Mosaics, Plenoptic Function, and Light Field Rendering

Topics in Image-Based Modeling and Rendering

CSE291 J00

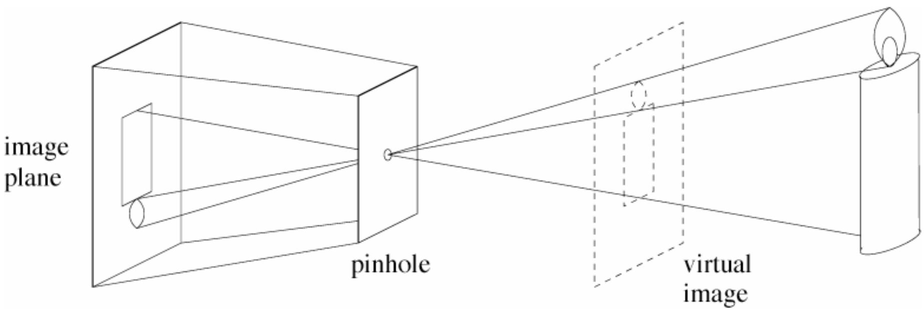
Lecture 3

Last Lecture

- Camera Models
  - Pinhole perspective
  - Affine/Orthographic models
- Homogeneous coordinates
- Coordinate transforms
- Lenses
- Radiometry
  - Irradiance
  - Radiance
  - BRDF

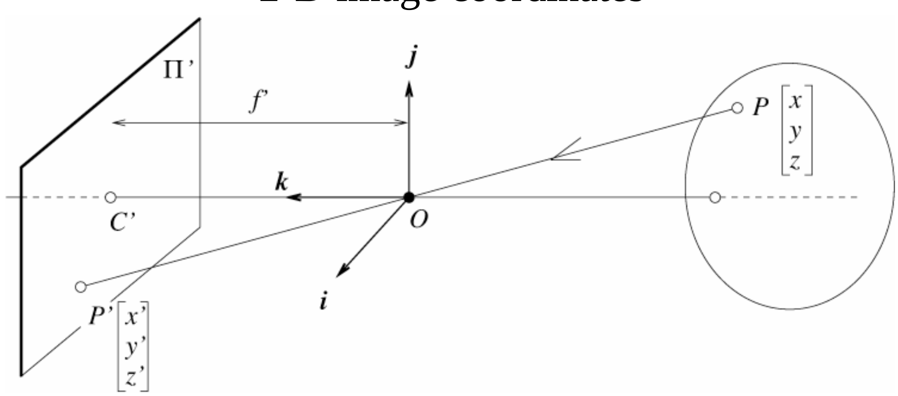
Pinhole cameras

- Abstract camera model - box with a small hole in it
- Pinhole cameras work in practice



The equation of projection:

Mapping from 3-D world coordinates to 2-D image coordinates



Cartesian coordinates:

- We have, by similar triangles, that (x, y, z) -> (f x/z, f y/z, -f)
- Ignore the third coordinate, and get

$$(x,y,z) \rightarrow (f\frac{x}{z}, f\frac{y}{z})$$

The camera matrix

Turn previous expression into Homogenous Coordinates

- HC's for 3D point are (X,Y,Z,T)
- HC's for point in image are (U,V,W)

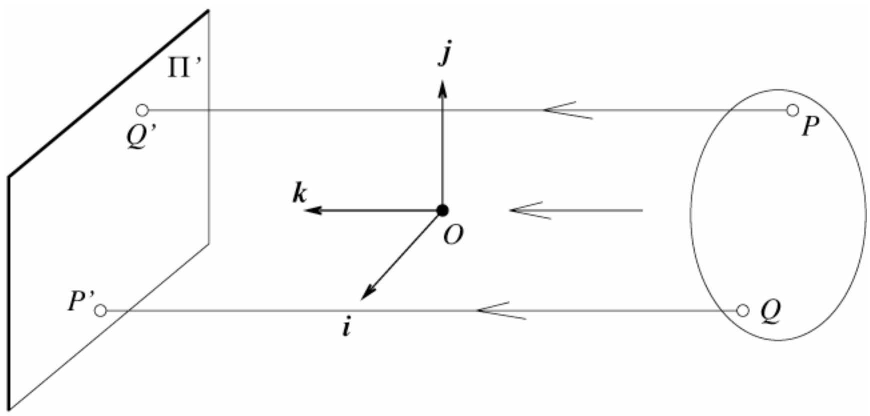
$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{1}{f} & 0 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \\ T \end{pmatrix}$$

Affine Camera Model

- Take Perspective projection equation, and perform Taylor Series Expansion about (some point (x_0,y_0,z_0).
- Drop terms of higher order than linear.
- Resulting expression is affine camera model

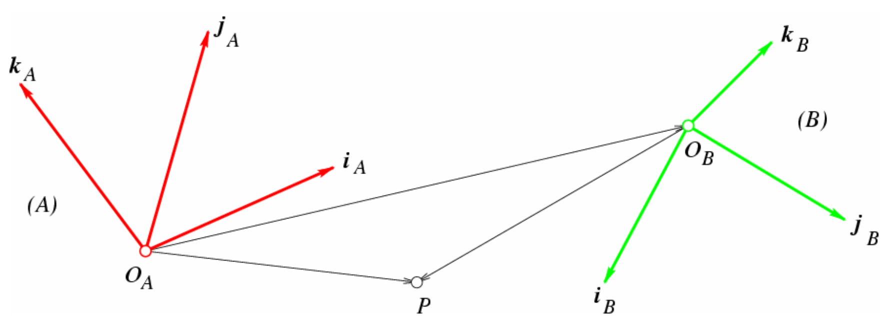
Orthographic projection

Take Taylor series about $(0, 0, z_0)$ – a point on optical axis



CS348, Fall 2001

Coordinate Changes: Rigid Transformations



$$^{B}P = {}^{B}_{A}R\, {}^{A}P + {}^{B}O_A$$

CS348, Fall 2001

Block Matrix Multiplication

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \qquad B = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}$$

What is AB ?

$$AB = \begin{bmatrix} A_{11}B_{11} + A_{12}B_{21} & A_{11}B_{12} + A_{12}B_{22} \\ A_{21}B_{11} + A_{22}B_{21} & A_{21}B_{12} + A_{22}B_{22} \end{bmatrix}$$

Homogeneous Representation of Rigid Transformations

$$\begin{bmatrix} {}^{B}P \\ 1 \end{bmatrix} = \begin{bmatrix} {}^{B}_{A}R & {}^{B}O_{A} \\ \mathbf{0}^{T} & 1 \end{bmatrix} \begin{bmatrix} {}^{A}P \\ 1 \end{bmatrix} = \begin{bmatrix} {}^{B}_{A}R\,{}^{A}P + {}^{B}O_{A} \\ 1 \end{bmatrix} = {}^{B}_{A}T \begin{bmatrix} {}^{A}P \\ 1 \end{bmatrix}$$

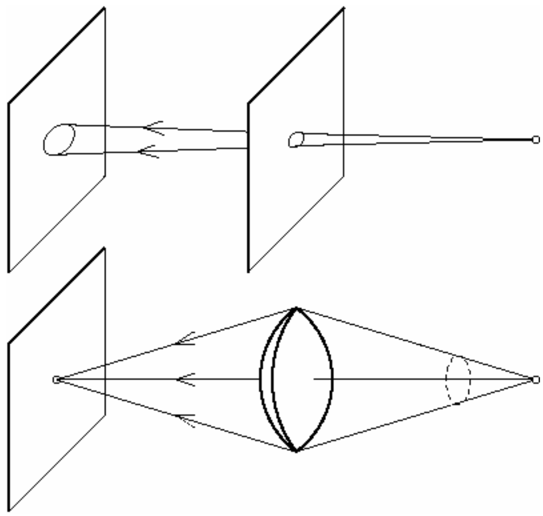
Camera parameters

- Issue
  - camera may not be at the origin, looking down the z-axis
    - extrinsic parameters
  - one unit in camera coordinates may not be the same as one unit in world coordinates
    - intrinsic parameters - focal length, principal point, aspect ratio, angle between axes, etc.

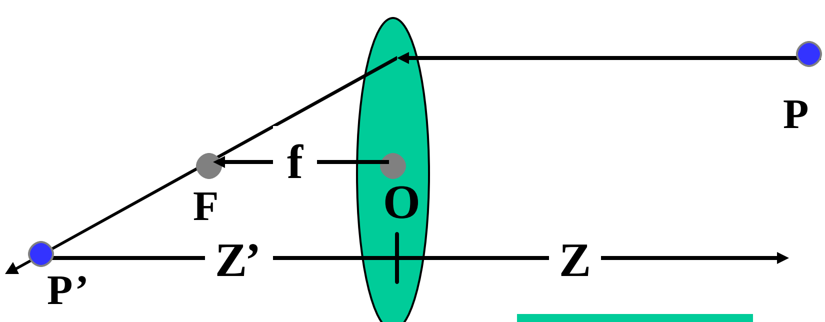
$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} \text{Transformation} \\ \text{representing} \\ \text{intrinsic parameters} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \text{Transformation} \\ \text{representing} \\ \text{extrinsic parameters} \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \\ T \end{pmatrix}$$

3 x 3   4 x 4

The reason for lenses



Thin Lens: Image of Point



$$\frac{1}{z'} - \frac{1}{z} = \frac{1}{f}$$

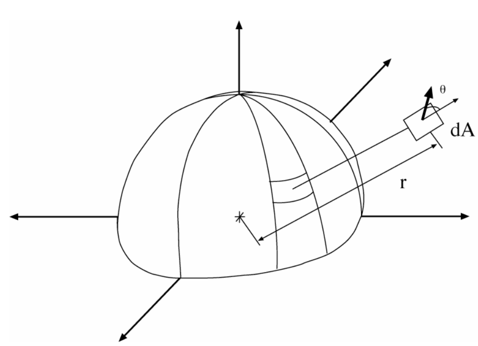
Radiometry

- Solid Angle
- Irradiance
- Radiance
- BRDF
- Lambertian/Phong BRDF

Solid Angle

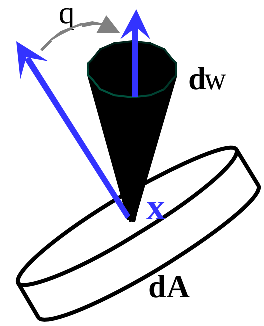
- By analogy with angle (in radians), the solid angle subtended by a region at a point is the area projected on a unit sphere centered at that point
- The solid angle subtended by a patch area dA is given by

$$dw = \frac{dA \cos q}{r^2}$$



Radiance

- Power is energy per unit time
- **Radiance: Power traveling at some point in a specified direction, per unit area perpendicular to the direction of travel, per unit solid angle**
- Symbol: L(**x**,θ,ϕ)
- Units: watts per square meter per steradian : w/($m^2 sr^1$)

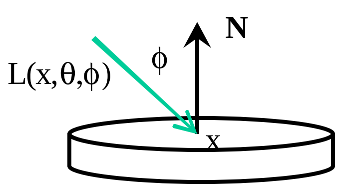


$$L = \frac{P}{(dA \cos q)dw}$$

Irradiance

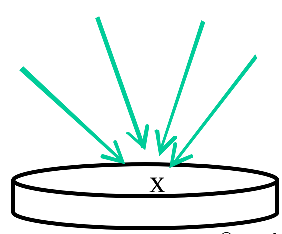
- How much light is arriving at a surface? E(x)
- Units w/m^2
- Incident power per unit area *not foreshortened*
- This is a function of incoming angle.
- A surface experiencing radiance L(x,θ,ϕ) coming in from solid angle dω experiences irradiance:

$$L(\underline{x}, q, f) \cos f \, dw$$



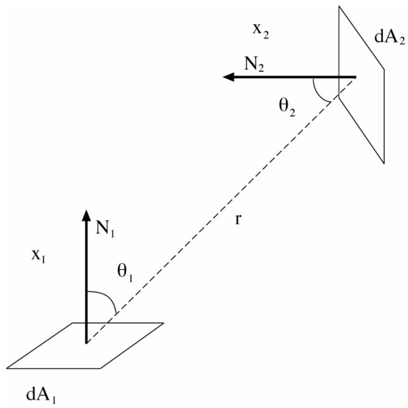
- Crucial property:
  Total power arriving at the surface is given by adding irradiance over all incoming angles Total power is

$$\int_{\Omega} L(\underline{x}, q, f) \cos f \sin q \, dq \, df$$



Radiance transfer

What is the power received by a small area dA_2 at distance r from a small emitting area dA_1?



From definition of radiance

$$L = \frac{P}{(dA\cos\theta)d\omega}$$

From definition of solid angle

$$d\omega = \frac{dA\cos\theta}{r^2}$$

$$P = \frac{L}{r^2} dA_1 dA_2 \cos\theta_1 \cos\theta_2$$

BRDF

With assumptions in previous slide

- Bi-directional Reflectance Distribution Function

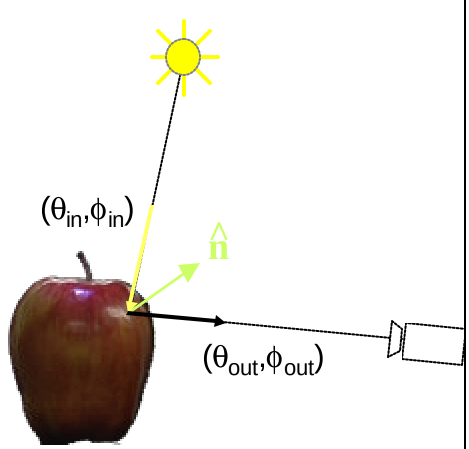
  $\rho(\theta_{in}, \phi_{in} ; \theta_{out}, \phi_{out})$

- **Ratio of incident irradiance to emitted radiance**

- Function of
  - Incoming light direction:

    θ_{in} , ϕ_{in}
  - Outgoing light direction:

    $\theta_{out} , \phi_{out}$



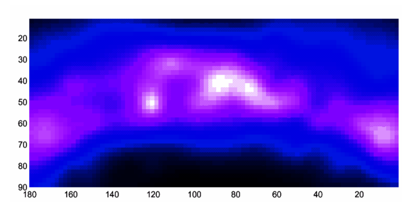
$$\rho(\underline{x};\theta_{in},\phi_{in};\theta_{out},\phi_{out}) = \frac{L_o(\underline{x};\theta_{out},\phi_{out})}{L_i(\underline{x};\theta_{in},\phi_{in})\cos\phi_{in}d\omega}$$

Surface Reflectance Models

Common Models

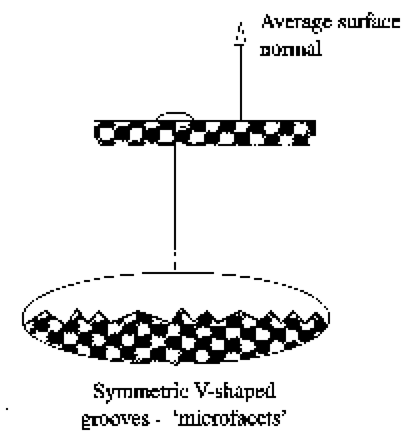
- Lambertian
- Phong
- Physics-based
  - Specular
    [Blinn 1977], [Cook-Torrance 1982], [Ward 1992]
  - Diffuse
    [Hanrahan, Kreuger 1993]
  - Generalized Lambertian
    [Oren, Nayar 1995]
  - Thoroughly Pitted Surfaces
    [Koenderink et al 1999]
- Phenomenological
  [Koenderink, Van Doorn 1996]

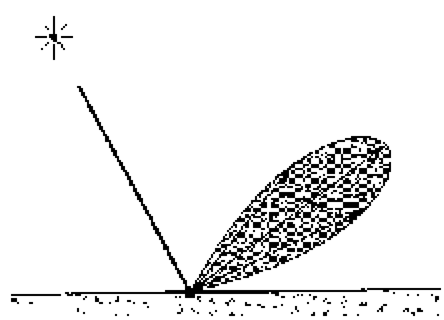
Arbitrary Reflectance



- Non-parametric model
- Anisotropic
- Non-uniform over surface
- BRDF Measurement *[Dana et al, 1999], [Marschner]*

Rough Specular Surface





Phong Lobe

Announcements

- Mailing list: cse291-j@cs.ucsd.edu
  Has been setup with class list as of Sunday night.
  If you're not on it, and want to be added (e.g. auditing, and not on course list, send the email msg to majordomo@cs.ucsd.edu with body saying:
  subscribe cse291-j my_email@something.something

- Class presentations: requests from
  - Sameer Agarwal
  - Jin-Su Kim
  - Satya Mallick
  - Peter Schwer
  - Diem Vu
  - Cindy Wang
  - Yang Yu

This lecture

S. Chen, Quicktime VR - an image-based approach to virtual environment navigation, SIGGRAPH, pages 29-38, Los Angeles, California, August 1995.

E. H. Adelson and J. R. Bergen. The plenoptic function and the elements of early vision. In M. Landy and J. A. Movshon, editors, Computational Models of Visual Processing, pages 3-20. MIT Press, Cambridge, MA, 1991.

S. J. Gortler, R. Grzeszczuk, R. Szeliski ,M. F. Cohen The Lumigraph, SIGGRAPH, pp 43--54, 1996

M. Levoy, P. Hanrahan Light Field Rendering , SIGGRAPH, 1996

Traditional Modeling and Rendering

Model

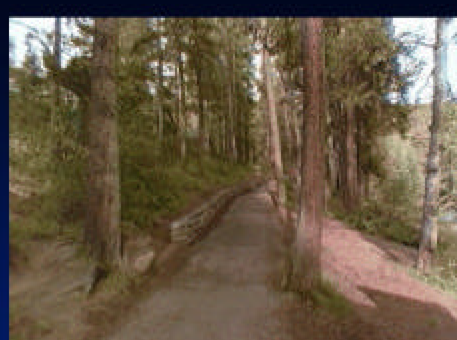
User Input (texture maps, survey data) → Modeling → Geometry / Reflectance / Light sources → Rendering → Images

For Photorealism:

Modeling is Hard **Rendering is Slow**

CS348, Fall 2001

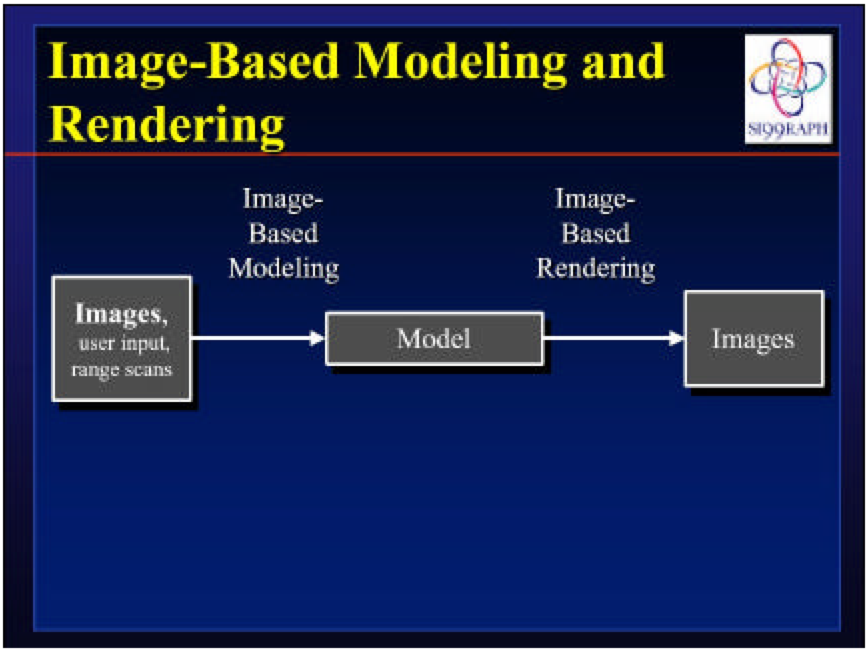
Next few slides courtesy Paul Debevec; SIGGRAPH 99 course notes



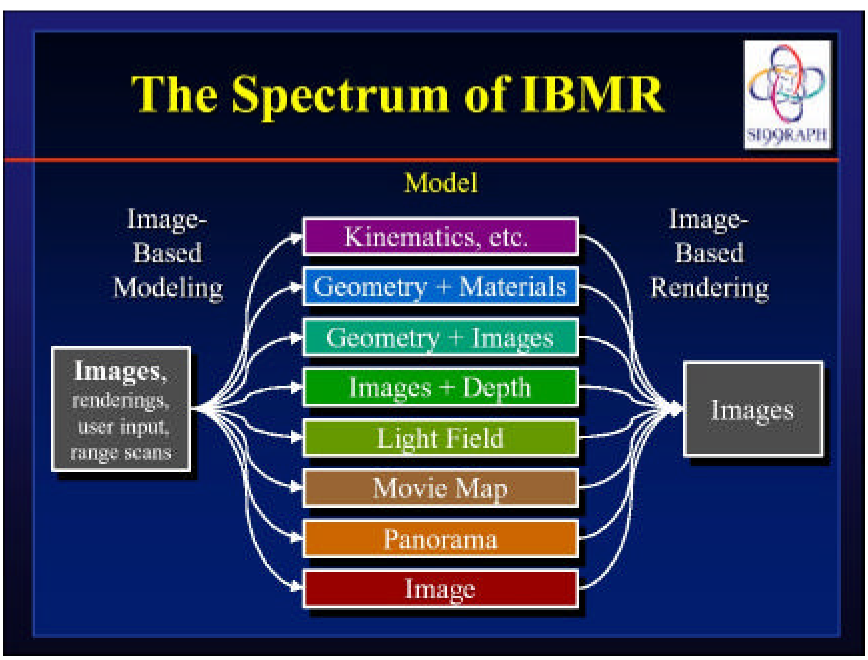
Can we model and render this?

What do we want to do with the model?

CS348, Fall 2001



CS348, Fall 2001



CS348, Fall 2001

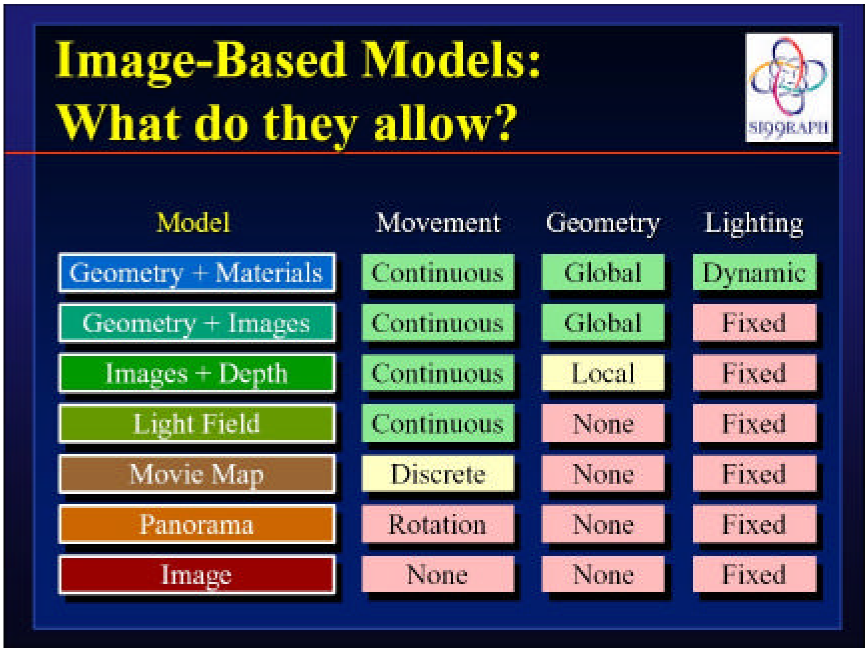


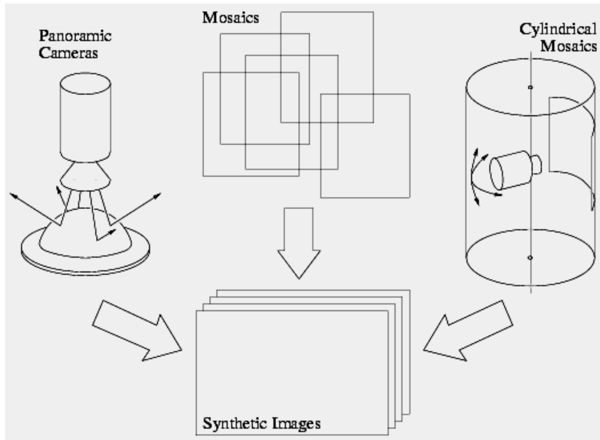
Image-Based Models: What do they allow?

Model	Movement	Geometry	Lighting
Geometry + Materials	Continuous	Global	Dynamic
Geometry + Images	Continuous	Global	Fixed
Images + Depth	Continuous	Local	Fixed
Light Field	Continuous	None	Fixed
Movie Map	Discrete	None	Fixed
Panorama	Rotation	None	Fixed
Image	None	None	Fixed

Mosaics & Quicktime VR

- S. Chen, **Quicktime VR - An image-based approach to virtual environment navigation**, SIGGRAPH, pages 29-38, Los Angeles, California, August 1995.

View Synthesis Without Motion Analysis



(Peri and Nayar, 1997)
(Shum and Szeliski, 1998)
(Quicktime VR, Chen, 1995)

Constructing Mosaic: Cylindrical images

- Easy to acquire with camera & tripod.
- Any two planar perspective projections of a scene which share a common viewpoint are related by a two-dimensional projective transform.

$$\begin{bmatrix} u_2 \\ v_2 \\ w_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} u_1 \\ v_1 \\ w_1 \end{bmatrix}$$

- Can be estimated from a minimum of four points correspondences in two images.

Stitched panoramic image from photos

Figure 9. A stitched panoramic image and some of the photographs the image stitched from.

CS348, Fall 2001

Perspective view created from region

Figure 5. A perspective view created from warping a region enclosed by the yellow box in the panoramic image.

CS348, Fall 2001

QuickTime VR

- continuous camera panning and zooming, jumping to selected points.
- cylindrical environment maps or panoramic images to accomplish camera rotation.

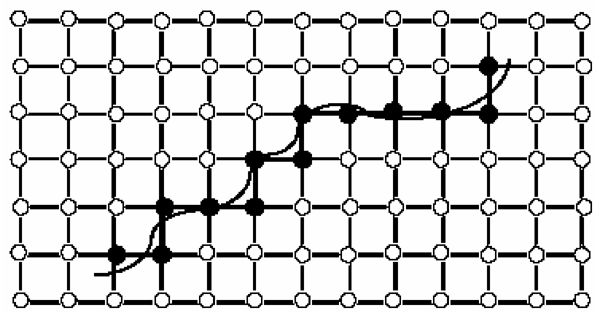
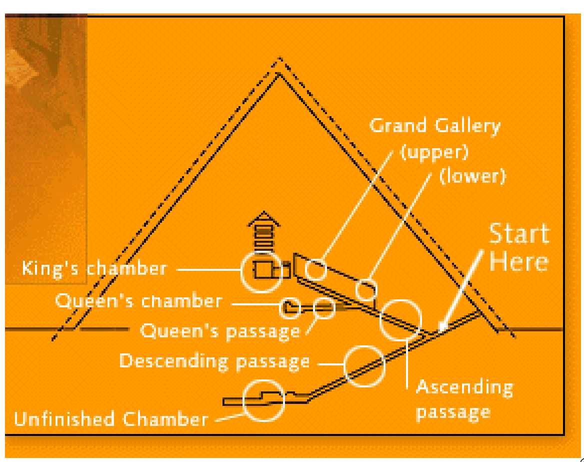


Figure 2. An unconstrained camera path and an approximated path along the grid lines.

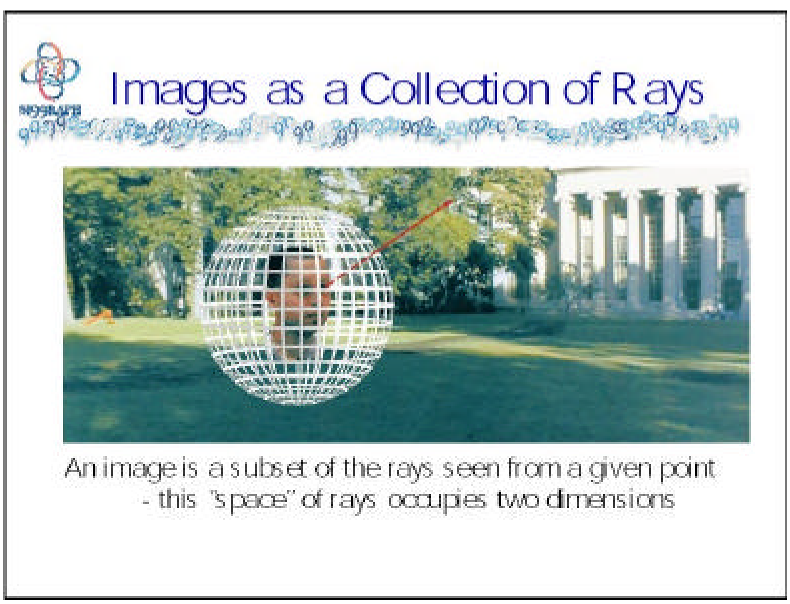
Quicktime VR: Example

http://www.pbs.org/wgbh/nova/pyramid/explore/khufuenter.html



Plenoptic Function

CS348, Fall 2001

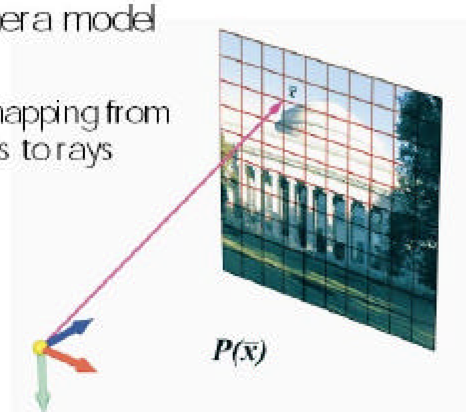


From Leonard McMillan's, SIGGRAPH 99 course notes

CS348, Fall 2001

Where to Begin?

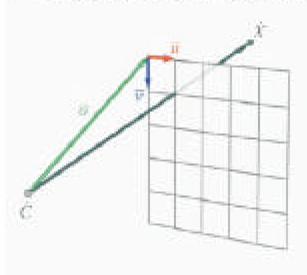
- Pinhole camera model
  - Defines a mapping from image points to rays in space



From Leonard McMillan's, SIGGRAPH 99 course notes

Mapping from Rays to Points

- Simple Derivation



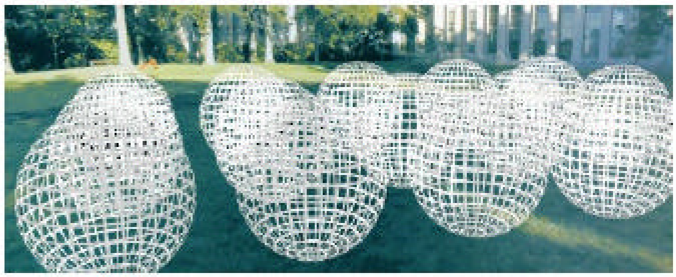
$$P = \begin{bmatrix} u_x & v_x & O_x \\ u_y & v_y & O_y \\ u_z & v_z & O_z \end{bmatrix}$$

$$\dot{X} = \dot{C} + t\, P\, \vec{x}$$

From Leonard McMillan's, SIGGRAPH 99 course notes

The Plenoptic Function

- The set of rays seen from all points ...

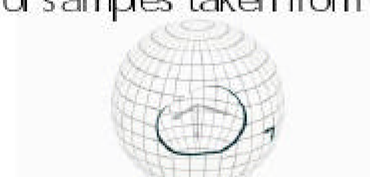


$$p = P(\theta, \phi, x, y, z, \lambda, t)$$

From Leonard McMillan's, SIGGRAPH 99 course notes

Image-based rendering is about

...reconstructing a plenoptic function from a set of samples taken from it.



- Ignoring time, and selecting a discrete set of wavelengths gives a 5-D plenoptic function

From Leonard McMillan's, SIGGRAPH 99 course notes

Lumigraph/Lightfield

S. J. Gortler, R. Grzeszczuk, R. Szeliski ,M. F. Cohen, **The Lumigraph**, SIGGRAPH, pp 43--54, 1996

M. Levoy, P. Hanrahan, **Light Field Rendering,** SIGGRAPH, 1996.

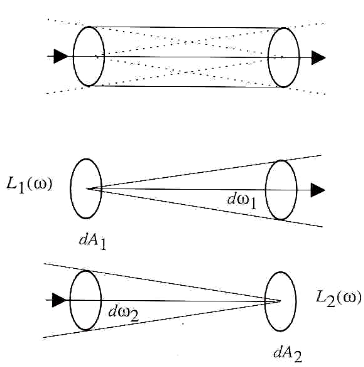
Historical roots in:

– Gershun, A., The Light Field, Moscow, 1936. Translated by P. Moon and G. Timoshenko in Journal of Mathematics and Physics, Vol. XVIII, MIT, 1939, pp. 51-151.
– Moon, P., Spencer, D.E., The Photic Field, MIT Press, 1981.

CS348, Fall 2001

Radiance properties

- In free space, radiance is constant as it propagates along a ray
  – Derived from conservation of flux
  – Fundamental in Light Transport.



$$d\Phi_1 = L_1 dw_1 dA_1 = L_2 dw_2 dA_2 = d\Phi_2$$

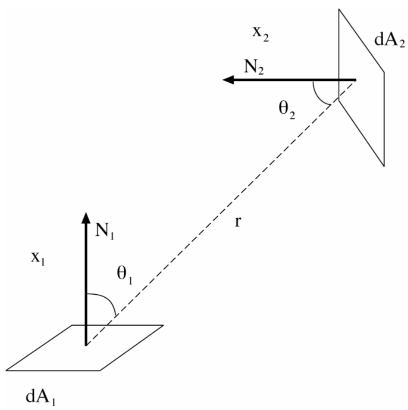
$$dw_1 = dA_2 / r^2 \qquad dw_2 = dA_1 / r^2$$

$$dw_1 dA_1 = \frac{dA_1 dA_2}{r^2} = dw_2 dA_2$$

$$\therefore L_1 = L_2$$

CS348, Fall 2001

Radiance is constant along straight lines



- Power 1->2, leaving 1:

$$L(\underline{x}_1, J, j)(dA_1 \cos J_1)\left(\frac{dA_2 \cos J_2}{r^2}\right)$$

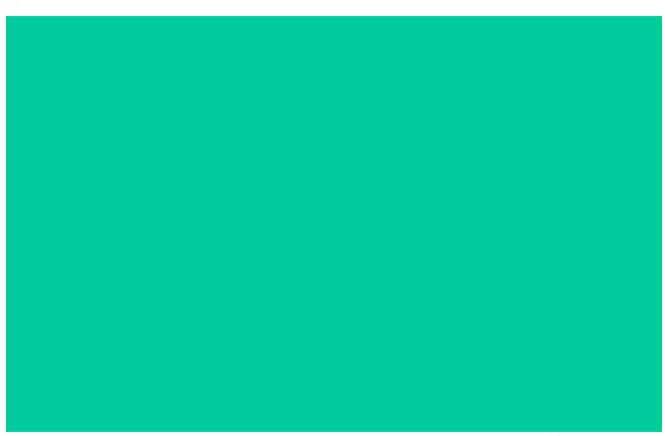
- Power 1->2, arriving at 2:

$$L(\underline{x}_2, J, j)(dA_2 \cos J_2)\left(\frac{dA_1 \cos J_1}{r^2}\right)$$

- But these must be the same, so that the two radiances are equal

Quiz

Does the brightness that a wall appears to the eye depend on the distance of the viewer to the wall?



Light Field/Lumigraph Main Idea

- In free space, the 5-D plenoptic function can be reduced to a 4-D function (radiances) on the space of light rays.
- Camera images measure the radiance over a 2-D set –
  a 2-D subset of the 4-D light field.
- Rendered images are also a 2-D subset of the 4-D lumigraph.