What is light?

Electromagnetic radiation (EMR) moving along rays in space

- $R(\lambda)$ is EMR, measured in units of power (watts)
  - $\lambda$ 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

2D image

Point of observation

Figures © Stephen E. Palmer, 2002
What do we see?

3D world

2D image

Painted backdrop
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, e.g. slowglass
  • Latest take: The Matrix

Physics:
  • Slowglass might be possible?

Computer Science:
  • Virtual Reality

To simulate we need to know:
  What does a person see?
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 viewpoint
- At a single time
- As a function of wavelength
A movie

\[ P(\theta, \phi, \lambda, t) \]

is intensity of light

- Seen from a single viewpoint
- 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:

5D

- 3D position
- 2D direction

\[ P(\theta, \phi, V_X, V_Y, V_Z) \]
How can we use this?

Surface → No Change in Radiance → Camera

Lighting
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

Empty

Stuff

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
Hold $s, t$ constant
Let $u, v$ vary
An image
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
Lumigraph - Rendering

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

Slide by Rick Szeliski and Michael Cohen
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

Subject

Main lens

Photosensor

uv-plane

st-plane

Main lens
Prototype camera

Contax medium format camera

Kodak 16-megapixel sensor

Adaptive Optics microlens array

125μ square-sided microlenses

- $4000 \times 4000 \text{ pixels} \div 292 \times 292 \text{ lenses} = 14 \times 14 \text{ pixels per lens}$
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

[Image: A row of crayons with a diagram below showing rays of light arriving at 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

All light rays through a point form a panorama
Totally captured in a 2D array -- $P(\theta,\phi)$
Where is the geometry???

See also: 2003 New Years Eve
http://www.panoramas.dk/fullscreen3/f1.html
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)

Painter  Lighting Designer  Sheet-metal worker

desired image
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

Want to minimize cost
Each one does what’s easiest for him

• Geometry – big things
• Images – detail
• Lighting – illumination effects
Midterm next Tuesday

- 80 minutes long (come on time!)
- Closed book, closed notes, closed laptops
- But can have a cheat sheet (1 page, both sides)

- Will cover all material up to this week!
Midterm Review

• Cameras
  • Pin-hole model, camera “knobs”, perspective projection, orthographic (parallel) projection, etc.

• Capturing & modeling Light
  • Physics of Light, light perception, color, The Plenoptic function, Lumigraph/Lightfields

• Image Processing
  • Point processing, histograms, filtering, correlation, convolution, 2D Fourier transform, low-pass/band-pass/high-pass filtering, edge detection, Gaussian and laplacian pyramids, blending, etc.

• Image Warping and Morphing
  • 2D parametric transformations, homogeneous coordinates, degrees of freedom, difference between affine and projective transformations, forward/inverse warping, morphing, etc.

• Data-driven Methods
  • Markov Chains, using data to model the world, face modeling with basis, video and texture synthesis