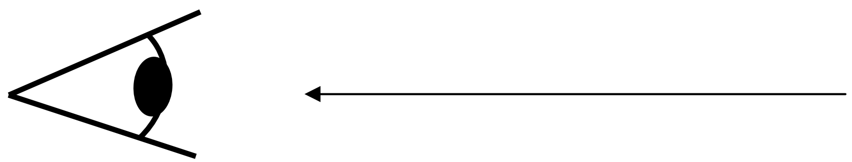
Modeling Light

15-463: Computational Photography
Alexei Efros, CMU, Fall 2005

What is light?

Electromagnetic radiation (EMR) moving along rays in space

- R(λ) is EMR, measured in units of power (watts)
  - λ is wavelength

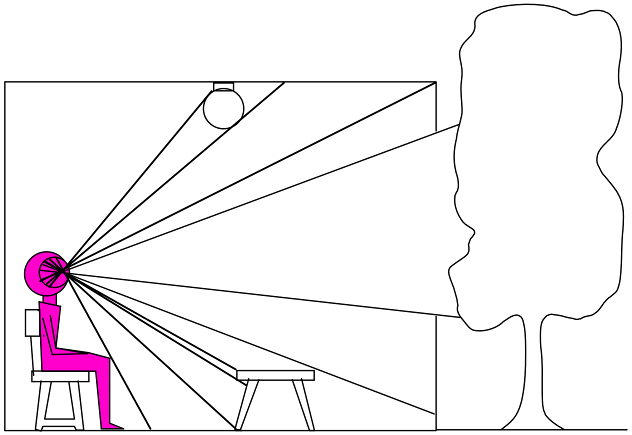


Useful things:

- Light travels in straight lines
- In vacuum, radiance emitted = radiance arriving
  - i.e. there is no transmission loss

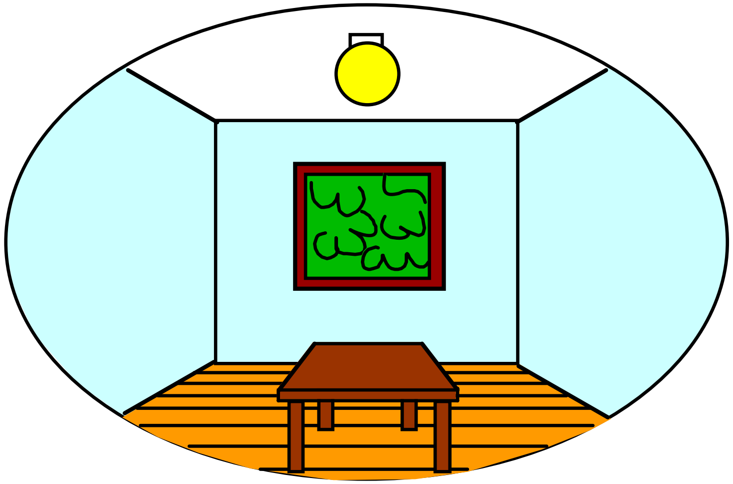
What do we see?

3D world



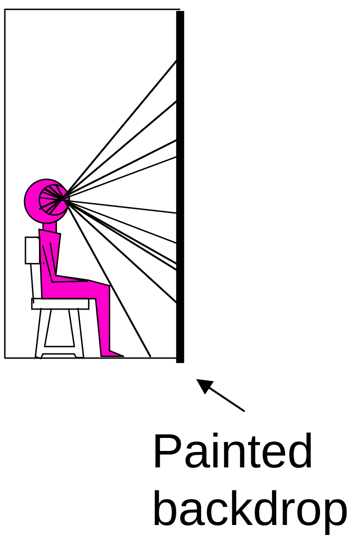
Point of observation

2D image

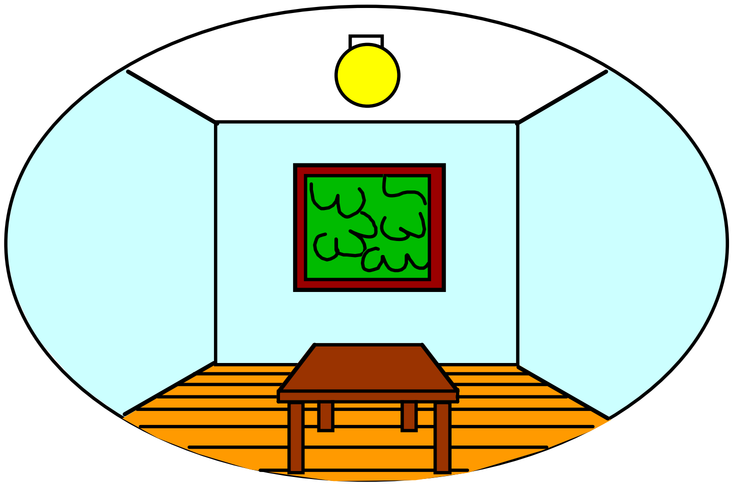


What do we see?

3D world



2D image



On Simulating the Visual Experience

Just feed the eyes the right data

- No one will know the difference!

Philosophy:

- Ancient question: “Does the world really exist?”

Science fiction:

- Many, many, many books on the subject
- Latest take: *The Matrix*

Physics:

- *Slowglass* might be possible?

Computer Science:

- Virtual Reality

To simulate we need to know:

What does a person see?

The Plenoptic Function

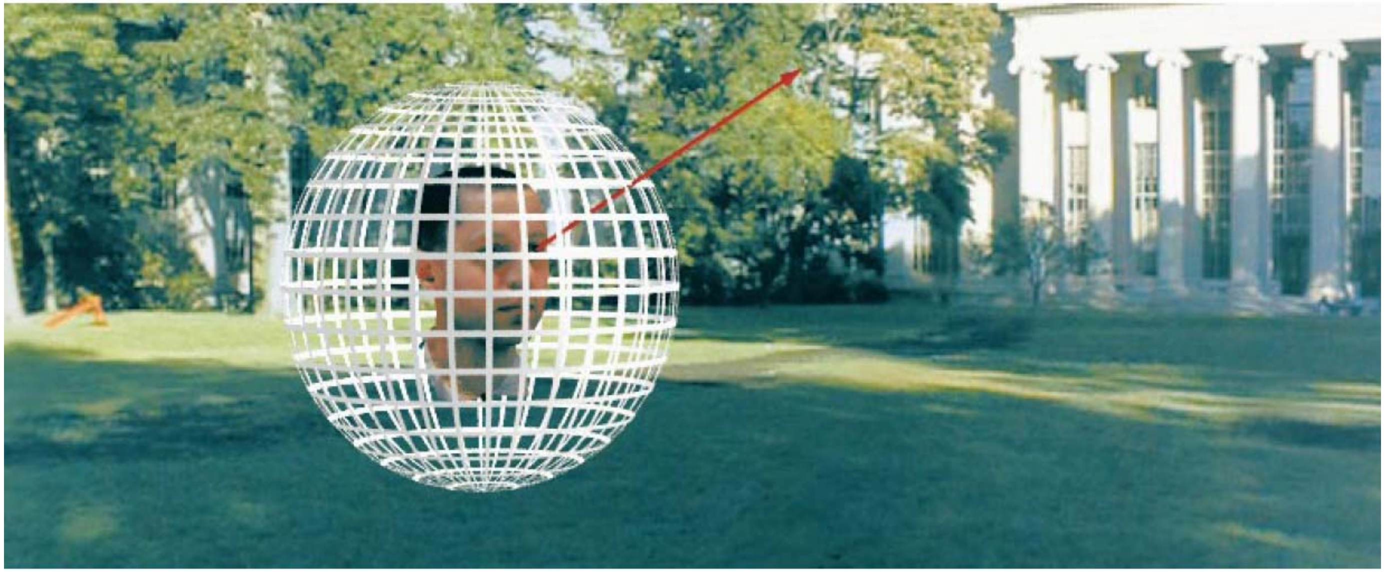


Figure by Leonard McMillan

Q: What is the set of all things that we can ever see?

A: The Plenoptic Function (Adelson & Bergen)

Let's start with a stationary person and try to parameterize everything that he can see…

Grayscale snapshot

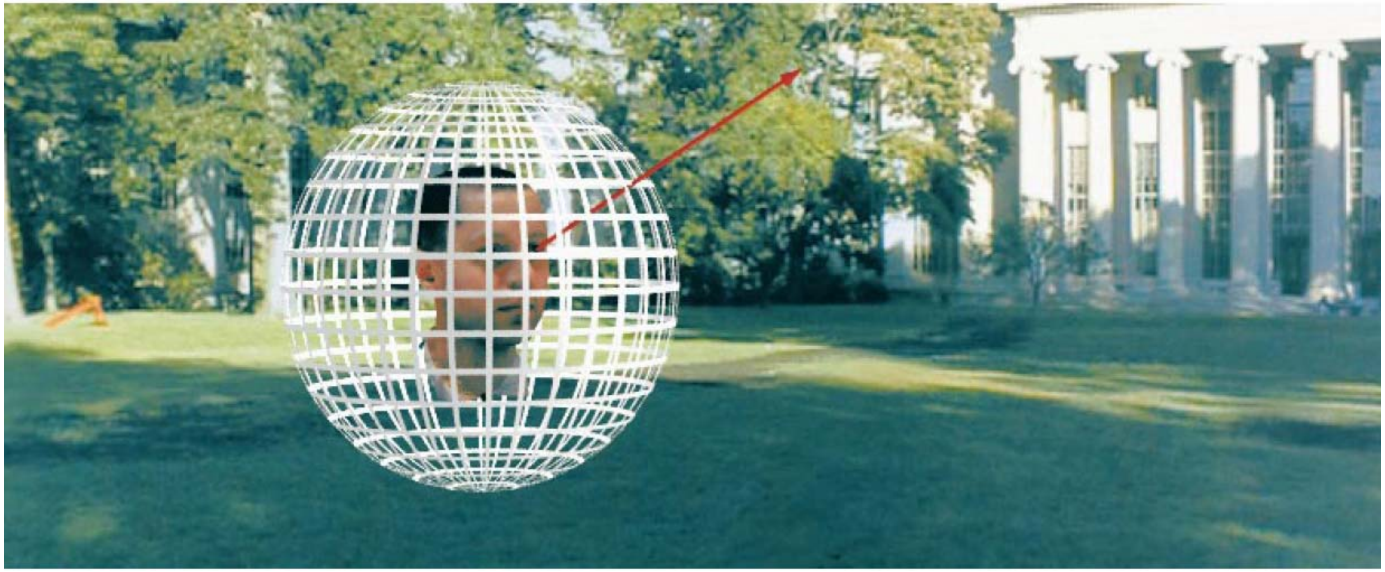
$$P(\theta,\phi)$$

is intensity of light

- Seen from a single view point
- At a single time
- Averaged over the wavelengths of the visible spectrum

(can also do *P(x,y),* but spherical coordinate are nicer)

Color snapshot

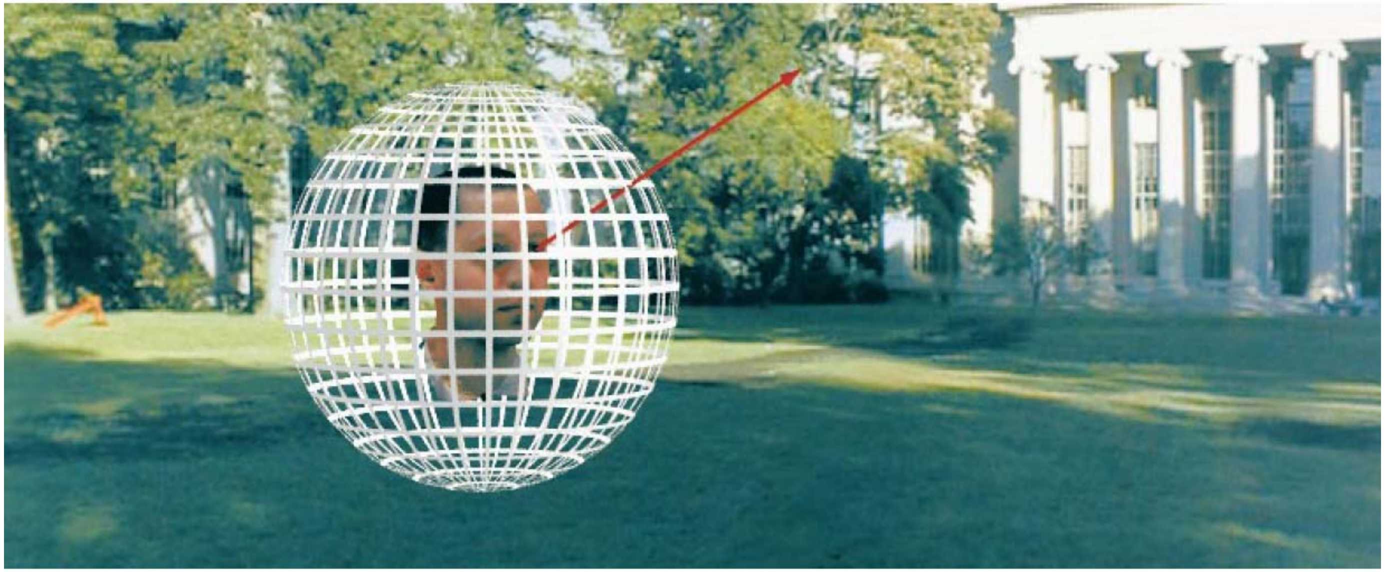


$$P(\theta,\phi,\lambda)$$

is intensity of light

- Seen from a single view point
- At a single time
- As a function of wavelength

A movie

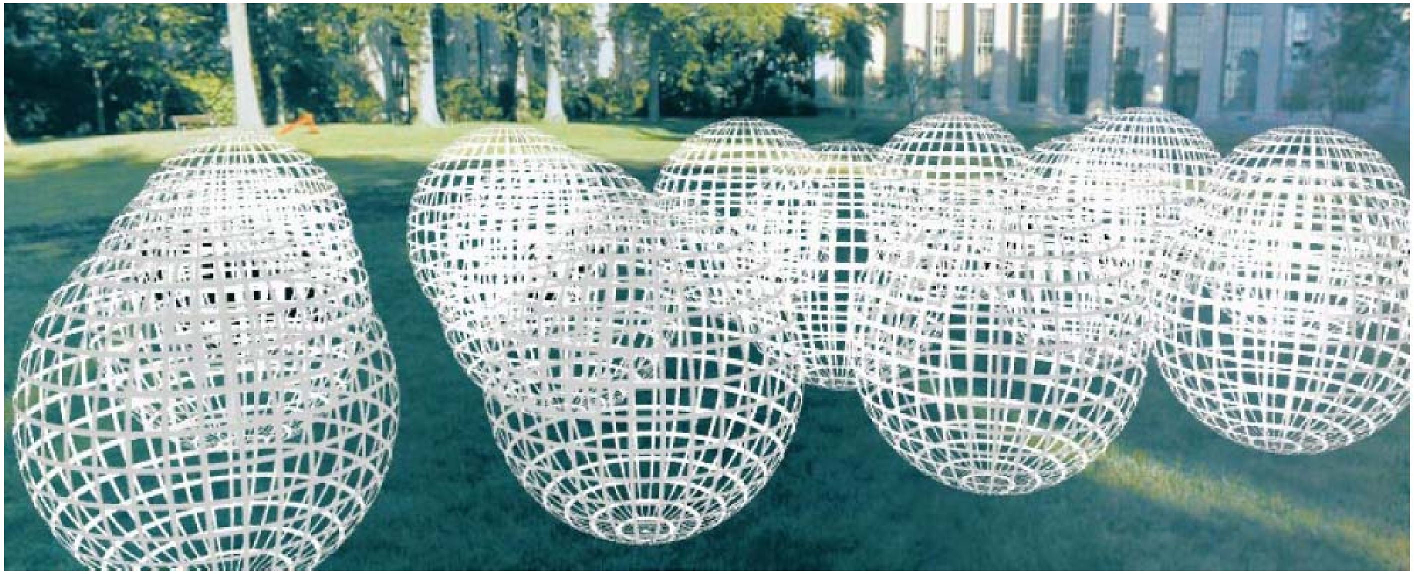


$$P(\theta,\phi,\lambda,t)$$

is intensity of light

- Seen from a single view point
- Over time
- As a function of wavelength

Holographic movie

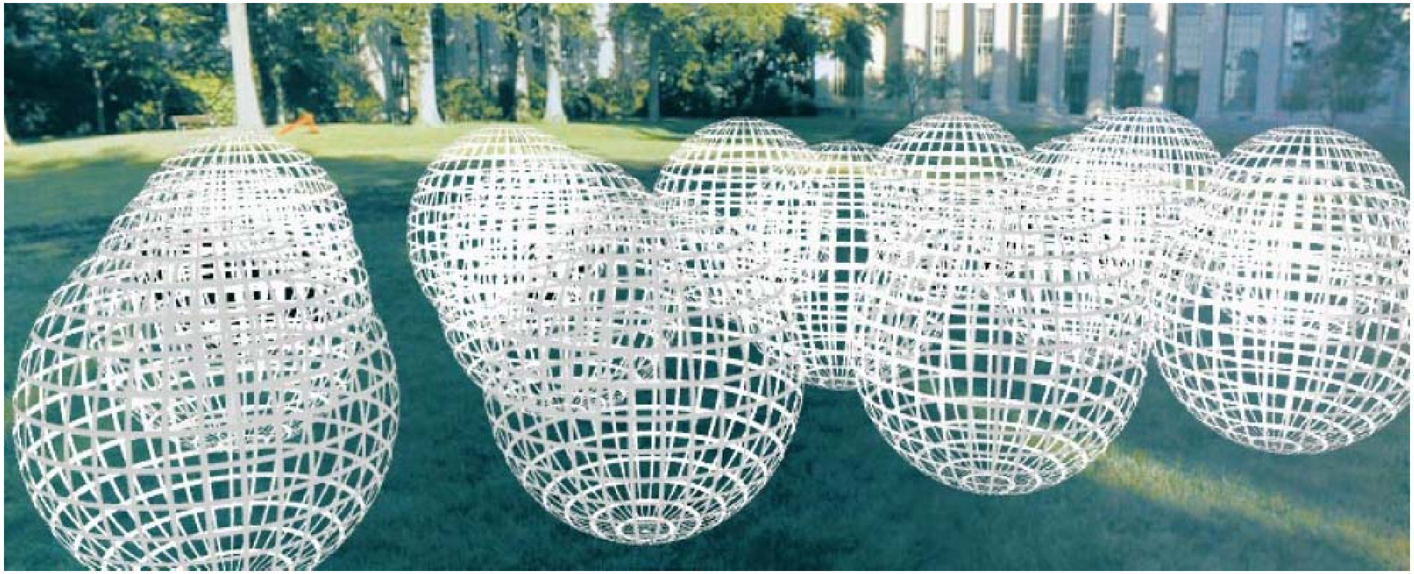


$$P(\theta,\phi,\lambda,t,V_X,V_Y,V_Z)$$

is intensity of light

- Seen from ANY viewpoint
- Over time
- As a function of wavelength

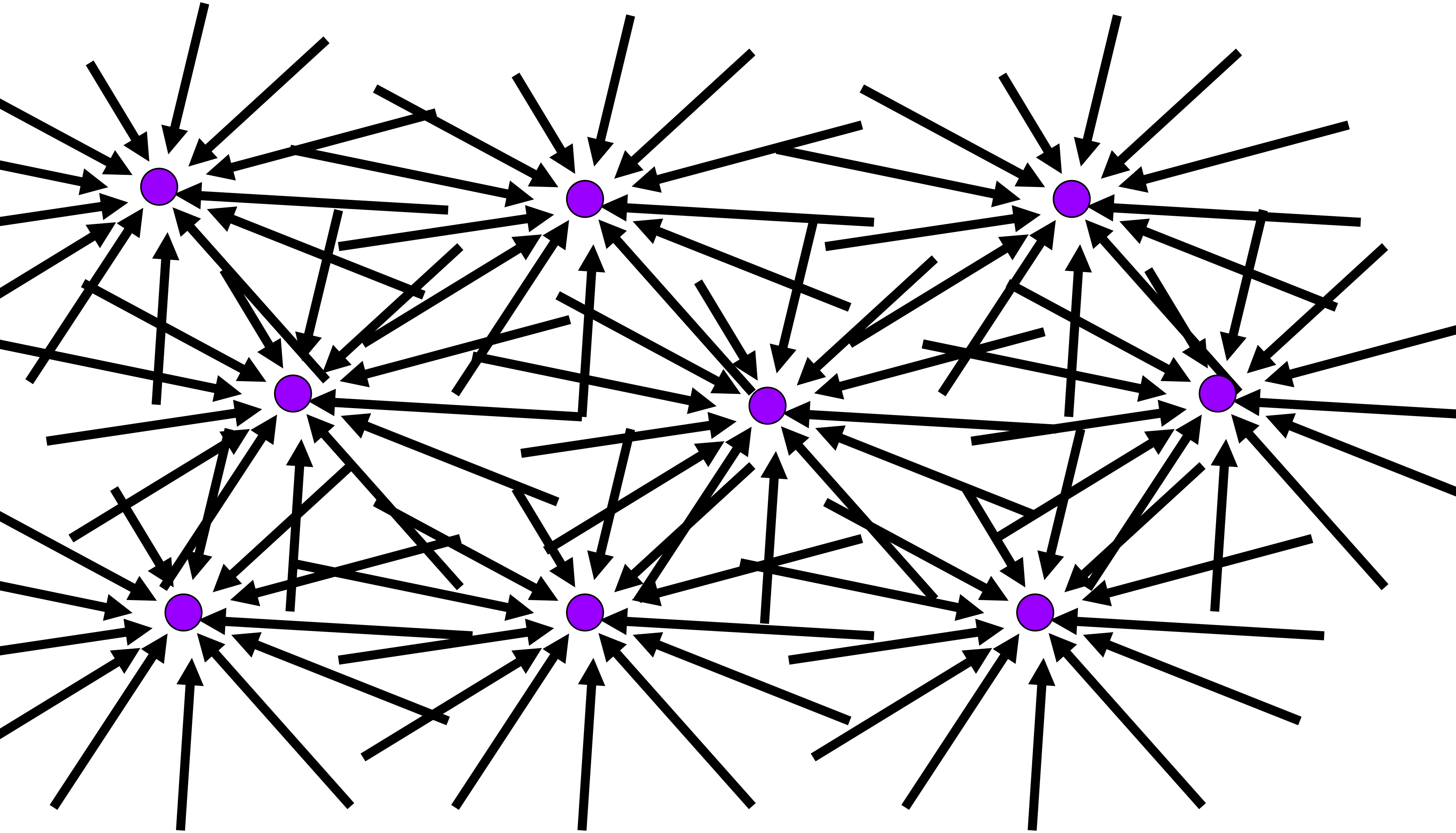
The Plenoptic Function



$$P(\theta,\phi,\lambda,t,V_X,V_Y,V_Z)$$

- Can reconstruct every possible view, at every moment, from every position, at every wavelength
- Contains every photograph, every movie, everything that anyone has ever seen! it completely captures our visual reality!   Not bad for a function…

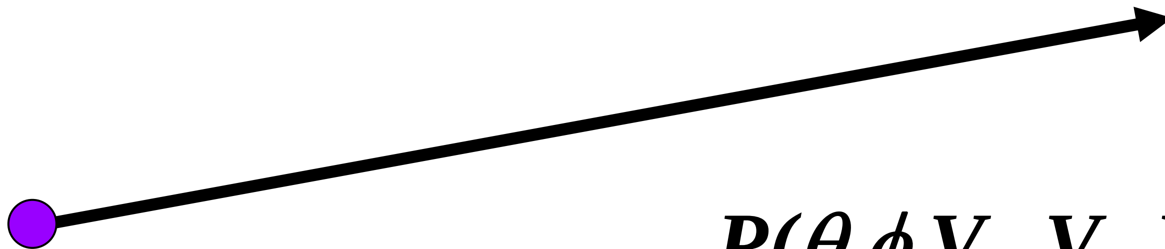
Sampling Plenoptic Function (top view)



Just lookup -- Quicktime VR

Ray

Let's not worry about time and color:

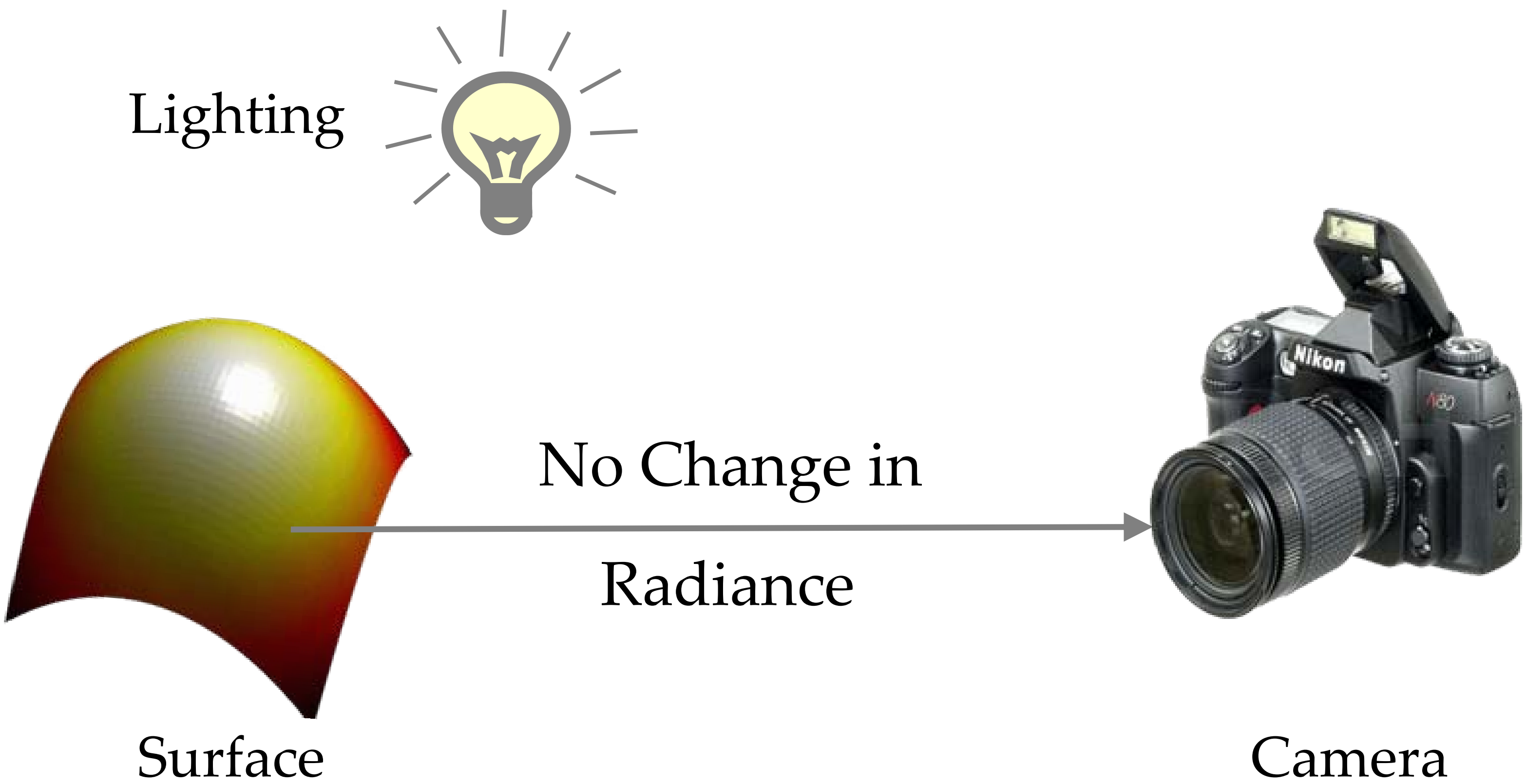


$$P(\theta,\phi,V_X,V_Y,V_Z)$$

5D

- 3D position
- 2D direction

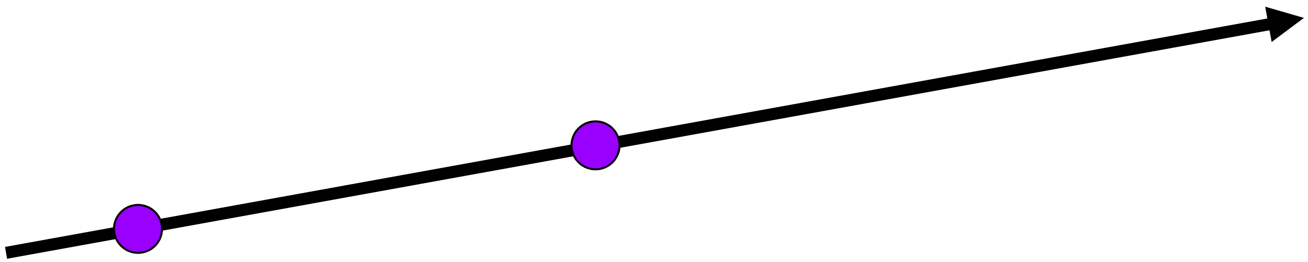
How can we use this?



Ray Reuse

Infinite line

- Assume light is constant (vacuum)



4D

- 2D direction
- 2D position
- non-dispersive medium

Slide by Rick Szeliski and Michael Cohen

Only need plenoptic surface

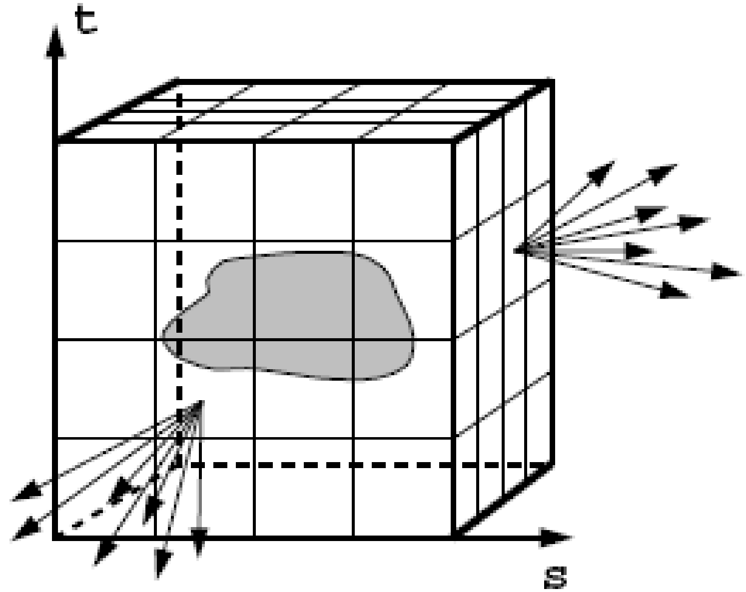
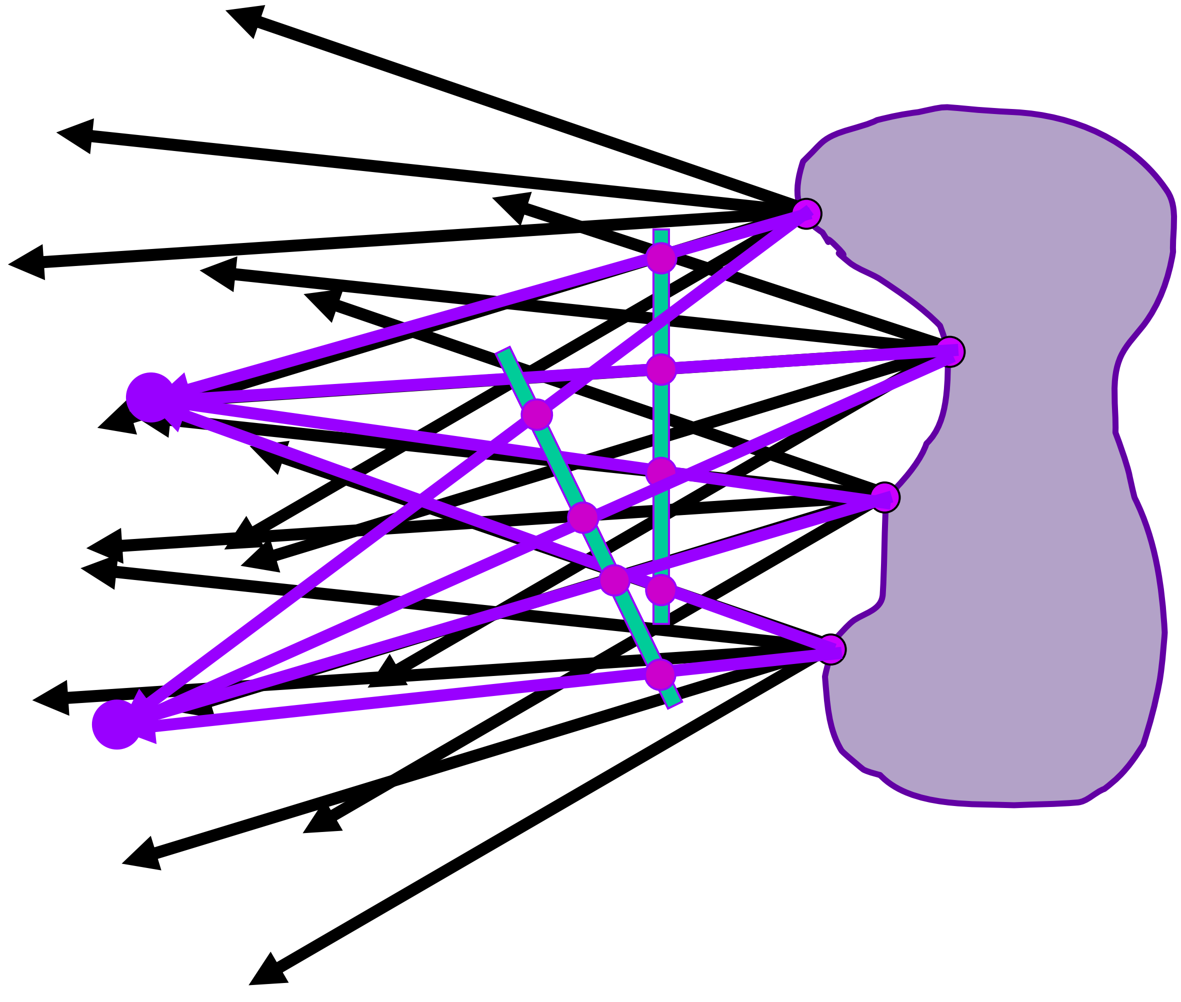


Figure 1: The surface of a cube holds all the radiance information due to the enclosed object.

Synthesizing novel views

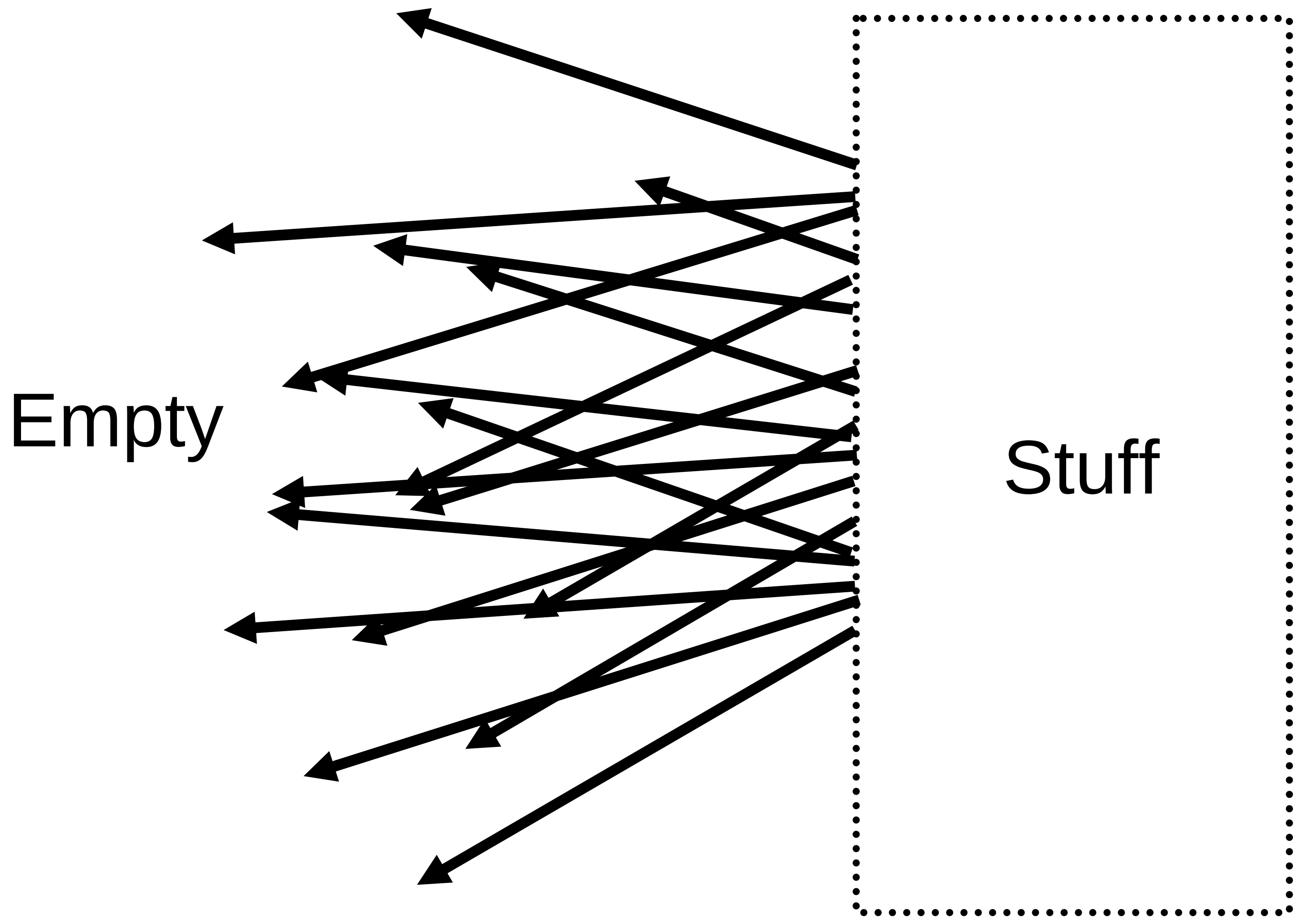


Slide by Rick Szeliski and Michael Cohen

Lumigraph / Lightfield

Outside convex space

4D

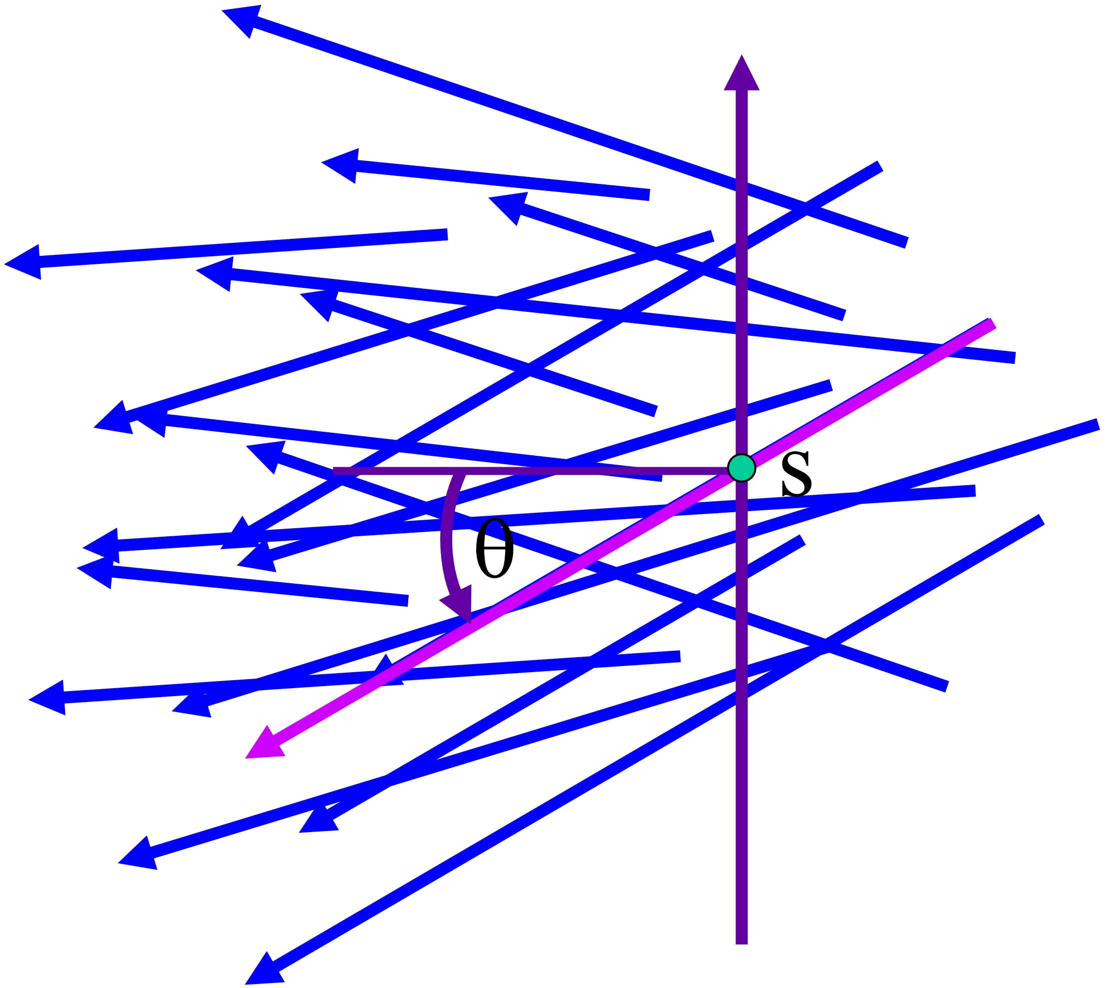


Slide by Rick Szeliski and Michael Cohen

Lumigraph - Organization

2D position

2D direction

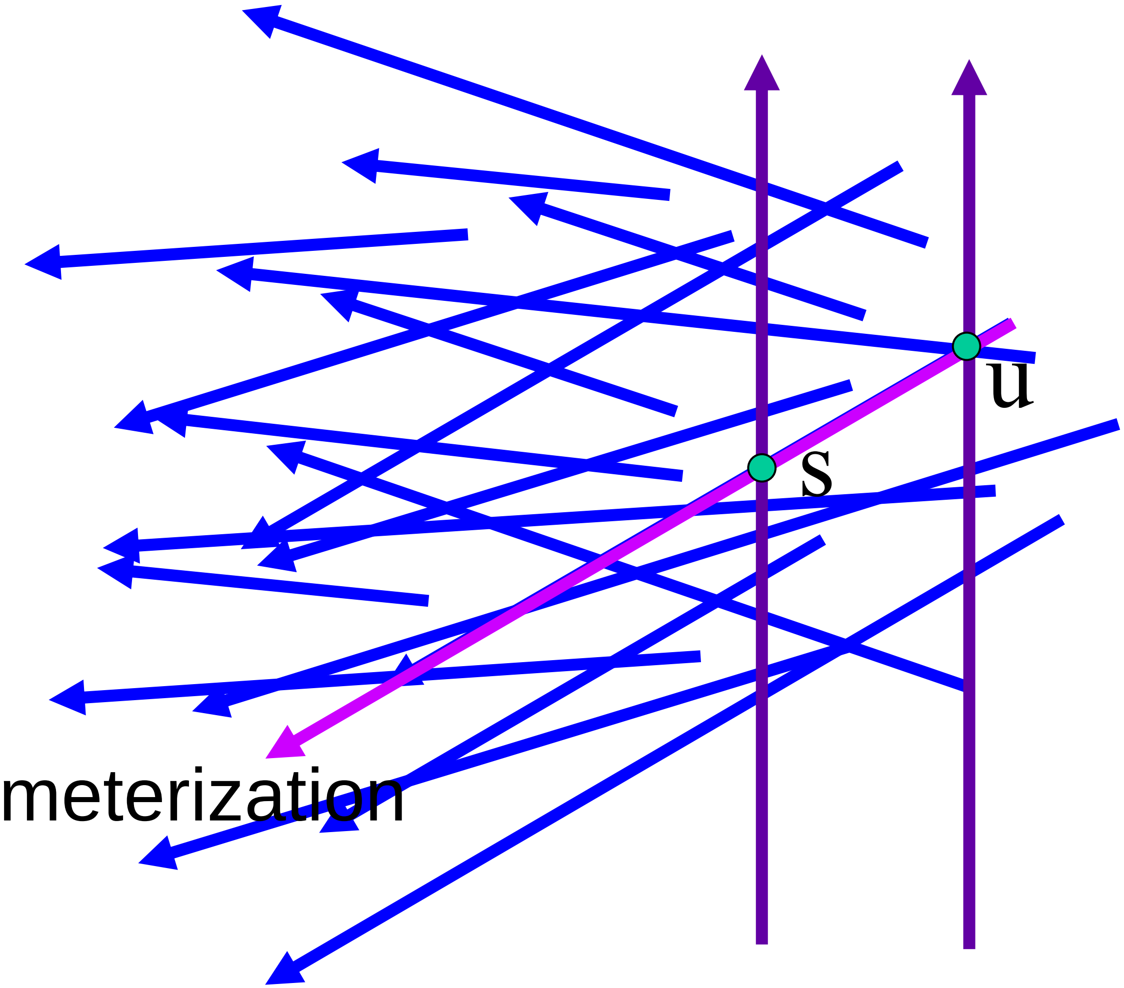


Slide by Rick Szeliski and Michael Cohen

Lumigraph - Organization

2D position

2D position



2 plane parameterization

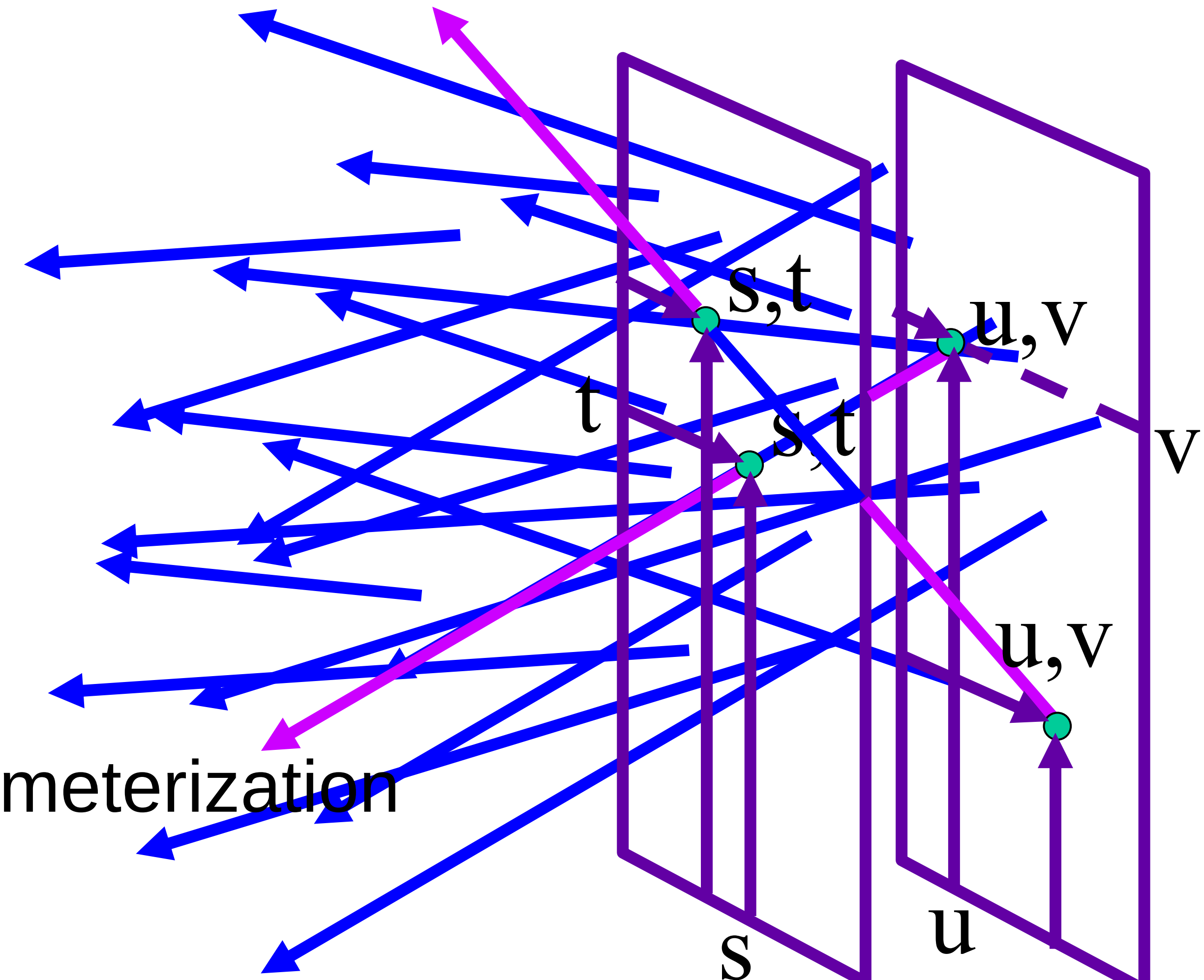
Slide by Rick Szeliski and Michael Cohen

Lumigraph - Organization

2D position

2D position

2 plane parameterization



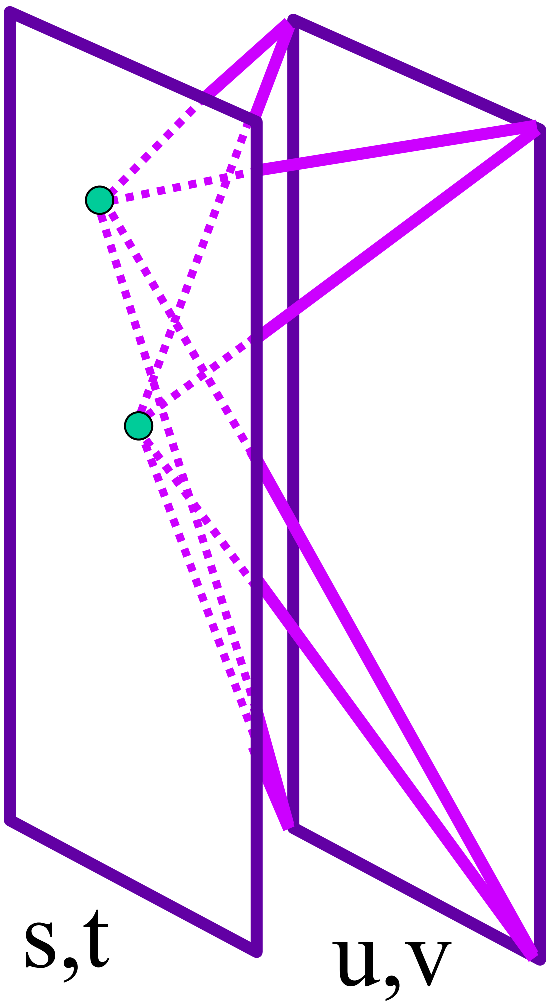
Slide by Rick Szeliski and Michael Cohen

Lumigraph - Organization

Hold s,t constant

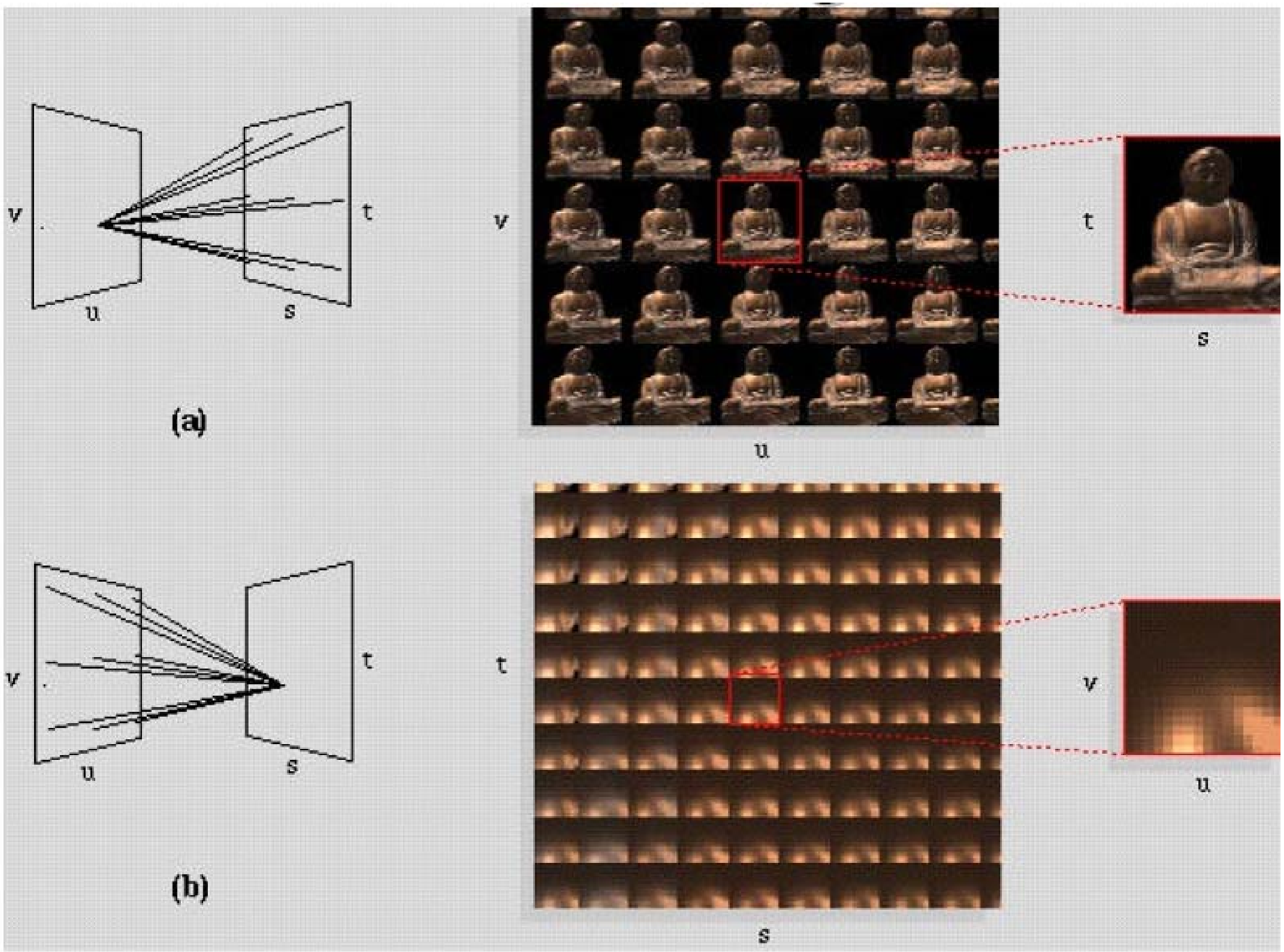
Let u,v vary

An image



Slide by Rick Szeliski and Michael Cohen

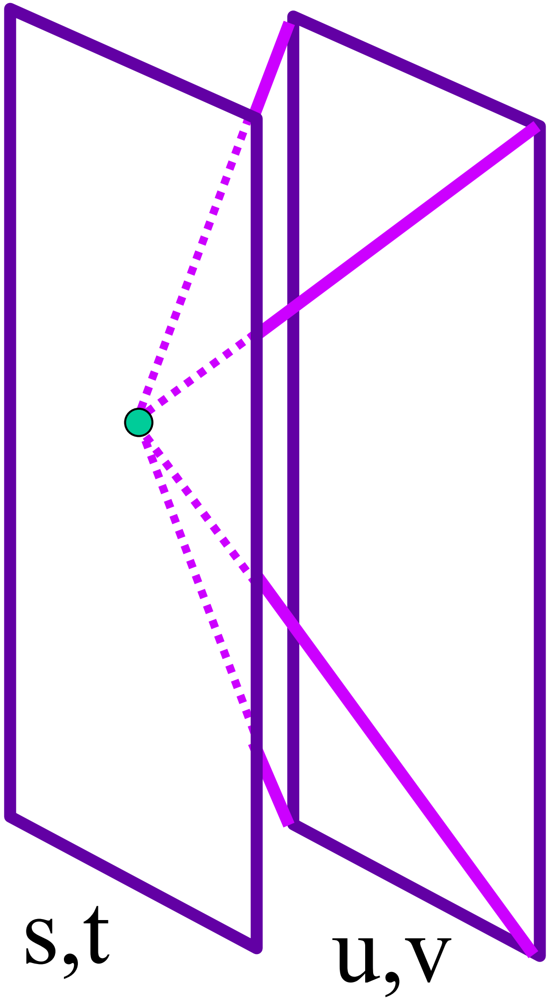
Lumigraph / Lightfield



Lumigraph - Capture

Idea 1

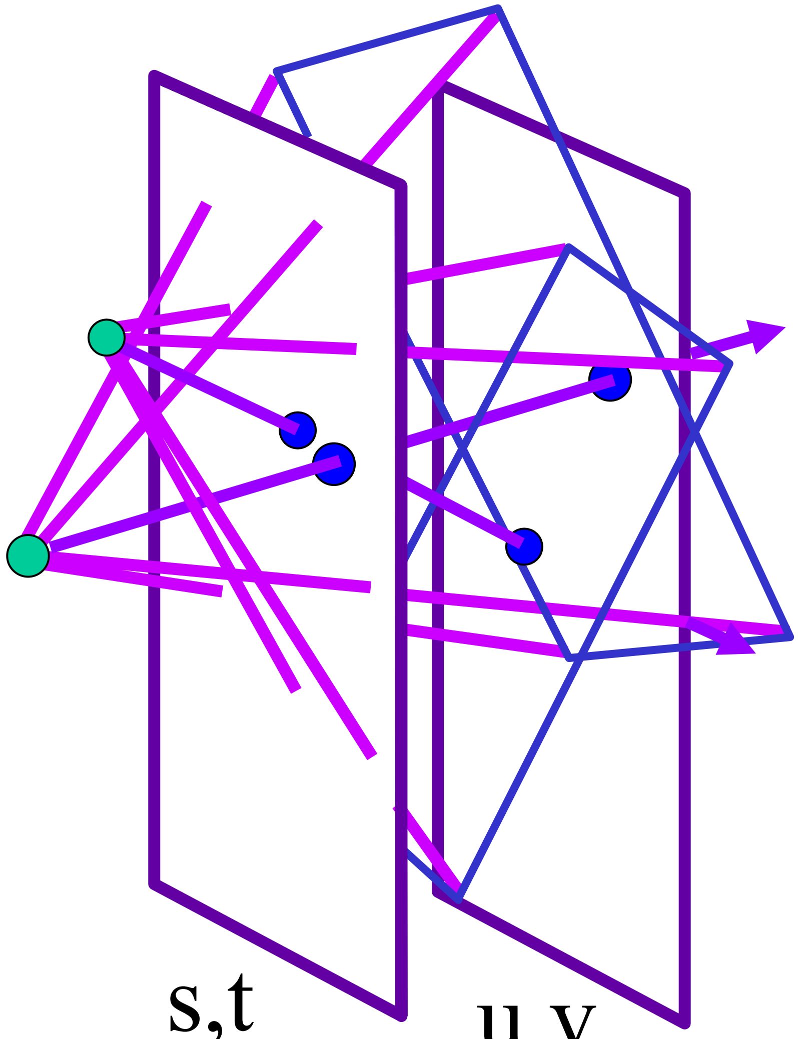
- Move camera carefully over s,t plane
- Gantry
  - see Lightfield paper



Lumigraph - Capture

Idea 2

- Move camera anywhere
- Rebinning
  - see Lumigraph paper



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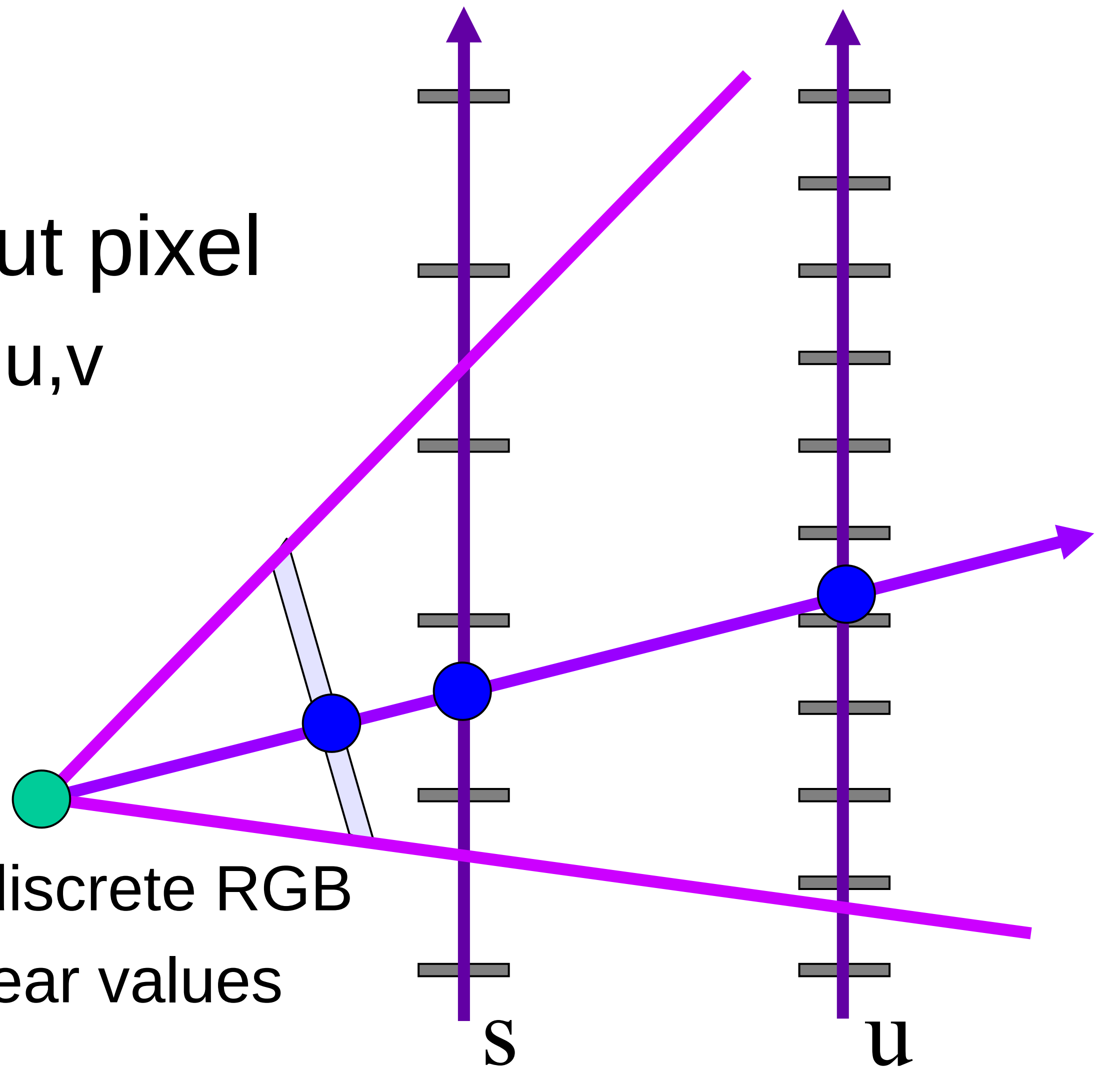
Lumigraph - Rendering

- For each output pixel
  - determine s,t,u,v
  - either
    - use closest discrete RGB
    - interpolate near values



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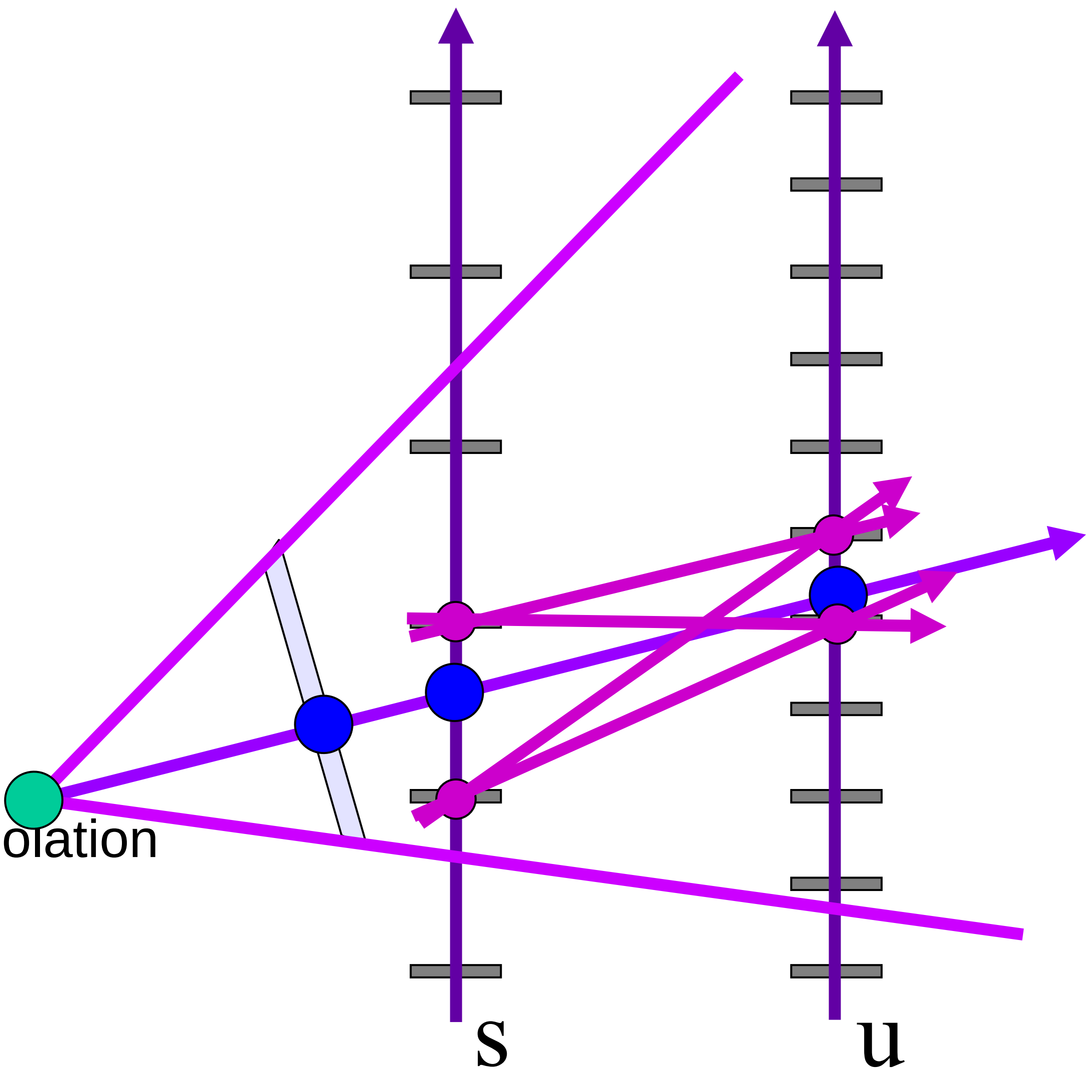
Lumigraph - Rendering

Nearest

- closest s
- closest u
- draw it

Blend 16 nearest

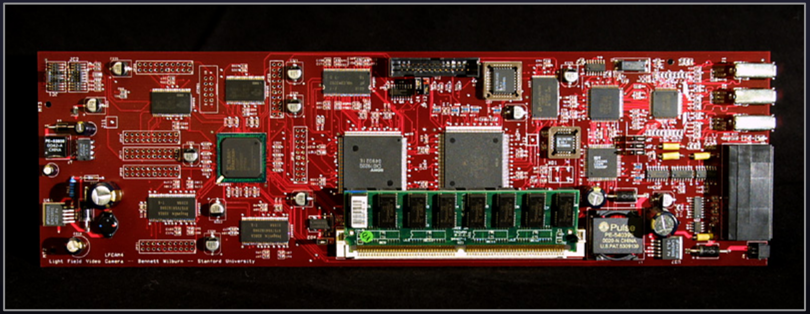
- quadrilinear interpolation



Stanford multi-camera array

- 640 × 480 pixels ×
  30 fps × 128 cameras

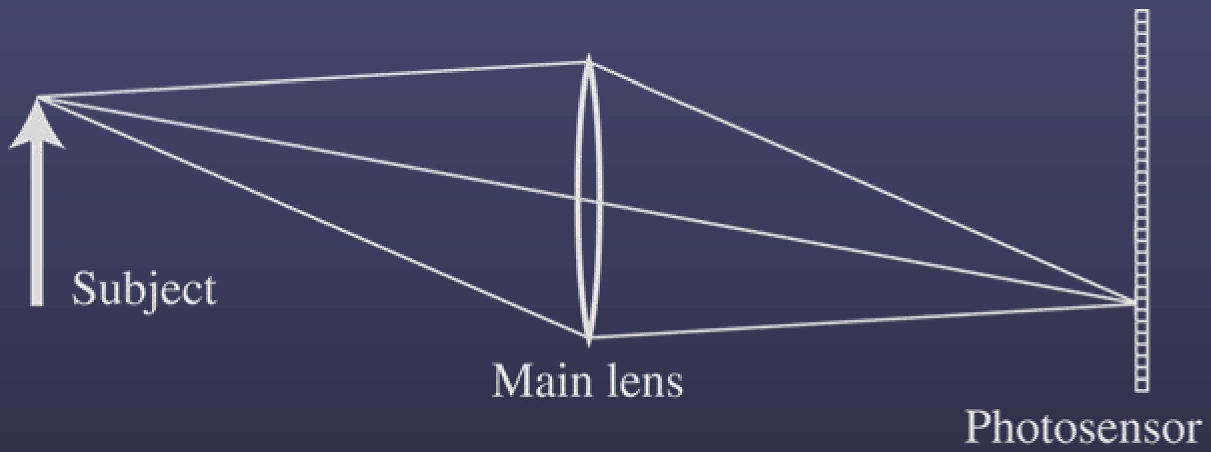
- synchronized timing
- continuous streaming
- flexible arrangement

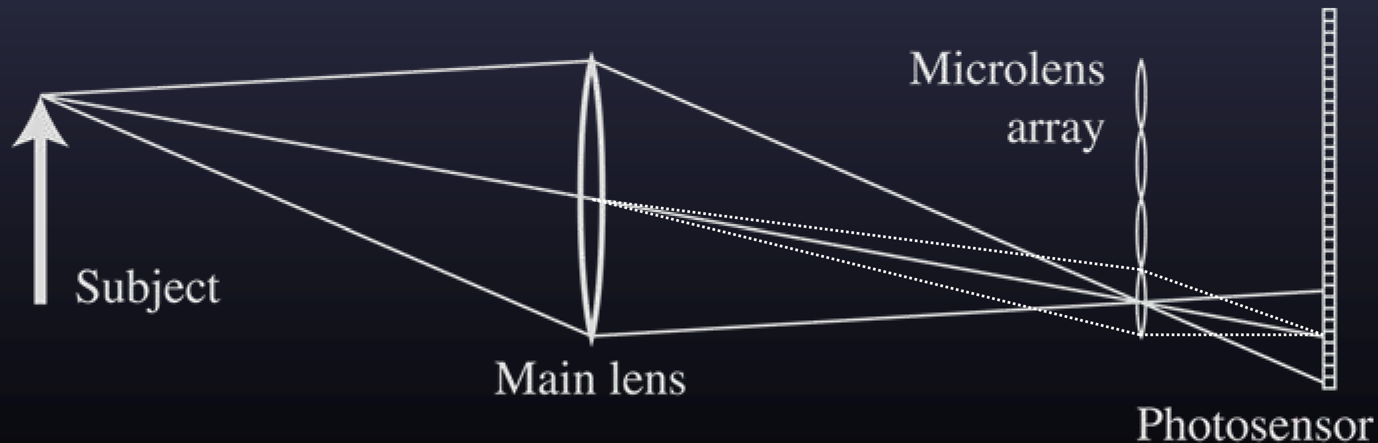


Light field photography using a handheld plenoptic camera

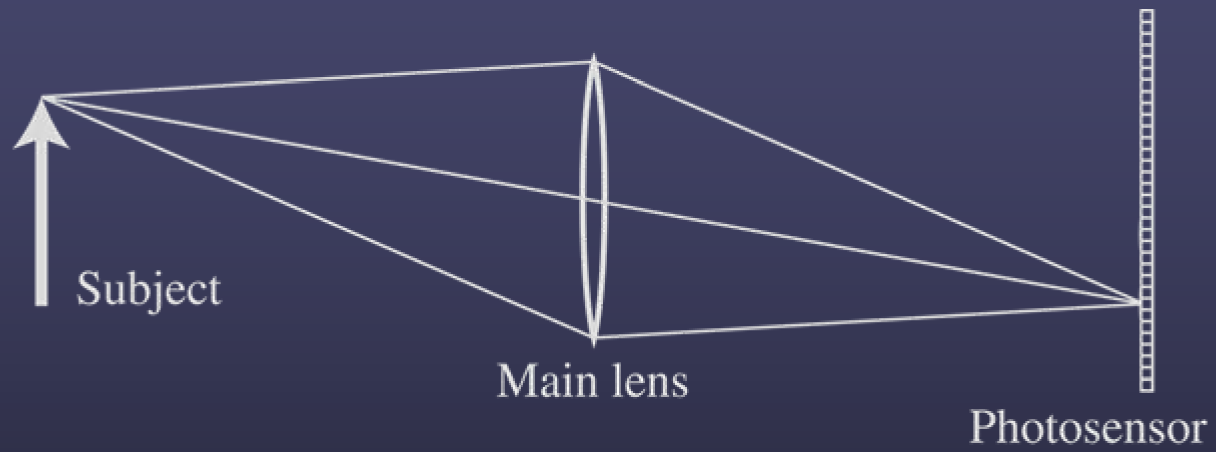
Ren Ng, Marc Levoy, Mathieu Brédif,
Gene Duval, Mark Horowitz and Pat Hanrahan

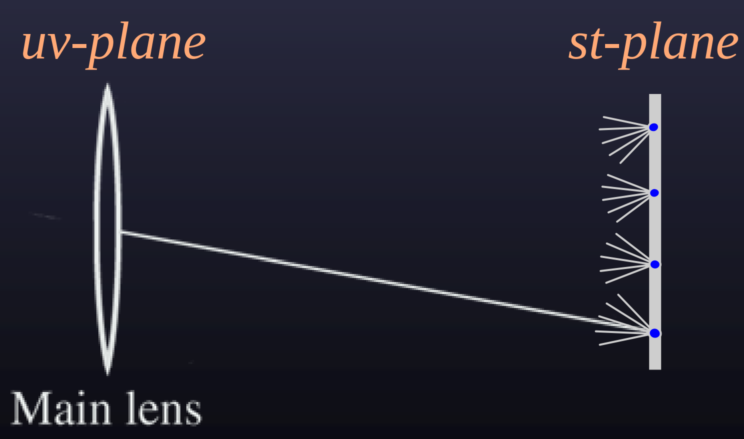
Conventional versus light field camera





Conventional versus light field camera

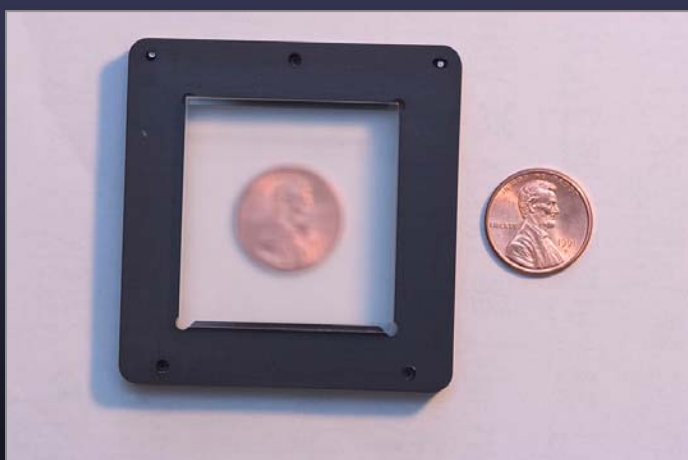


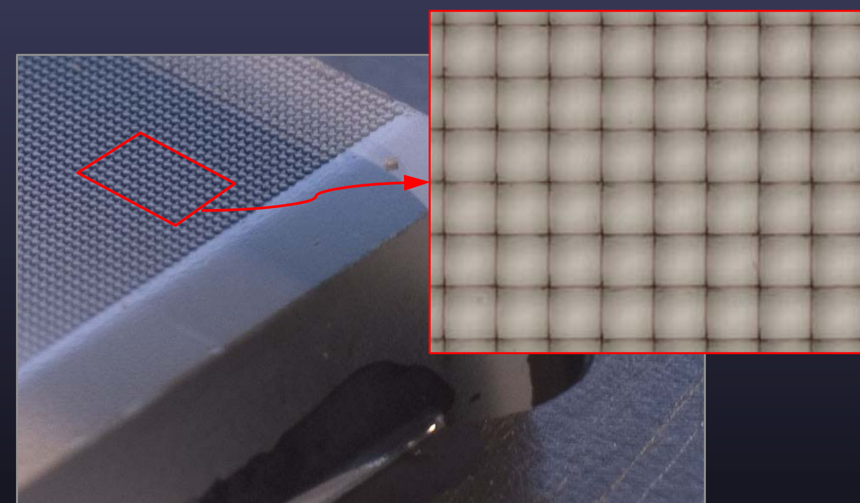


Prototype camera

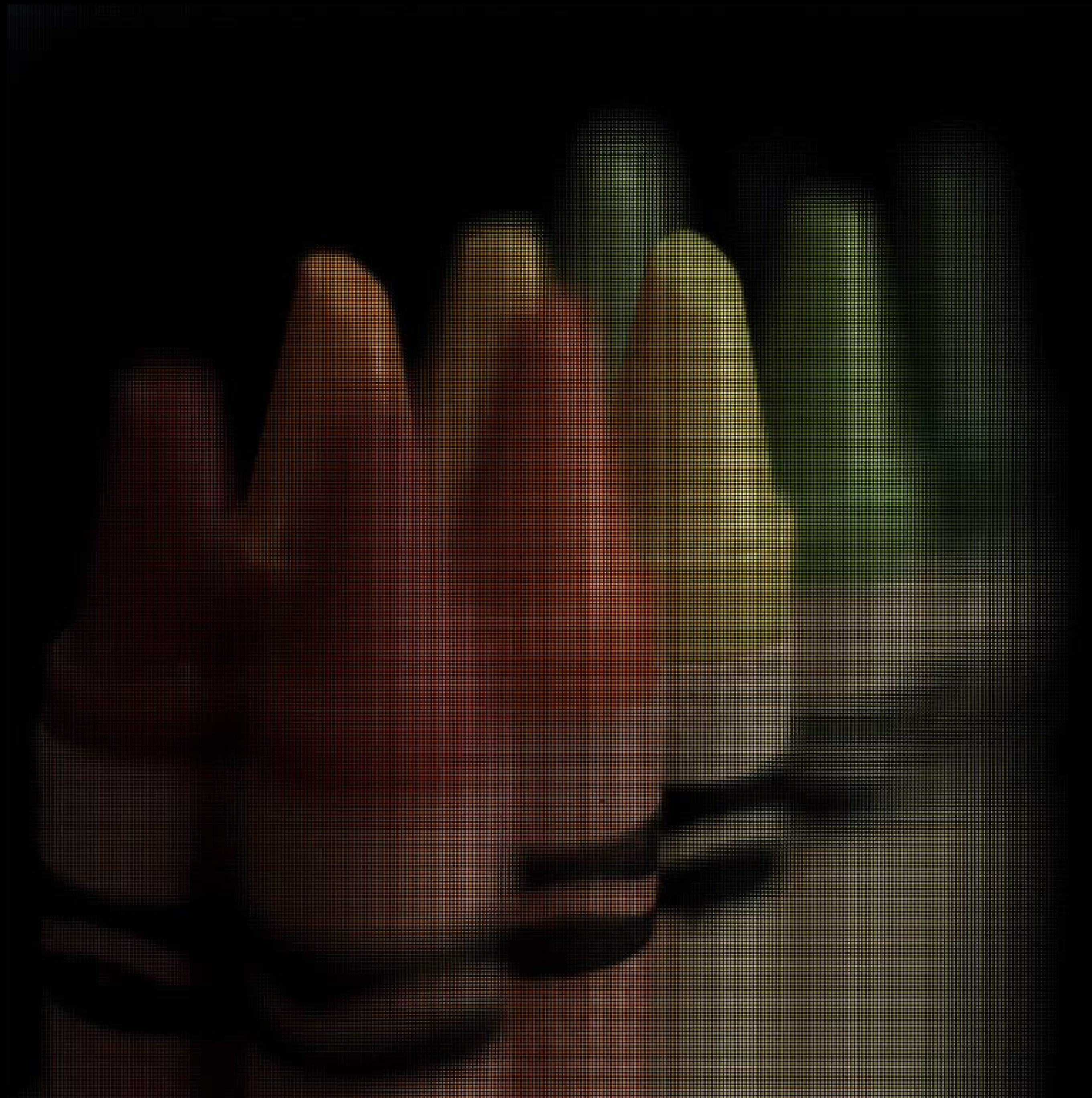
Contax medium format camera


Kodak 16-megapixel sensor

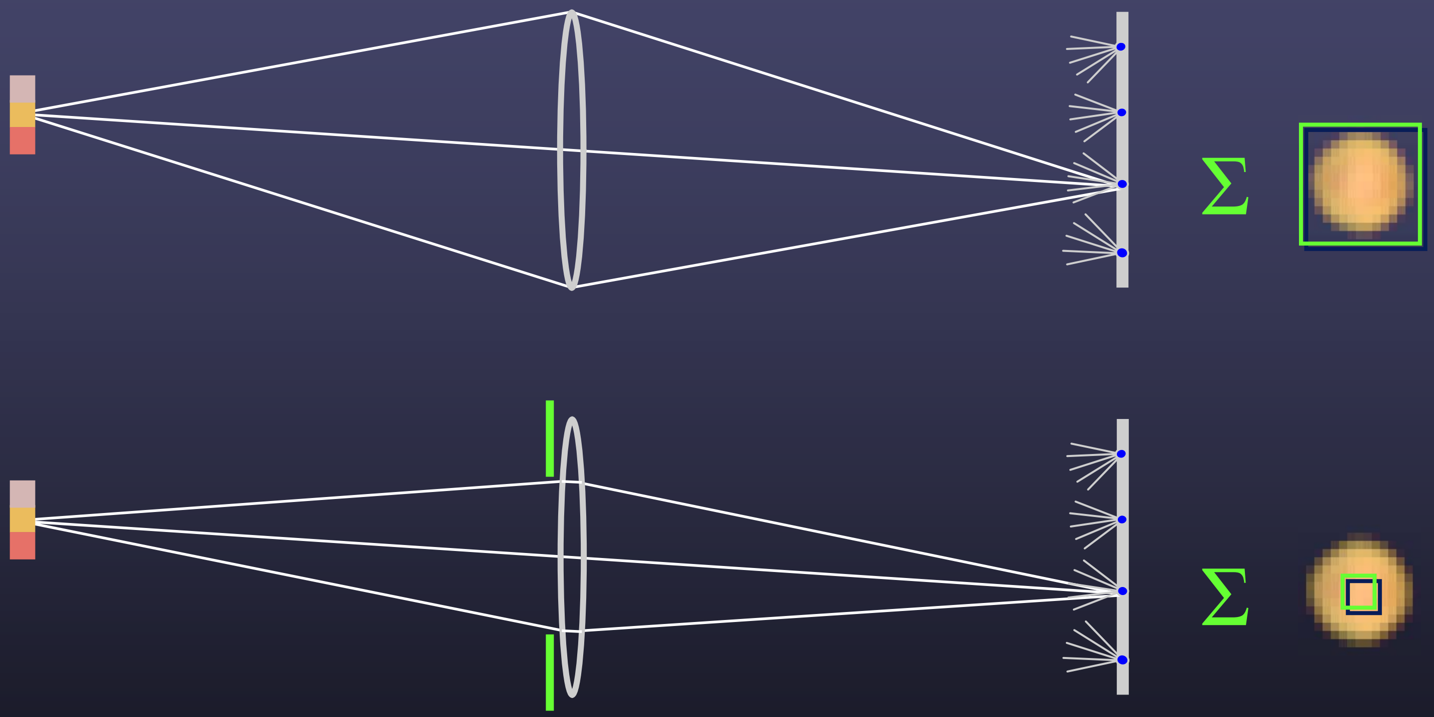

Adaptive Optics microlens array


125μ square-sided microlenses

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

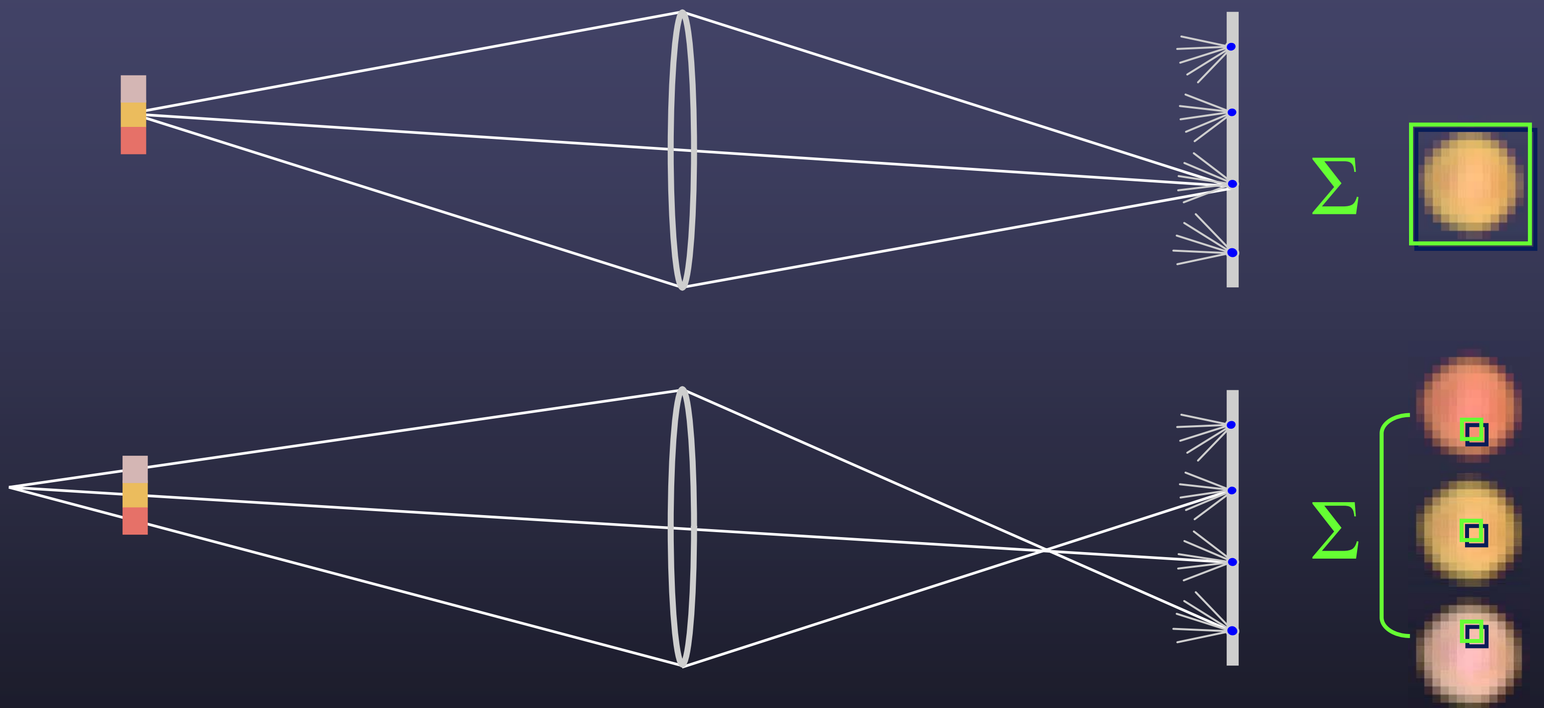


Digitally stopping-down



- stopping down = summing only the central portion of each microlens

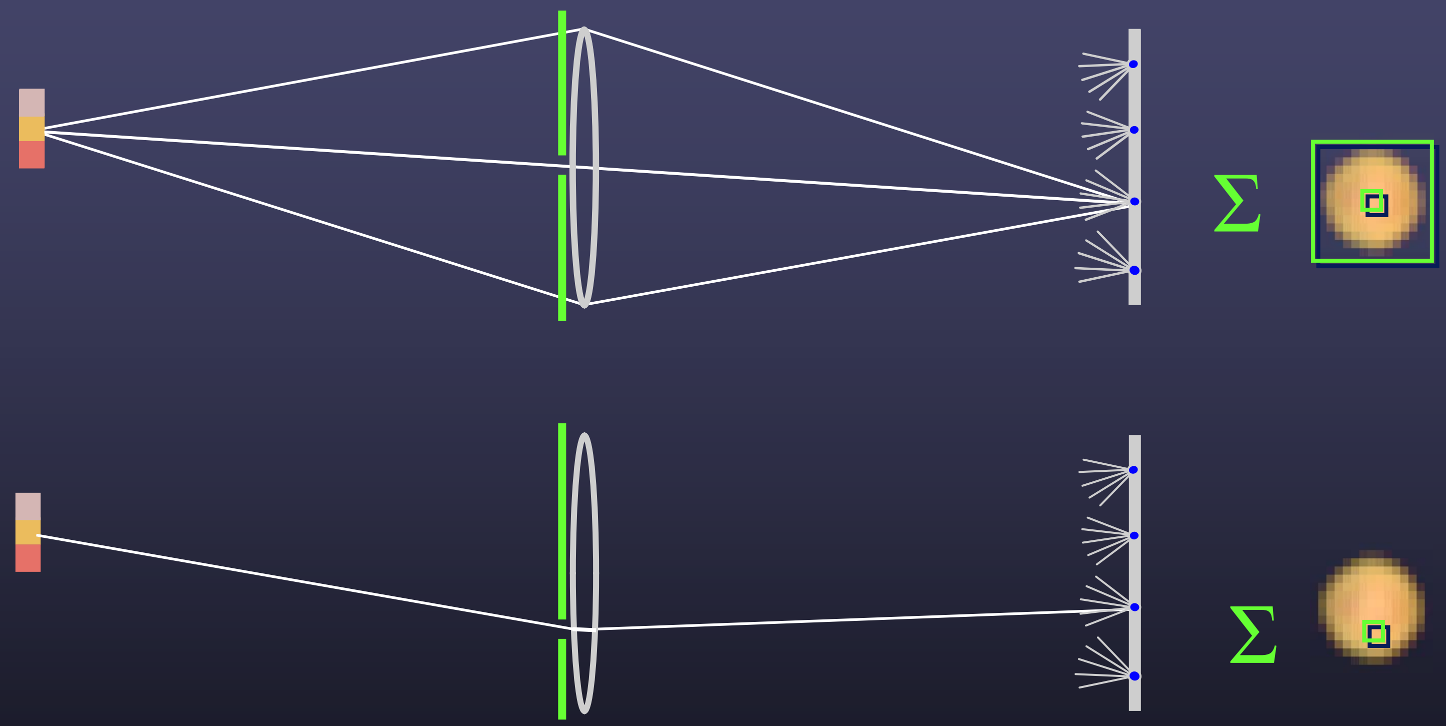
Digital refocusing



- refocusing = summing windows extracted from several microlenses

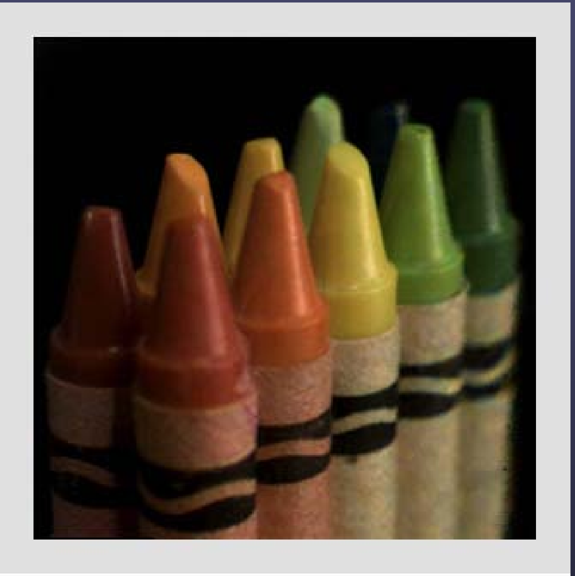
Example of digital refocusing

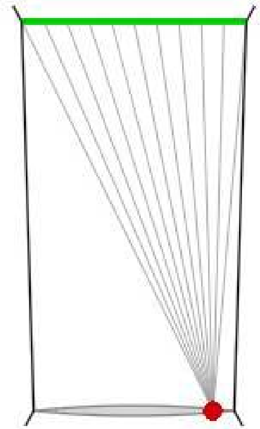
Digitally moving the observer



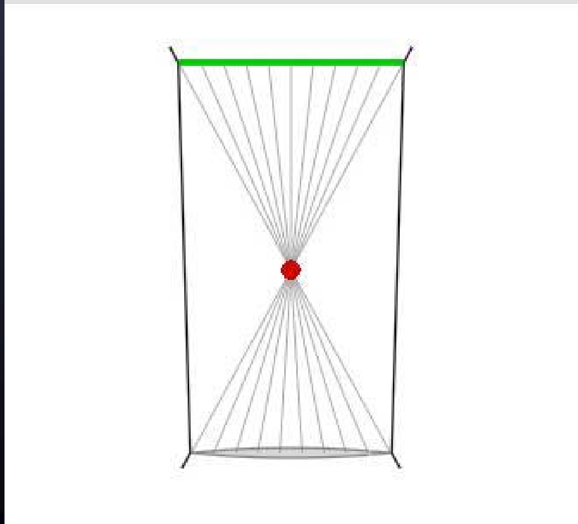
- moving the observer = moving the window we extract from the microlenses

Example of moving the observer





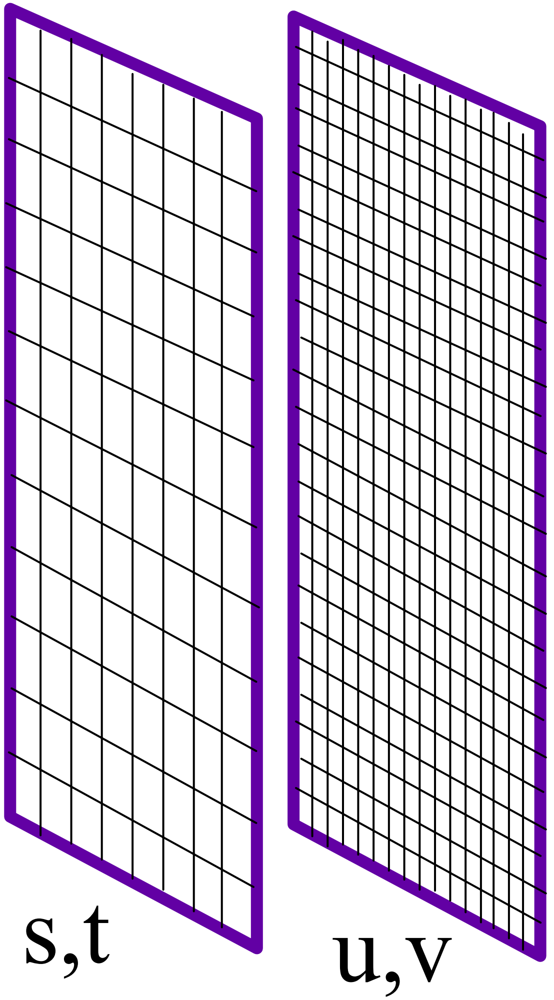
Moving backward and forward



3D Lumigraph

One row of s,t plane

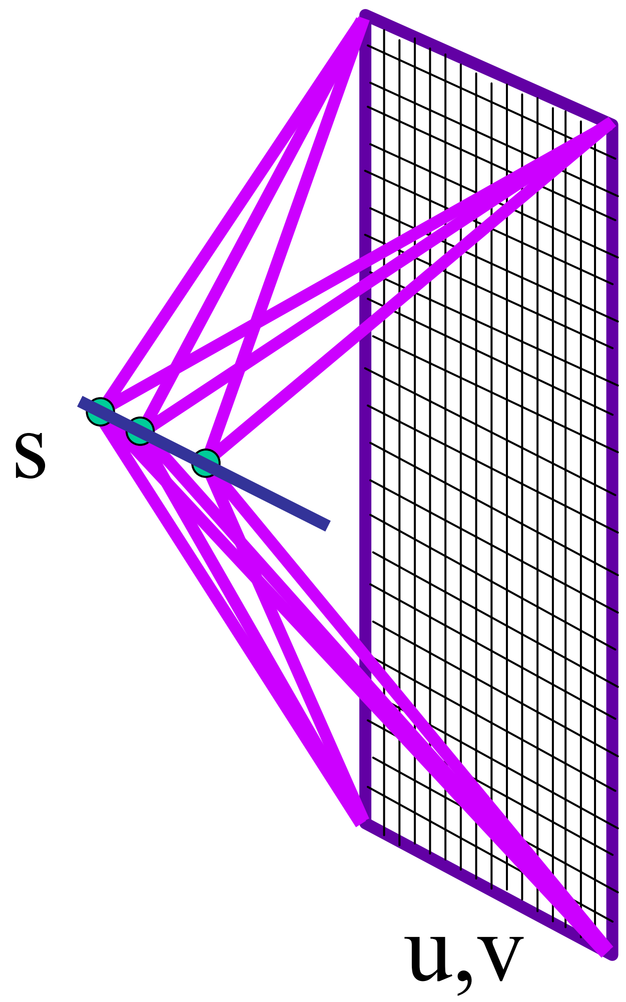
- i.e., hold t constant



3D Lumigraph

One row of s,t plane

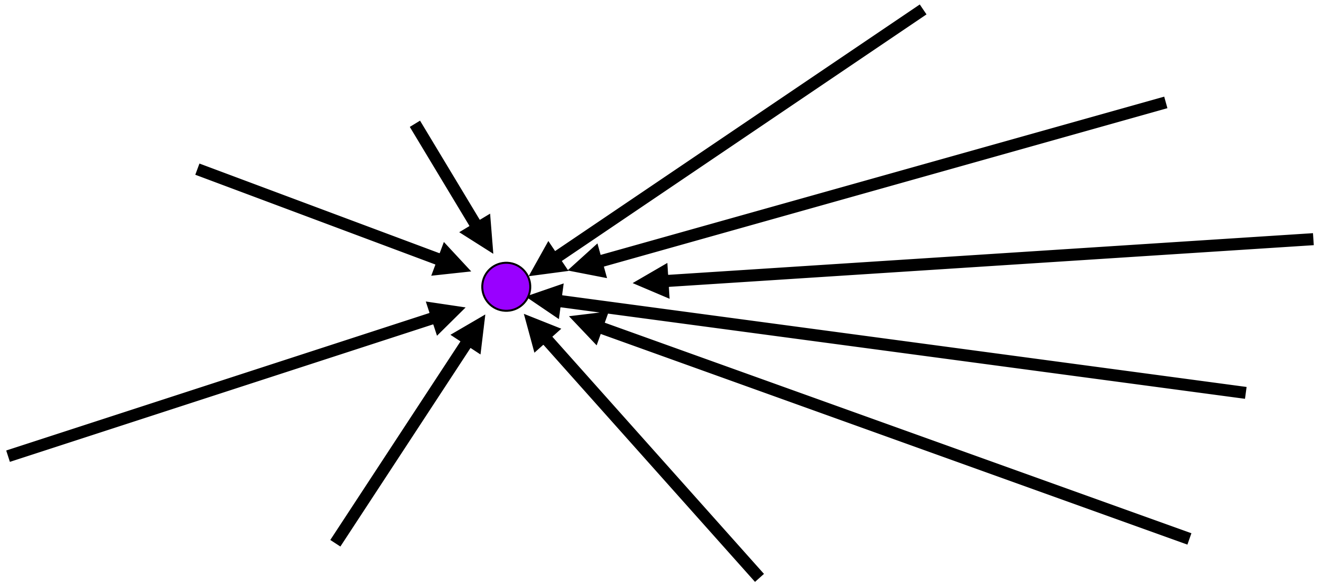
- i.e., hold t constant
- thus s,u,v
- a “row of images”



P(x,t) by David Dewey

2D: Image

What is an image?

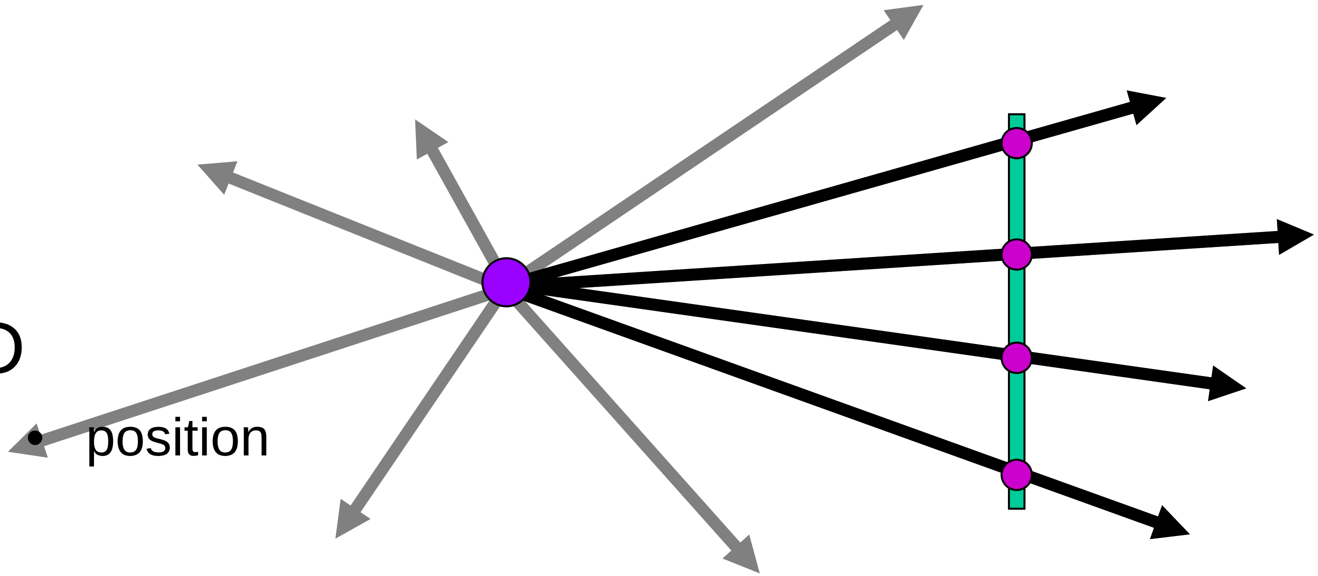


All rays through a point

- Panorama?

Image

Image plane



2D

- position

Spherical Panorama

See also: 2003 New Years Eve

http://www.panoramas.dk/fullscreen3/f1.html

All light rays through a point form a ponorama

Totally captured in a 2D array -- $P(\theta,\phi)$

Where is the geometry???

Other ways to sample Plenoptic Function

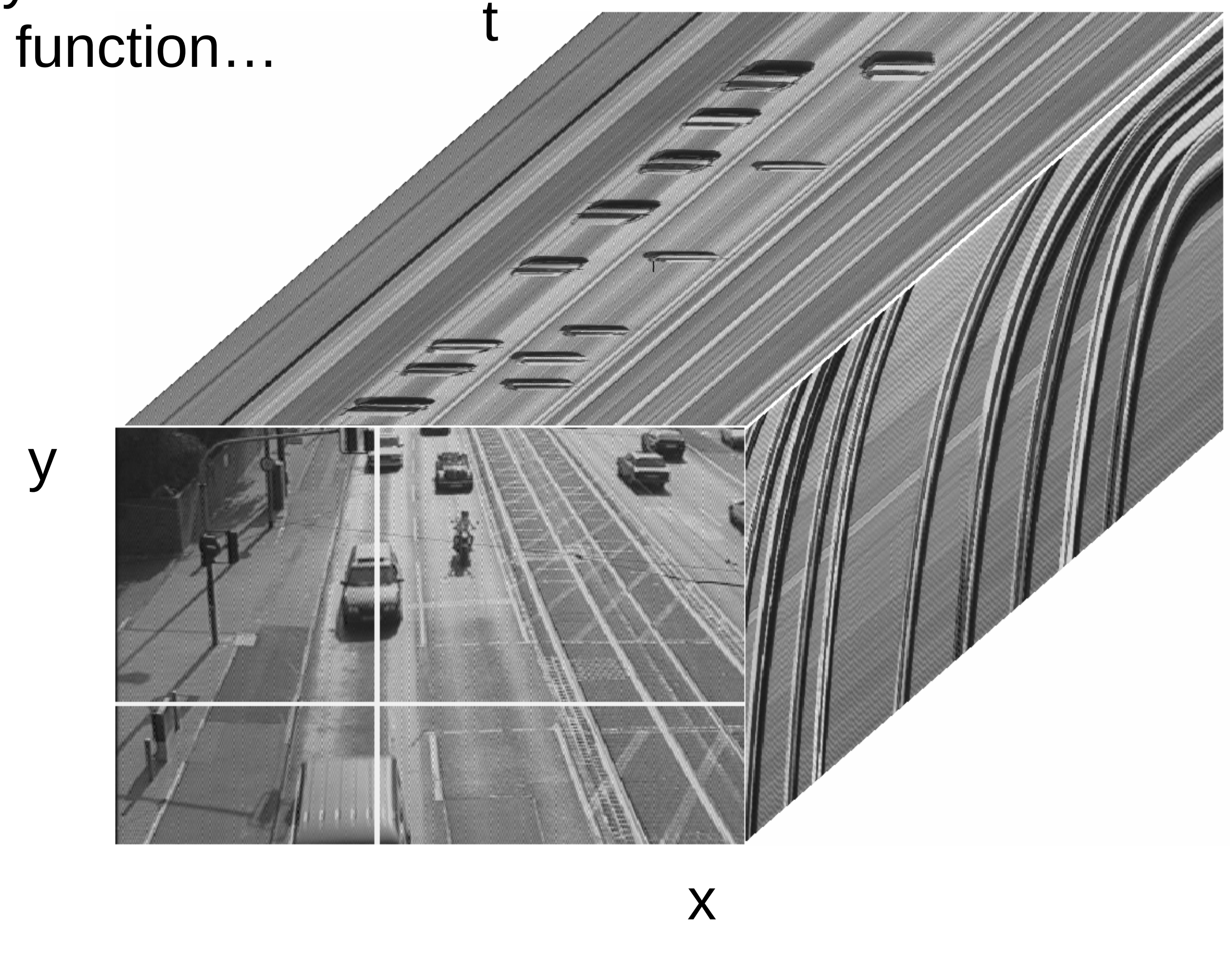
Moving in time:

- Spatio-temporal volume: $P(\theta,\phi,t)$
- Useful to study temporal changes
- Long an interest of artists:

Claude Monet, Haystacks studies

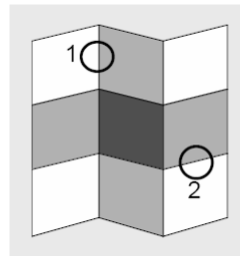
Space-time images

Other ways to slice the plenoptic function…

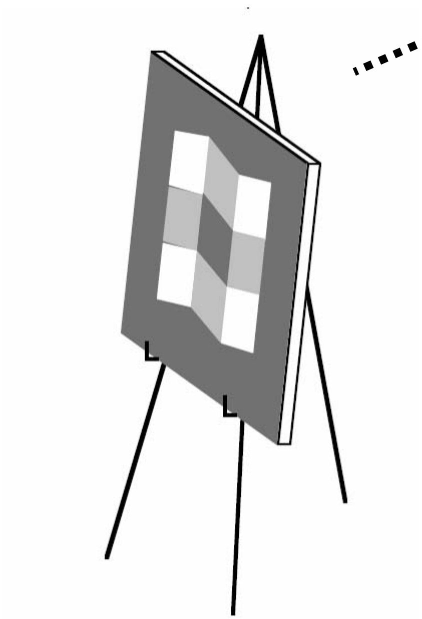


The “Theatre Workshop” Metaphor

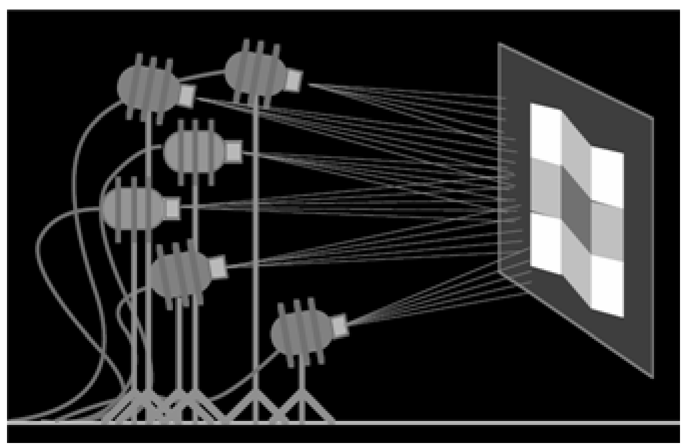
(Adelson & Pentland,1996)



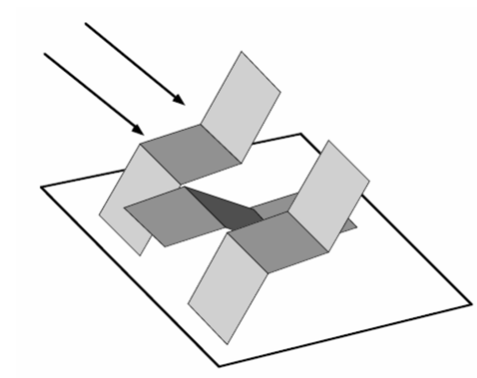
desired image



Painter



Lighting Designer



Sheet-metal worker

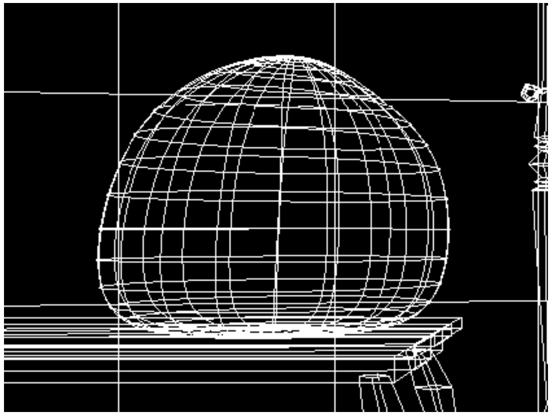
Painter (images)

Lighting Designer (environment maps)

Show Naimark SF MOMA video

http://www.debevec.org/Naimark/naimark-displacements.mov

Sheet-metal Worker (geometry)



Let surface normals do all the work!

… working together

clever Italians

Want to minimize cost

Each one does what’s easiest for him

- Geometry – big things
- Images – detail
- Lighting – illumination effects