6.098 Digital and Computational Photography
6.882 Advanced Computational Photography

Refocusing & Light Fields

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MIT - EECS

Final projects

- **Send your slides by noon on Thrusday.**
- **Send final report**

Wavefront coding

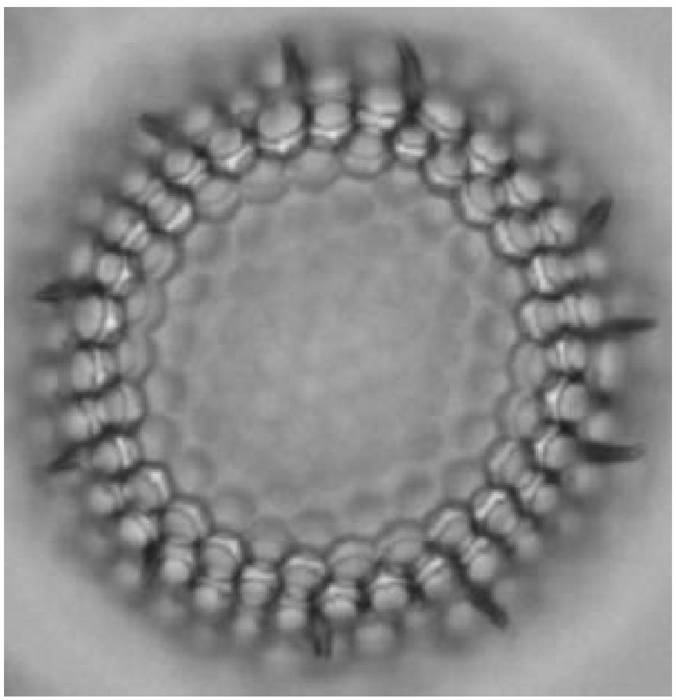
Is depth of field a blur?

- **Depth of field is NOT a convolution of the image**
- **The circle of confusion varies with depth**
- **There are interesting occlusion effects**
- **(If you really want a convolution, there is one, but in 4D space… more soon)**

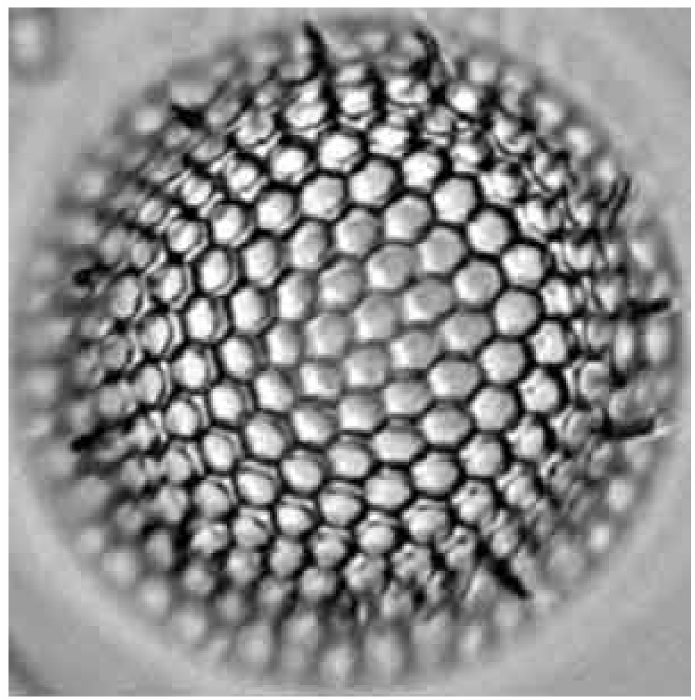
From Macro Photography

Wavefront coding

- CDM-Optics, U of Colorado, Boulder
- The worst title ever: "A New Paradigm for Imaging Systems", Cathey and Dowski, Appl. Optics, 2002
- Improve depth of field using weird optics & deconvolution
- http://www.cdm-optics.com/site/publications.php



Single-cell algae imaged without wavefront coding.



Single-cell algae imaged with wavefront coding.

Wavefront coding

- **Idea: deconvolution to deblur out of focus regions**
- **Convolution = filter (e.g. blur, sharpen)**
- **Sometimes, we can cancel a convolution by another convolution**
  - Like apply sharpen after blur (kind of)
  - This is called deconvolution
- **Best studied in the Fourier domain (of course!)**
  - Convolution = multiplication of spectra
  - Deconvolution = multiplication by inverse spectrum

Deconvolution

- **Assume we know blurring kernel k**

  $f' = f \otimes k$

  $\Rightarrow$ F' = F K (in Fourier space)

- **Invert by: F=F'/K (in Fourier space)**

- **Well-known problem with deconvolution:**
  - Impossible to invert for ω where $K(\omega)=0$
  - Numerically unstable when $K(\omega)$ is small

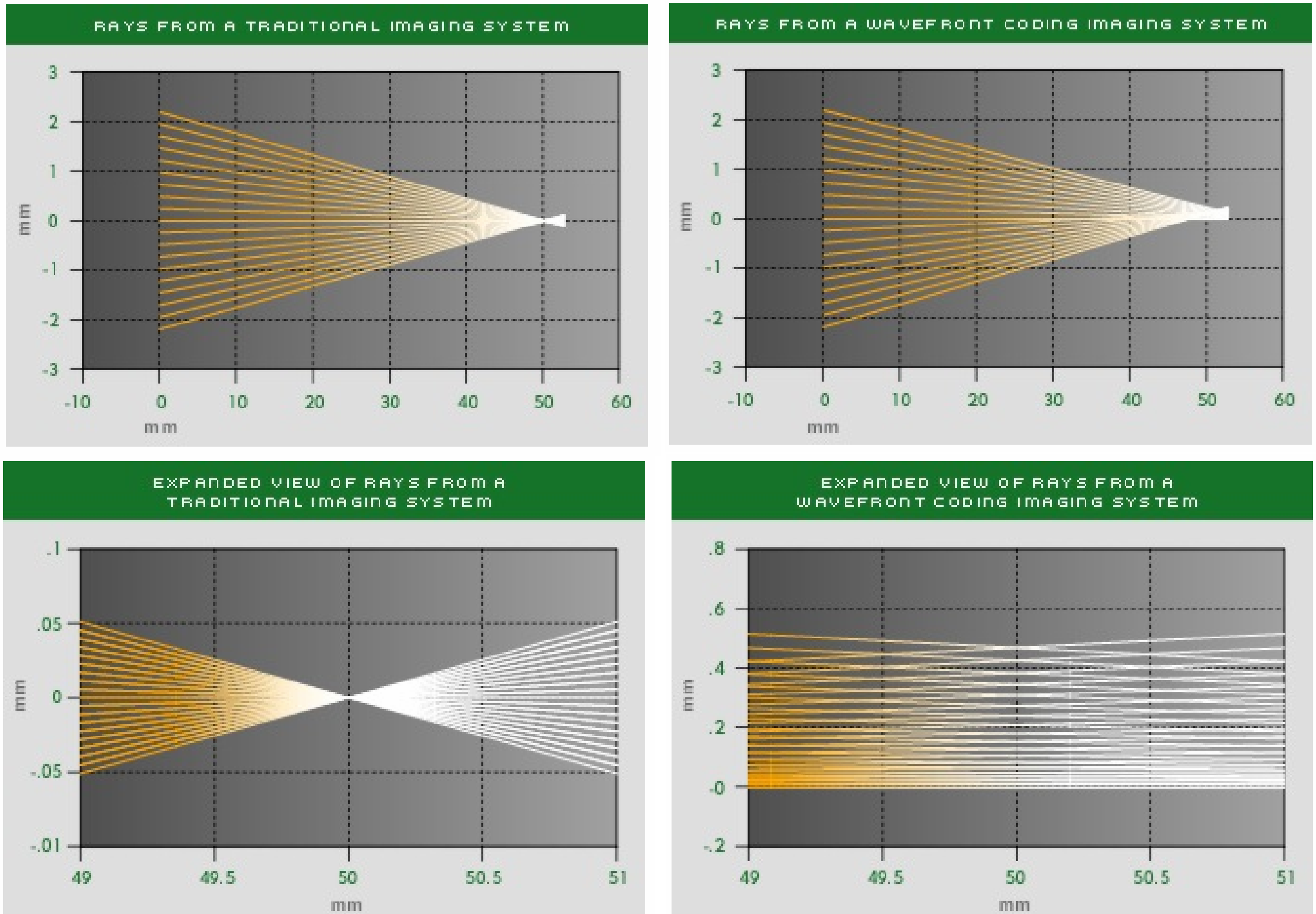
Wavefront coding

- **Idea: deconvolution to deblur out of focus regions**
- **Problem 1: depth of field blur is not shift-invariant**
  – Depends on depth
  ➔If depth of field is not a convolution, it's harder to use deconvolution ;-(
- **Problem 2: Depth of field blur "kills information"**
  – Fourier transform of blurring kernel has lots of zeros
  – Deconvolution is ill-posed

Wavefront coding

- **Idea: deconvolution to deblur out of focus regions**
- **Problem 1: depth of field blur is not shift-invariant**
- **Problem 2: Depth of field blur "kills information"**
- **Solution: change optical system so that**
  - Rays don't converge anymore
  - Image blur is the same for all depth
  - Blur spectrum does not have too many zeros
- **How it's done**
  - Phase plate (wave optics effect, diffraction)
  - Pretty much bends light
  - Will do things similar to spherical aberrations

Ray version


RAYS FROM A TRADITIONAL IMAGING SYSTEM
RAYS FROM A WAVEFRONT CODING IMAGING SYSTEM
EXPANDED VIEW OF RAYS FROM A TRADITIONAL IMAGING SYSTEM
EXPANDED VIEW OF RAYS FROM A WAVEFRONT CODING IMAGING SYSTEM
mm
mm
-10
0
10
20
30
40
50
60
3
2
1
0
-1
-2
-3
49
49.5
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.4
.2
-0
-.2

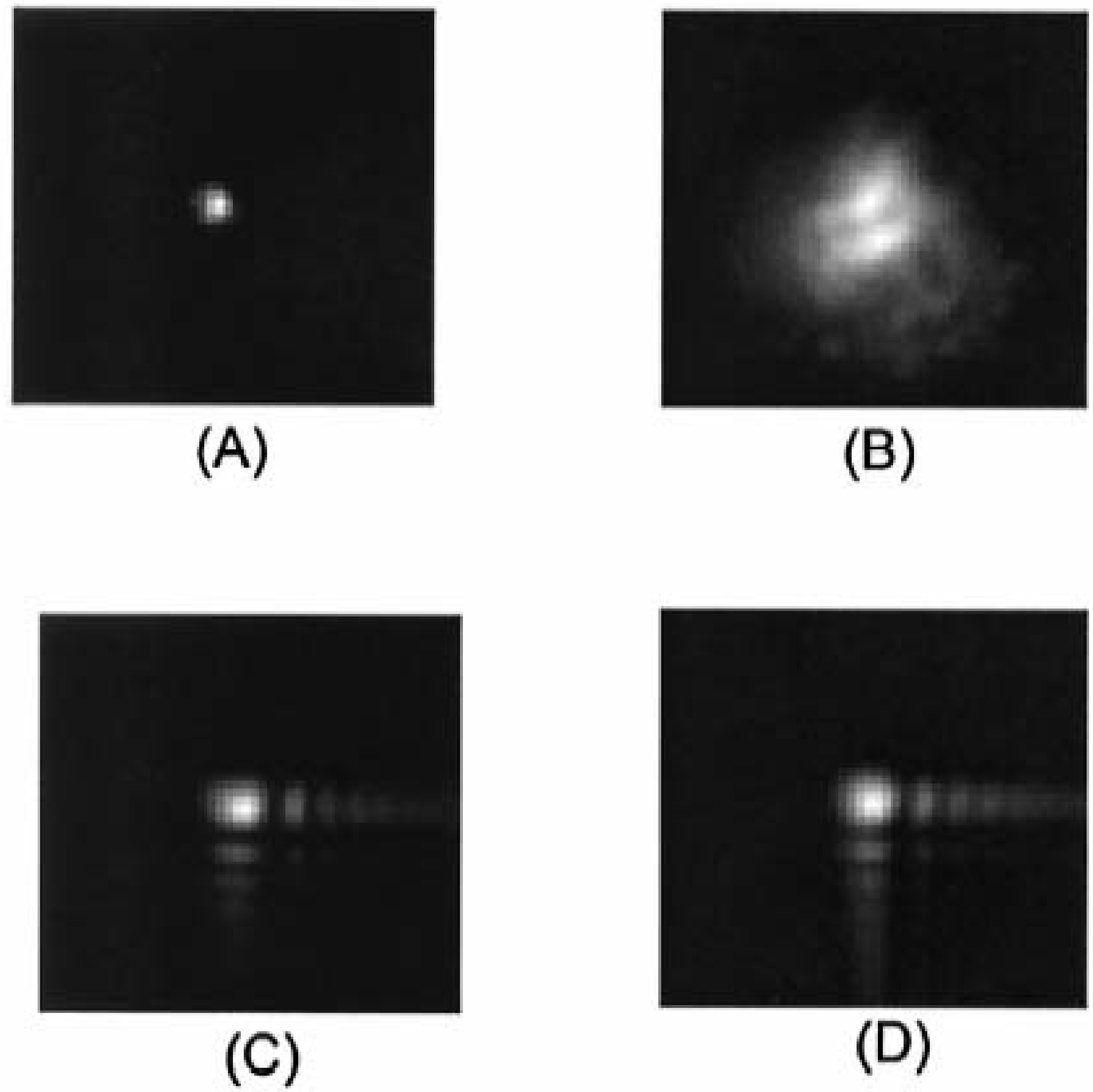


Fig. 3. PSFs associated with the rays of Fig. 2. The PSFs for a normal system are shown for (A) in focus and (B) out of focus. The PSFs for a coded system are shown (C) in the normal region of focus and (D) in the out-of-focus region.

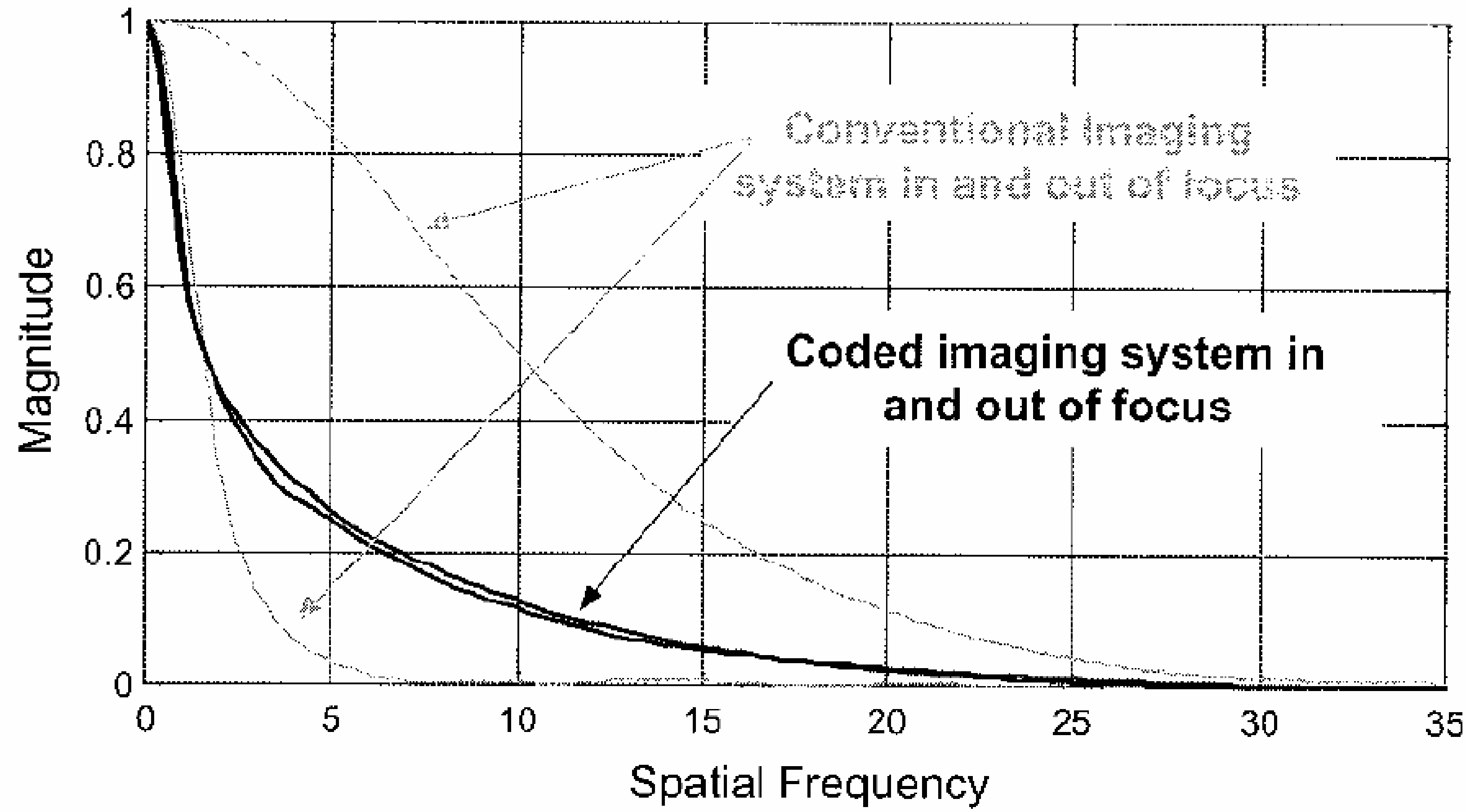


Fig. 5. MTFs corresponding with the PSFs of Fig. 3 for a conventional image in and out of focus and a coded image for the same misfocus values.

Traditional Optical System Image

Intermediate Extended Depth of Field Image

Stopped Down Traditional System Image

Final Wavefront Coded™ Image

Other application

- **Single-image depth sensing**
  - Blur depends A LOT on depth
  - Passive Ranging Through Wave-Front Coding: Information and Application. Johnson, Dowski, Cathey
  - http://graphics.stanford.edu/courses/cs448a-06-winter/johnson-ranging-optics00.pdf

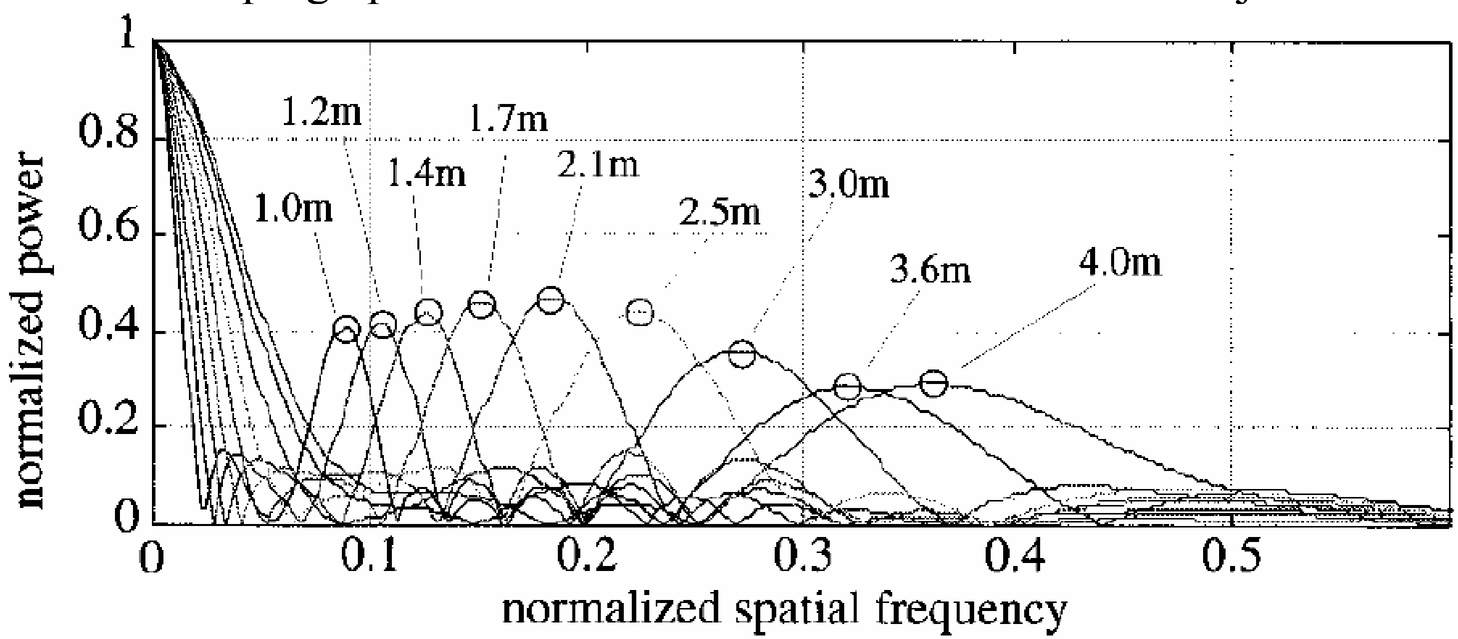


Fig. 9. Example MTF's for the simulated 1–4-m system. The peaks are marked with the range for the simulated MTF.

Single image depth sensing

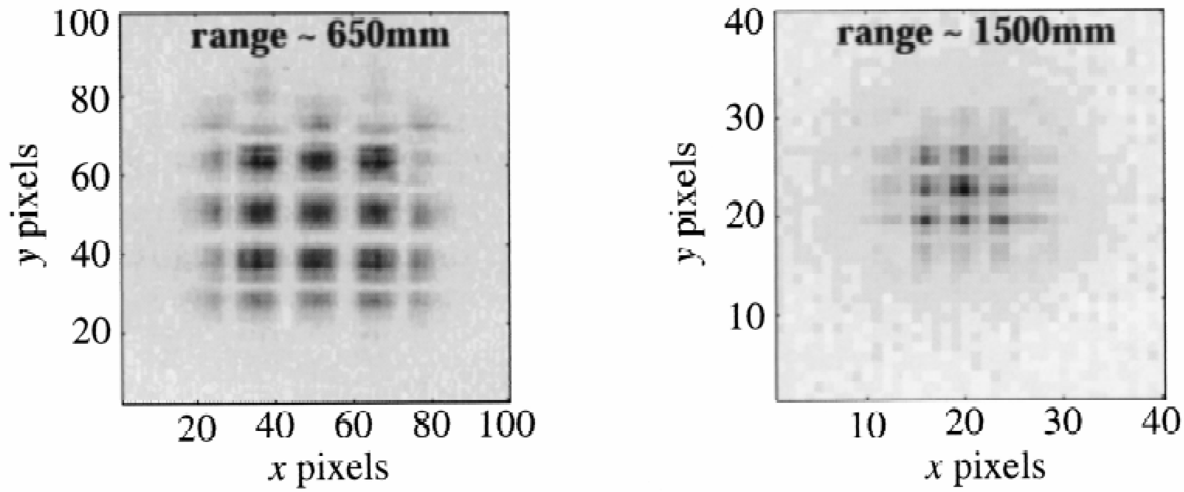


Fig. 16. Images of a point-source object located approximately 650 mm and 1.5 m away from the principle plane of the experimental optical system.

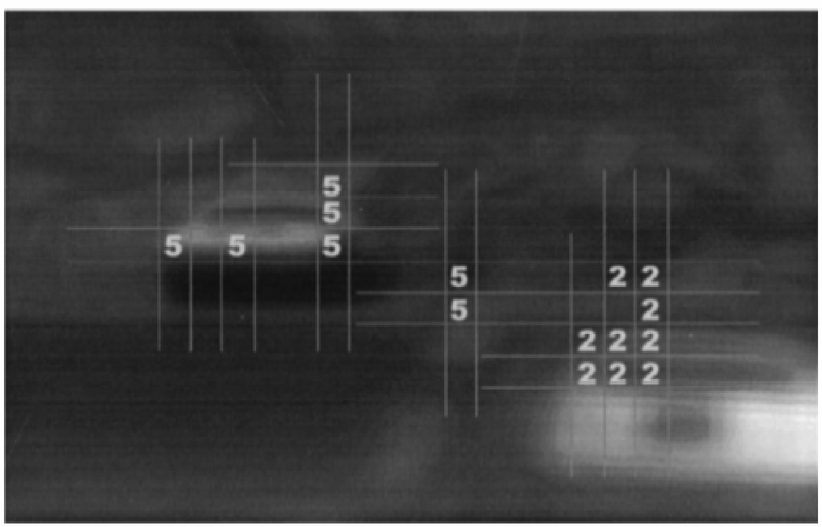
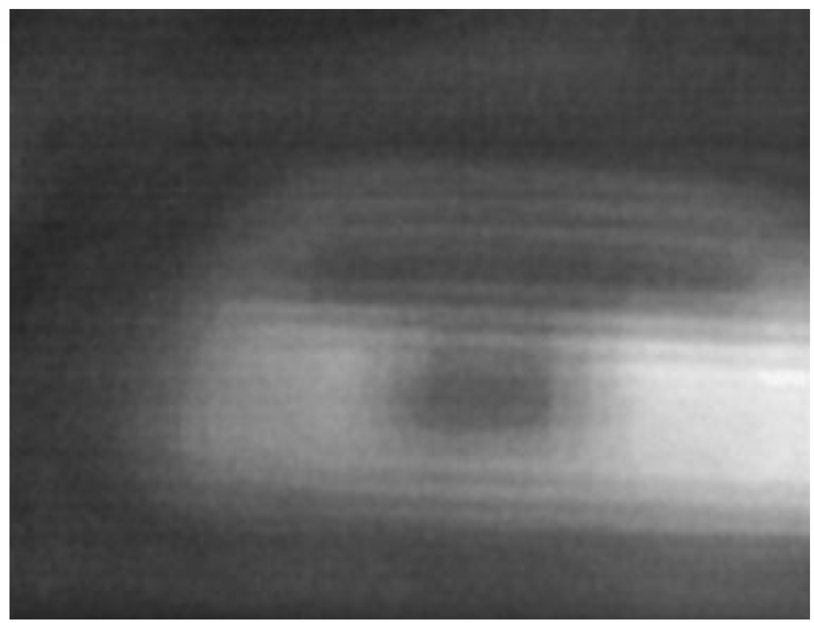


Fig. 21. Proximity map for the wave-front coded image shown in Fig. 20.



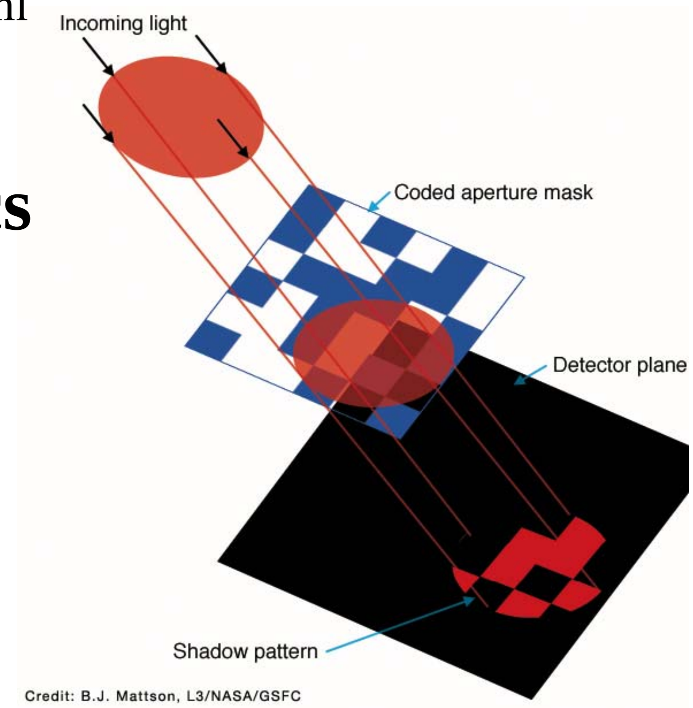
Important take-home idea

Coded imaging

- **What the sensor records is not the image we want, it's been coded (kind of like in cryptography)**
- **Image processing decodes it**

Other forms of coded imaging

- **Tomography**
  - e.g. http://en.wikipedia.org/wiki/Computed_axial_tomography
  - Lots of cool Fourier transforms there
- **X-ray telescopes & coded aperture**
  - e.g. http://universe.gsfc.nasa.gov/cai/coded_intr.html
- **Ramesh's motion blur**
- **and to some extend, Bayer mosaics**

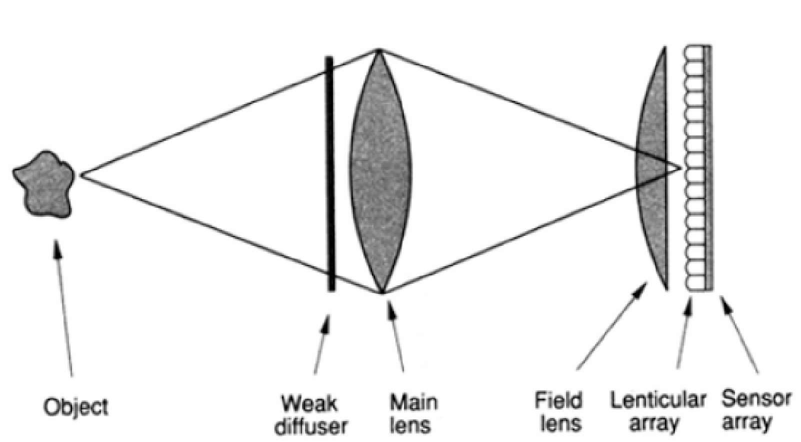


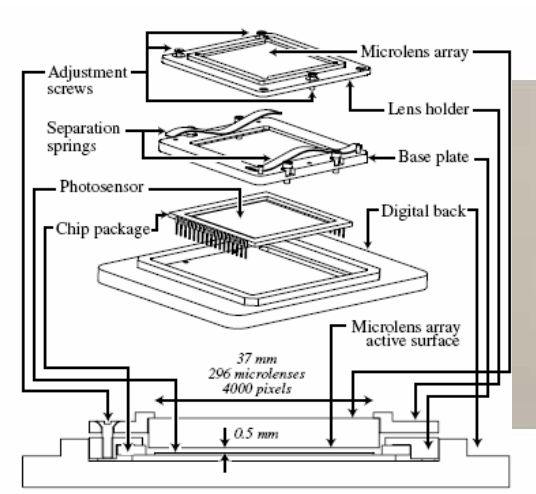
See Berthold Horn's course

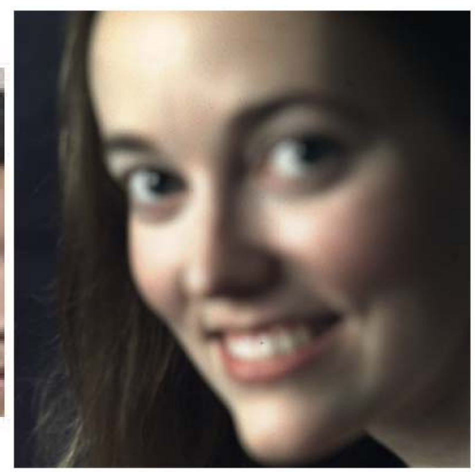
Plenoptic camera refocusing

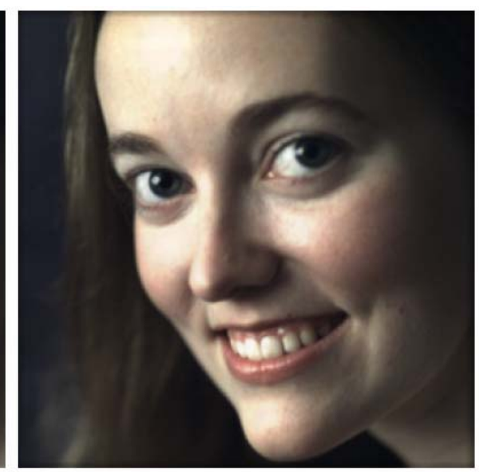
Plenoptic/light field cameras

- **Lipmann 1908**
  - "Window to the world"
- **Adelson and Wang, 1992**
  - Depth computation
- **Revisited by Ng et al. for refocusing**









The Plenoptic Function

Back to the images that surround us

- **How to describe (and capture) all the possible images around us?**

The Plenoptic function

- [Adelson & Bergen 91] http://web.mit.edu/persci/people/adelson/pub_pdfs/elements91.pdf
- From the greek "total"
- See also http://www.everything2.com/index.pl?node_id=989303&lastnode_id=1102051

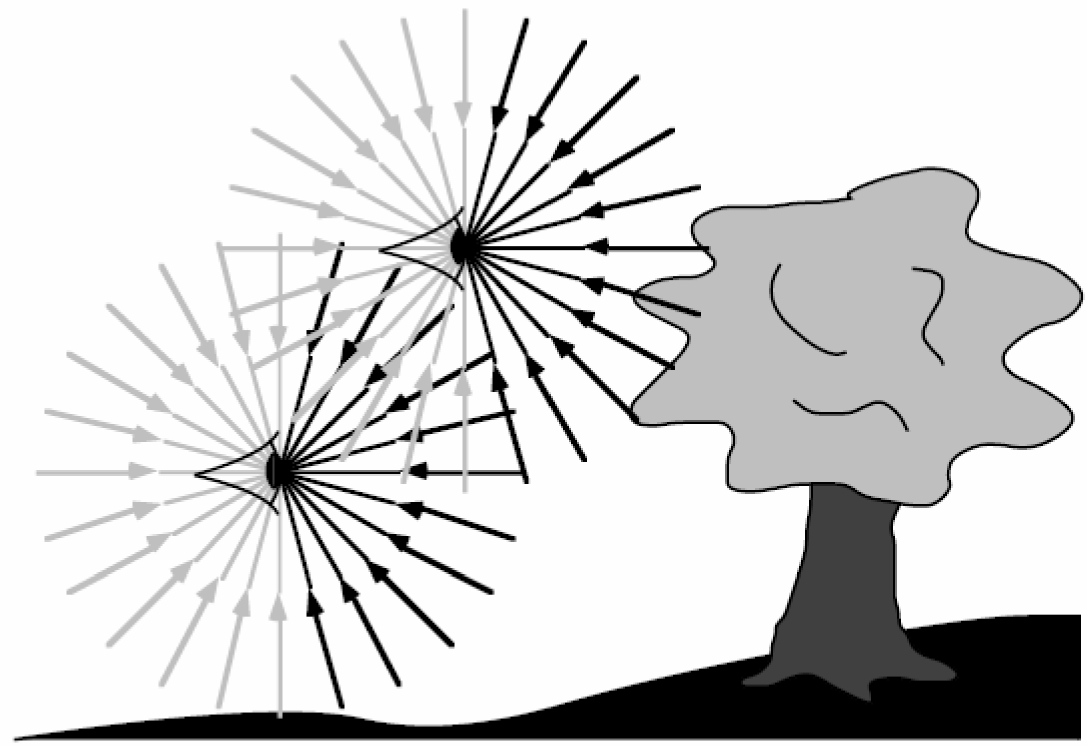


Fig.1.3
The plenoptic function describes the information available to an observer at any point in space and time. Shown here are two schematic eyes-which one should consider to have punctate pupils-gathering pencils of light rays. A real observer cannot see the light rays coming from behind, but the plenoptic function does include these rays.

Plenoptic function

- **3D for viewpoint**
- **2D for ray direction**
- **1D for wavelength**
- **1D for time**

- **can add polarization**

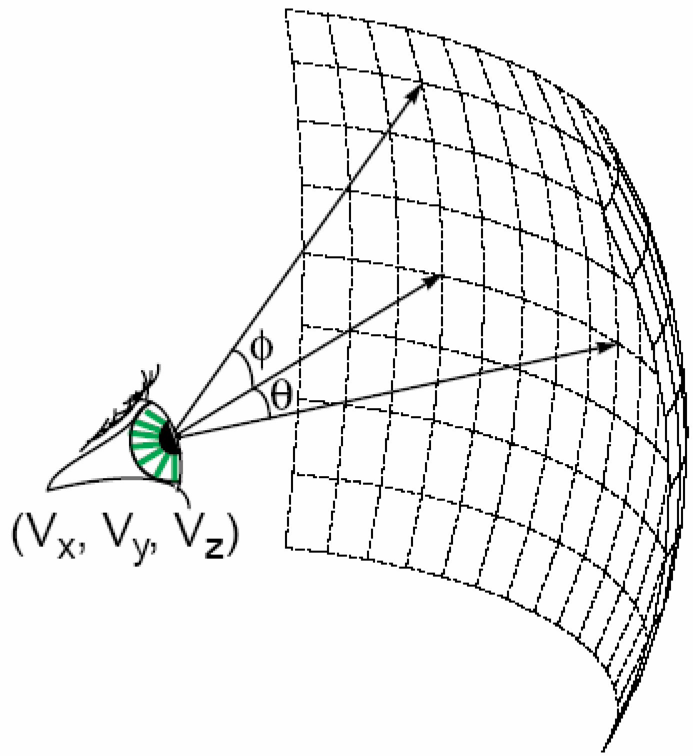


FIGURE 1. The plenoptic function describes all of the image information visible from a particular viewing position.

From McMillan 95

Light fields

Idea

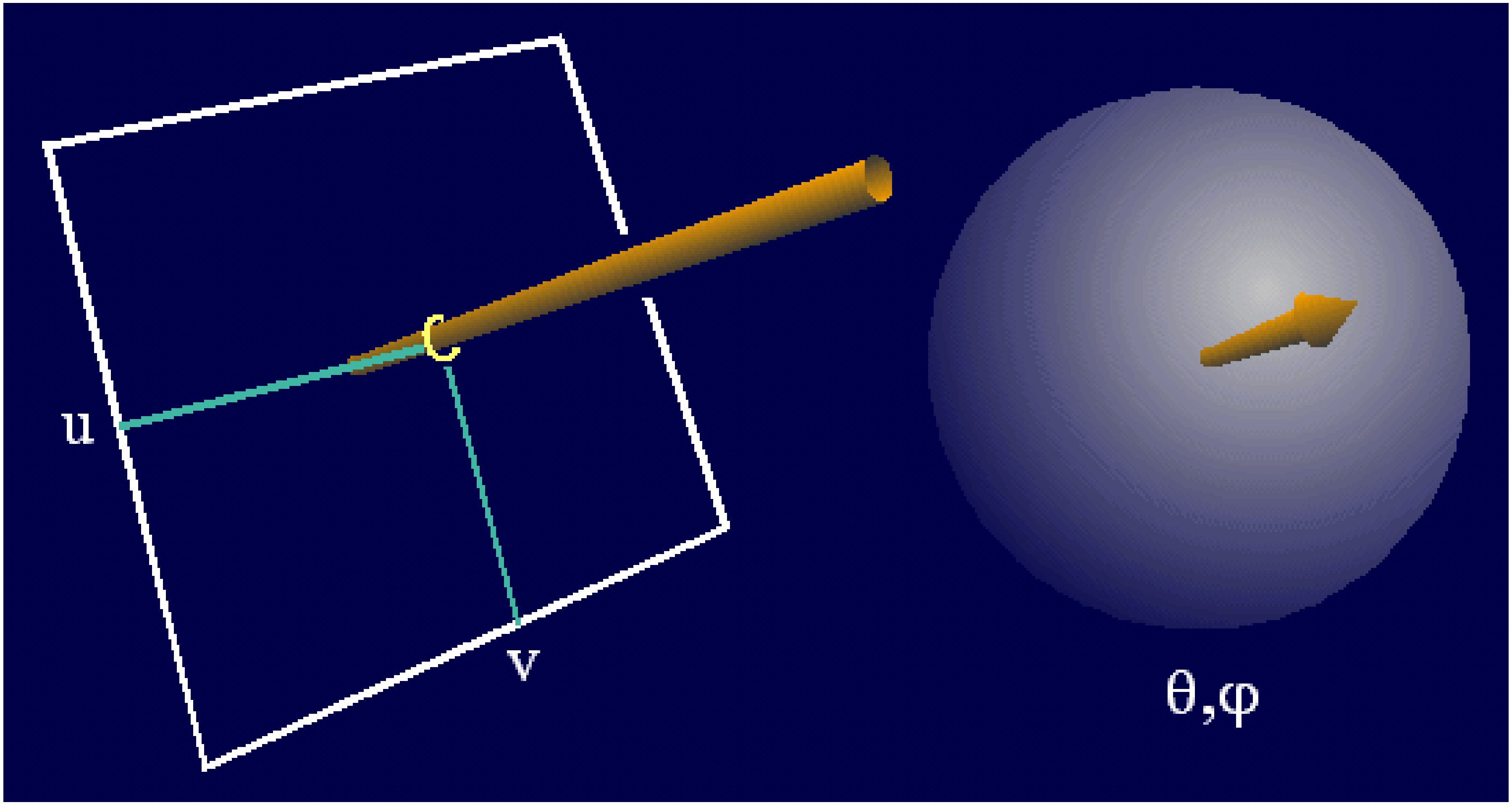
- **Reduce to outside the convex hull of a scene**
- **For every line in space**
- **Store RGB radiance**

- **Then rendering is just a lookup**

- **Two major publication in 1996:**
  - Light field rendering [Levoy & Hanrahan]
    - http://graphics.stanford.edu/papers/light/
  - The Lumigraph [Gortler et al.]
    - Adds some depth information
    - http://cs.harvard.edu/~sjg/papers/lumigraph.pdf

How many dimensions for 3D lines ?

- **4: e.g. 2 for direction, 2 for intersection with plane**



Two-plane parameterization

- **Line parameterized by intersection with 2 planes**
  – Careful, there are different "isotopes" of such parameterization (slightly different meaning of stuv)

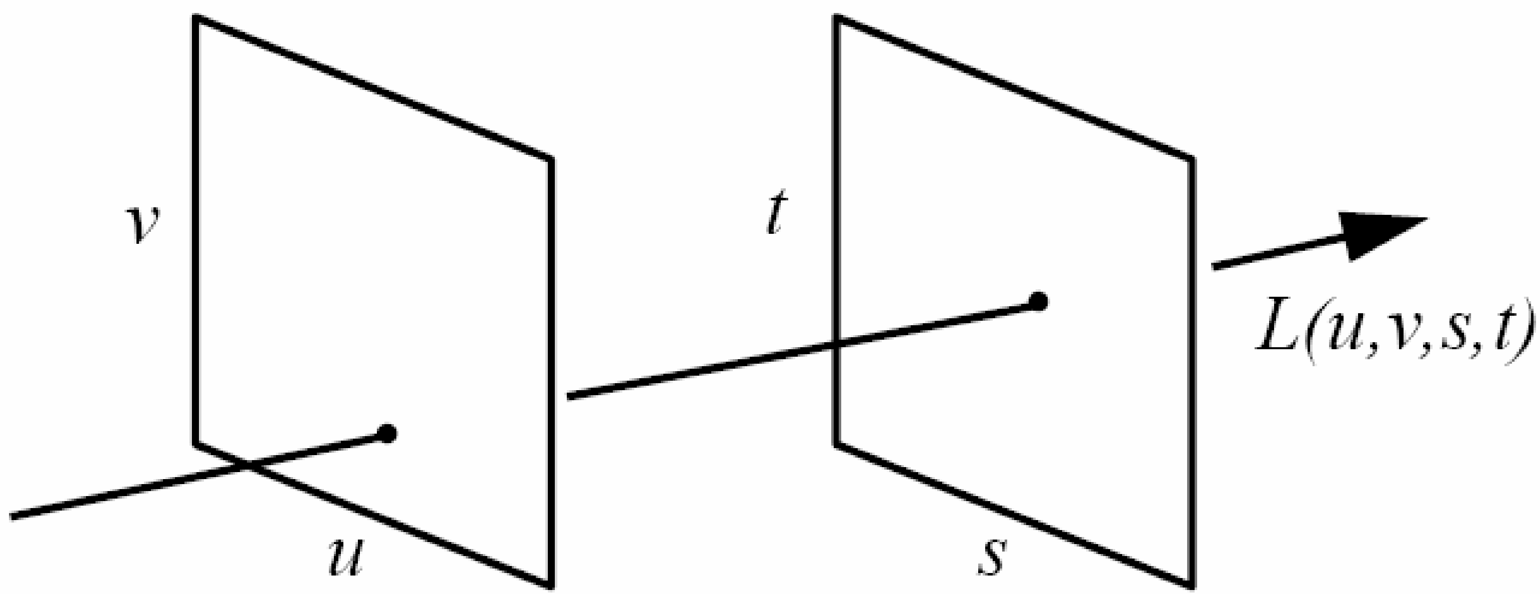


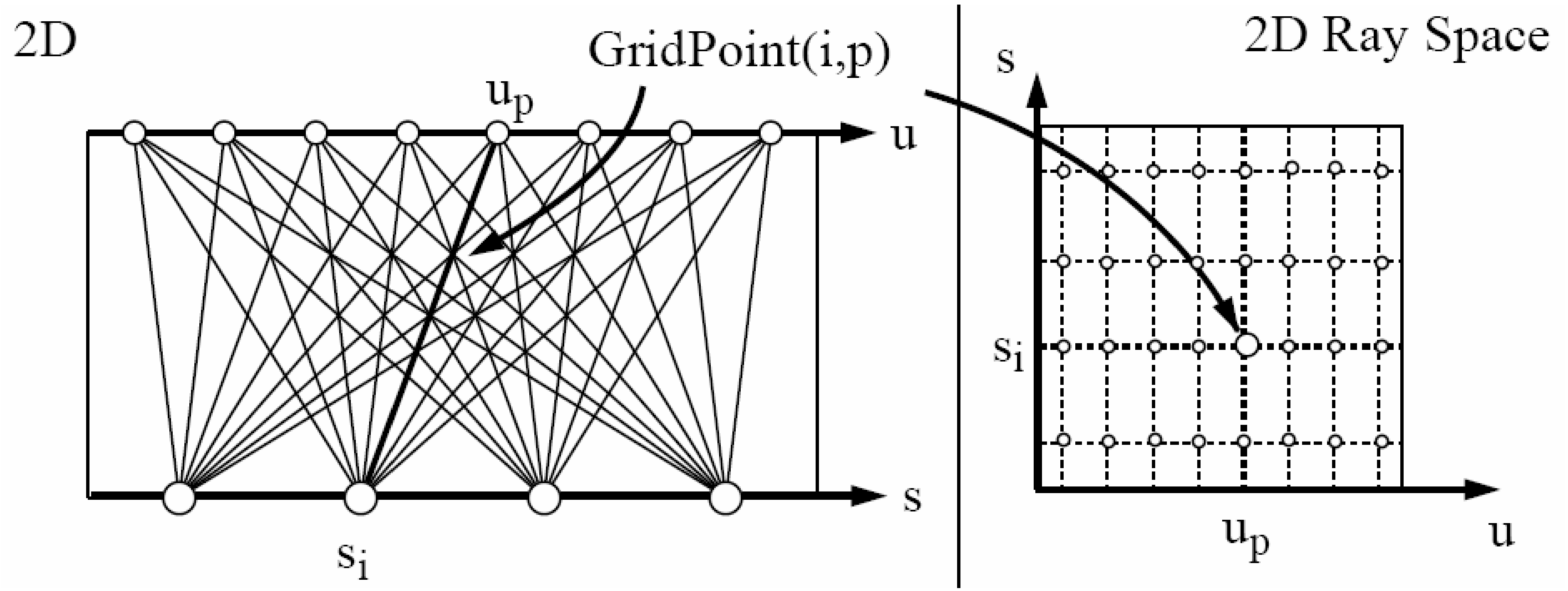
Figure 1: The light slab representation.

Let's make life simpler: 2D

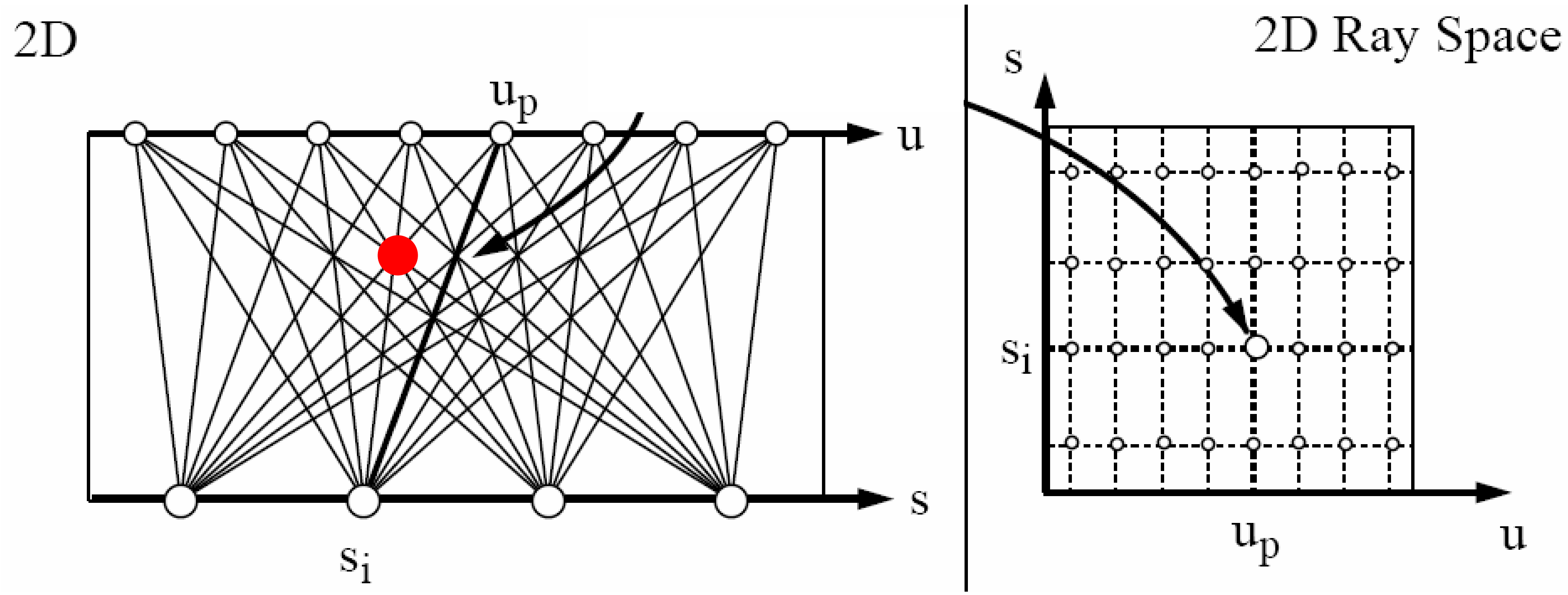
- **How many dimensions for 2D lines?**
  - Only 2, e.g. y=ax+b <> (a,b)

Let's make life simpler: 2D

- **2-line parameterization**

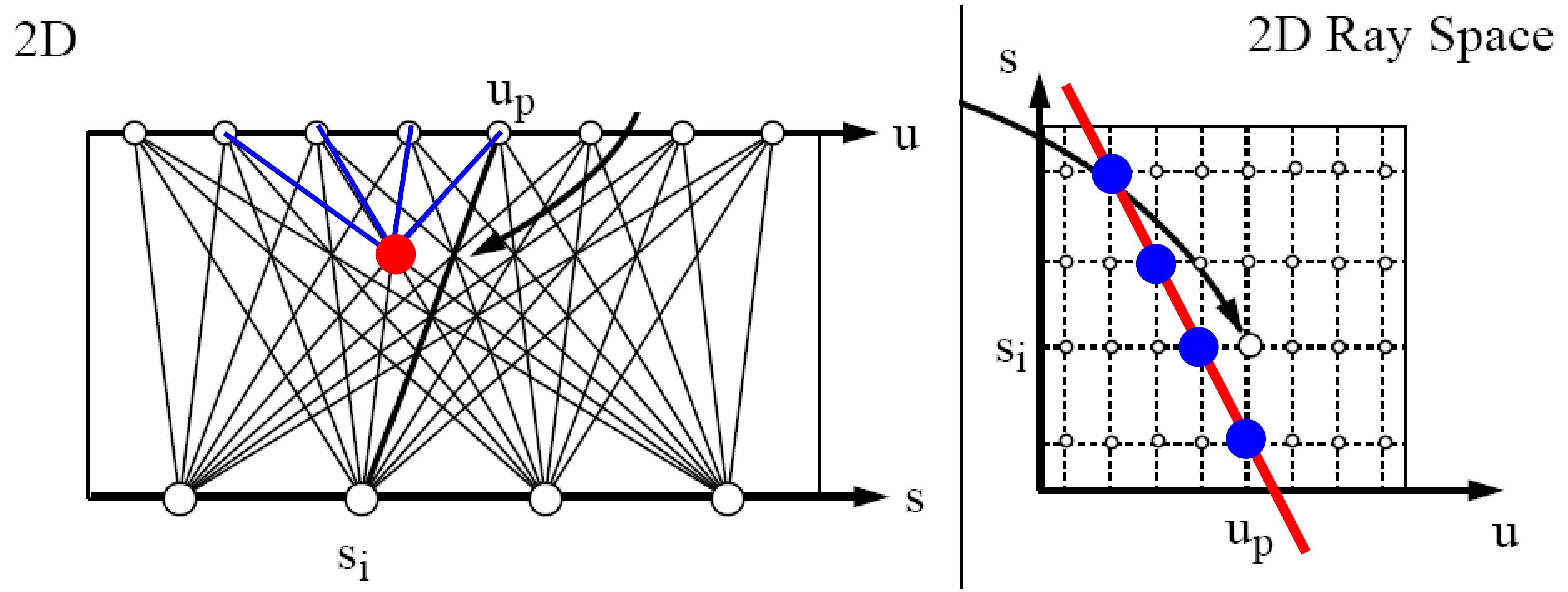


View?

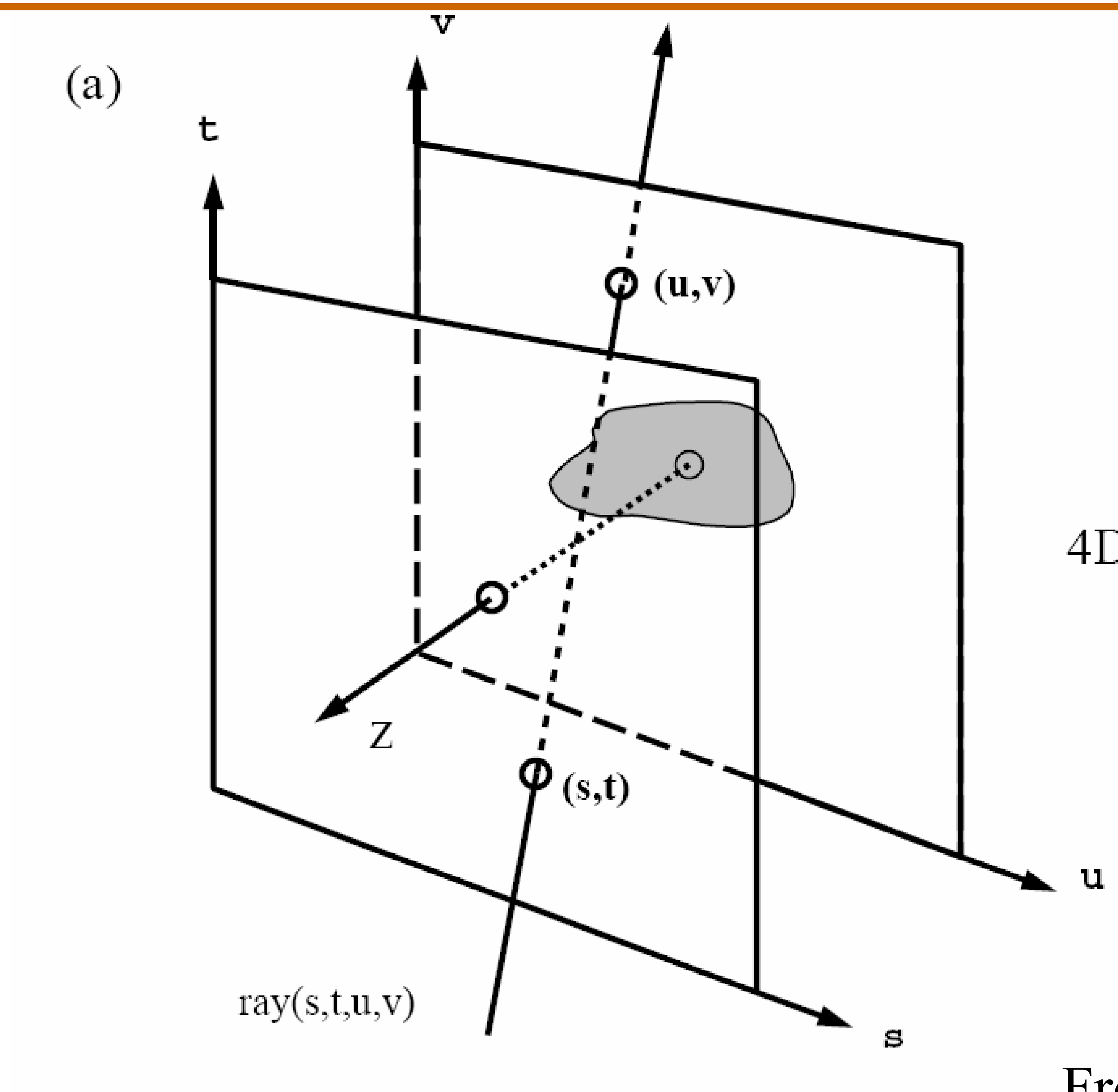


View?

- View ➔ line in Ray space
- Kind of cool: ray ➔ point, and view around point ➔line
- There is a duality



Back to 3D/4D



4D parameterization of rays

From Gortler et al.

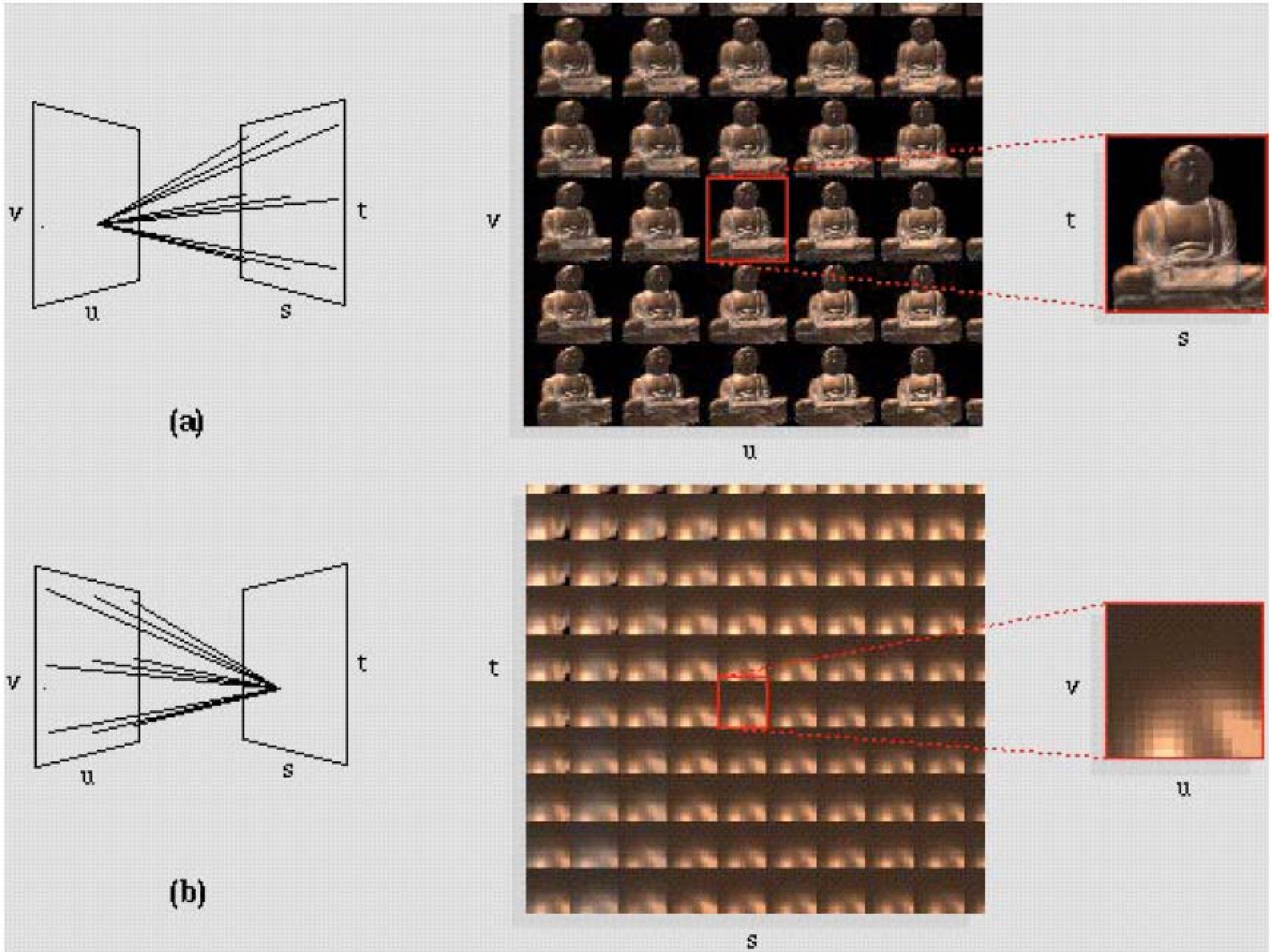


Figure 6: Two visualizations of a light field. (a) Each image in the array represents the rays arriving at one point on the uv plane from all points on the st plane, as shown at left. (b) Each image represents the rays leaving one point on the st plane bound for all points on the uv plane. The images in (a) are off-axis (i.e. sheared) perspective views of the scene, while the images in (b) look like reflectance maps. The latter occurs because the object has been placed astride the focal plane, making sets of rays leaving points on the focal plane similar in character to sets of rays leaving points on the object.

Cool visualization

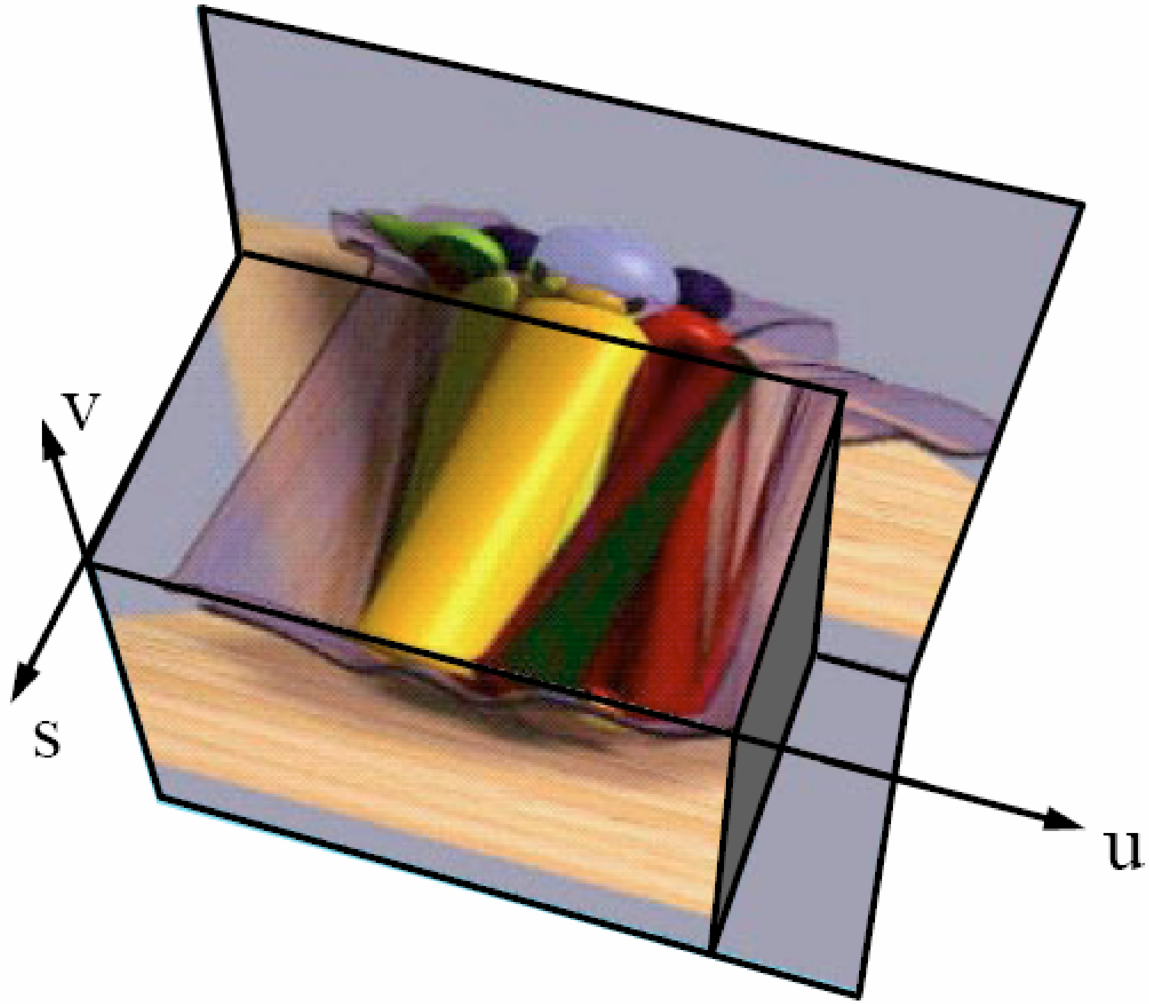


Figure 7: An (s, u, v) slice of a Lumigraph

From Gortler et al.

View = 2D plane in 4D

- **With various resampling issues**

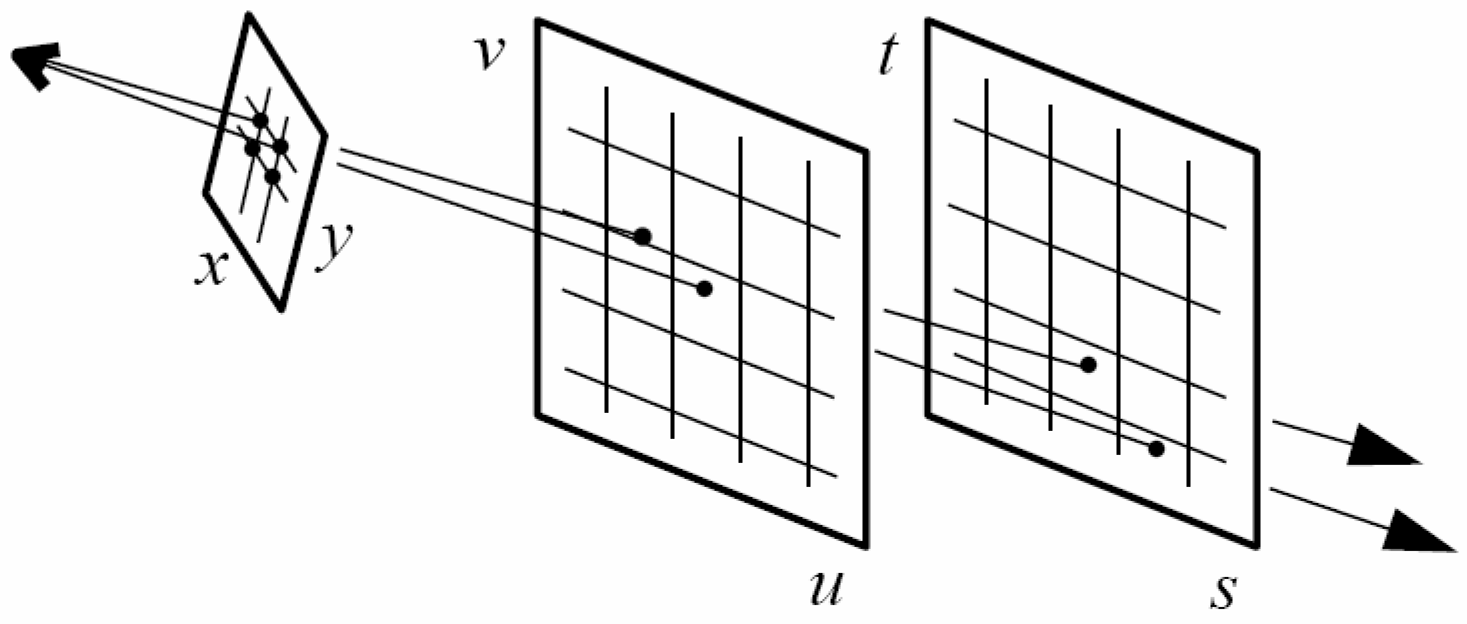
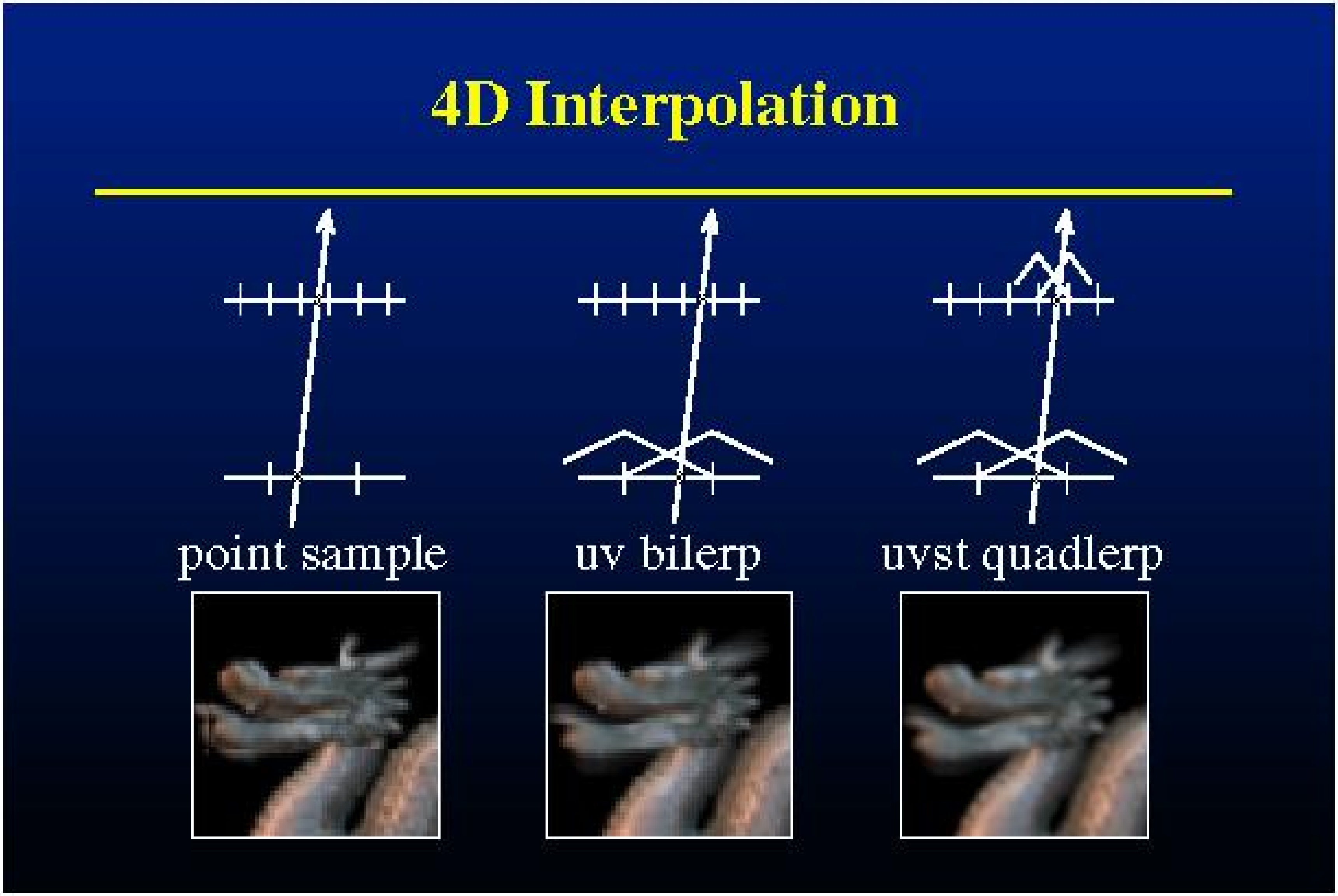


Figure 12: The process of resampling a light slab during display.

Demo light field viewer

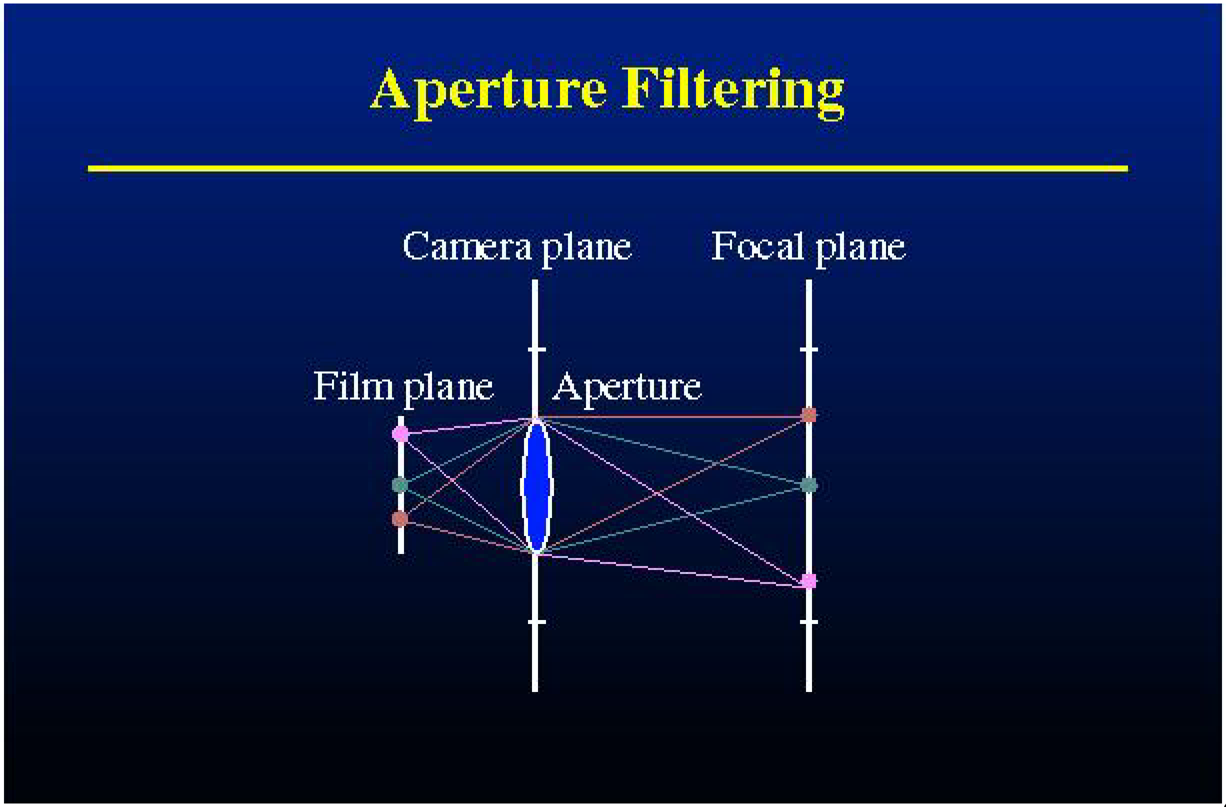
Reconstruction, antialiasing, depth of field



Slide by Marc Levoy

Aperture reconstruction

- **So far, we have talked about pinhole view**
- **Aperture reconstruction: depth of field, better antiliasing**



Slide by Marc Levoy

Small aperture

Image Isaksen et al.

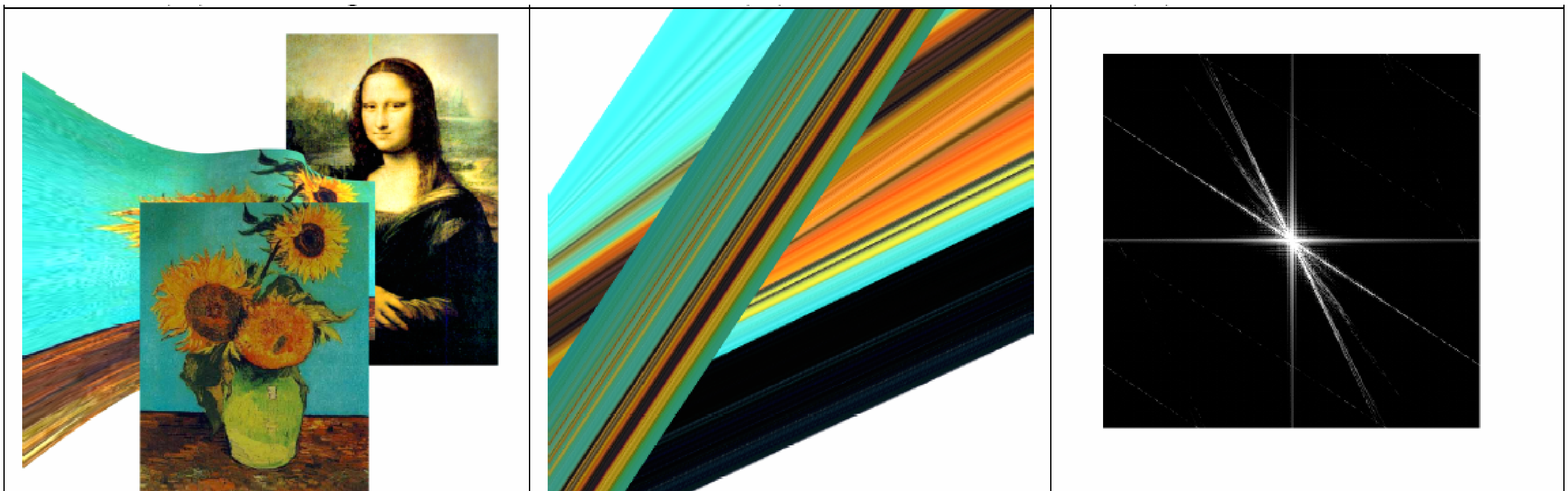
Big aperture

Image Isaksen et al.

Light field sampling

[Chai et al. 00, Isaksen et al. 00, Stewart et al. 03]

- Light field spectrum as a function of object distance
- Slope inversely proportional to depth
- http://graphics.cs.cmu.edu/projects/plenoptic-sampling/ps_projectpage.htm
- http://portal.acm.org/citation.cfm?id=344779.344929



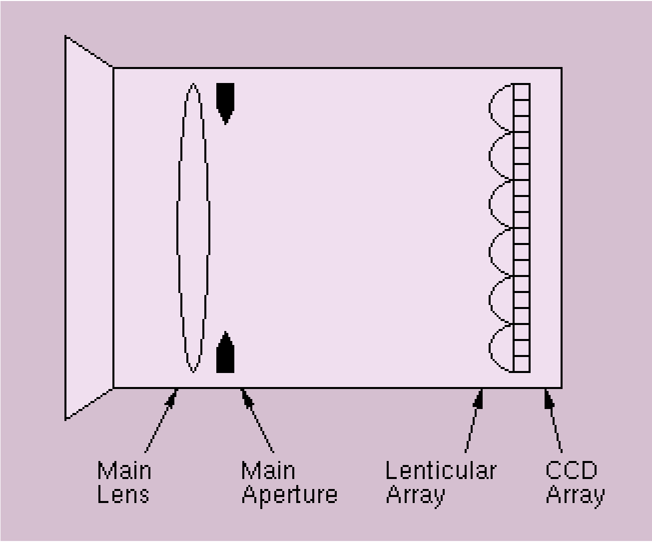
(d1)Scene image | (d2) EPI | (d3) Fourier transform of EPI

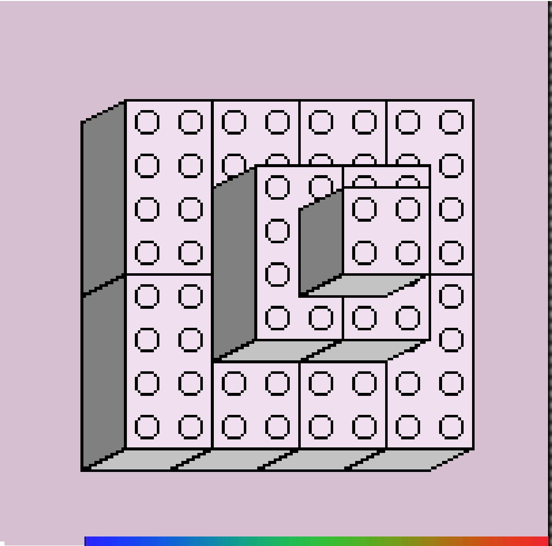
From [Chai et al. 2000]

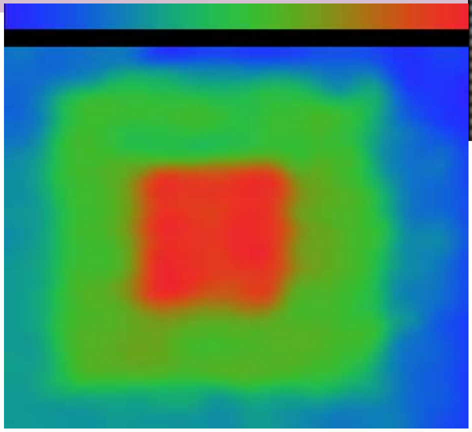
Light field cameras

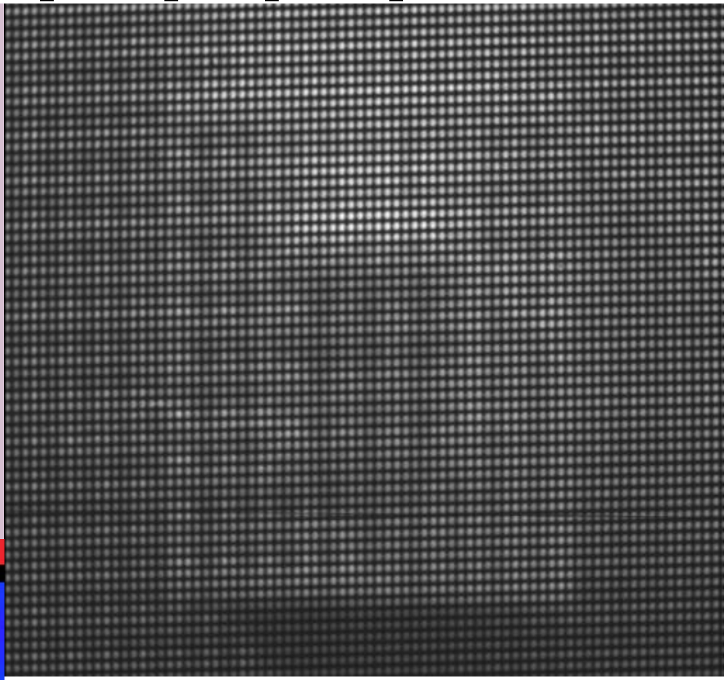
Plenoptic camera

- For depth extraction
- Adelson & Wang 92
  http://www-bcs.mit.edu/people/jyawang/demos/plenoptic/plenoptic.html



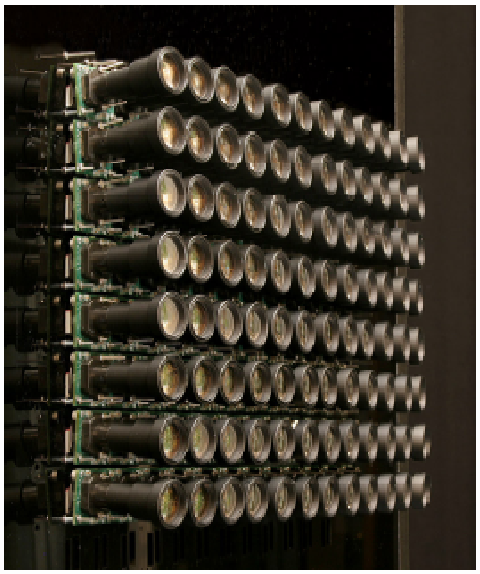


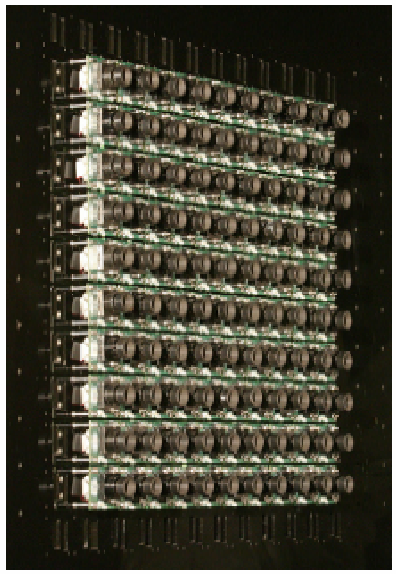




Camera array

- **Willburn et al.** http://graphics.stanford.edu/papers/CameraArray/





Camera arrays

- **http://graphics.stanford.edu/projects/array/**

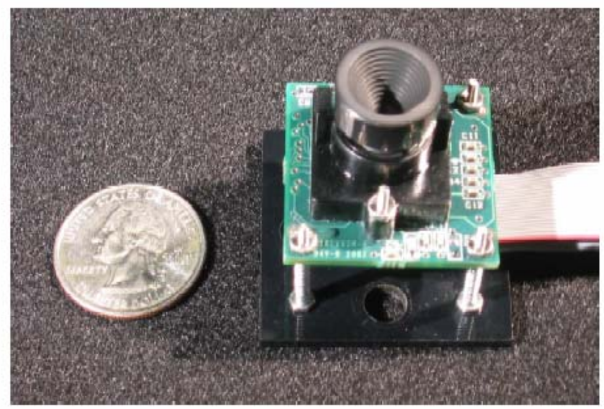


Figure 2: Our camera tiles contain an Omnivision 8610 image sensor, passive electronics, and a lens mount. The ribbon cables carry video data, synchronization signals, control signals, and power between the tile and the processing board. To keep costs low, we use fixed-focus, fixed-aperture lenses.

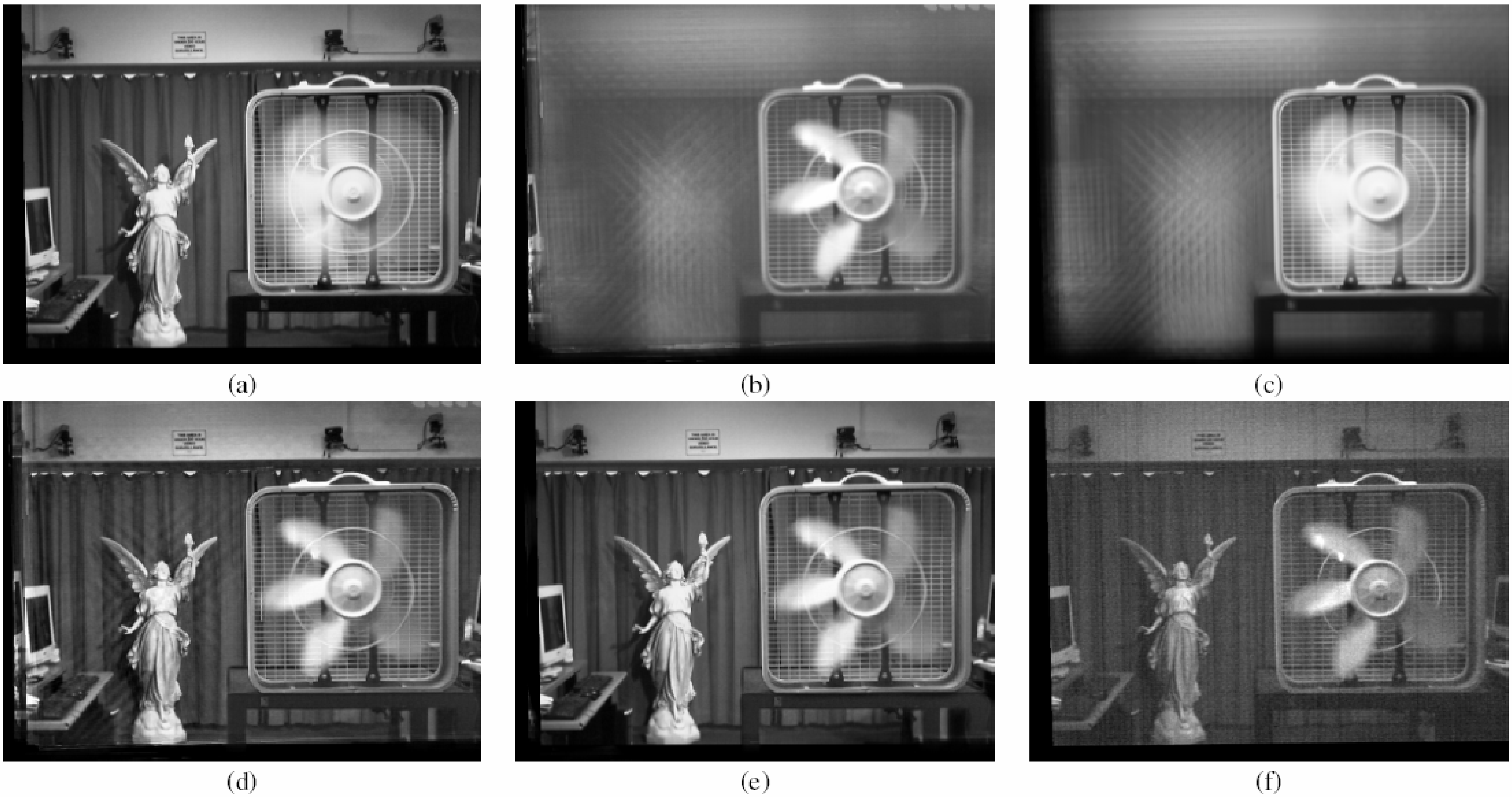
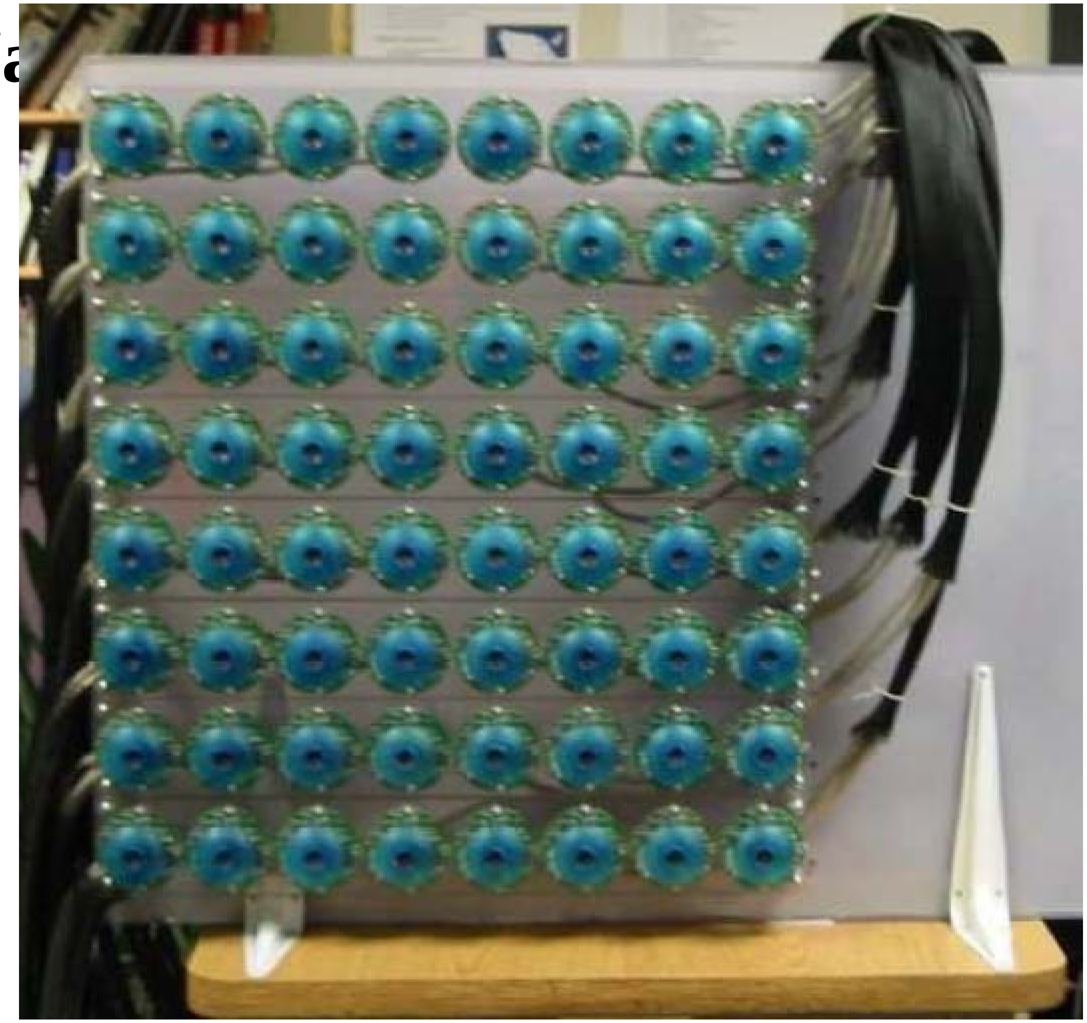


Figure 12: Hybrid synthetic aperture photography for combining high depth of field and low motion blur. (a-c) Images captured of a scene simultaneously through three different apertures: a single camera with a long exposure time (a), a large synthetic aperture with short exposure time (b), and a large synthetic aperture with a long exposure time. Computing (a+b-c) yields image (d), which has aliasing artifacts because the synthetic apertures are sampled sparsely from slightly different locations. Masking pixels not in focus in the synthetic aperture images before computing the difference (a + b - c) removes the aliasing (e). For comparison, image (f) shows the image taken with an aperture that is narrow in both space and time. The entire scene is in focus and the fan motion is frozen, but the image is much noisier.

MIT version

- **Jason Ya**



Bullet time

- **Time splice http://www.ruffy.com/frameset.htm**

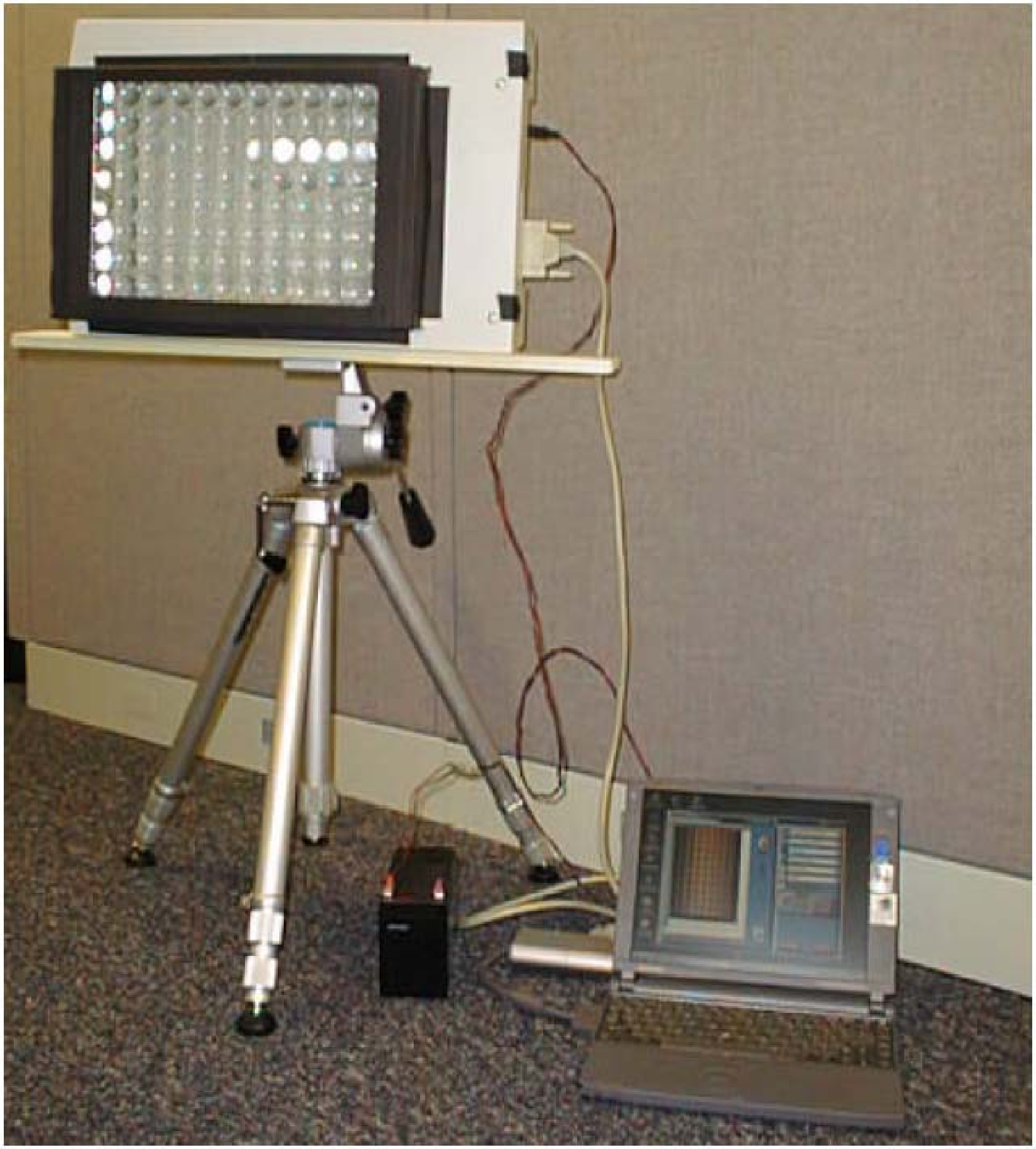
Robotic Camera

Image Leonard McMillan

Image Levoy et al.

Flatbed scanner camera

- By Jason Yang

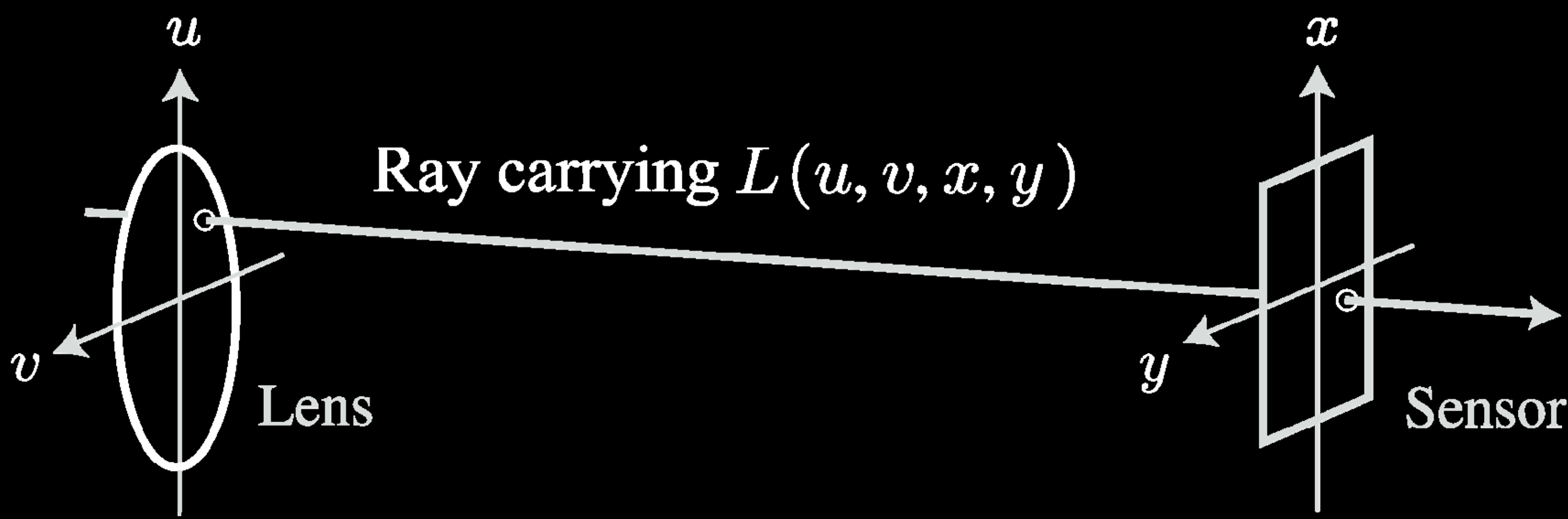


Plenoptic camera refocusing

Conventional Photograph

Slide by Ren Ng.

Light Field Photography



- **Capture the light field inside the camera body**

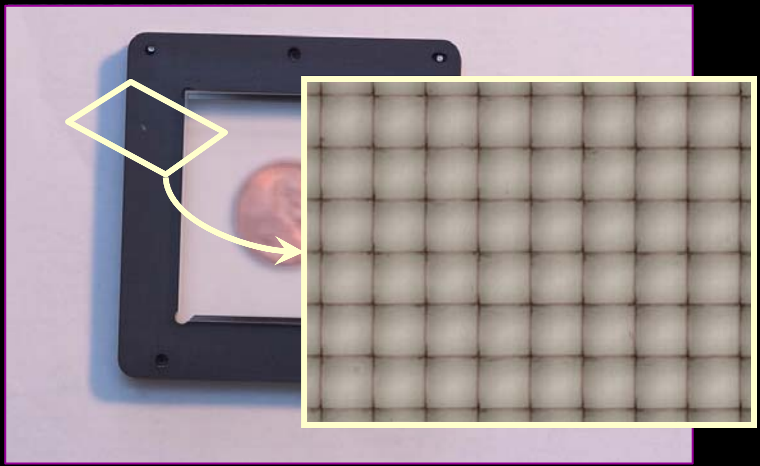
Slide by Ren Ng.

Hand-Held Light Field Camera

Medium format digital camera

Camera in-use

16 megapixel sensor



Microlens array

Slide by Ren Ng.

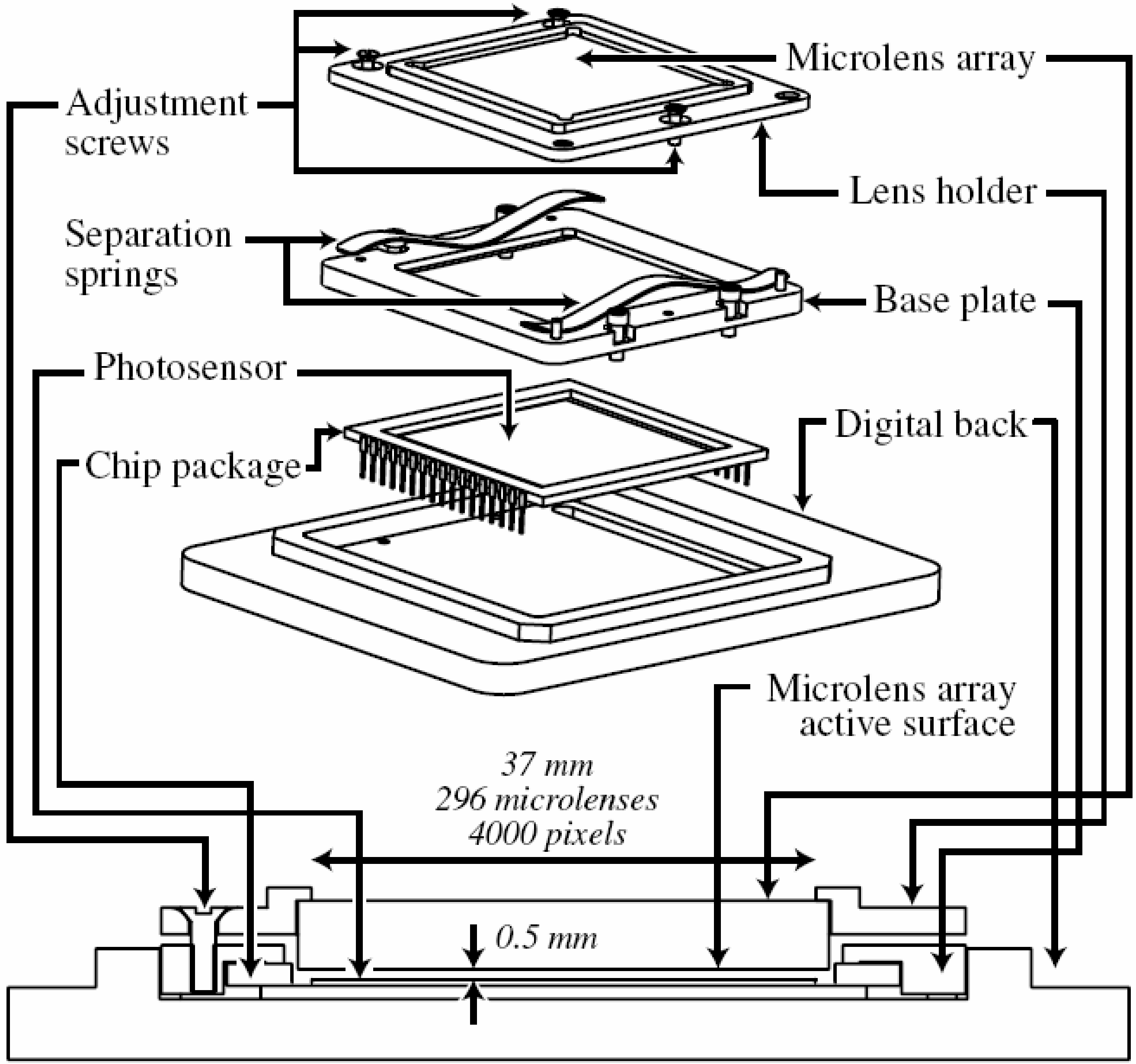
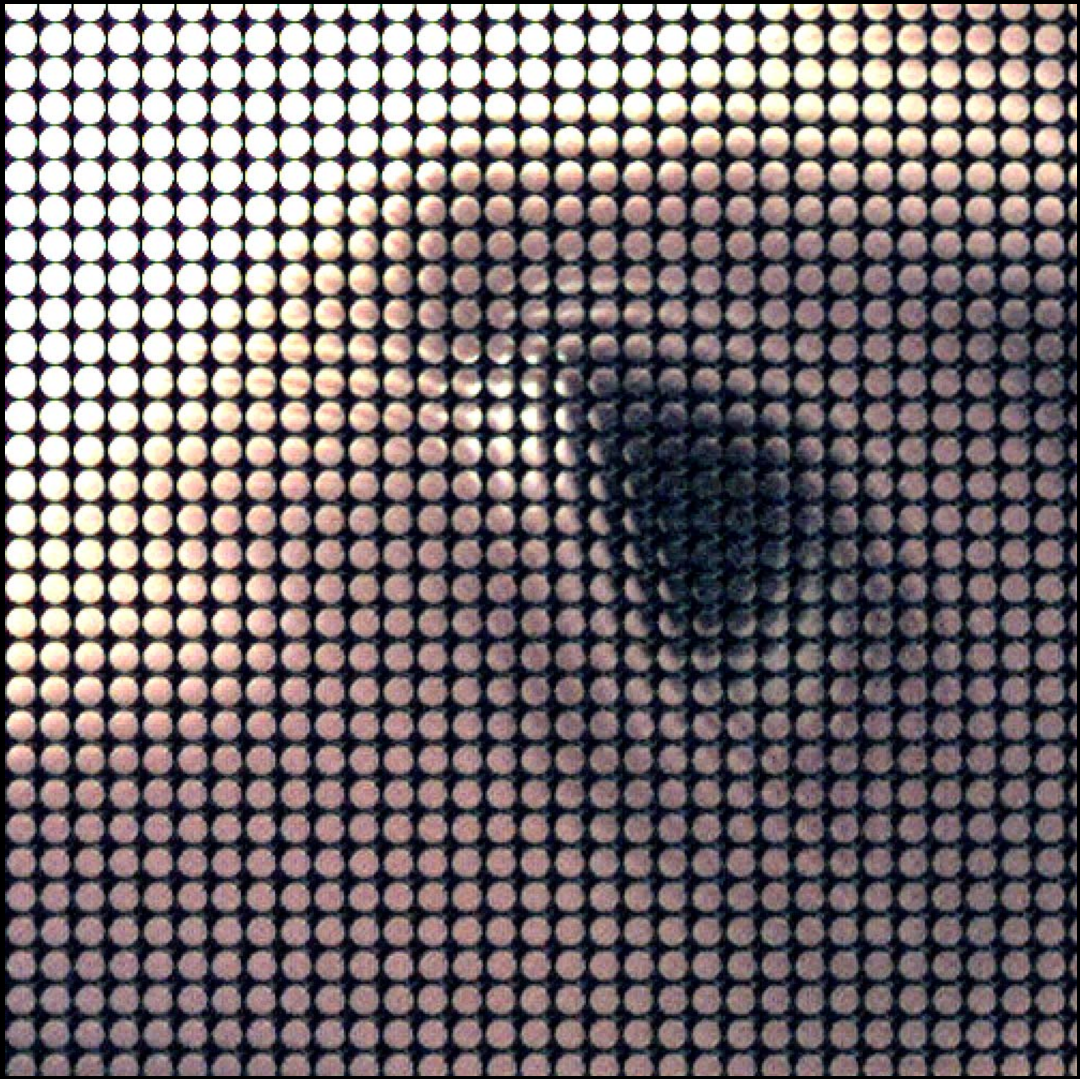


Figure 8: *Top:* Exploded view of assembly for attaching the microlens array to the digital back. *Bottom:* Cross-section through assembled parts.

Light Field in a Single Exposure

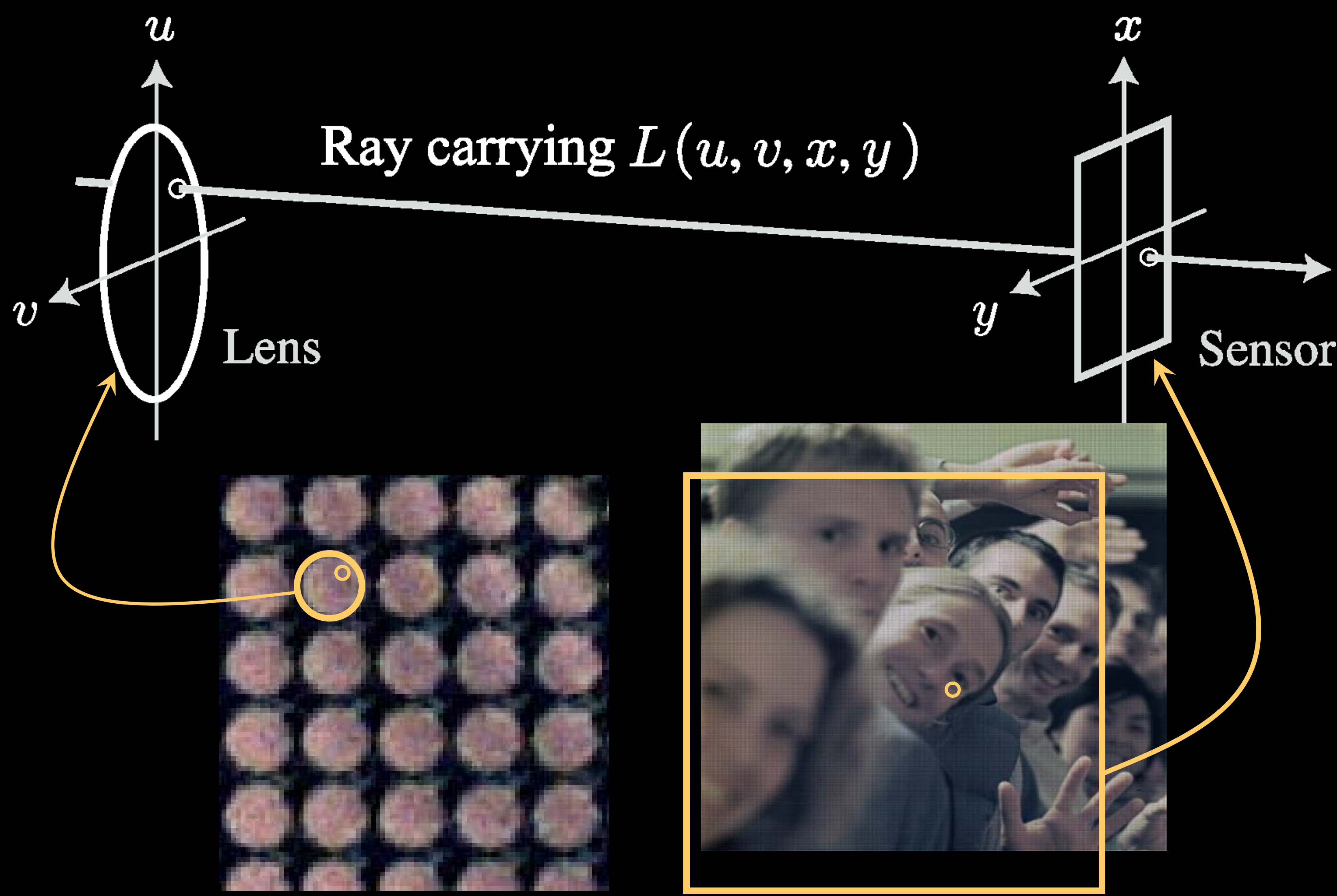
Slide by Ren Ng.

Light Field in a Single Exposure



Slide by Ren Ng.

Light Field Inside the Camera Body



Slide by Ren Ng.

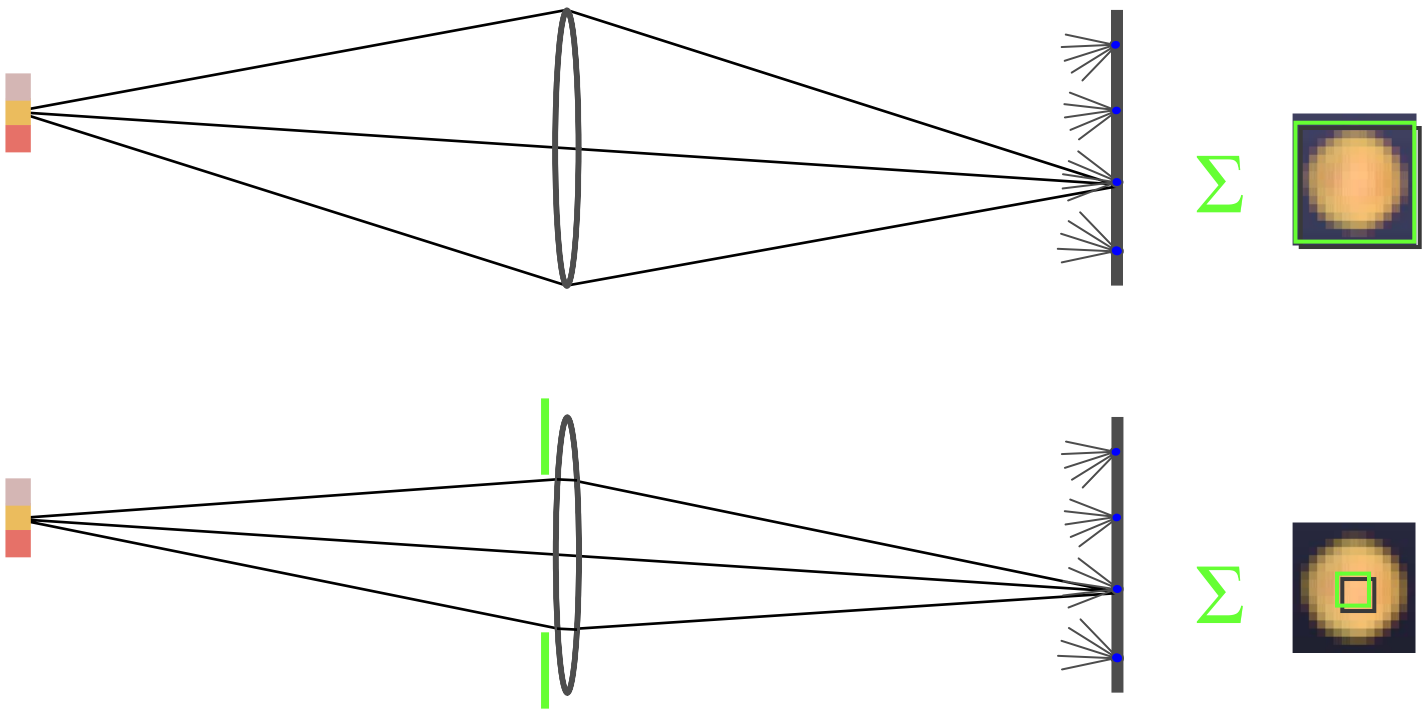
Digital Refocusing

Slide by Ren Ng.

Digital Refocusing

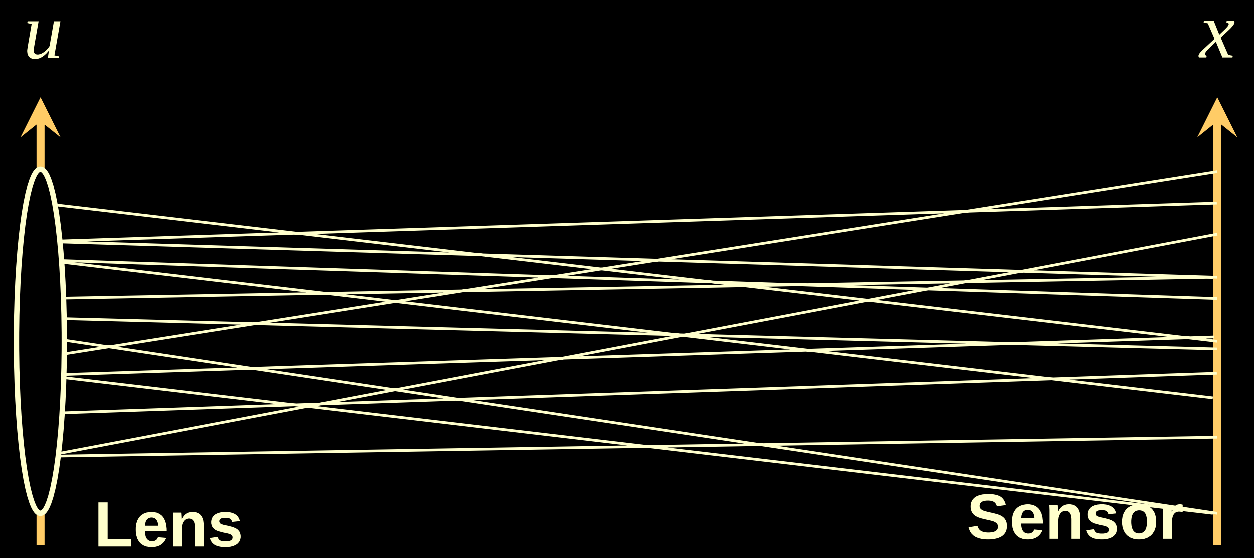
Slide by Ren Ng.

Digitally stopping-down



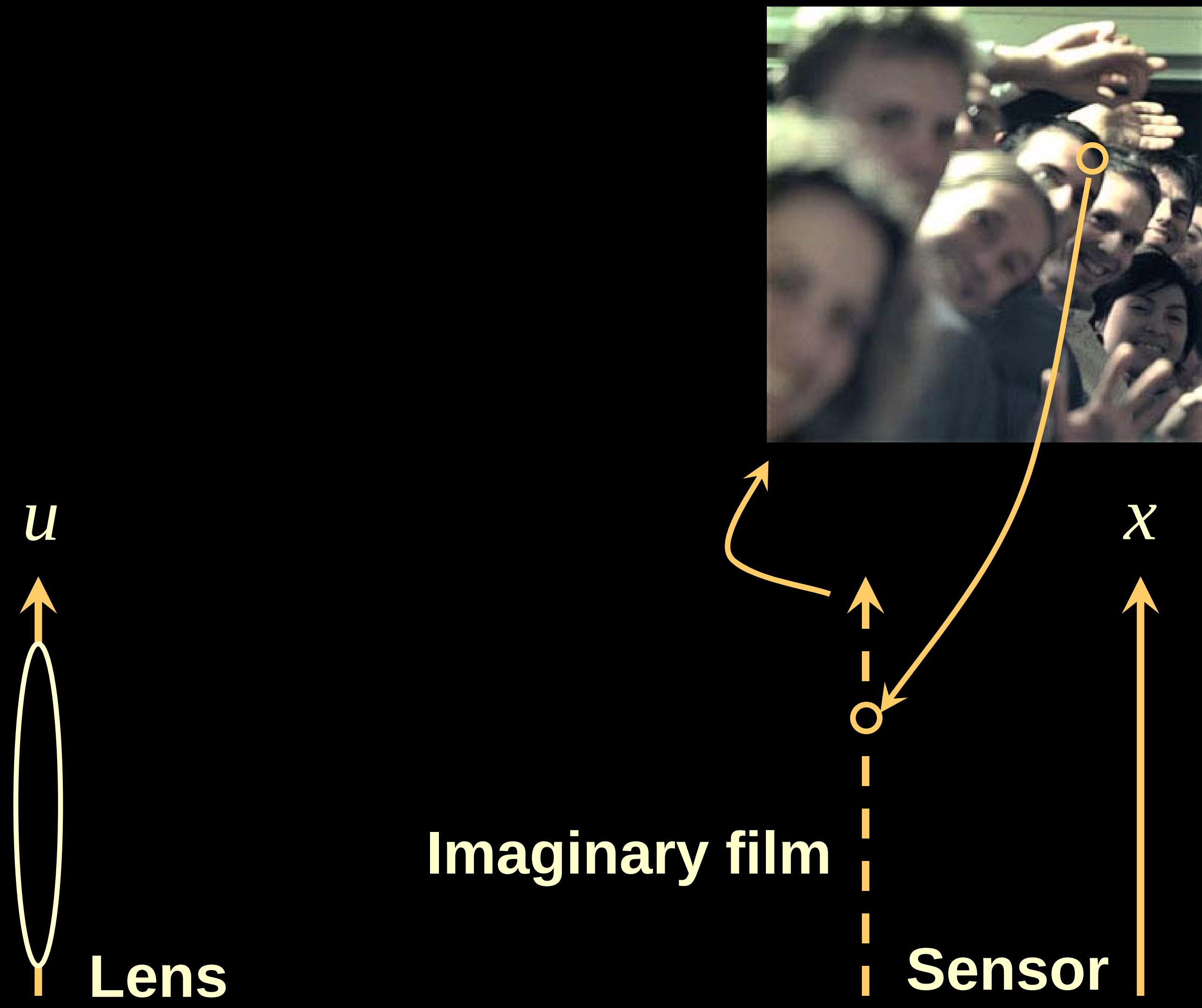
stopping down = summing only the central portion of each microlens

Digital Refocusing by Ray-Tracing



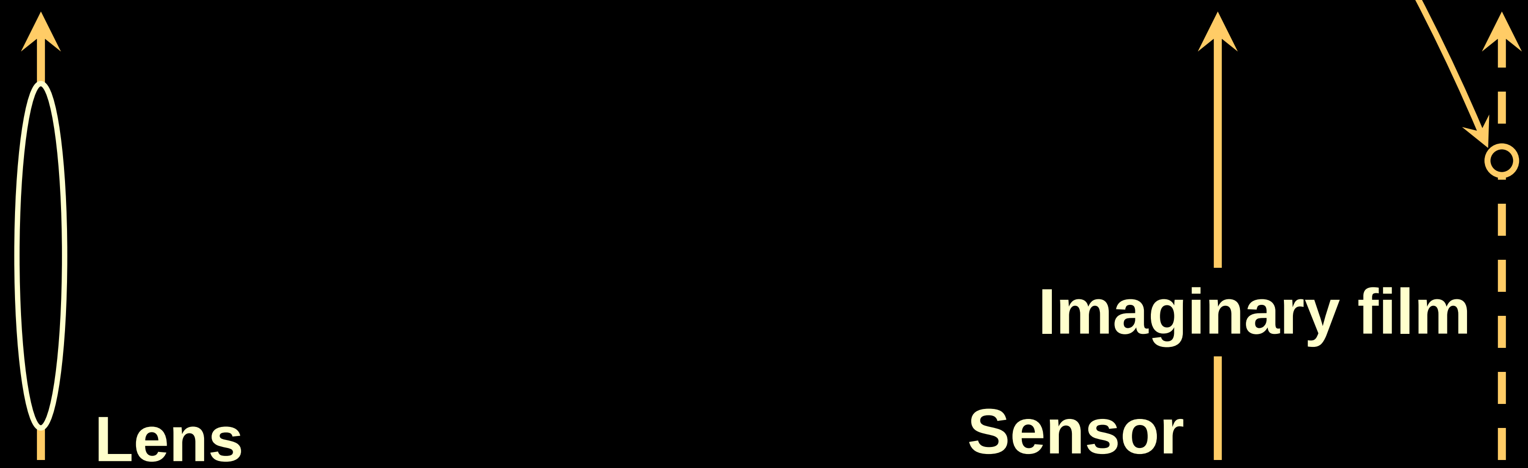
Slide by Ren Ng.

Digital Refocusing by Ray-Tracing



Slide by Ren Ng.

Digital Refocusing by Ray-Tracing



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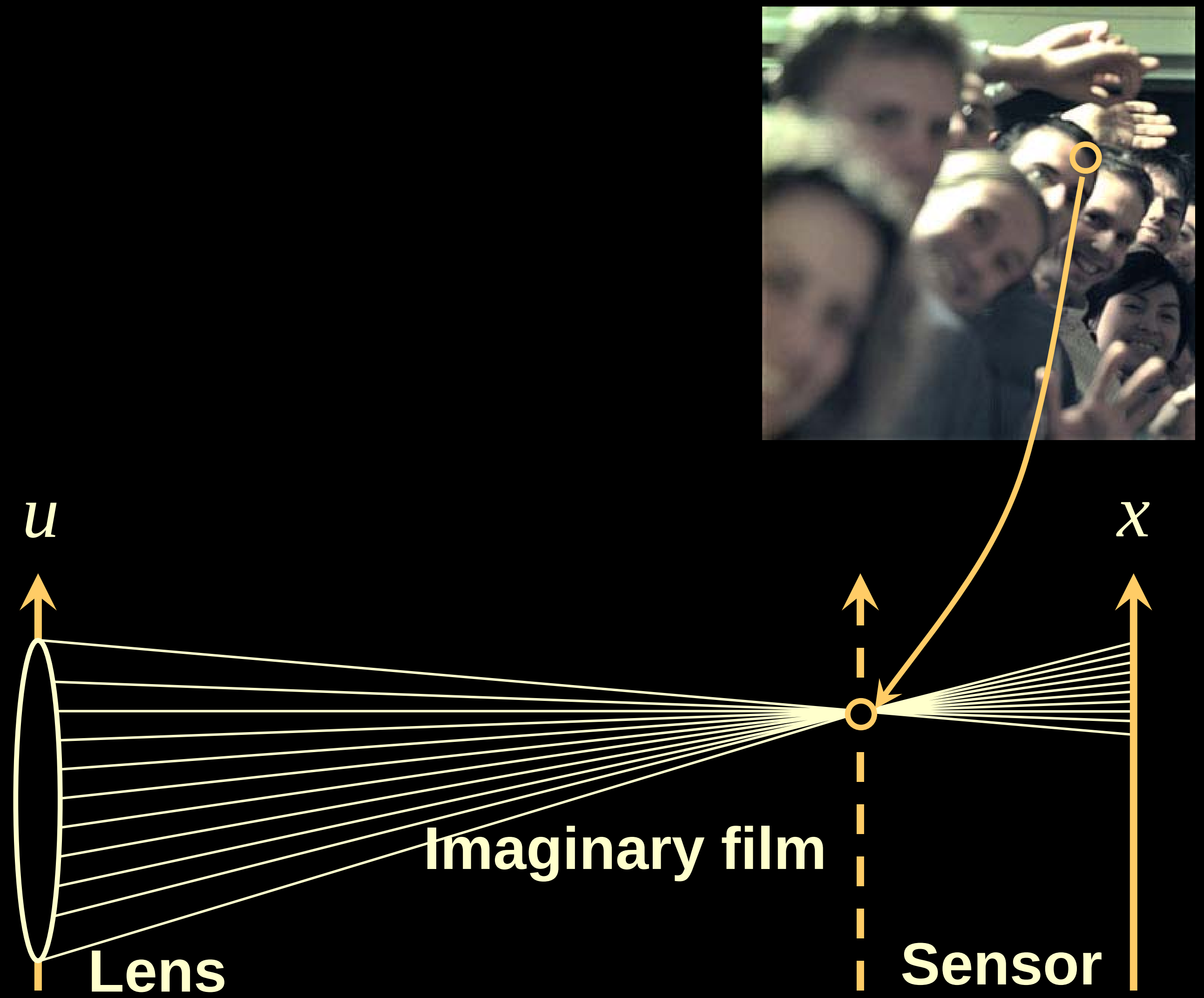
Digital Refocusing by Ray-Tracing



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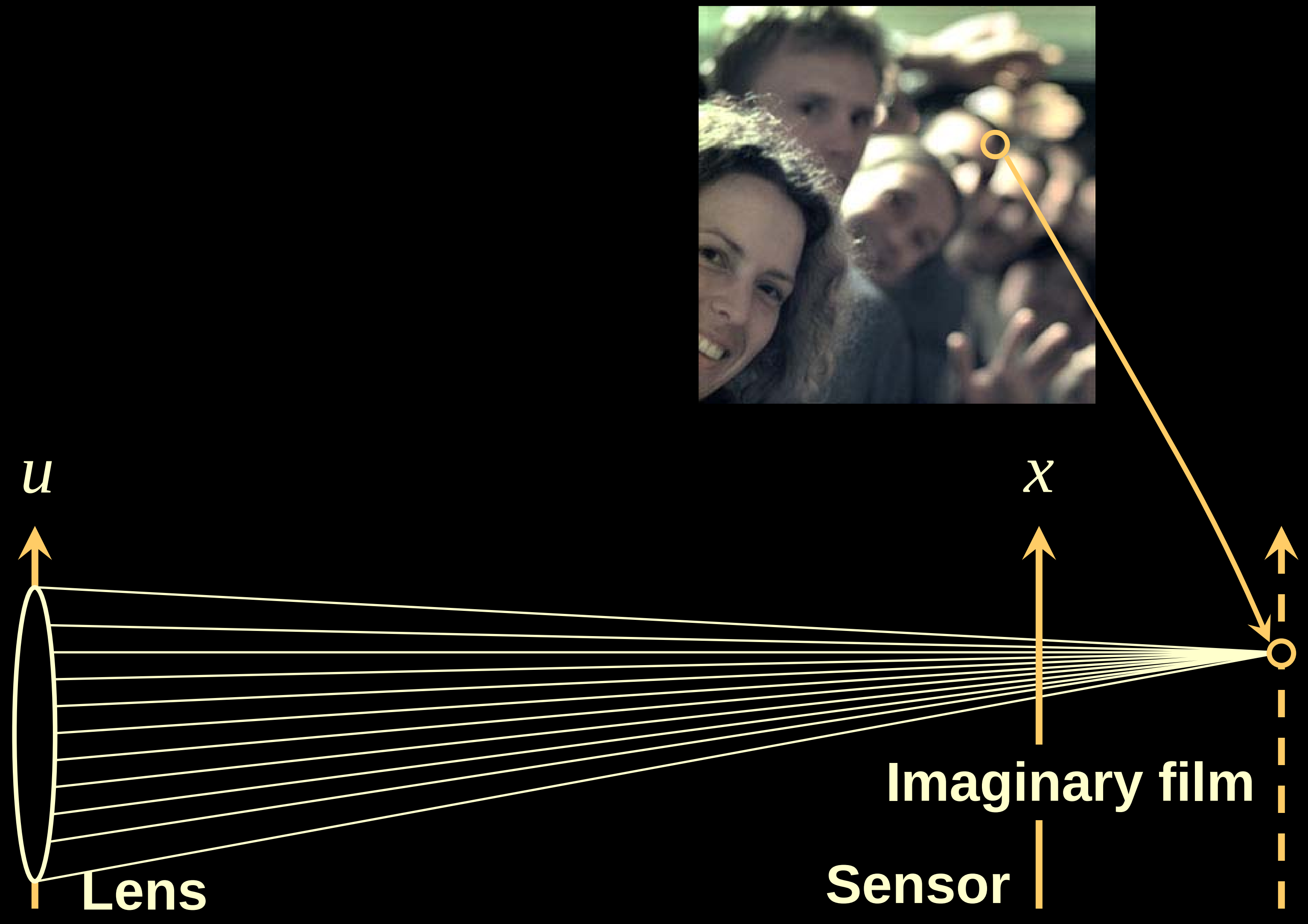
Digital Refocusing by Ray-Tracing



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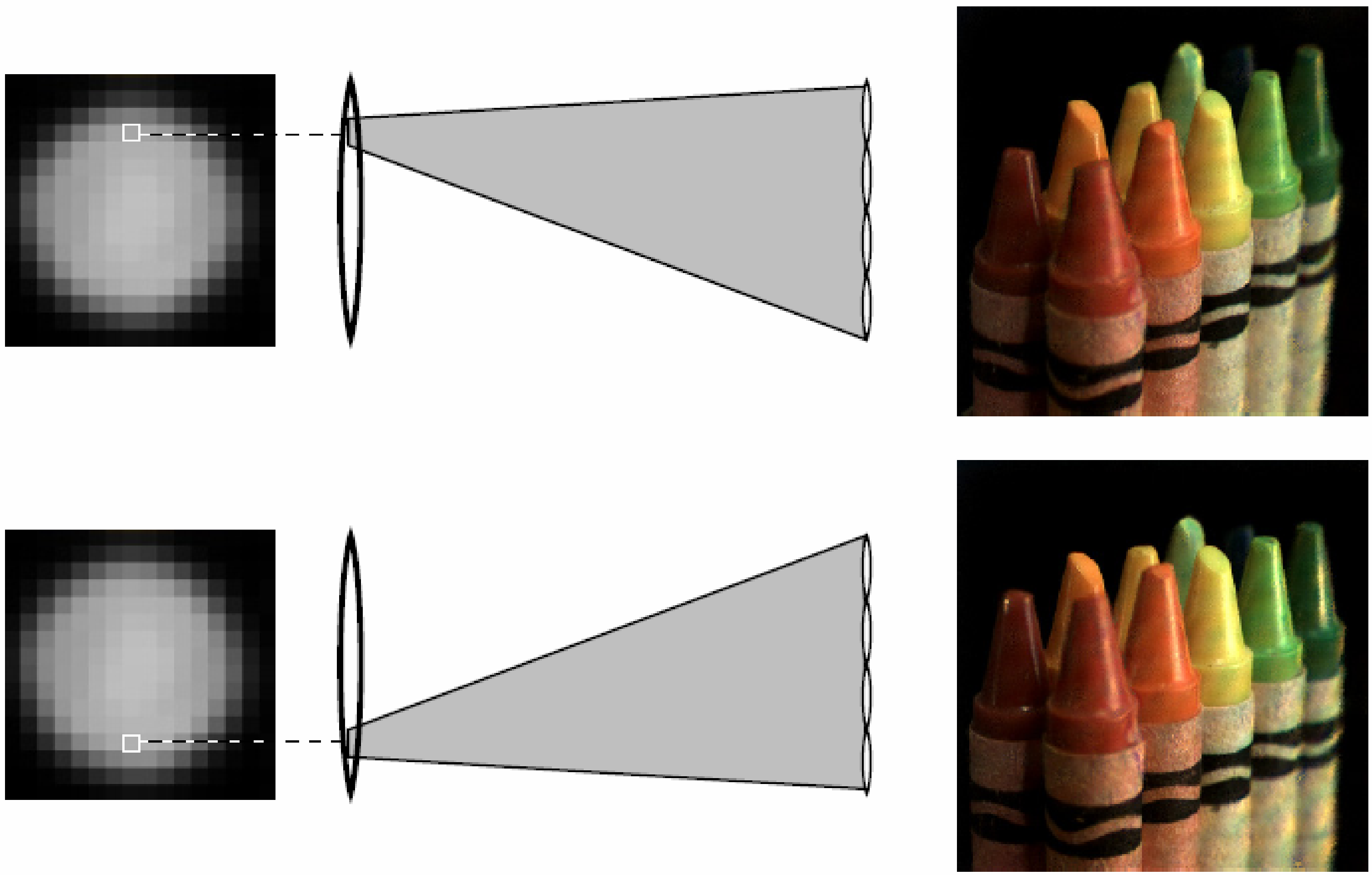

Figure 4: Two sub-aperture photographs obtained from a light field by extracting the shown pixel under each microlens (depicted on left). Note that the images are not the same, but exhibit vertical parallax.

Results of Band-Limited Analysis

- **Assume a light field camera with**
  - An *f* /*A* lens
  - *N* x *N* pixels under each microlens
- **From its light fields we can**
  - Refocus *exactly* within
    depth of field of an *f* /(*A* □ *N*) lens
- **In our prototype camera**
  - Lens is *f* /4
  - 12 x 12 pixels under each microlens
- **Theoretically refocus within**
  depth of field of an *f*/48 lens

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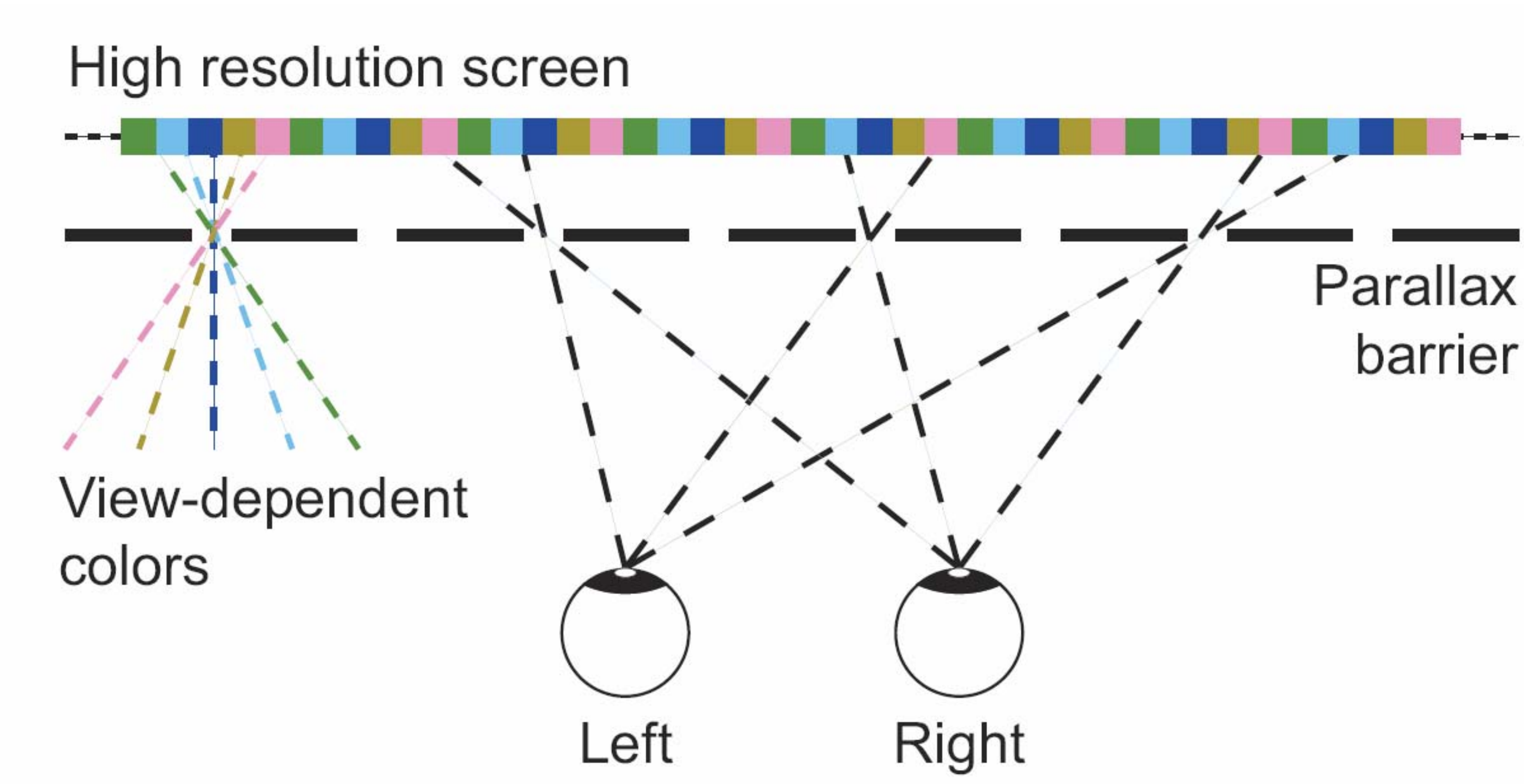
Show result video

Automultiscopic displays

3D displays

- **With Matthias, Wojciech & Hans**
- **View-dependent pixels**
  - Lenticular optics (microlenses)



Lenticular optics

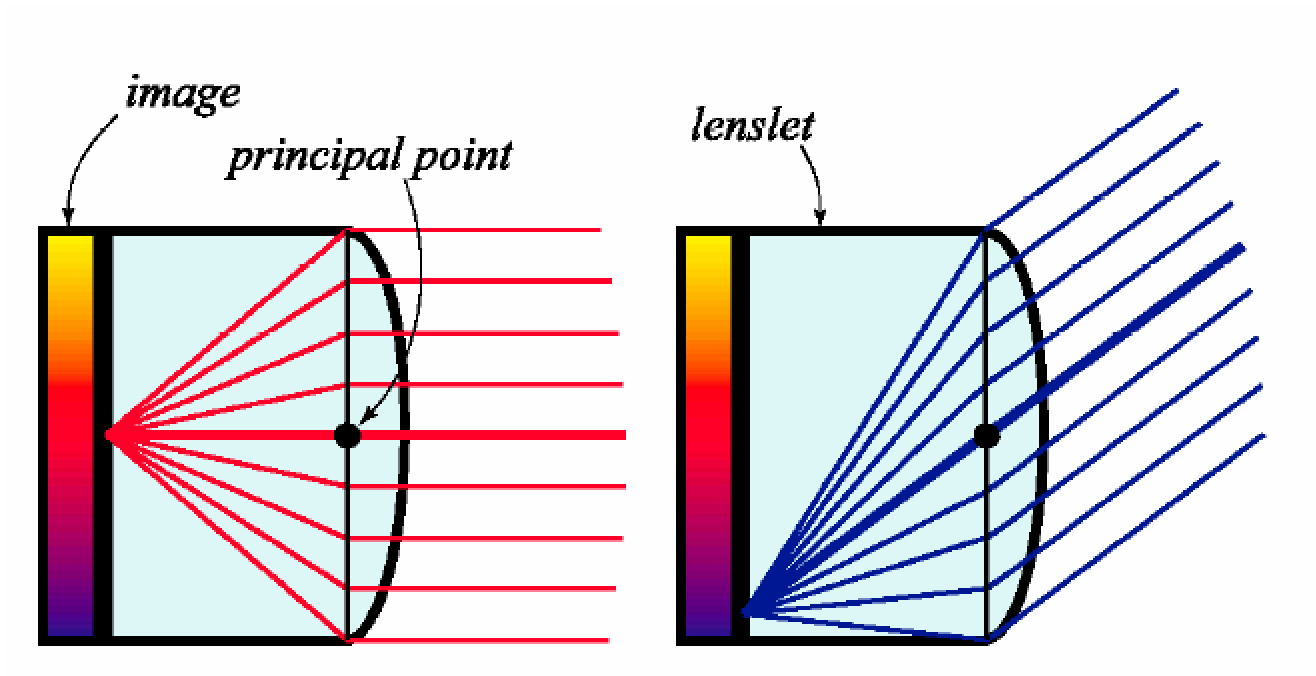


Figure by Isaksen et al.

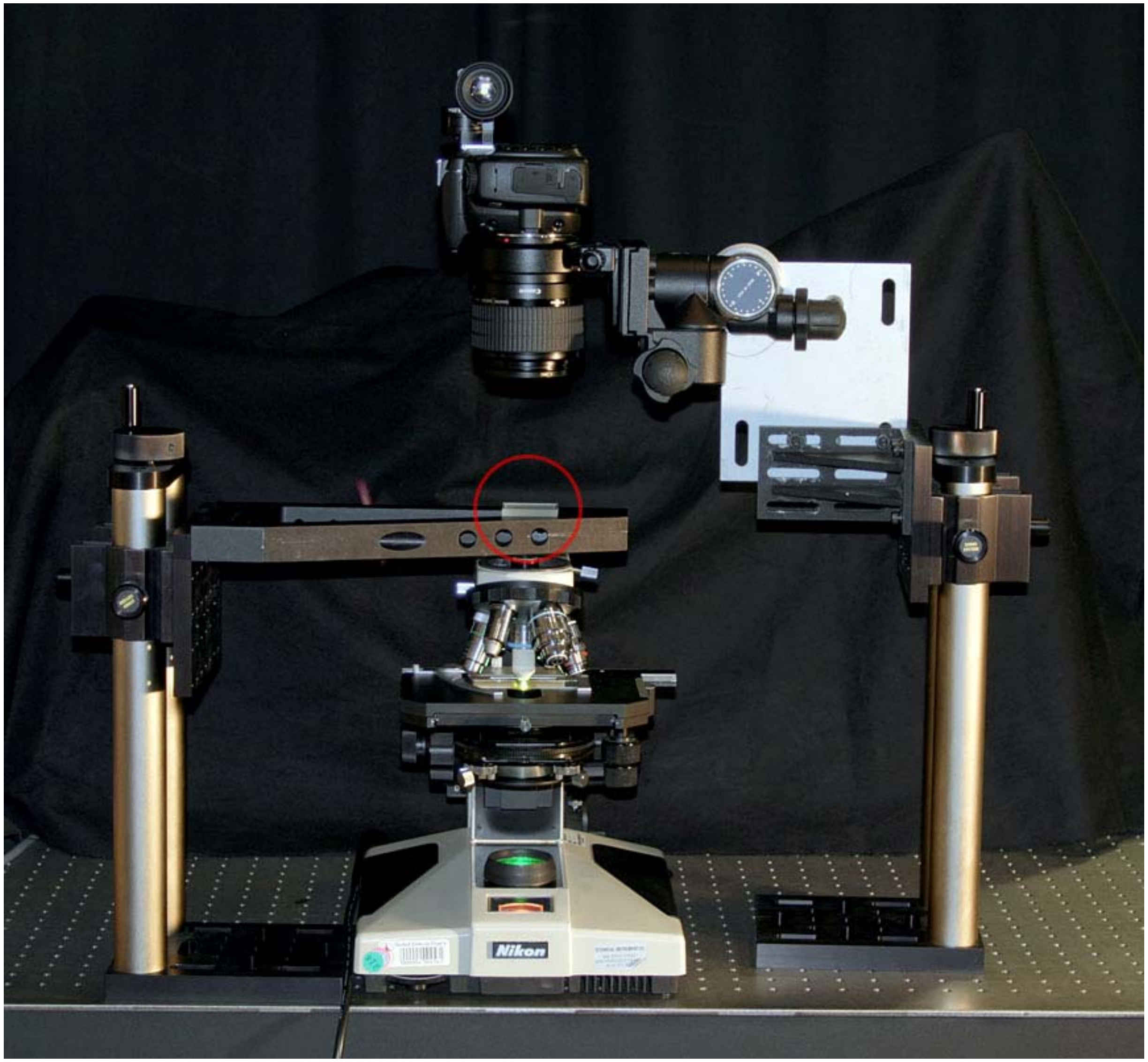
Application

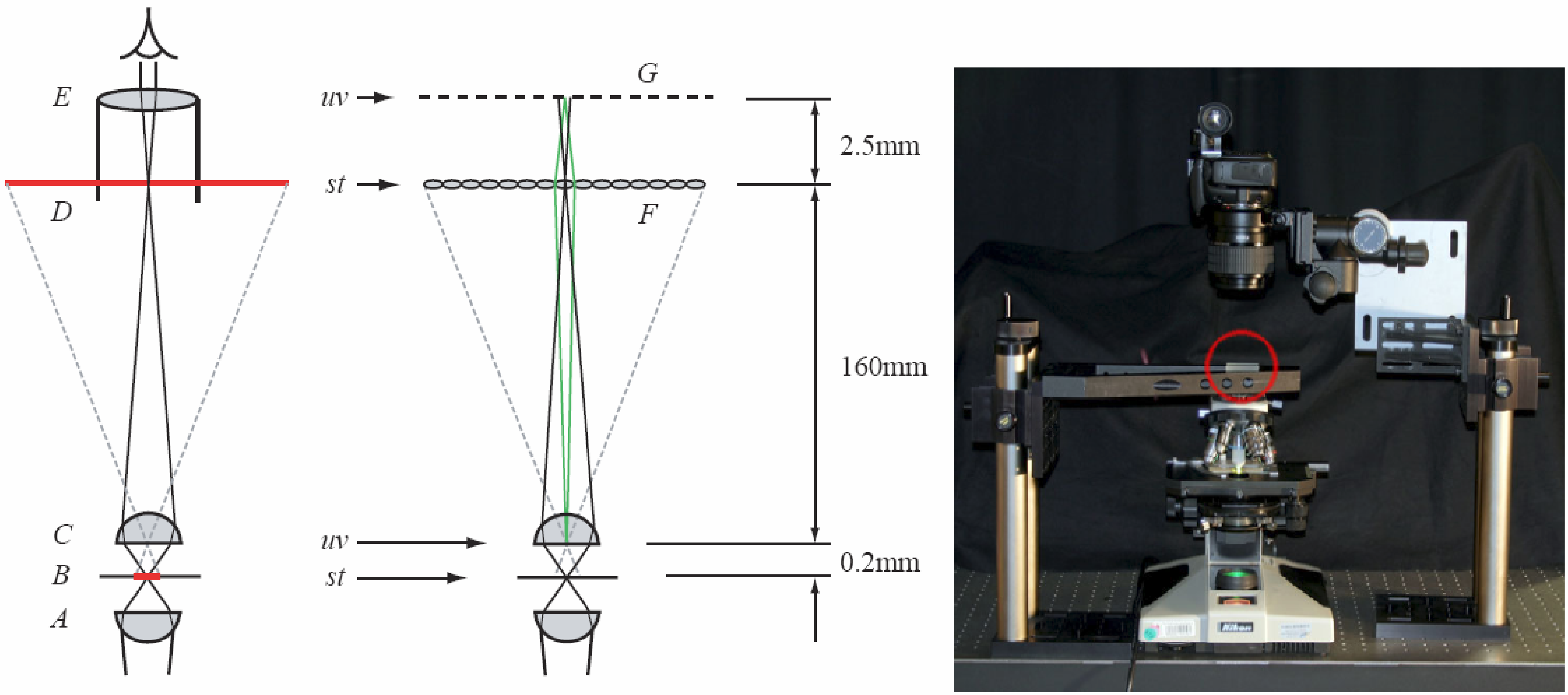
- **3D screens are shipping!**

Light Field Microscopy

Light field microscopy

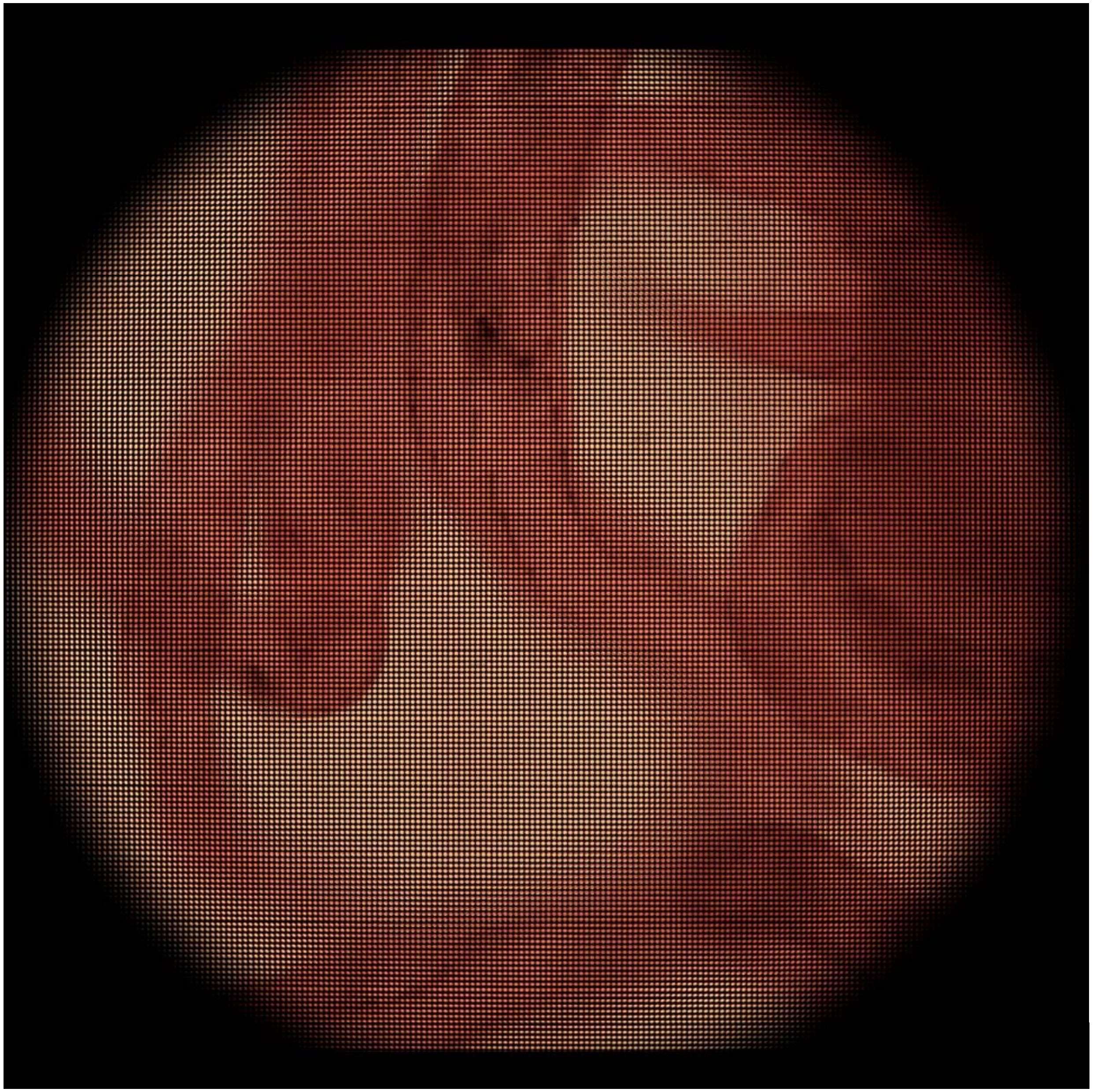
- **http://graphics.stanford.edu/projects/lfmicroscope/**





(a) ordinary microscope (b) light field microscope (c) our prototype

Figure 2: Optical layout of our light field microscope. (a) In a transmission-mode light microscope, an illumination source is focused by a condenser lens at *A* onto a specimen at *B*. An objective lens at *C* magnifies the specimen, creating a real image at intermediate image plane *D*. In older microscopes, this plane is located inside the microscope tube. An ocular (eyepiece) at *E* further magnifies the central portion of this image, creating a second image focused at infinity. (b) In our design the ocular is removed, a microlens array *F* is placed at the intermediate image plane, and a camera sensor is placed behind this at *G*, positioned so that each microlens records an in-focus image of the objective (green rays). In light field parlance, if the objective aperture and specimen constitute the *uv* and *st* planes, then the camera sensor and microlens array constitute a reimaging of these two planes. This drawing is not to scale; typical distances are shown beside it. (c) Our prototype consists of a Nikon Optiphot and custom microlens array (red circle). To avoid building a special camera, we re-image *G* using a Canon 5D 35mm SLR with a 1:1 macro lens.



Show video

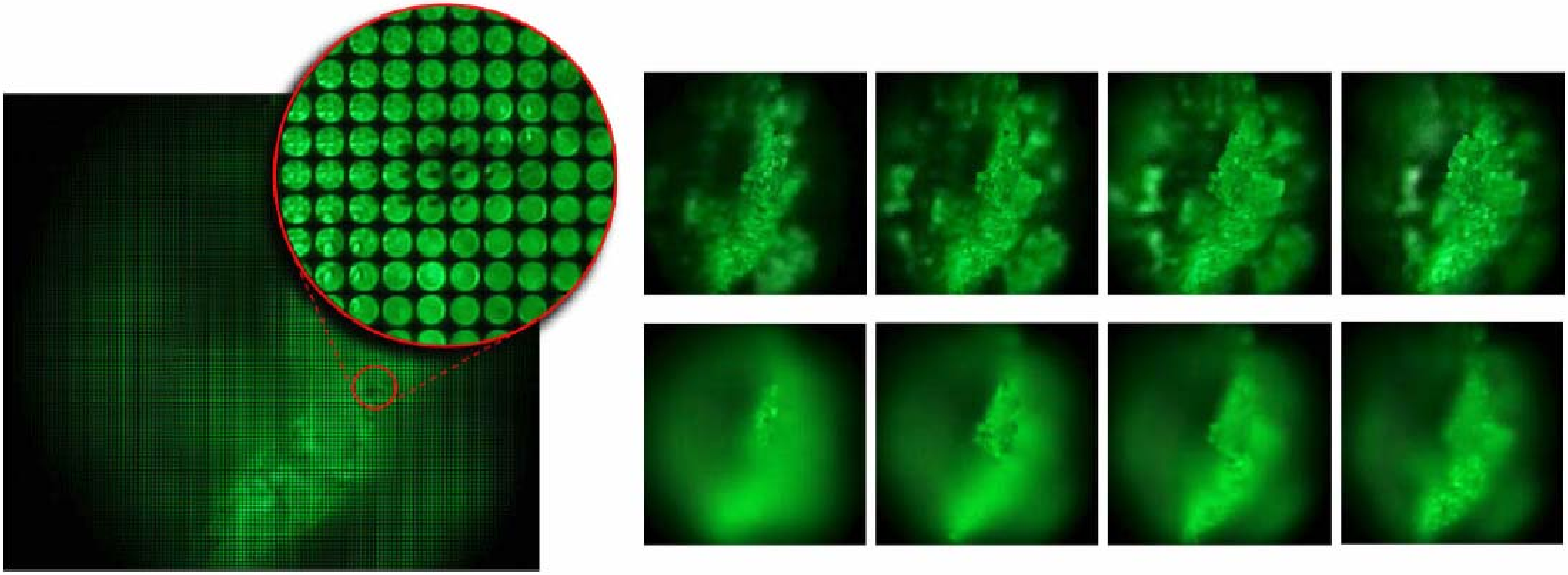


Figure 1: At left is a light field captured by photographing a speck of fluorescent crayon wax through a microscope objective and microlens array. The objective magnification is 16×, and the field of view is 1.3mm wide. The image consists of 170^2 subimages, one per microlens, each depicting a different part of the specimen. An individual subimage contains 20^2 pixels, each representing a different point on the objective lens and hence a unique direction of view. By extracting one pixel from each subimage, we can produce perspective views of the specimen, a sequence of which is shown at top-right. Alternatively, by summing the pixels in each subimage, we can produce orthographic views with a shallow depth of field, like an ordinary microscope but of lower spatial resolution. Shearing the light field before summing, we can focus at different depths, as shown in the sequence at bottom-right. These images were computed in real-time on a PC.

Conclusions

Computational Photography

Slide by Ramesh