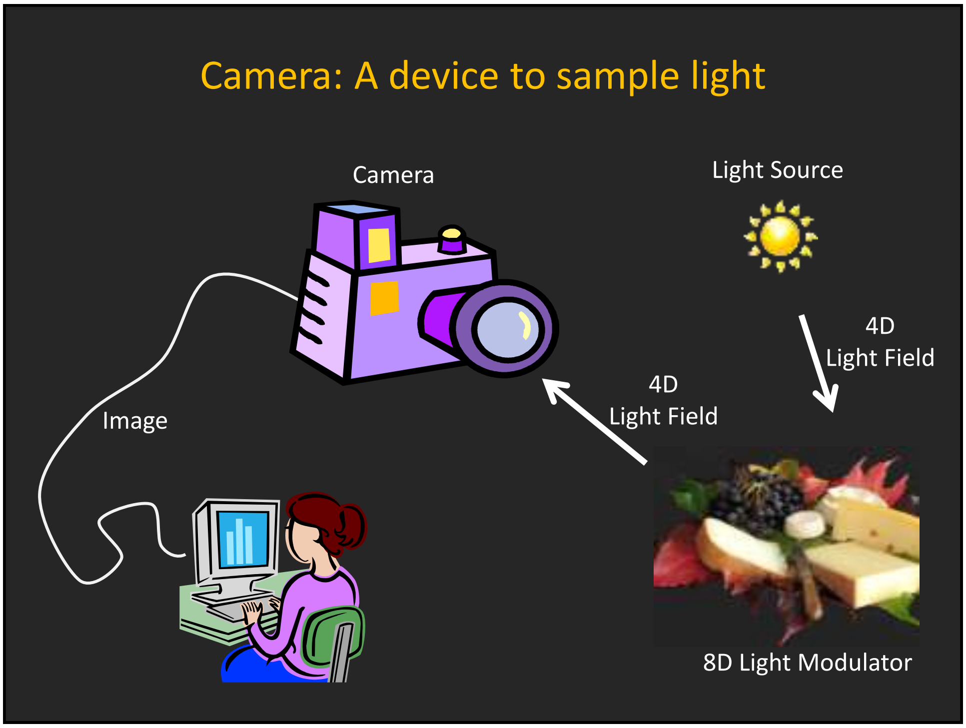
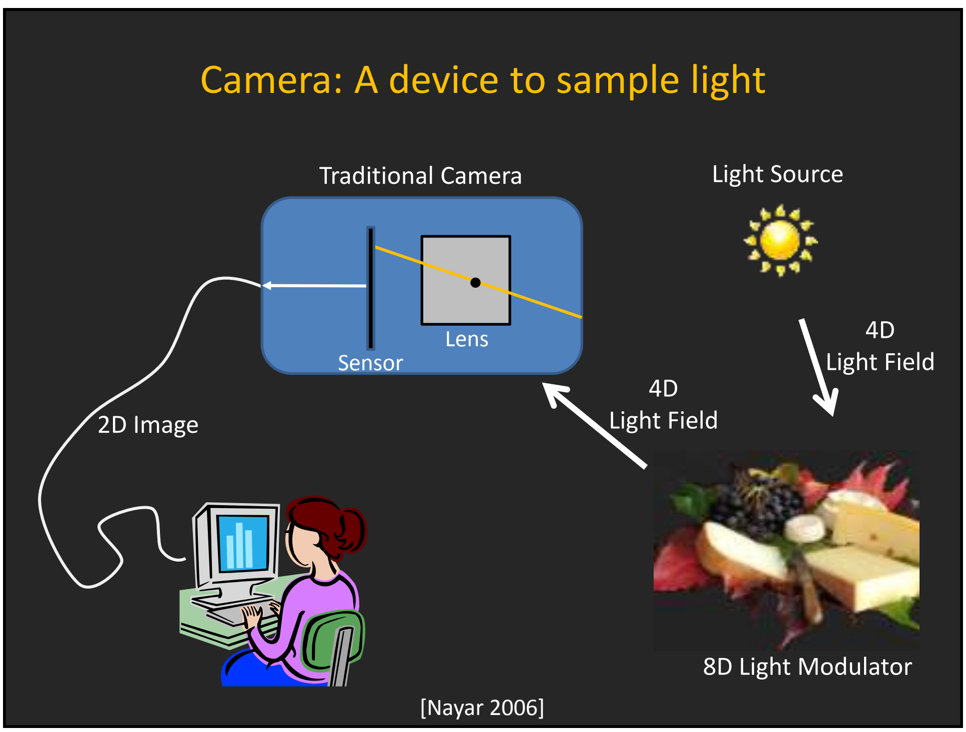
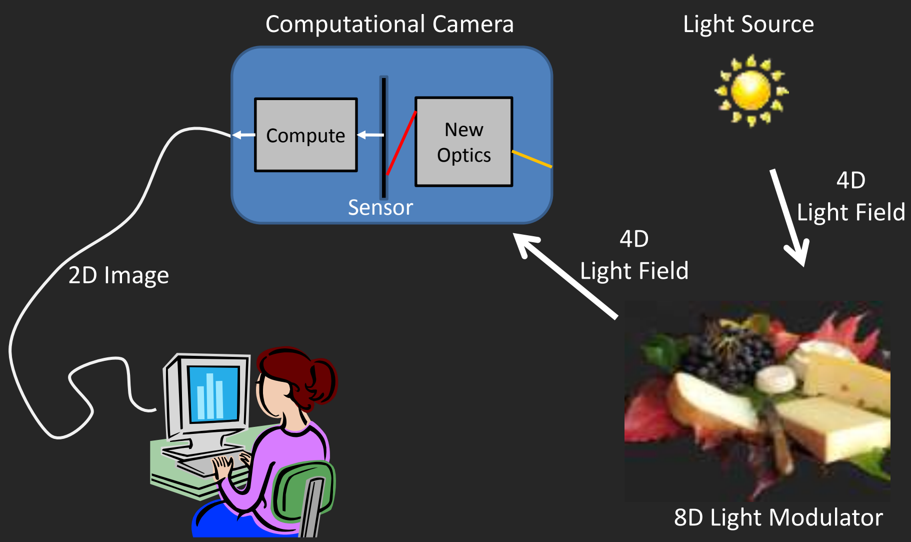
Camera: A device to sample light




Camera: A device to sample light
Camera
Light Source
4D
Light Field
4D
Light Field
Image
8D Light Modulator


Camera: A device to sample light
Traditional Camera
Light Source
Lens
Sensor
4D
Light Field
4D
Light Field
2D Image
8D Light Modulator
[Nayar 2006]

Computational Camera: Samples light in new ways

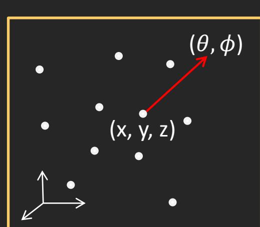


[Nayar 2006]

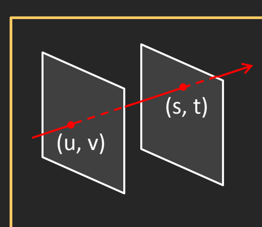
Light Fields

[Faraday1846][Gershun1936] [Adelson1991][Levoy1996][Gortler1996]

- Light Field: Radiance function of position and direction in regions of space free of occluders. (bynames: plenoptic function, lumigraph)

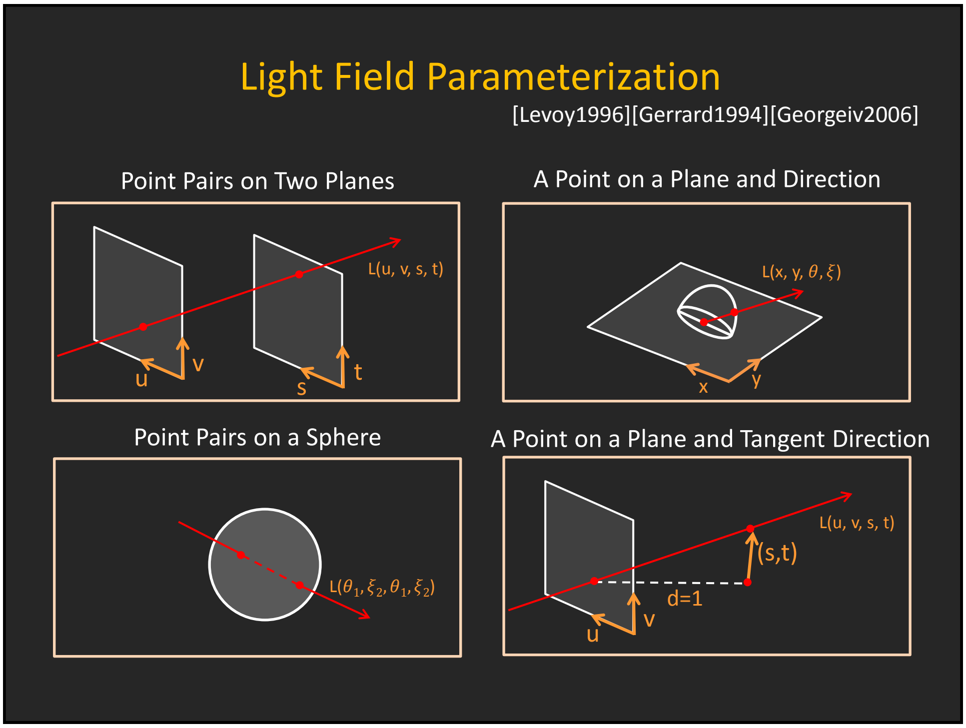


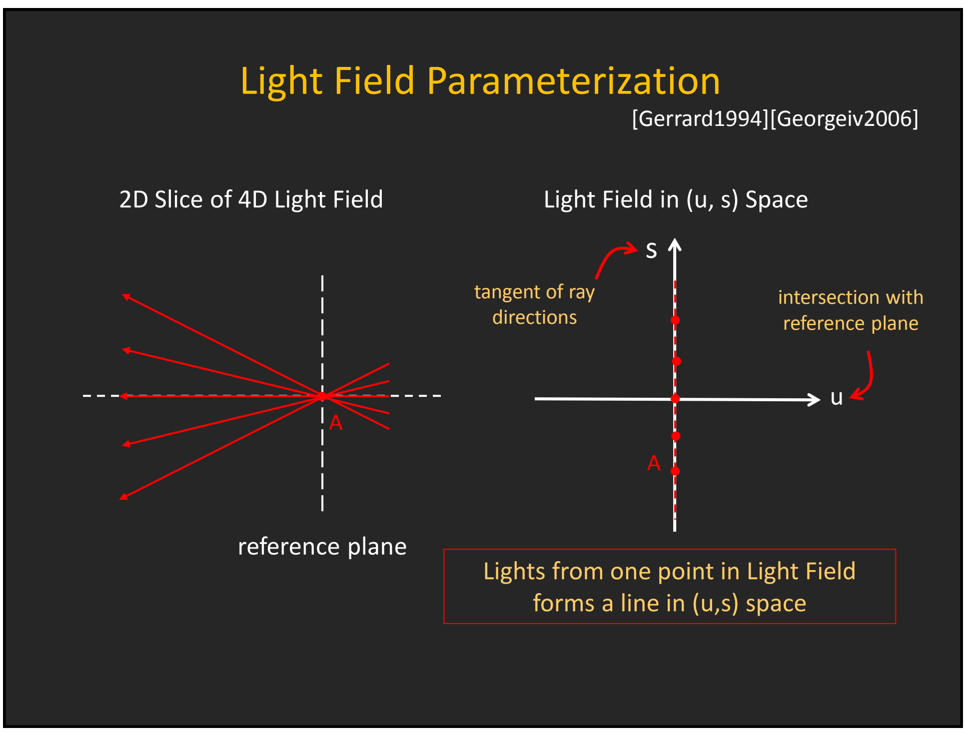
5D Light Field



4D Light Field in free space

"The body of the air is full of an infinite number of radiant pyramids caused by the objects located in it. These pyramids intersect and interweave without interfering with each other during the independent passage throughout the air in which they are infused." -- *Leonardo da Vinci (Kemp, 1969)*

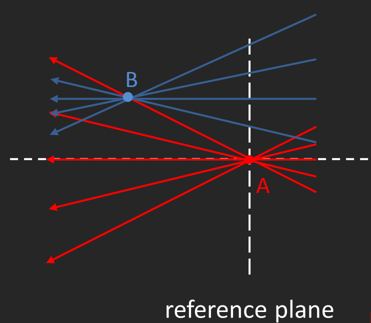

Light Field Parameterization
[Levoy1996][Gerrard1994][Georgeiv2006]
Point Pairs on Two Planes
L(u, v, s, t)
u
v
s
t
A Point on a Plane and Direction
L(x, y, θ, ξ)
x
y
Point Pairs on a Sphere
L(θ_1, ξ_2, θ_1, ξ_2)
A Point on a Plane and Tangent Direction
L(u, v, s, t)
(s,t)
d=1
u
v


Light Field Parameterization
[Gerrard1994][Georgeiv2006]
2D Slice of 4D Light Field
A
reference plane
Light Field in (u, s) Space
s
tangent of ray directions
intersection with reference plane
u
A
Lights from one point in Light Field forms a line in (u,s) space

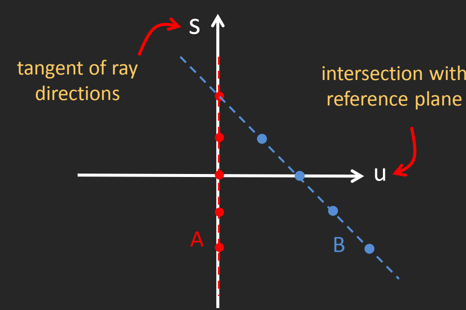
Light Field Parameterization

[Gerrard1994][Georgeiv2006]

2D Slice of 4D Light Field



Light Field in (u, s) Space

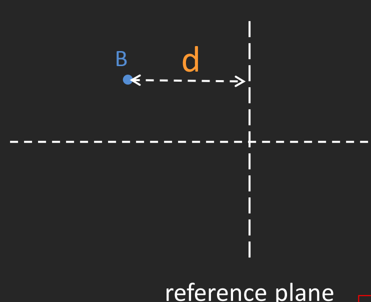


Lights from one point in Light Field forms a line in (u,s) space

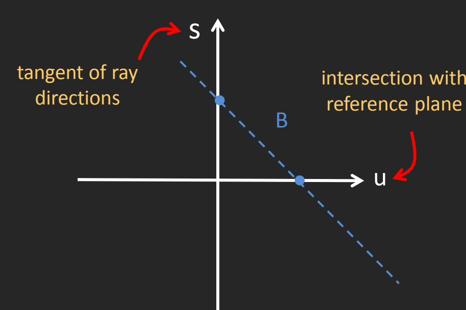
Light Field Parameterization

[Gerrard1994][Georgeiv2006]

2D Slice of 4D Light Field



Light Field in (u, s) Space



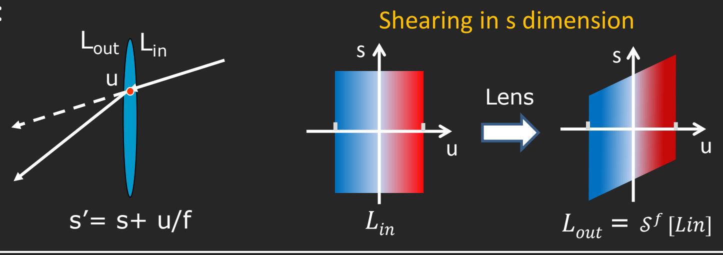
The slope of the line = -1/d

- Vertical Lines for points on the reference plane.
- Horizontal Lines for infinite points

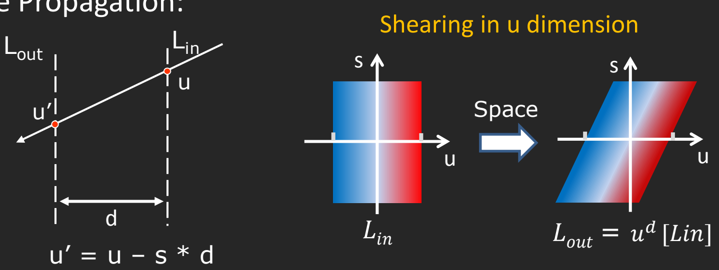
Optical Devices and Light Field Transforms (1)

[Halbach1964] [Gerrard1994][Georgeiv2006]

- Lens:



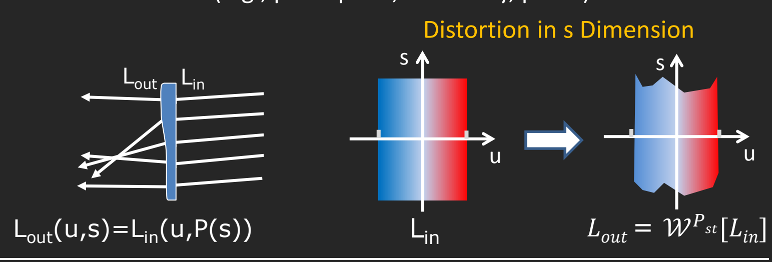
- Space Propagation:



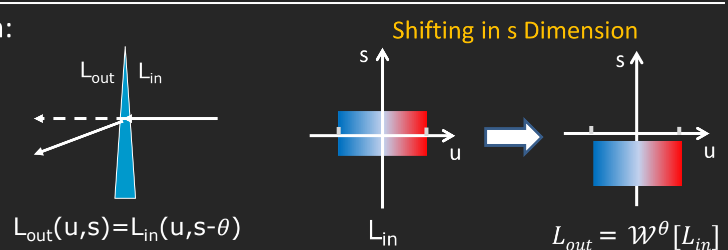
Optical Devices and Light Field Transforms (2)

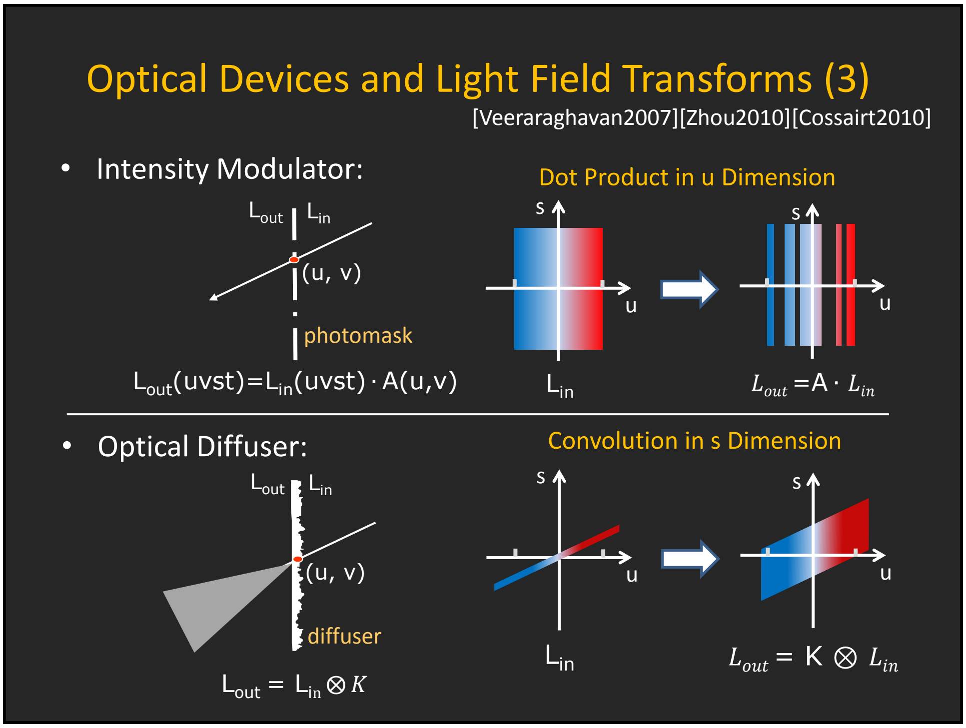
[Halbach1964][Gerrard1994][Georgeiv2006]

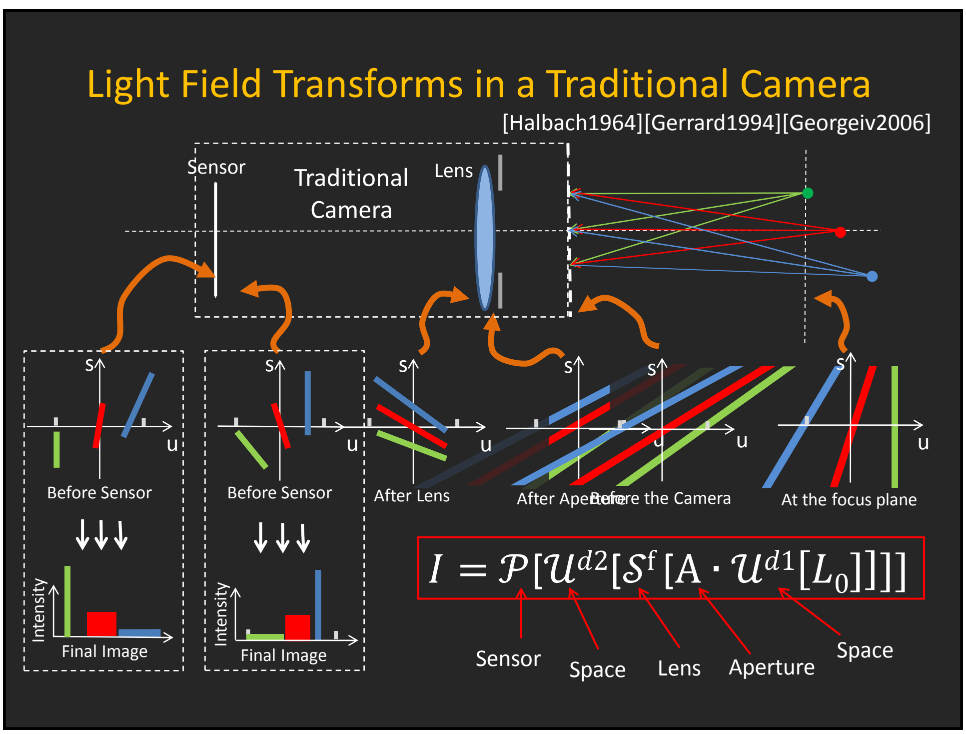
- Phase Modulator (e.g., phaseplate, lens array, prism):



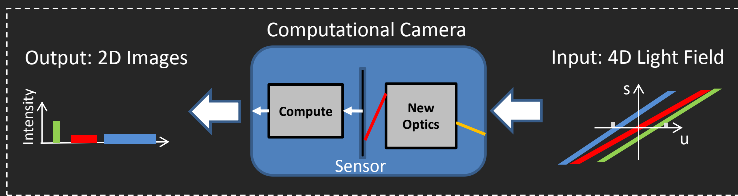
- Prism:




Optical Devices and Light Field Transforms (3)
[Veeraraghavan2007][Zhou2010][Cossairt2010]
Intensity Modulator:
Lout Lin
(u, v)
photomask
Lout(uvst)=Lin(uvst)·A(u,v)
Dot Product in u Dimension
s
u
Lin
Lout =A · Lin
Optical Diffuser:
Lout Lin
(u, v)
diffuser
Lout = Lin ⊗ K
Convolution in s Dimension
Lout = K ⊗ Lin

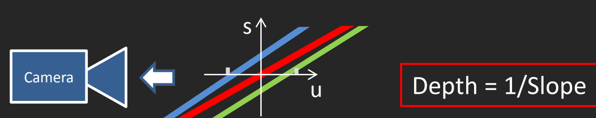

Light Field Transforms in a Traditional Camera
[Halbach1964][Gerrard1994][Georgeiv2006]
Sensor
Traditional Camera
Lens
Before Sensor
Final Image
Intensity
After Lens
After Aperture
Before the Camera
At the focus plane
I = P[U^d2[S^f[A · U^d1[L0]]]]
Sensor
Space
Lens
Aperture
Space

Computational Camera to Extract Information from Light Field



- The primary task of early vision is to deliver a small set of useful measurements about each observable location in the plenoptic function. [Adelson1991]
- The ***traditional camera*** performs a special and restrictive sampling of the light field, essentially capturing the rays that pass through its center of projection. ***Computational cameras*** sample the light field in radically different ways to create new and useful forms of visual information. [Nayar2006]

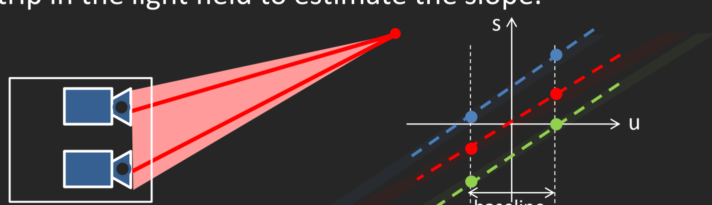
Computational Cameras for Depth Estimation



Input Light Field

Depth can be estimated by finding the slope of each strip.

- In binocular stereo, two samples are captured from each strip in the light field to estimate the slope.



A Binocular Camera

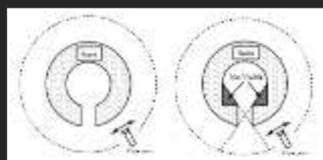
The Effective Input Light Field

[Scharstein2002][Levin2008]]

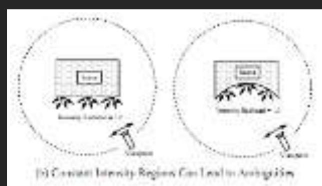
Computational Cameras for Depth Estimation

[Baker2001]

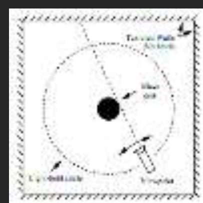
- Can shapes be uniquely determined from Lambertian Light Fields?
  - ✓ Yes, when there is no non-visible regions and no constant intensity regions.



Non-Visible Regions are Ambiguous



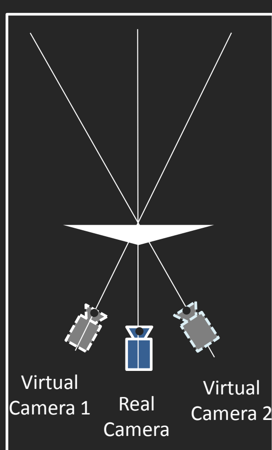
Constant Intensity Regions Can Lead to Ambiguities



Uniqueness by Shape from Silhouette

Depth Estimation: Bi-prism Stereo Camera

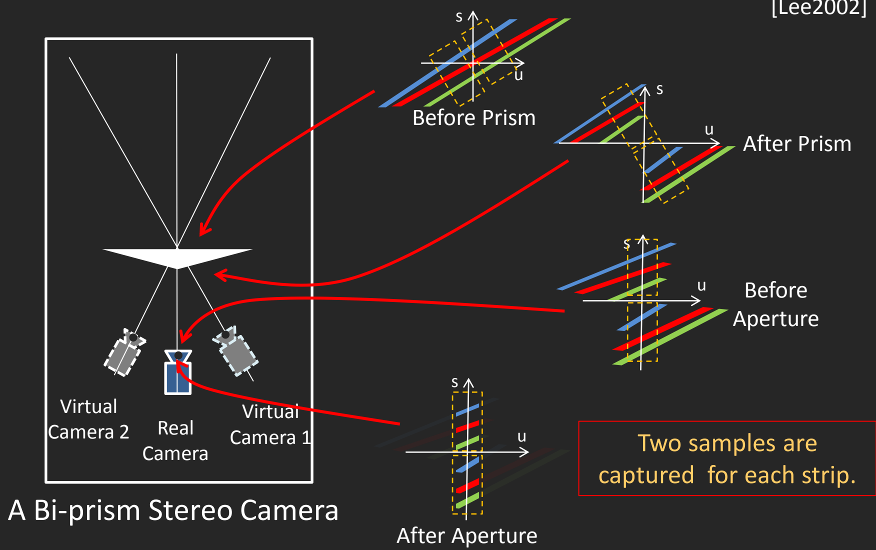
[Lee2002]



A Bi-prism Stereo Camera

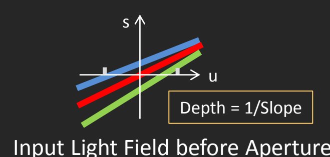
Depth Estimation: Bi-prism Stereo Camera

[Lee2002]

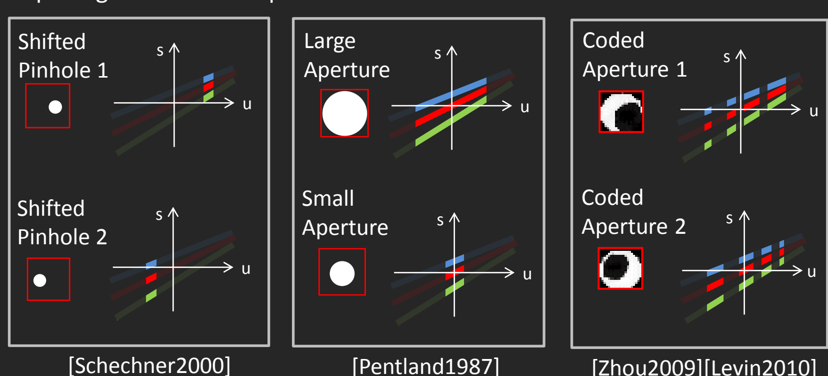


Depth Estimation: Depth from Defocus

- Depth from Defocus estimates the slopes by capturing different integrals along each strip.

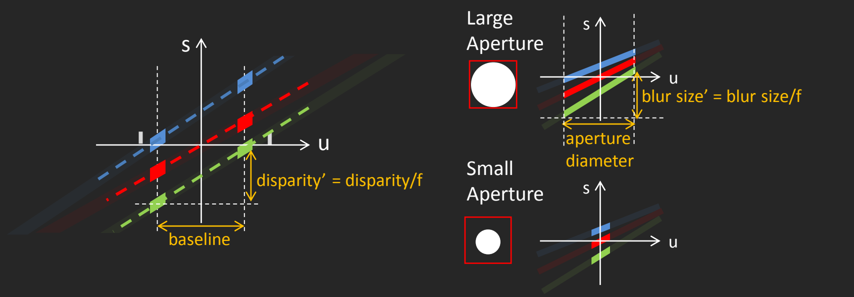


Input Light Field after Apertures:



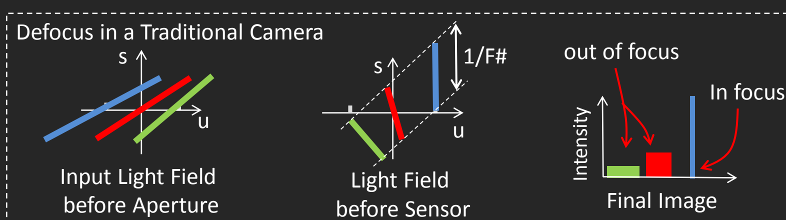
Stereo v.s Depth from Defocus

[Schechner2000]



	Stereo	Depth from Defocus
Depth =	baseline/disparity'	aperture diameter/blur size'
Algorithm:	Stereo matching	Blur size estimation
Depth Sensitivity:	High	Low
Reliability:	Low	High

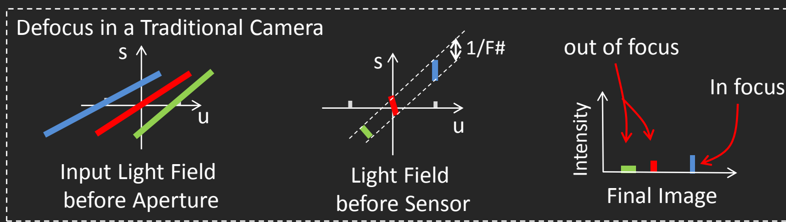
Computational Cameras for Extended Depth of Field



Extended Depth of Field (EDOF):
Map each stripe into one pixel.

f # = 1.4 T: 360ms

Computational Cameras for Extended Depth of Field



Extended Depth of Field (EDOF):
Map each stripe into one pixel.

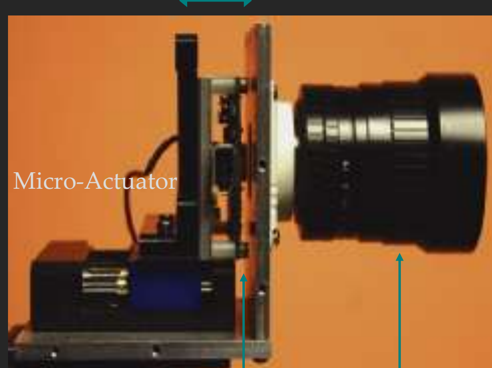
- Increase DOF by stopping down the aperture (increasing F#)

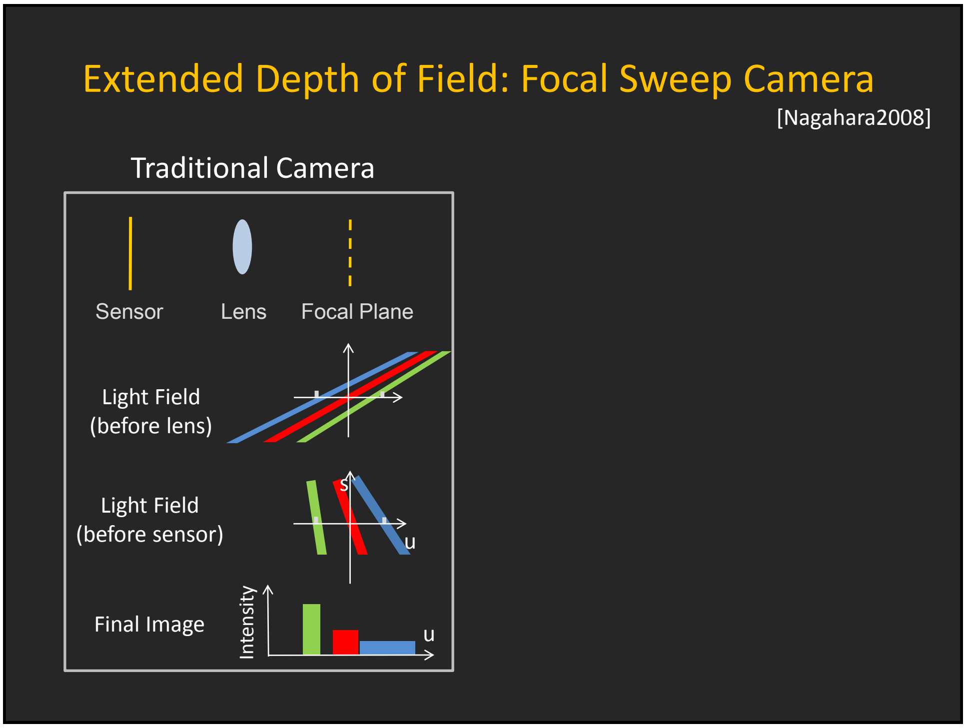
Tradeoff between DOF and SNR

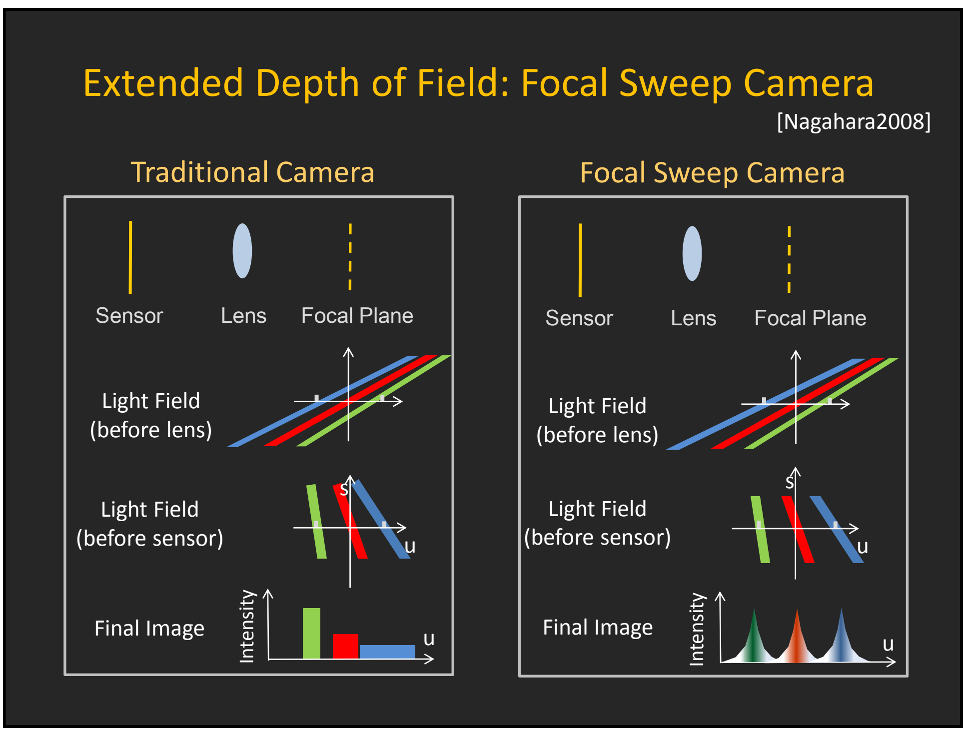
$f\# = 8.4$ T: 360ms

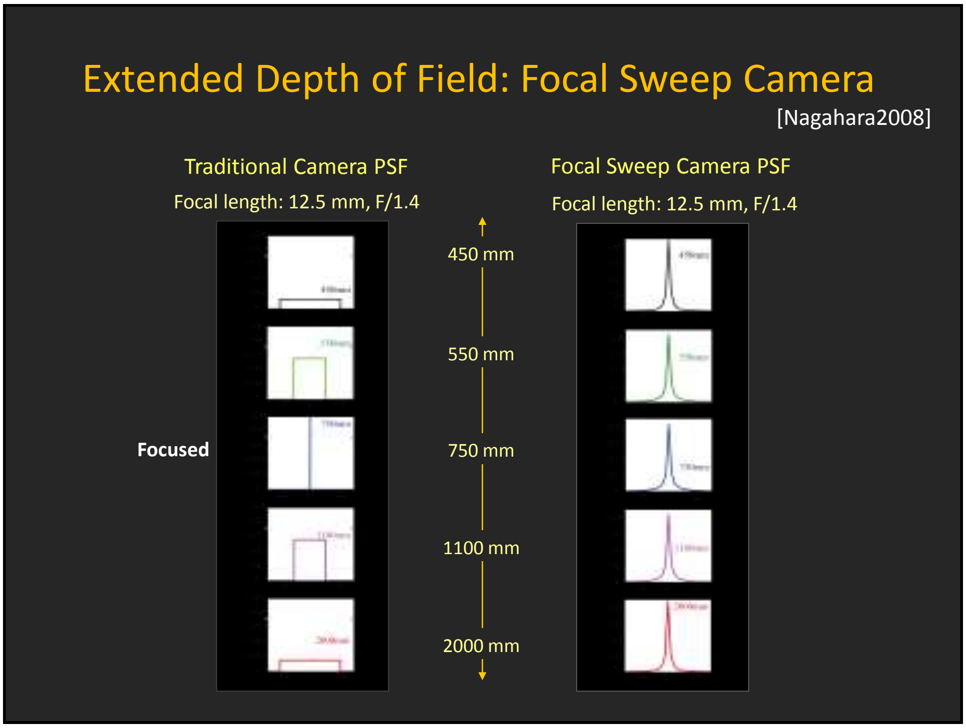
Extended Depth of Field: Focal Sweep Camera

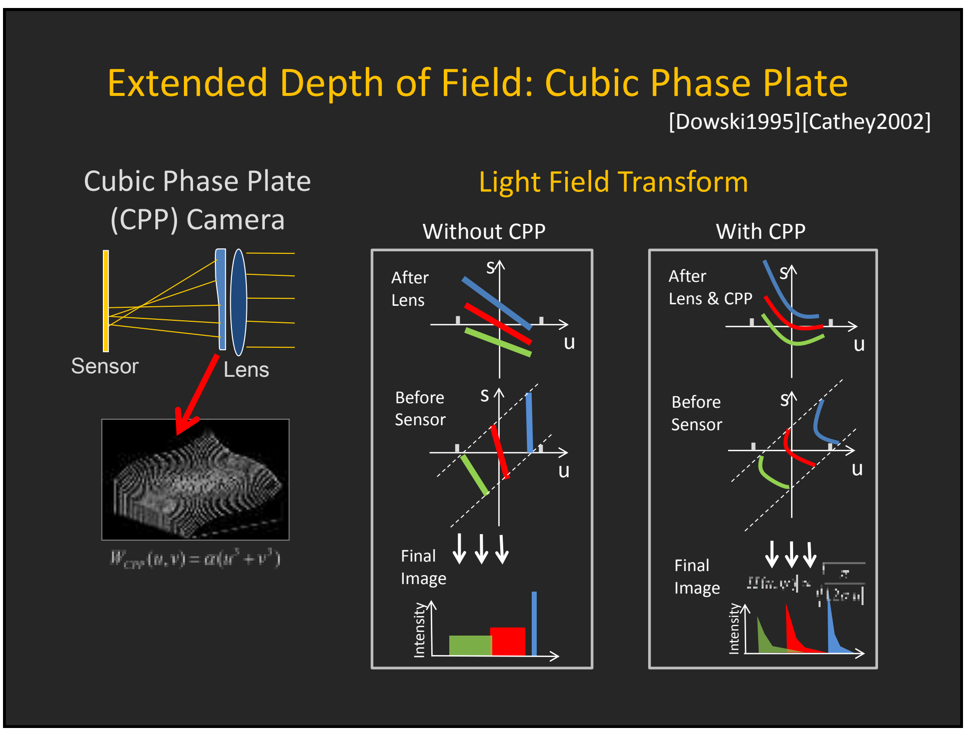
[Nagahara2008]




Extended Depth of Field: Focal Sweep Camera
[Nagahara2008]
Traditional Camera
Sensor
Lens
Focal Plane
Light Field
(before lens)
Light Field
(before sensor)
s
u
Final Image
Intensity
u


Extended Depth of Field: Focal Sweep Camera
[Nagahara2008]
Traditional Camera
Focal Sweep Camera
Sensor
Lens
Focal Plane
Light Field
(before lens)
Light Field
(before sensor)
s
u
Final Image
Intensity
u

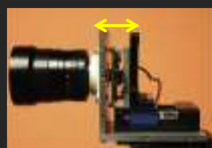

Extended Depth of Field: Focal Sweep Camera
[Nagahara2008]
Traditional Camera PSF
Focal length: 12.5 mm, F/1.4
Focal Sweep Camera PSF
Focal length: 12.5 mm, F/1.4
Focused
450 mm
550 mm
750 mm
1100 mm
2000 mm


Extended Depth of Field: Cubic Phase Plate
[Dowski1995][Cathey2002]
Cubic Phase Plate
(CPP) Camera
Sensor
Lens
Light Field Transform
Without CPP
With CPP
After
Lens
After
Lens & CPP
Before
Sensor
Final
Image
Intensity
s
u

EDOF Camera MTF Comparison

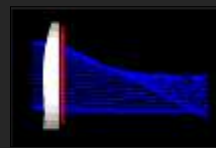
[Levin2009]

Focus sweep [Nagahara2008]



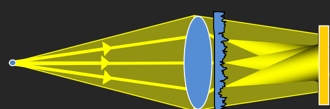
MTF: $|K(\omega_x,\omega_y)| \approx \frac{A}{S|\omega_{x,y}|}$

Cubic Phase Plate [Cathey2002]



MTF: $|K(\omega_x,\omega_y)| \approx \frac{A}{S\sqrt{|\omega_x||\omega_y|}}$

Diffusion Coding [Cossairt2010]

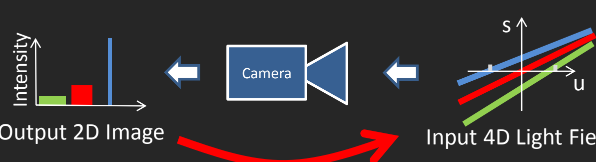


MTF: $|K(\omega_x,\omega_y)| \approx \frac{A}{S|\omega_{x,y}|}$

Lattice-focal lens [Levin2009]

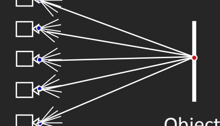
MTF: $|K(\omega_x,\omega_y)| \approx \frac{A^{4/3}}{S^{2/3}\Omega^{1/6}\sqrt{|\omega_{x,y}|}}$

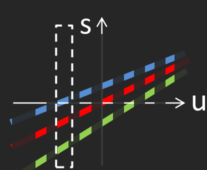
Computational Cameras for Light Field Capture



Recover the 4D Light Field from 2D image(s)

- Camera array for light field capturing: Sample the 4D light field slice by slice. [Wilburn2005]



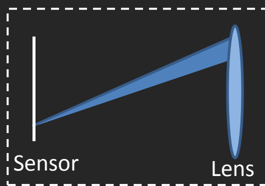


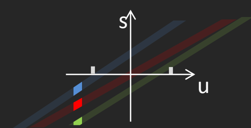
Each camera captures one slice

Light Field Capture: Programmable Aperture Camera

[Liang2008][Nagahara2010]

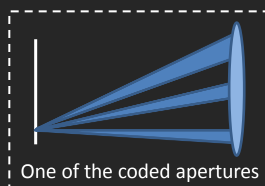
- Method 1: Capture one slice at a time using shifted pinholes

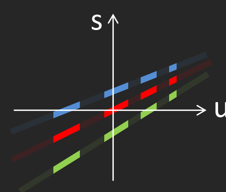




Input Light Field
(After Aperture)

- Method 2: Multiplexing using coded apertures to increase SNR

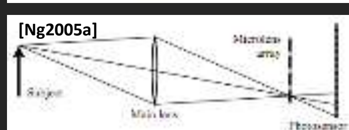




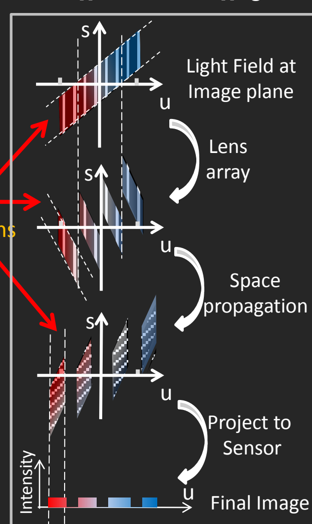
Light Field Capture: Plenoptic Camera

[Ives1930][Adelson1992][Ng2005a]

Place a lens array at image plane



F# of
Primary Lens

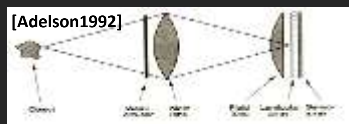


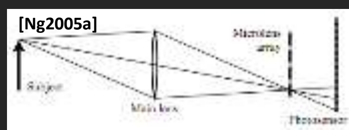
- Sacrifice spatial resolution
- Require high precision sensor positioning
  - Main lens is focused on the sensor by lenslets
- Require careful F# settings
  - F/# of main lens > F/# of Lenslet: waster pixels
  - F/# of main lens < F/# of lenslet: Overlapping

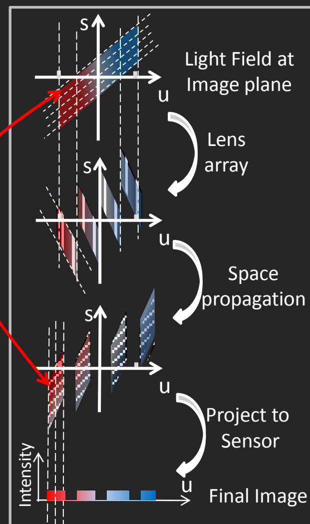
Light Field Capture: Plenoptic Camera

[Ives1930][Adelson1992][Ng2005a]

Place a lens array at image plane







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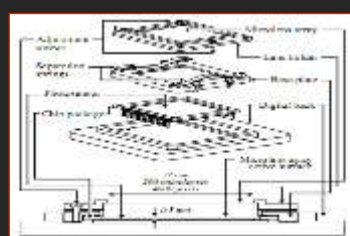
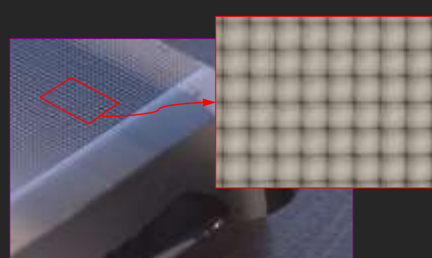
Handheld Plenoptic Camera [Ng2005a]

Contax medium format camera



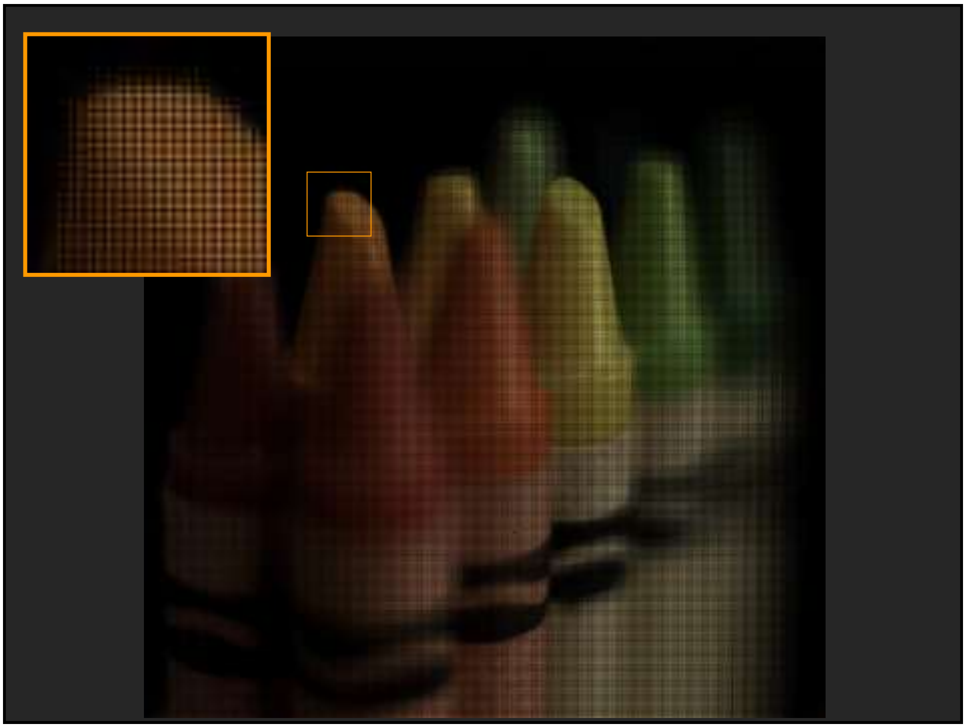
Attaching microlens array to the sensor

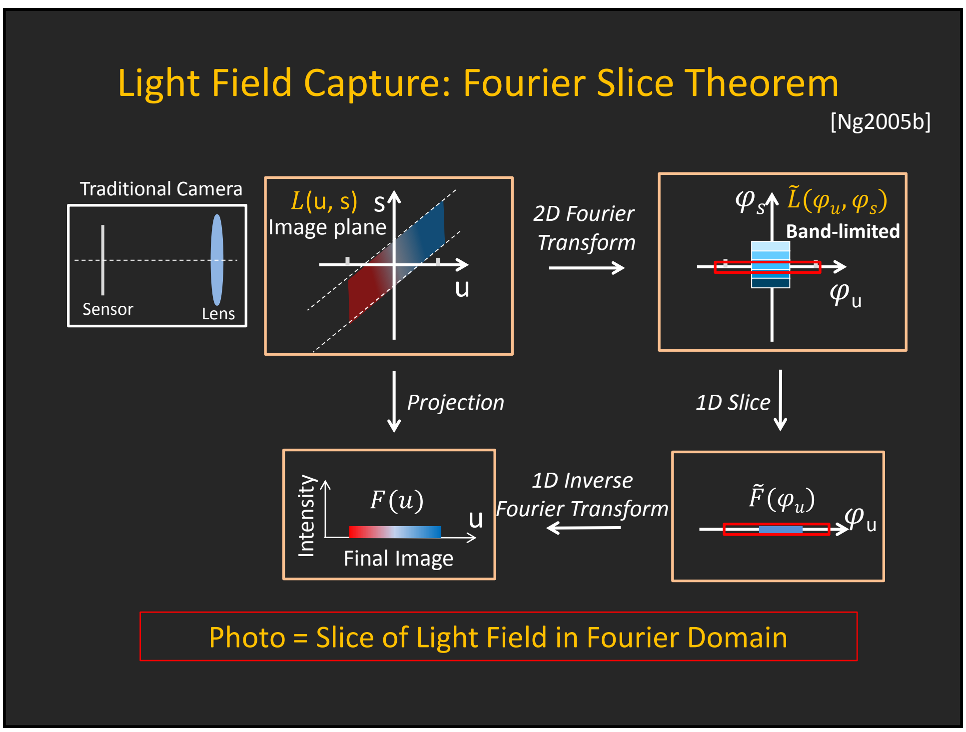
Adaptive Optics microlens array

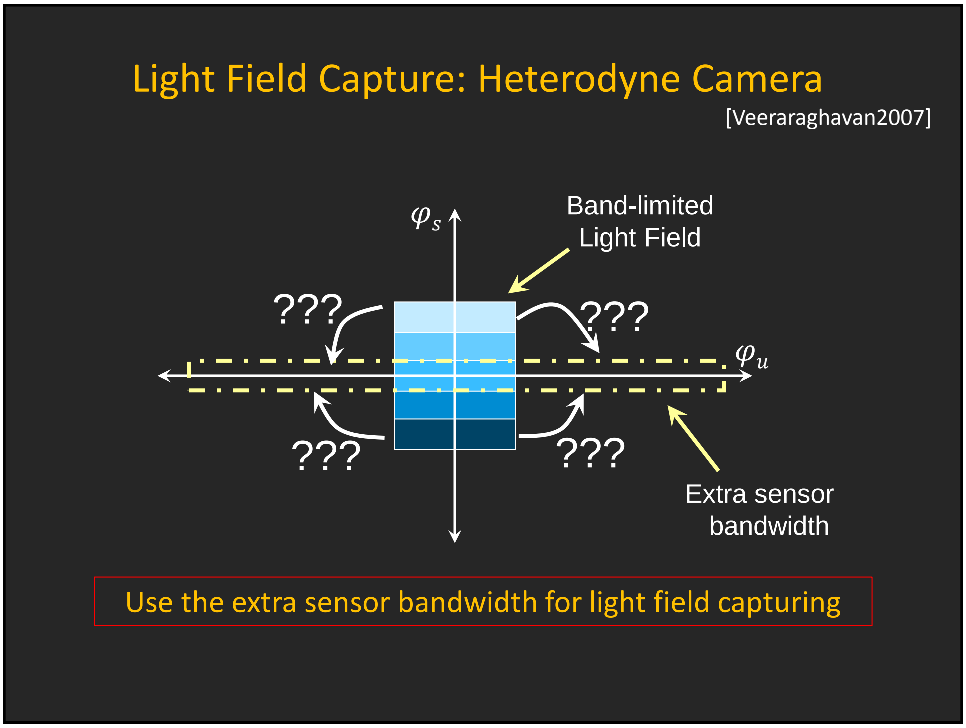


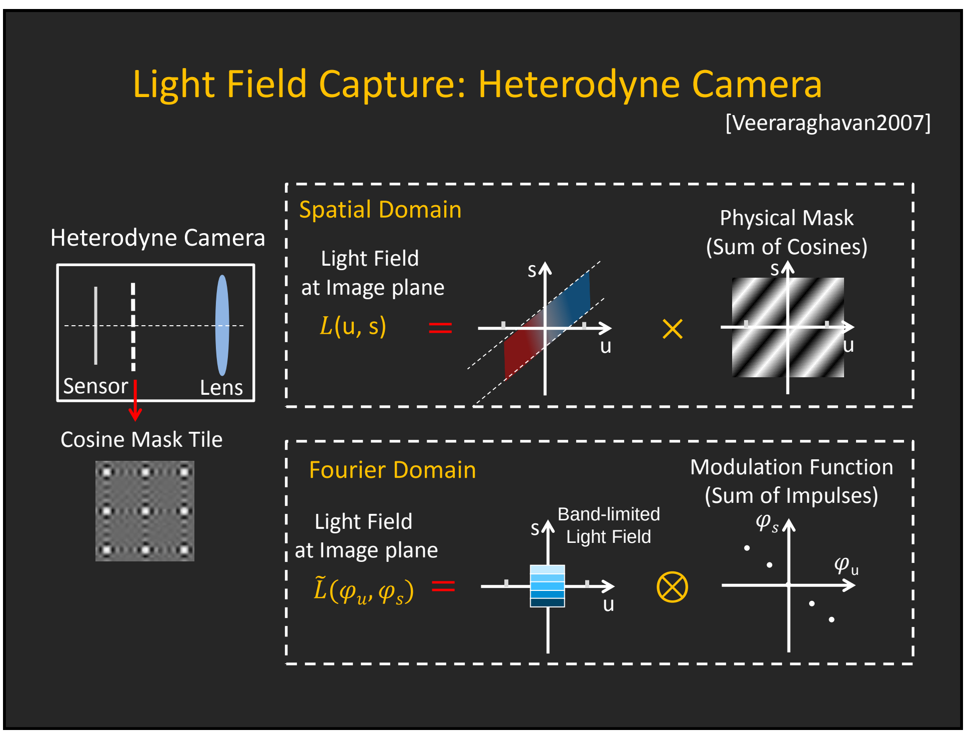
125µ square-sided microlenses

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



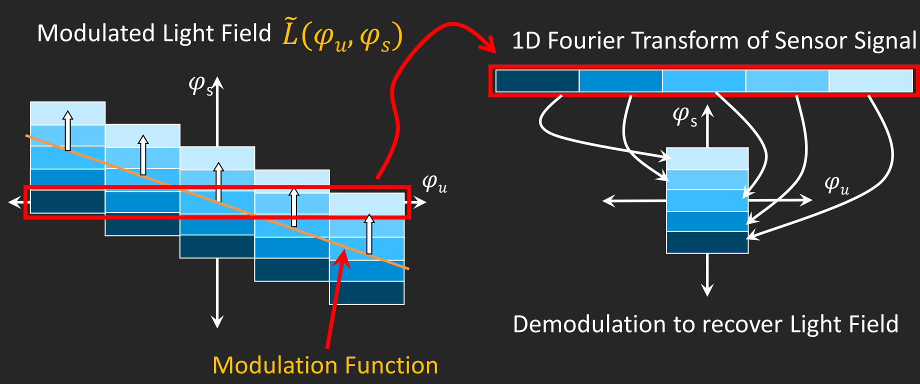

Light Field Capture: Fourier Slice Theorem
[Ng2005b]
Traditional Camera
Sensor
Lens
L(u, s)
s
Image plane
u
2D Fourier Transform
φs
L̃(φu, φs)
Band-limited
φu
Projection
1D Slice
Intensity
F(u)
u
Final Image
1D Inverse Fourier Transform
F̃(φu)
φu
Photo = Slice of Light Field in Fourier Domain


Light Field Capture: Heterodyne Camera
[Veeraraghavan2007]
φ_s
Band-limited Light Field
???
???
φ_u
???
???
Extra sensor bandwidth
Use the extra sensor bandwidth for light field capturing


Light Field Capture: Heterodyne Camera
[Veeraraghavan2007]
Heterodyne Camera
Sensor
Lens
Cosine Mask Tile
Spatial Domain
Light Field at Image plane
$L(u, s)$ =
s
u
×
Physical Mask (Sum of Cosines)
s
u
Fourier Domain
Light Field at Image plane
$\tilde{L}(\varphi_u, \varphi_s)$ =
s
Band-limited Light Field
u
⊗
Modulation Function (Sum of Impulses)
φ_s
φ_u

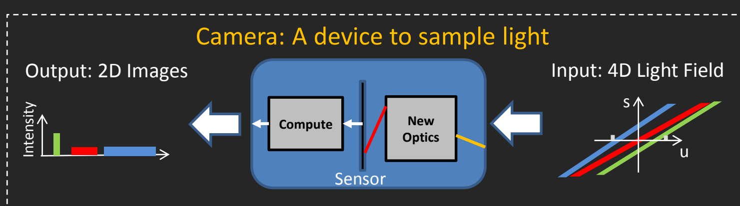
Light Field Capture: Heterodyne Camera

[Veeraraghavan2007]



Sensor Slice captures entire Light Field

Summary



- Computational Camera: Process light field and extract useful information.
  - Depth: the slope of each strip
  - Image (EDOF): the integral of each strip
  - Light Field: everything
  - …
- Computational Camera Design: Choose right optical devices, and put in right positions.
  - What: Lens, Lens Array, Prism, Phaseplate, Diffuser, Photomasks, …
  - Where: External, Pupil Plane, Sensor Plane, …

Devices	External	Aperture Plane	Sensor Plane*
Photomask, Color Filter, Polarizer		[Hiura1998] [Subramanian et al. 2000] [Levin2007][Zhou2009b][Levin2010] [Bando 2008] [Indebetouw1984][Neifeld 2007][Welford 1960] [Poon1987]: EDOF [Gottesman1989][Zhou2009a]: Deblurring [Liang2008][Nagahara2010]	[Veeraraghavan 2007]
Lens Array, Lenslets	[Lippman1908] [Ive1928] [Ohay1997] [Georgiev 2006]	[Levin2009]	[Adelson1992][Ng05] [Georgiev2009]
Diffuser	[Zhou2010]	[Ashok2007] [Cor10, Gar07] [Cossairt 2010]	
Phaseplate		[Dowski95b] [Greengard 2006] [Dowski 1995a][Chi2001][Castro2004] [Cathey2002]…	
Prism, Plate	[Lee 1998][Xiao2007] [Chunyu2006]		
Others (e.g., sensor motion)			[Ben-Ezra2005] [Nagahara2008]

Red: Depth
Green: Image
Blue: Light Field

Devices	External	Aperture Plane	Sensor Plane*
Photomask, Color Filter, Polarizer	[Raskar 2006] [Wolff 1991][Nayar1997] [Schechner2001a] [Schechner2001b]*	[Hiura1998] [Subramanian et al. 2000] [Levin2007][Zhou2009b][Levin2010] [Bando 2008] [Indebetouw1984][Neifeld 2007][Welford 1960] [Poon1987]: EDOF [Gottesman1989][Zhou2009a]: Deblurring [Liang2008][Nagahara2010] [Aggarwal 2004]	[Veeraraghavan 2007] [Nayar2006]* [Yasuma2010] [Lukac2005]
Lens Array, Lenslets	[Lippman1908] [Ive1928] [Ohay1997] [Georgiev 2006]	[Levin2009]	[Adelson1992][Ng05] [Georgiev2009]
Diffuser	[Zhou2010]	[Ashok2007] [Cor10, Gar07] [Cossairt 2010]	
Phaseplate		[Dowski95b] [Greengard 2006] [Dowski 1995a][Chi2001][Castro2004] [Cathey2002]…	
Prism, Plate	[Lee 1998][Xiao2007] [Chunyu2006] [Xiao2007] [Du 2009]		
Others (e.g., sensor motion)			[Ben-Ezra2005] [Nagahara2008] [Levin 2008][Gu2010]

Red: Depth
Green: Image
Blue: Light Field
Orange: HDR
Yellow: Time
Pink: Wavelength /Polarization