COS526: Advanced Computer Graphics

Tom Funkhouser
Fall 2016

Background

Image Processing
- Basic signal processing
- Filtering, resampling, warping, ...

Rendering
- Polygon rendering pipeline
- Basic ray tracing

Modeling
- Basic 3D object representations
- Polygonal meshes

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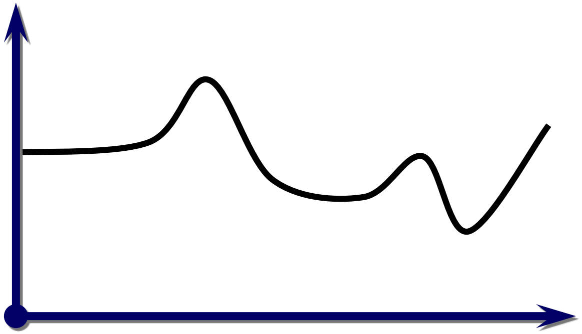
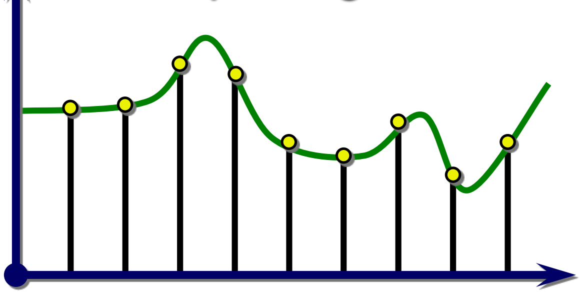
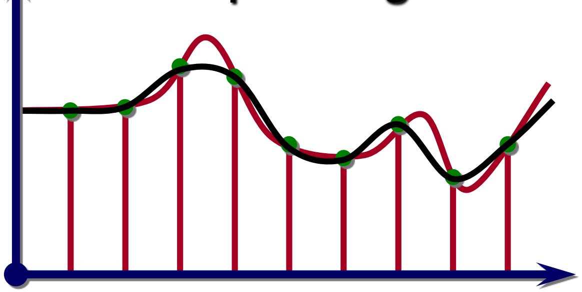


Input signal



Sampled signal



Reconstructed signal

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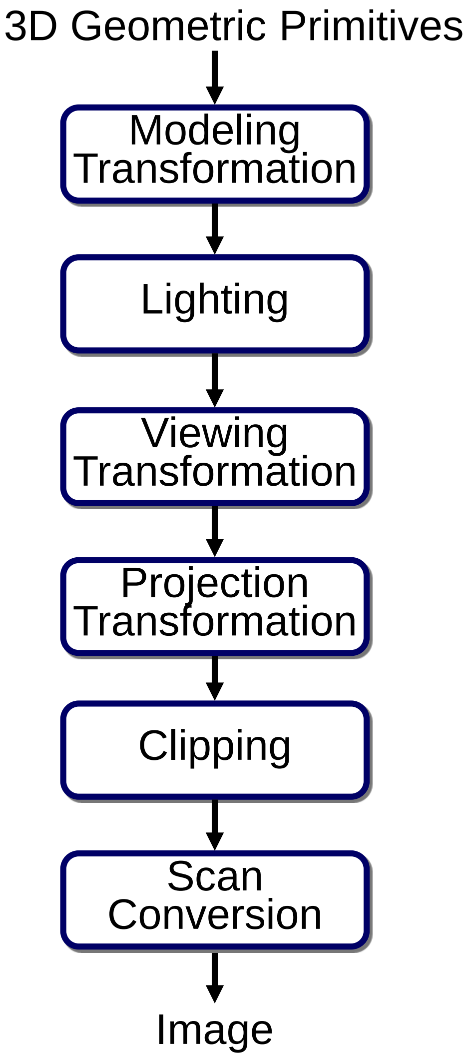

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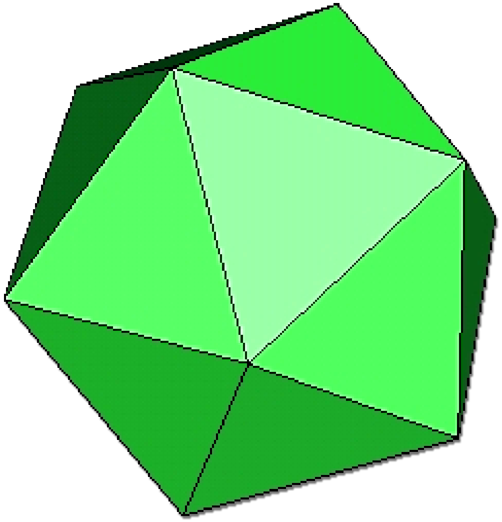

CS526 Syllabus

- Global illumination
  - Monte Carlo path tracing
  - Photon mapping
- RGBD point sets
  - Image processing
  - Image-based rendering
  - 3D reconstruction
- Polygonal meshes
  - Mesh representations
  - Mesh analysis
  - Shape collections
- Special topics
  - Computational photography?
  - Fabrication?
  - Others?

Jensen

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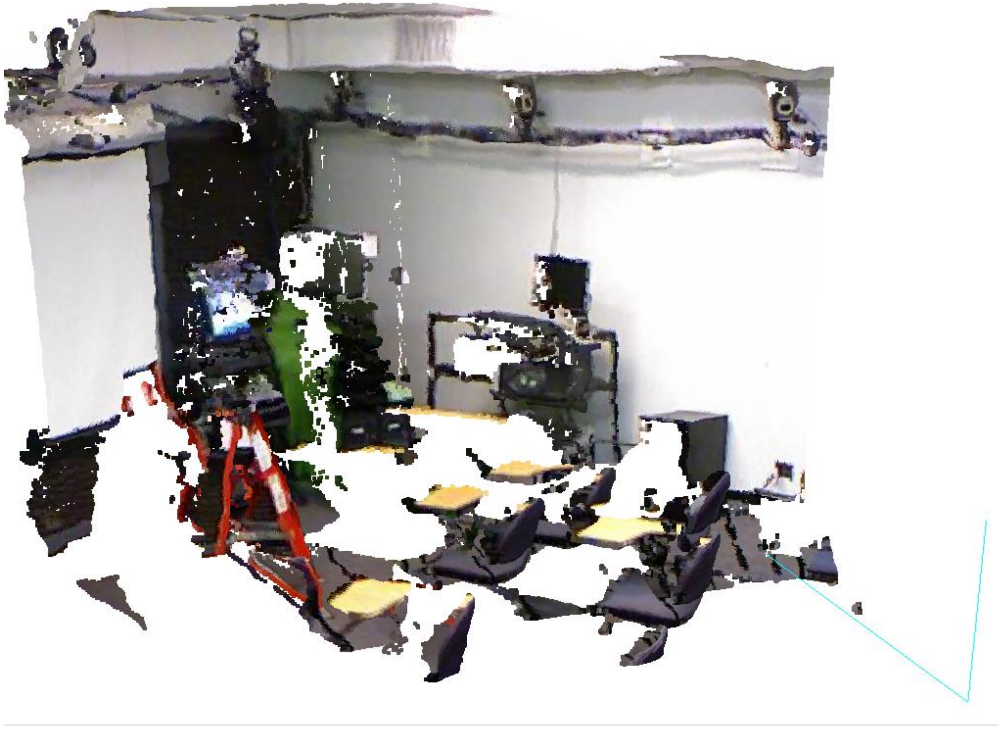

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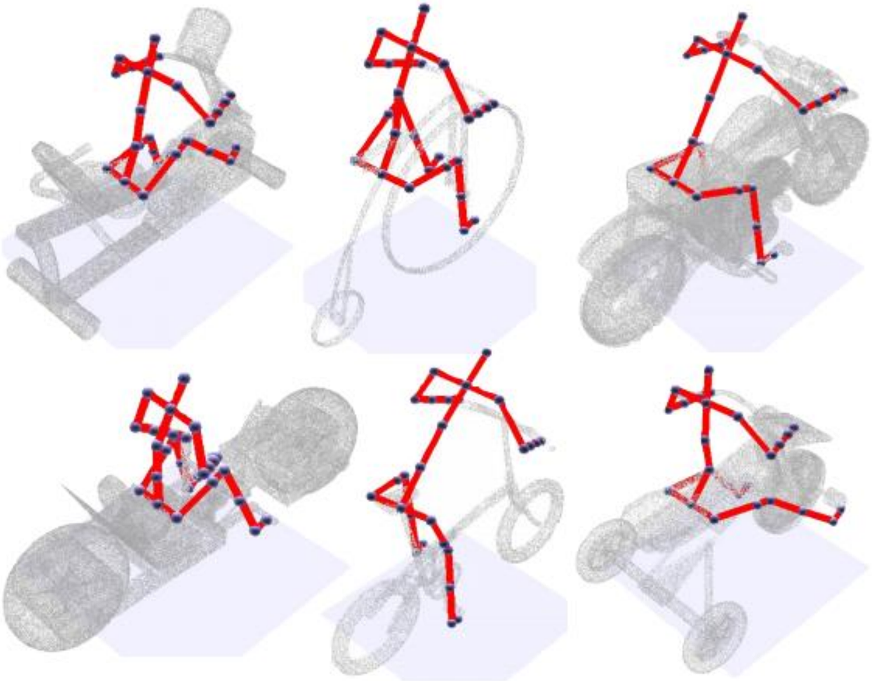

Kim

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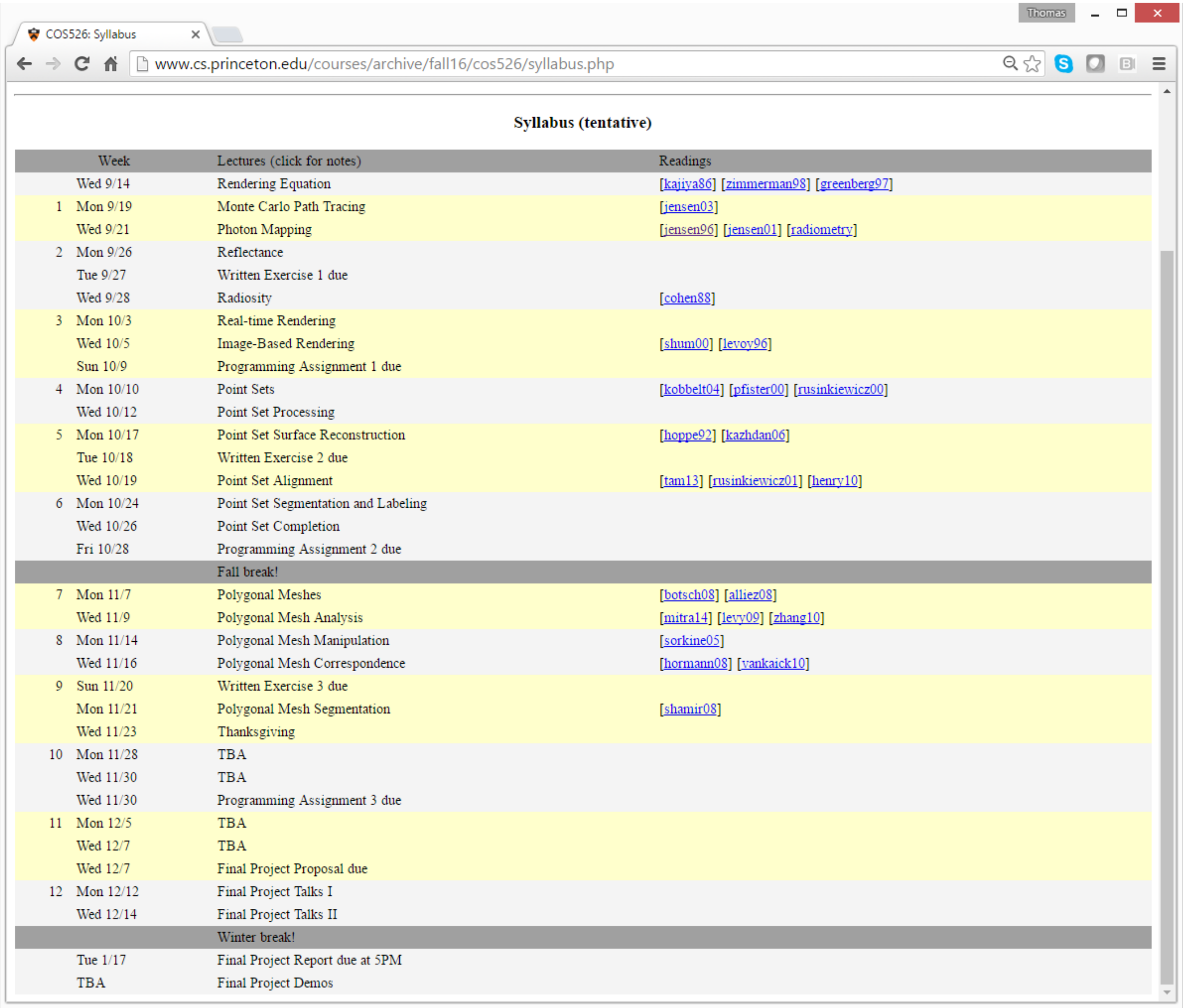
CS526 Syllabus



Syllabus (tentative)

Week		Lectures (click for notes)	Readings
	Wed 9/14	Rendering Equation	[kajiya86] [zimmerman98] [greenberg97]
1	Mon 9/19	Monte Carlo Path Tracing	[jensen03]
	Wed 9/21	Photon Mapping	[jensen96] [jensen01] [radiometry]
2	Mon 9/26	Reflectance	
	Tue 9/27	Written Exercise 1 due	
	Wed 9/28	Radiosity	[cohen88]
3	Mon 10/3	Real-time Rendering	
	Wed 10/5	Image-Based Rendering	[shum00] [levoy96]
	Sun 10/9	Programming Assignment 1 due	
4	Mon 10/10	Point Sets	[kobbelt04] [pfister00] [rusinkiewicz00]
	Wed 10/12	Point Set Processing	
5	Mon 10/17	Point Set Surface Reconstruction	[hoppe92] [kazhdan06]
	Tue 10/18	Written Exercise 2 due	
	Wed 10/19	Point Set Alignment	[tam13] [rusinkiewicz01] [henry10]
6	Mon 10/24	Point Set Segmentation and Labeling	
	Wed 10/26	Point Set Completion	
	Fri 10/28	Programming Assignment 2 due	
		Fall break!	
7	Mon 11/7	Polygonal Meshes	[botsch08] [alliez08]
	Wed 11/9	Polygonal Mesh Analysis	[mitra14] [levy09] [zhang10]
8	Mon 11/14	Polygonal Mesh Manipulation	[sorkine05]
	Wed 11/16	Polygonal Mesh Correspondence	[hormann08] [vankaick10]
9	Sun 11/20	Written Exercise 3 due	
	Mon 11/21	Polygonal Mesh Segmentation	[shamir08]
	Wed 11/23	Thanksgiving	
10	Mon 11/28	TBA	
	Wed 11/30	TBA	
	Wed 11/30	Programming Assignment 3 due	
11	Mon 12/5	TBA	
	Wed 12/7	TBA	
	Wed 12/7	Final Project Proposal due	
12	Mon 12/12	Final Project Talks I	
	Wed 12/14	Final Project Talks II	
		Winter break!	
	Tue 1/17	Final Project Report due at 5PM	
	TBA	Final Project Demos	

Coursework

3 Short written exercises

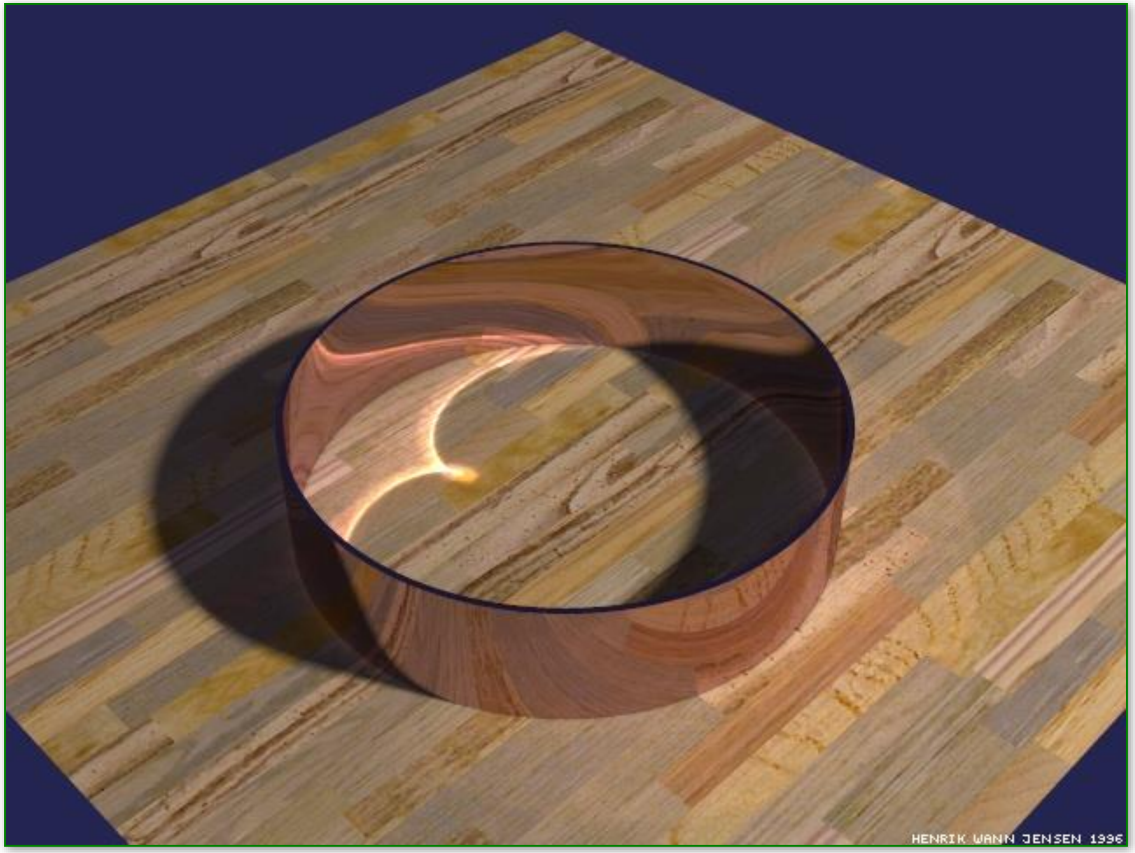
3 Programming assignments

Final project

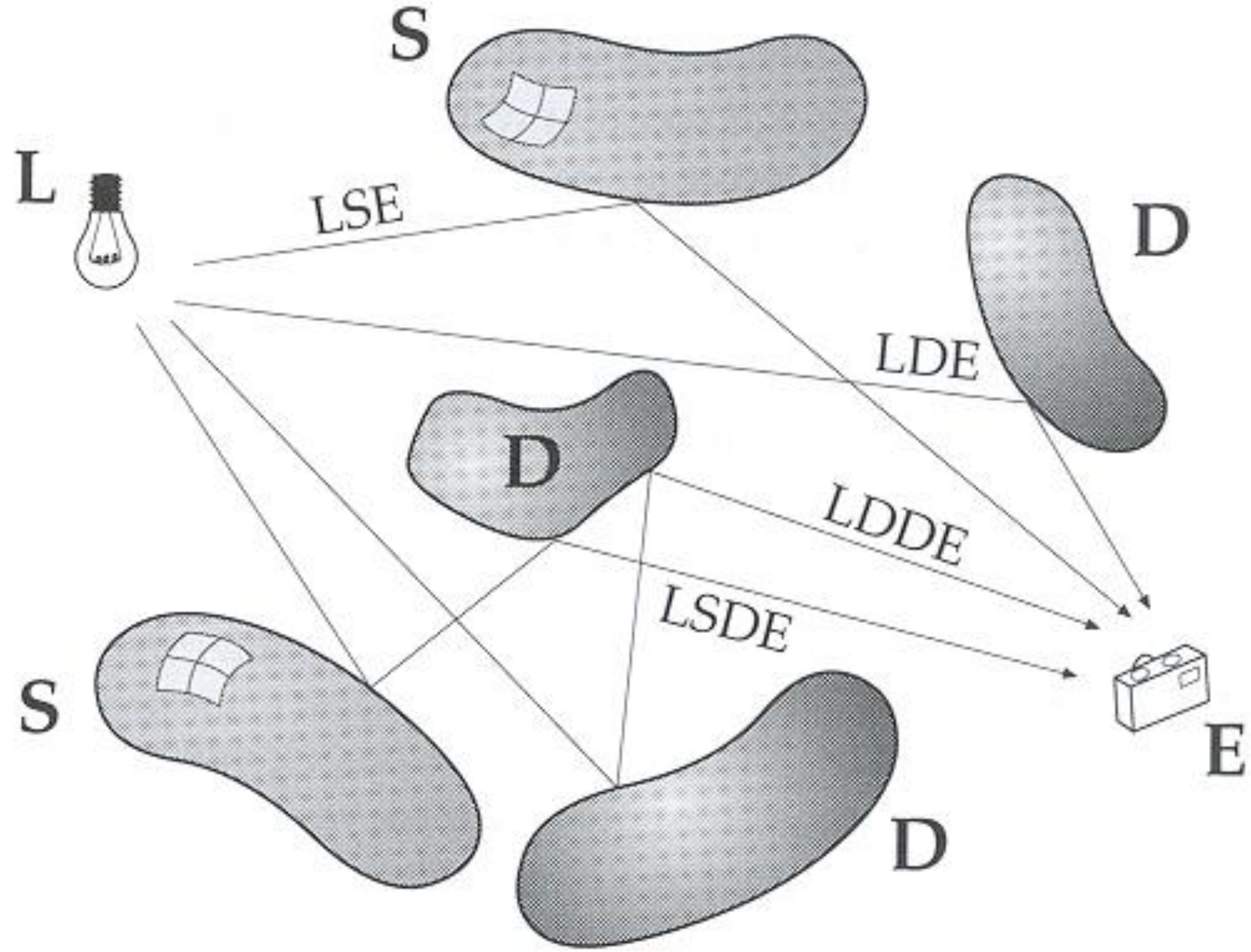
Let’s Get Started

Goal

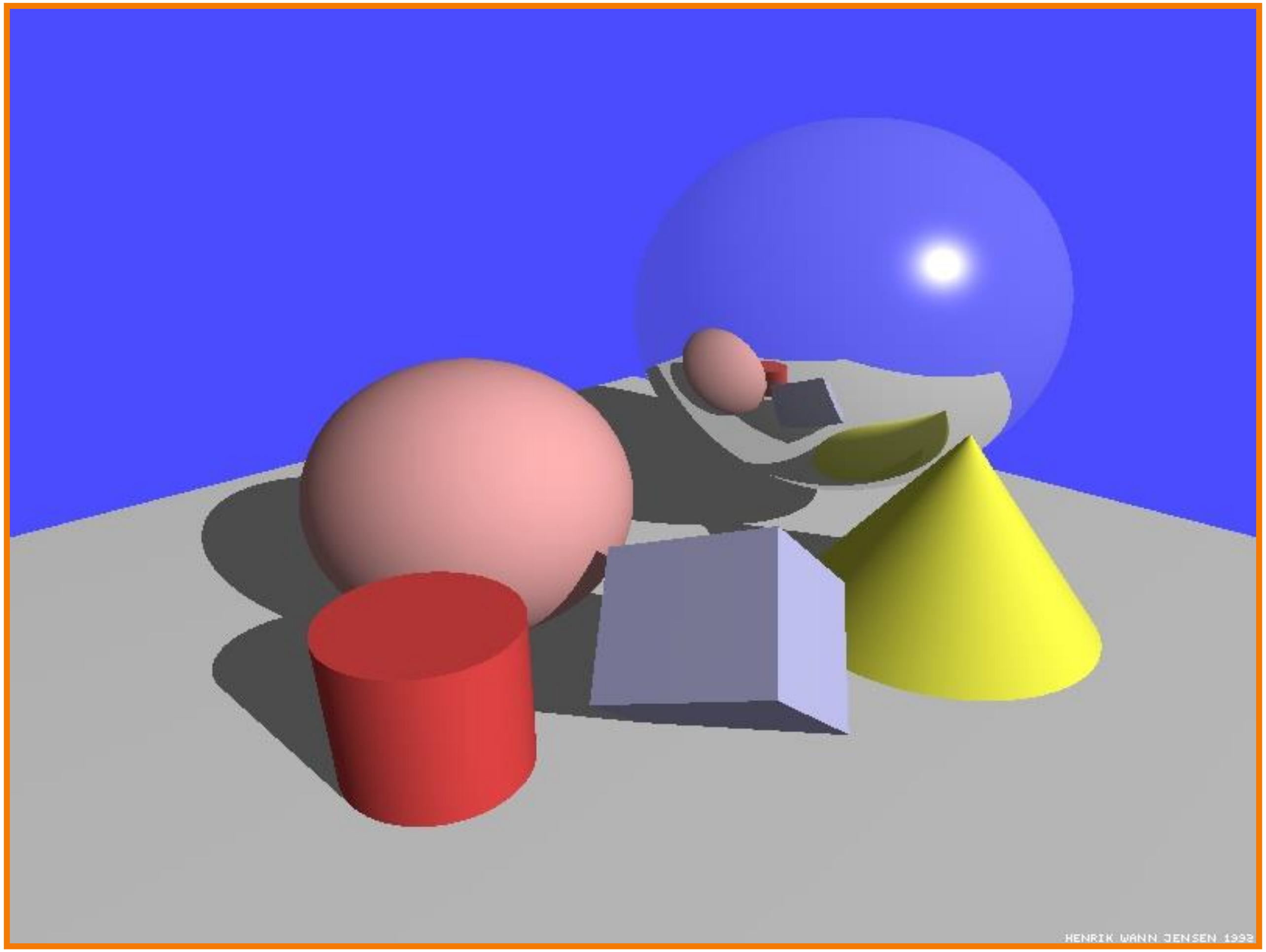
Synthesize image of a 3D scene accounting for all paths of light transport (including indirect illumination)



Path Types



Path Types?

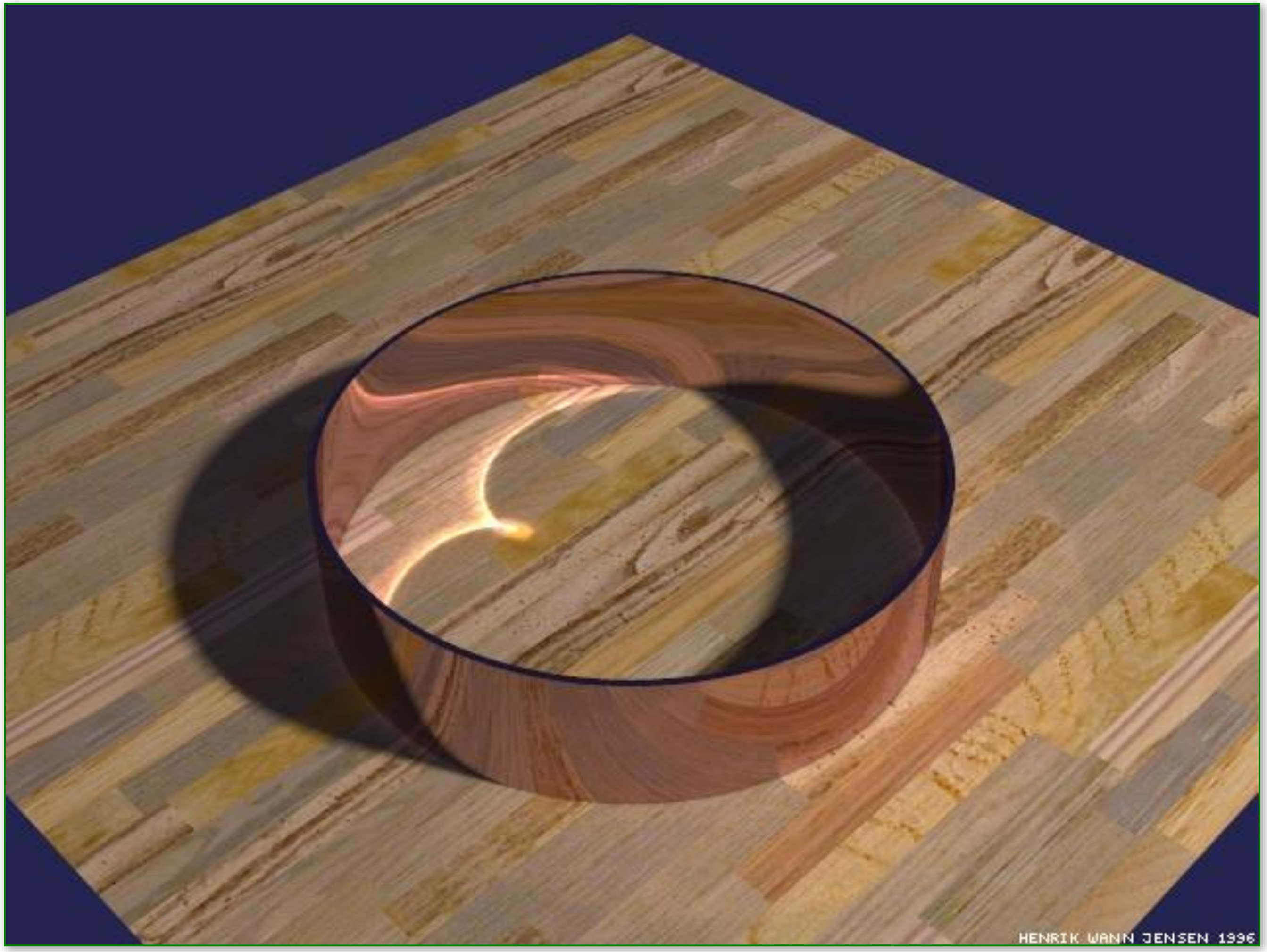


Henrik Wann Jensen

Path Types?

Paul Debevec

Path Types?



Henrik Wann Jensen

Path Types?

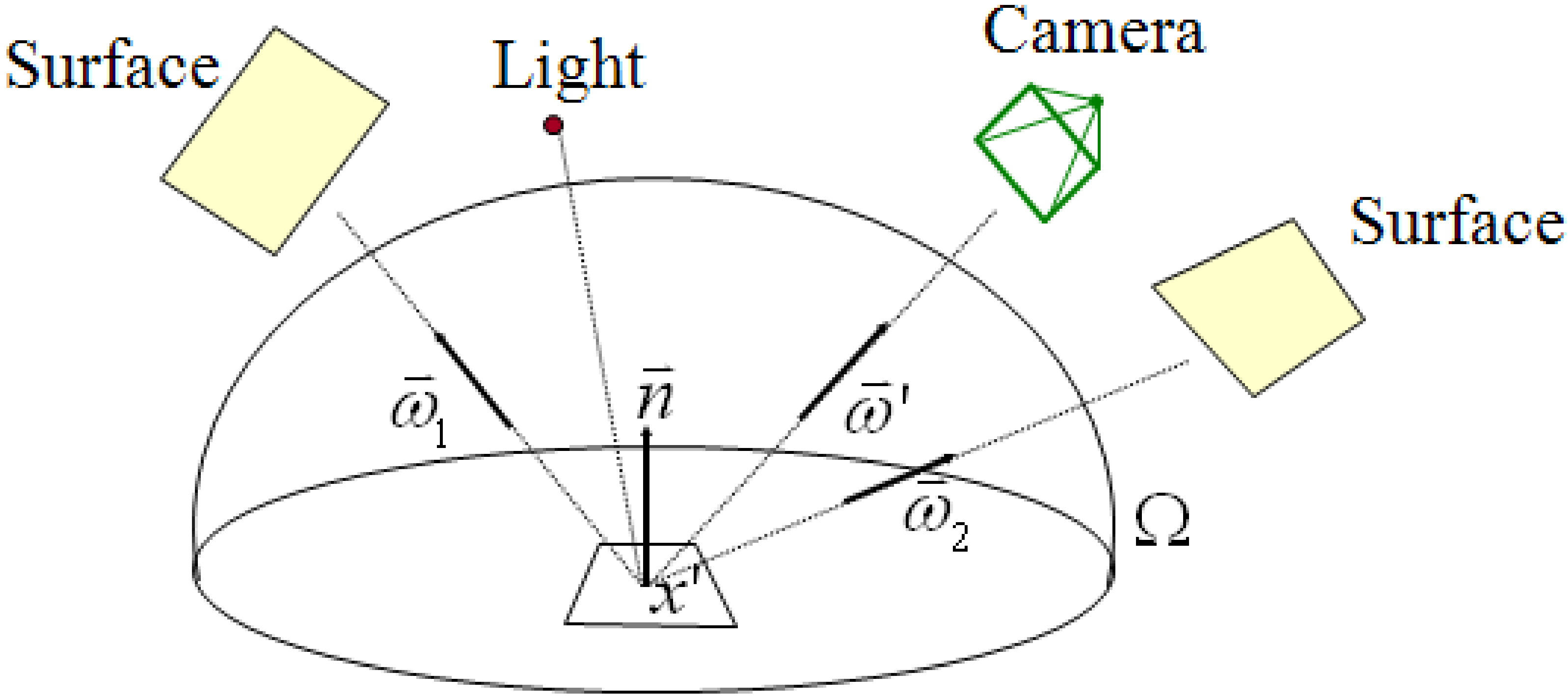
Outline

- Rendering equation
  - Explanation of terms

- Solution methods
  - Direct illumination
  - Recursive ray tracing
  - Distribution ray tracing
  - Path tracing
  - Photon Mapping
  - Radiosity
  - etc.

Rendering Equation (1)

Compute radiance in outgoing direction by integrating reflections over all incoming directions

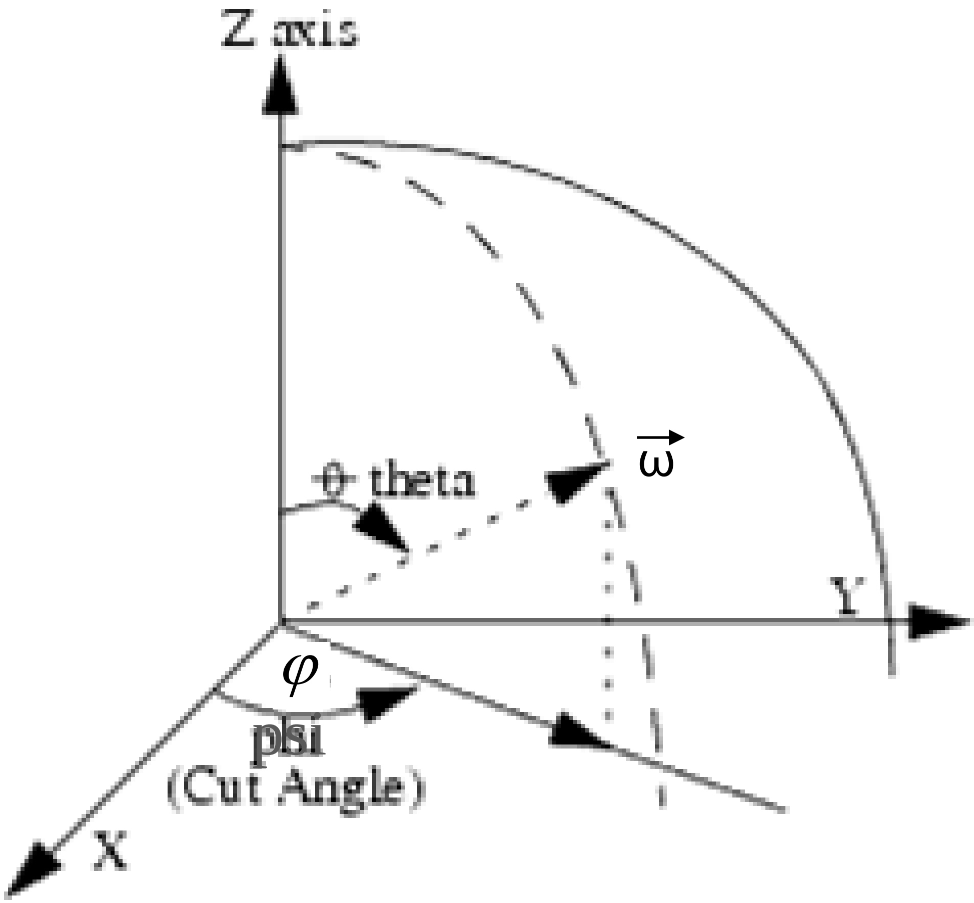


$$L_o(x', \bar{\omega}') = L_e(x', \bar{\omega}') + \int_{\Omega} f_r(x', \bar{\omega}, \bar{\omega}') L_i(x', \bar{\omega})(\bar{\omega} \bullet \bar{n}) d\bar{\omega}$$

What is $\vec{\omega}$?

$\vec{\omega}$ is a direction

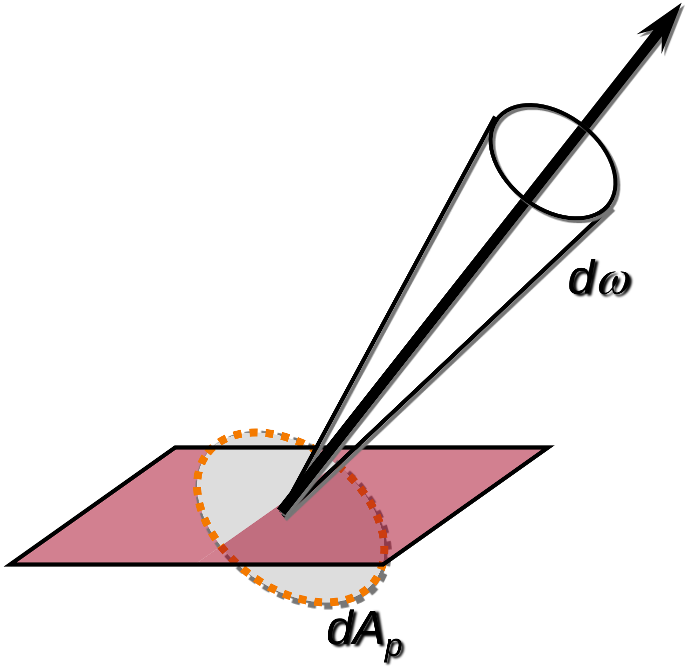
- 2-dimensional: (φ,θ)



What is L?

Radiance = power emitted from a surface in a direction

- Power dΦ per unit area dA_p per unit solid angle dω



$$L = \frac{d\Phi}{dA_p \, d\vec{\omega}}$$

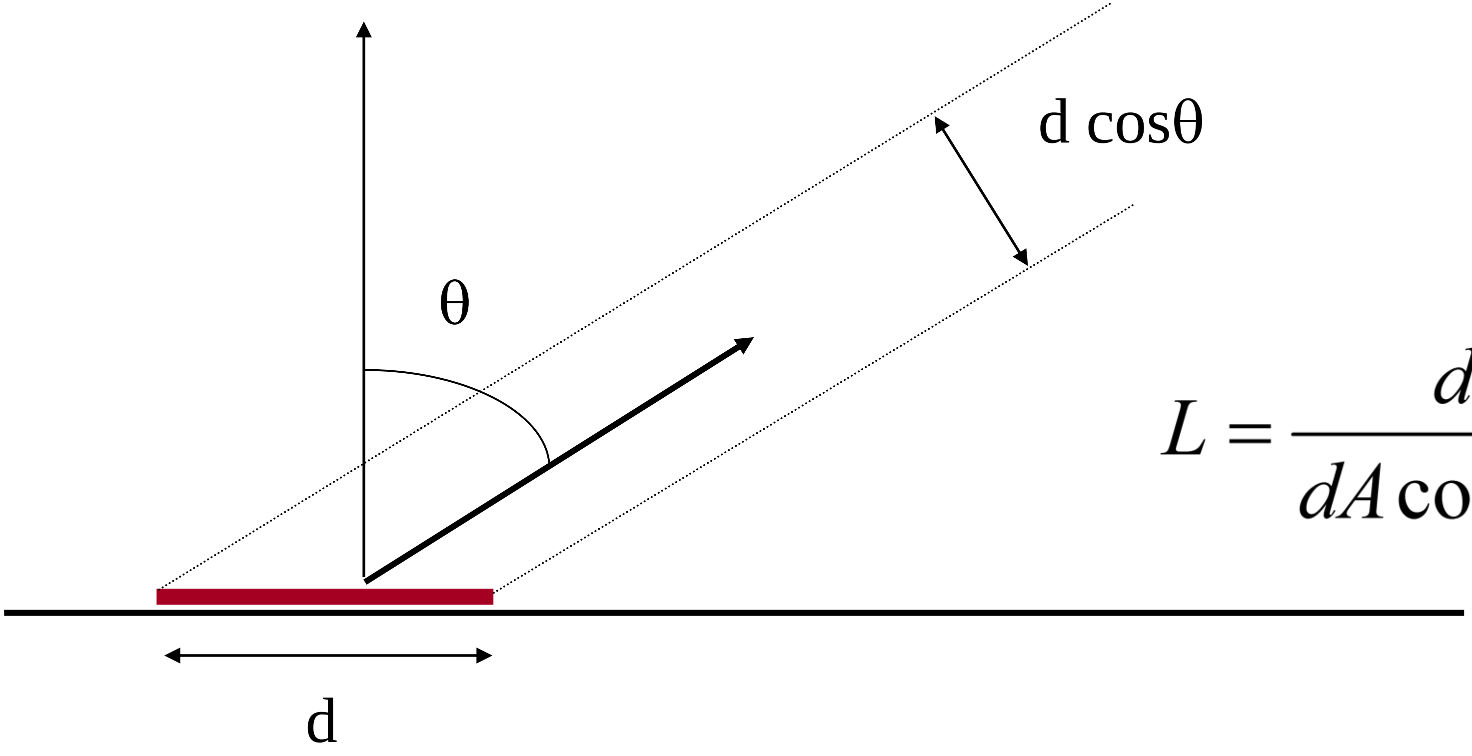
A_p = area perpendicular to given direction

$$L = \frac{d\Phi}{dA \cos\theta \;\; d\vec{\omega}}$$

Digression – Why Cosine Term?

Foreshortening is by cosine of angle.

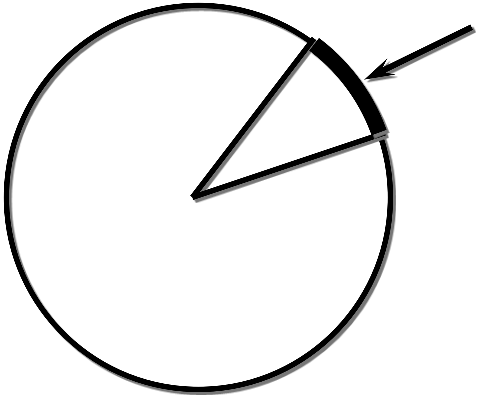
Radiance gives energy by *effective* surface area.



$$L = \frac{d\Phi}{dA \cos\theta \, d\vec{\omega}}$$

Digression – What is Solid Angle?

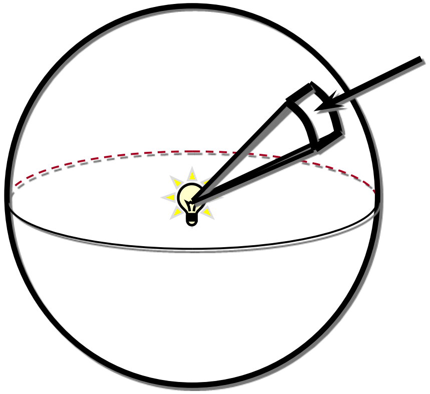
Angle in radians



Length l

Angle $\theta = l/r$

Solid angle in steradians



Area A

Solid angle $\omega = A/r^2$

Digression – Why Radiance?

Radiance doesn't change with distance

- Therefore it's the quantity we want to measure in a path tracer

Radiance is proportional to what a sensor (camera, eye) measures.

- Therefore it's what we want to output

Digression – What Units?

Light is a form of energy

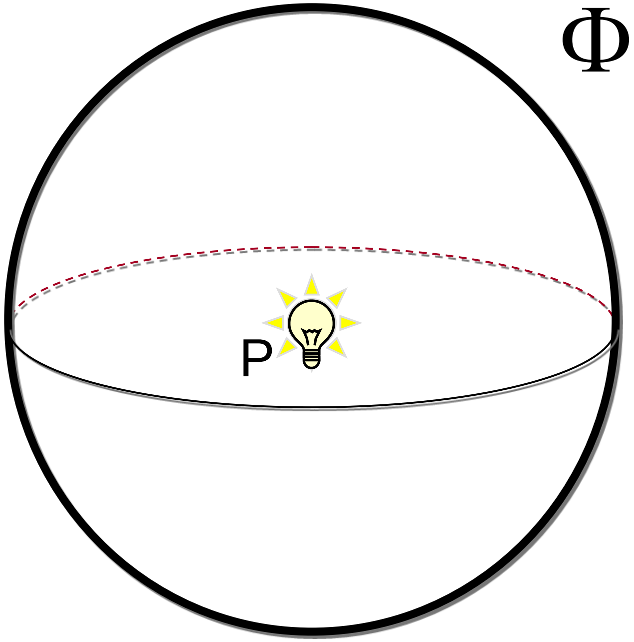
- Measured in Joules (J)

Power: energy per unit time

- Measured in Joules/sec = Watts (W)
- Also called Radiant Flux (Φ)

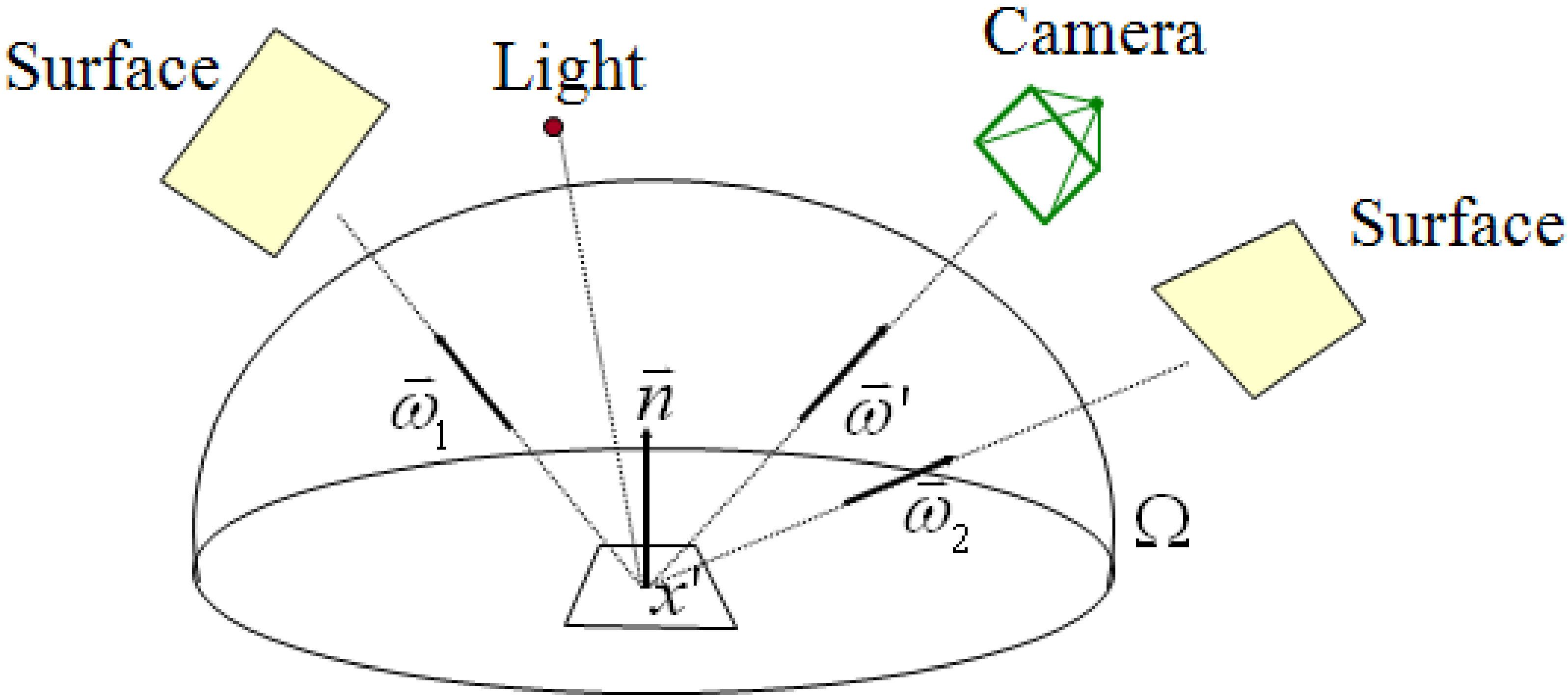
Radiance:

- Measured in $W/m^2/sr$



Rendering Equation (1) … Again

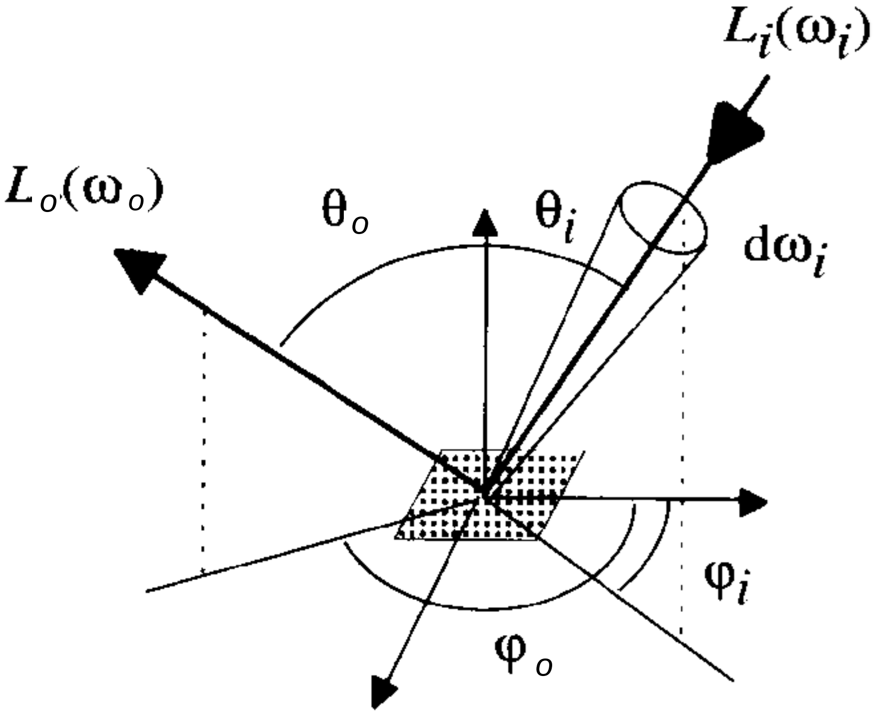
Compute radiance in outgoing direction by integrating reflections over all incoming directions



$$L_o(x',\bar{\omega}') = L_e(x',\bar{\omega}') + \int_{\Omega} f_r(x',\bar{\omega},\bar{\omega}') L_i(x',\bar{\omega})(\bar{\omega} \bullet \bar{n}) d\bar{\omega}$$

What is f_r?

Bidirectional Reflectance Distribution Function (f_r) = fraction of irradiance E_i in incoming direction $\vec{\omega}_i$ reflected in outgoing direction $\vec{\omega}_o$



$$f_r(\omega_i \rightarrow \omega_o) = \frac{L_o(\omega_o)}{E_i(\omega_i)}$$

$$E_i(\vec{\omega}_i) \equiv L_i(\vec{\omega}_i)\cos\theta_i d\omega$$

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o) \equiv \frac{L_o(\vec{\omega}_o)}{L_i(\vec{\omega}_i)\cos\theta_i d\omega_i}$$

What is f_r?

BRDF (f_r) is usually a 4-dimensional function for each of three frequencies:

$$f_r(\theta_i, \varphi_i, \theta_o, \varphi_o) = \frac{L_o(\theta_o, \varphi_o)}{E_i(\theta_i, \varphi_i)}$$

BRDF (f_r) is an intrinsic property of a surface material

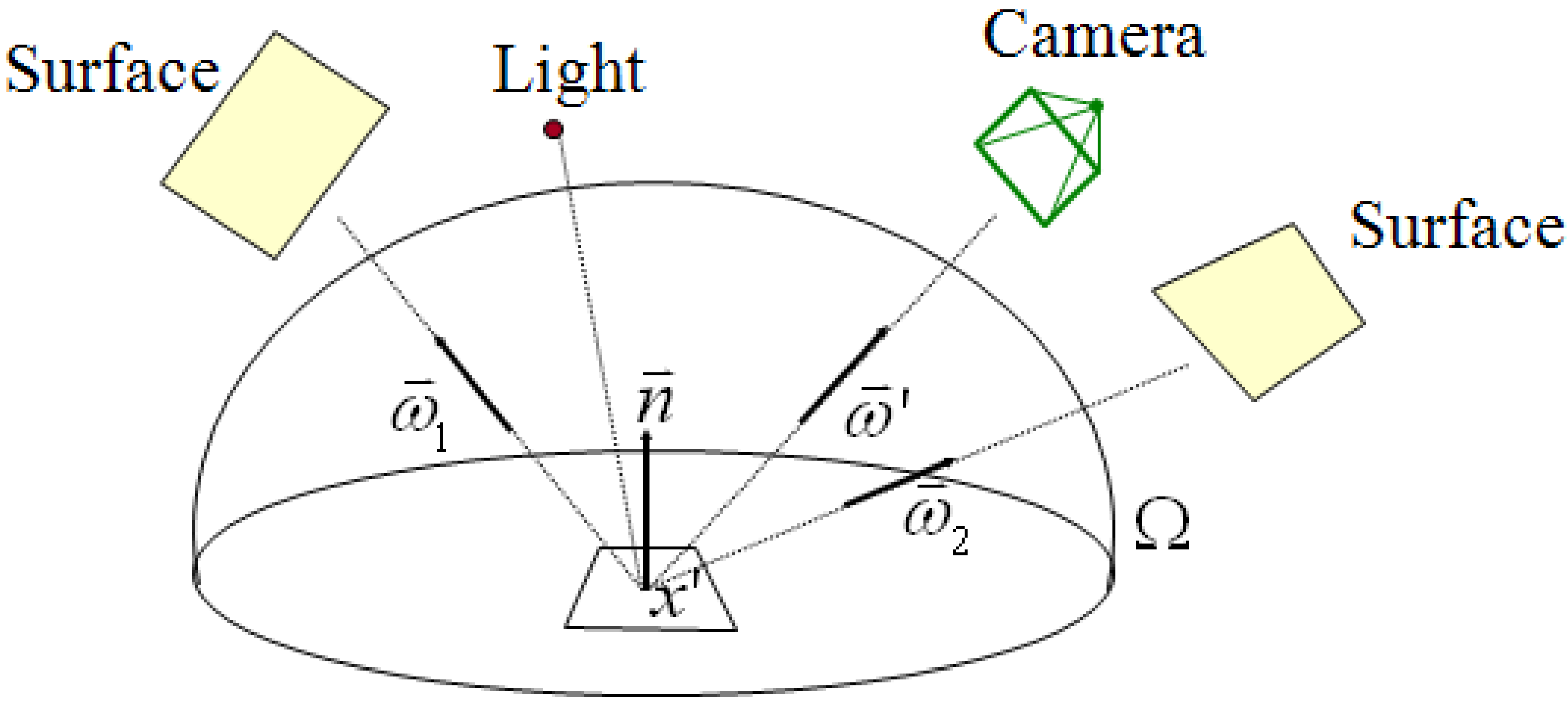
- Provided as part of material with scene description

Outgoing radiance and incoming irradiance are proportional to one another:

$$dL_o(\vec{\omega}_o) \propto dE_i(\vec{\omega}_i)$$

Rendering Equation (1) … Again

Compute radiance in outgoing direction by integrating reflections over all incoming directions

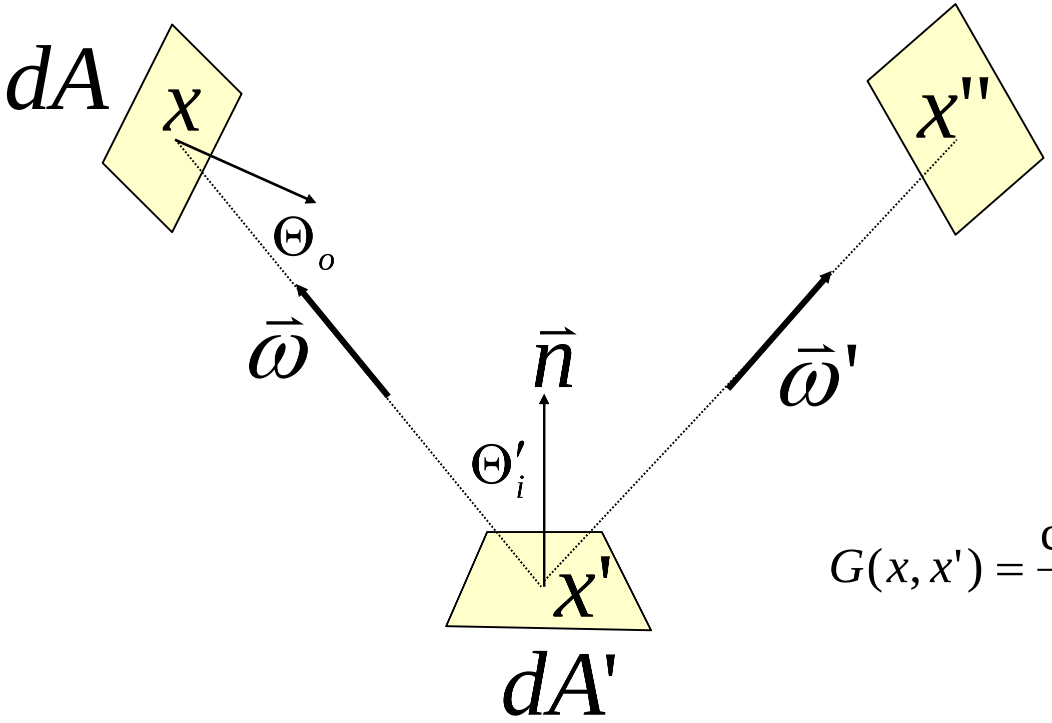


$$L_o(x',\bar{\omega}') = L_e(x',\bar{\omega}') + \int_{\Omega} f_r(x',\bar{\omega},\bar{\omega}')L_i(x',\bar{\omega})(\bar{\omega} \bullet \bar{n})d\bar{\omega}$$

Rendering Equation (2)

Kajiya 1986

Compute radiance in outgoing direction by integrating reflections of light from other surfaces

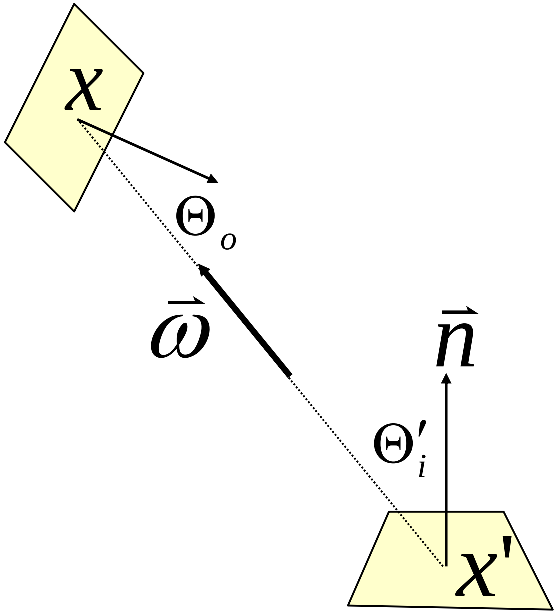


$$G(x,x') = \frac{\cos\Theta_i' \cos\Theta_o}{\|x - x'\|^2}$$

$$L(x' \to x'') = L_e(x' \to x'') + \int_S f_r(x \to x' \to x'') L(x \to x') V(x,x') G(x,x') dA$$

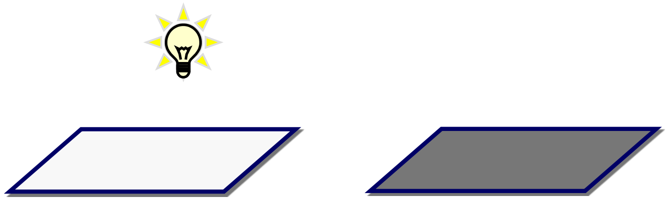
What is V(x,x’)G(x, x’)?

Irradiance at x in direction $\vec{\omega}$ as a fraction of radiance leaving x’ in direction $\vec{\omega}$

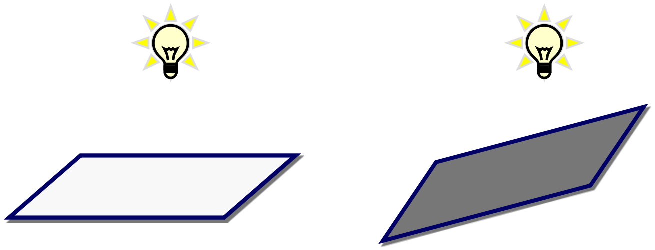


$$G(x,x') = \frac{\cos\Theta_i' \cos\Theta_o}{\left\|x - x'\right\|^2}$$

Move surface away from light:
Inverse square law: E ~ 1/r^2



Tilt surface away from light:
Cosine law: E ~ $\mathbf{n} \cdot \mathbf{l}$



Outline

Rendering equation

- Explanation of terms

➢ Solution methods

- Direct illumination
- Recursive ray tracing
- Distribution ray tracing
- Path tracing
- Photon Mapping
- Radiosity
- etc.

Outline

Rendering equation

- Rendering is integration

Solution methods

- ➢ Direct illumination
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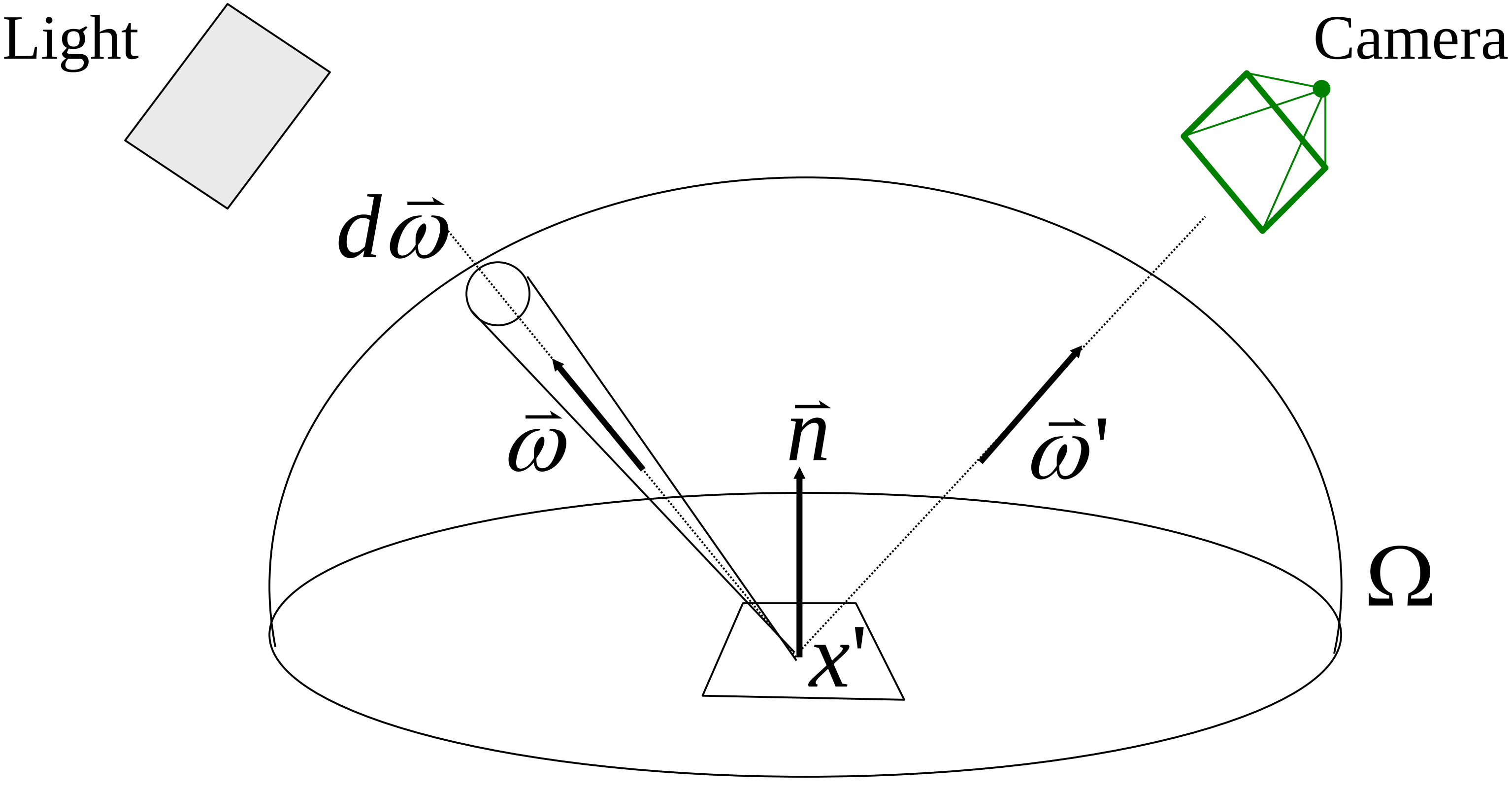
Direct Illumination

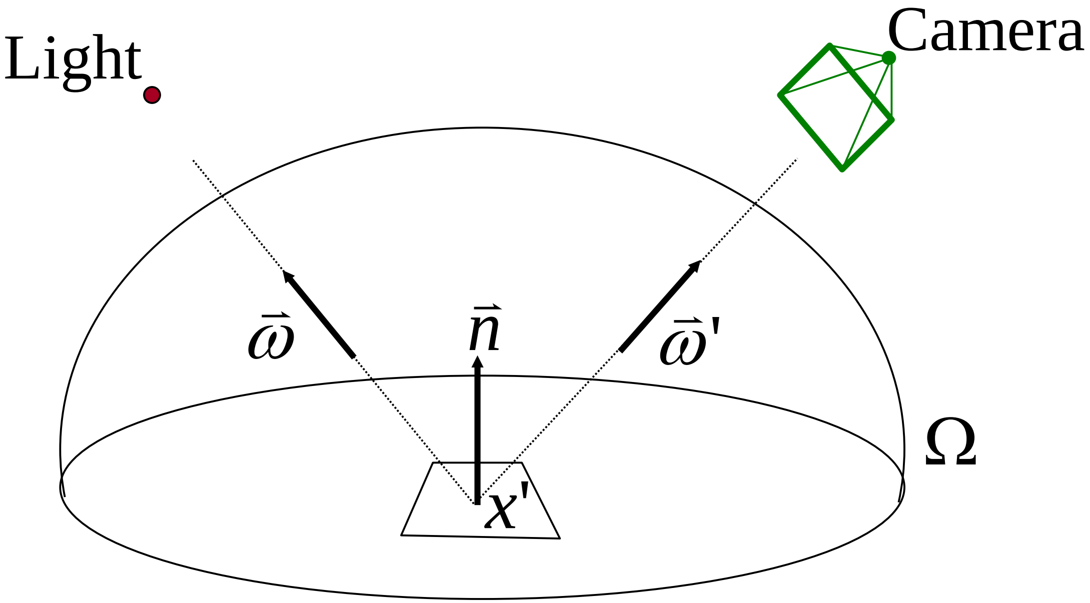
$$L_o(x',\vec{\omega}') = L_e(x',\vec{\omega}') + \int_{\Omega_L} f_r(x',\vec{\omega},\vec{\omega}') L_i(x',\vec{\omega})(\vec{\omega}\bullet\vec{n})\,d\vec{\omega}$$



OpenGL

$$L_o(x',\vec{\omega}') = L_e(x',\vec{\omega}') + \int_{\Omega} f_r(x',\vec{\omega},\vec{\omega}')L_i(x',\vec{\omega})(\vec{\omega}\bullet\vec{n})d\vec{\omega}$$

Assume direct illumination from point lights and ignore visibility



$$L_o(x',\vec{\omega}') = L_e(x',\vec{\omega}') + \sum_{i=1}^{nlights} f_r(x',\vec{\omega},\vec{\omega}')L_i(x',\vec{\omega})(\vec{\omega}\bullet\vec{n})$$

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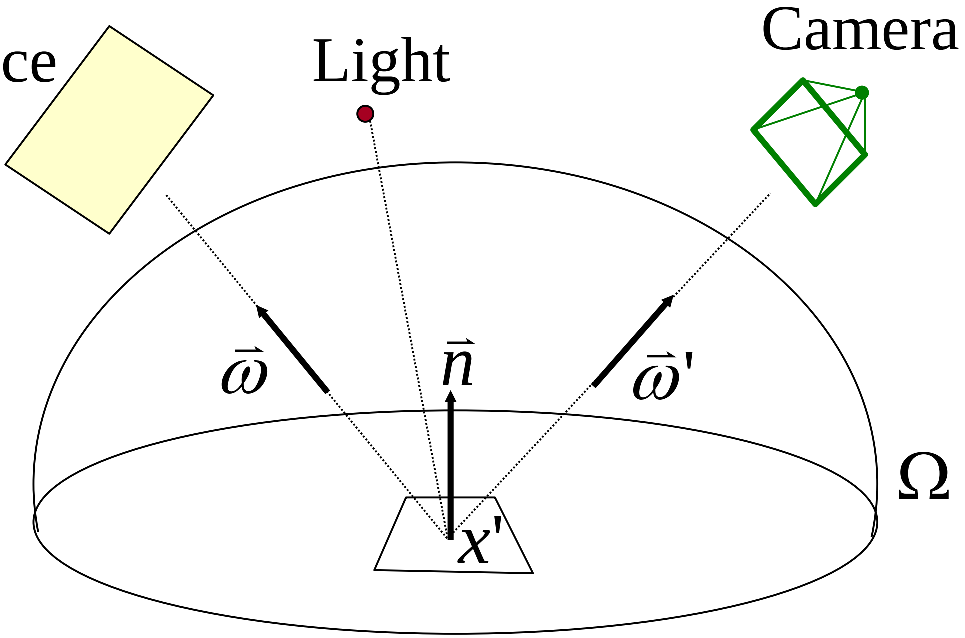
Recursive Ray Tracing

$$L_o(x',\vec{\omega}') = L_e(x',\vec{\omega}') + \int_{\Omega} f_r(x',\vec{\omega},\vec{\omega}')L_i(x',\vec{\omega})(\vec{\omega}\bullet\vec{n})d\vec{\omega}$$



Assume only significant indirect illumination due to perfect specular reflection and refraction

$$L_o(x',\vec{\omega}') = L_e(x',\vec{\omega}') + \sum_{i=1}^{nlights} f_r(x',\vec{\omega},\vec{\omega}')L_i(x',\vec{\omega})(\vec{\omega}\bullet\vec{n}) + specular$$

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- Direct illumination
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- ➢ Distribution ray tracing
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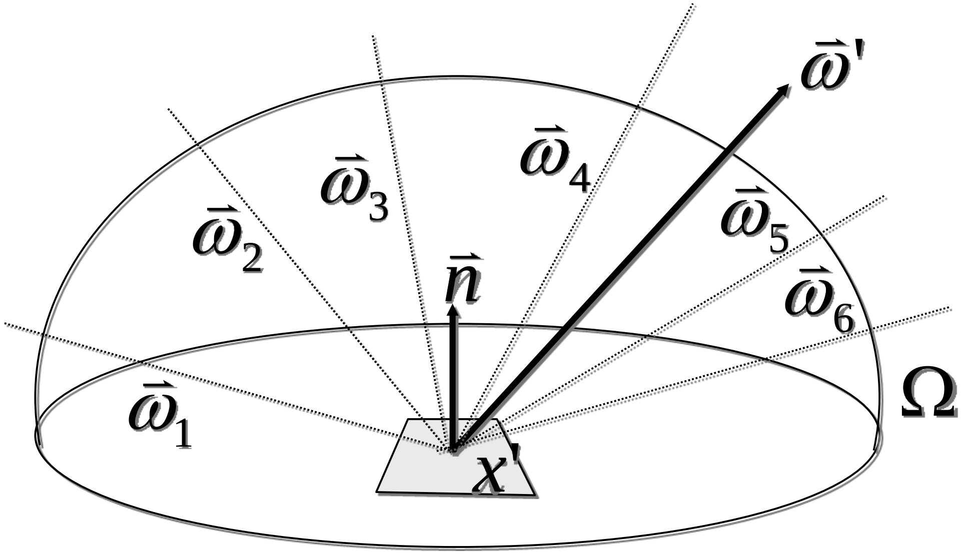
Distribution Ray Tracing

$$L_o(x',\vec{\omega}') = L_e(x',\vec{\omega}') + \int_{\Omega} f_r(x',\vec{\omega},\vec{\omega}')L_i(x',\vec{\omega})(\vec{\omega} \bullet \vec{n})d\vec{\omega}$$

Estimate integral
for each reflection
by random sampling



Also:

- Depth of field
- Motion blur
- etc.

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Rendering equation

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- Direct illumination
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- ➢Path tracing
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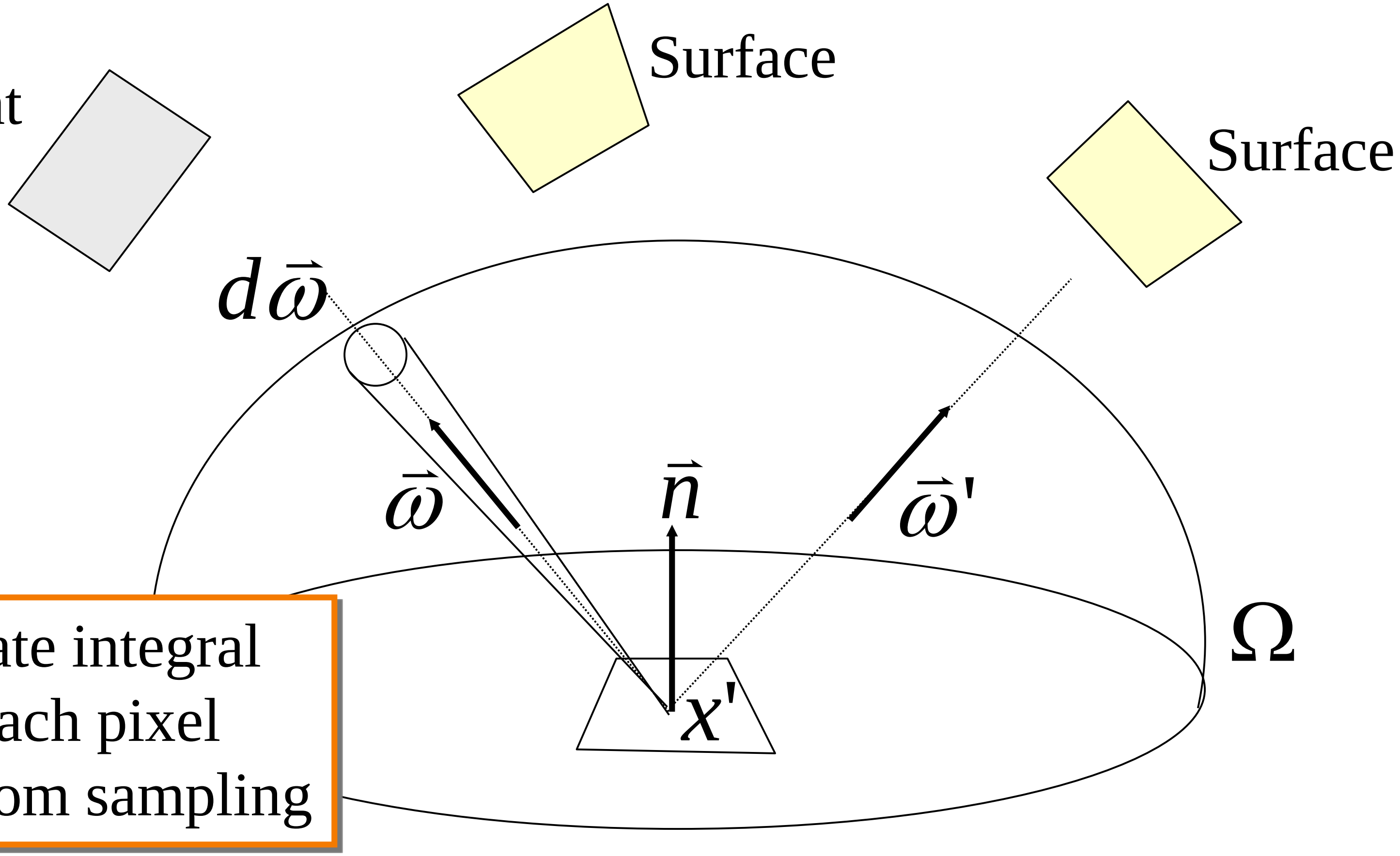
Path Tracing

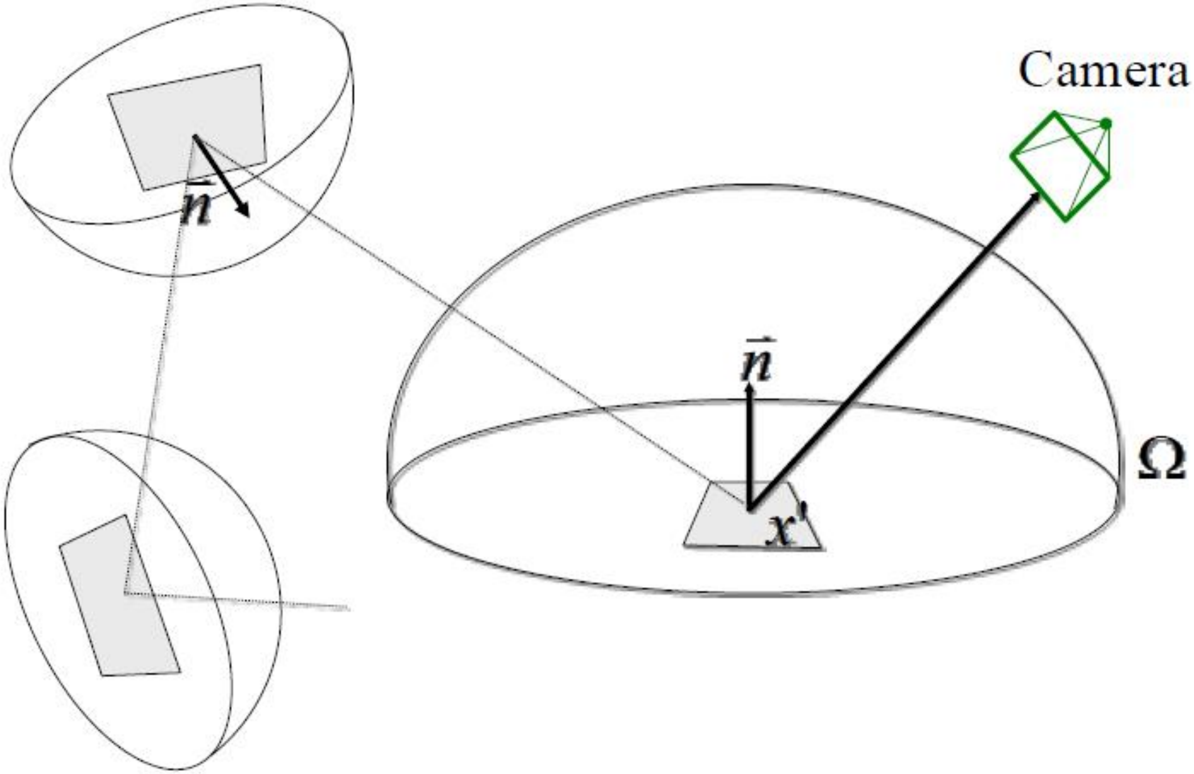
$$L_o(x',\vec{\omega}') = L_e(x',\vec{\omega}') + \int_{\Omega} f_r(x',\vec{\omega},\vec{\omega}')L_i(x',\vec{\omega})(\vec{\omega}\bullet\vec{n})d\vec{\omega}$$



Estimate integral
for each pixel
by random sampling

Path Tracing

Estimate integral for each pixel by sampling paths from the camera



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Rendering equation

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Photon Mapping

Two pass method:

1. Build photon map by tracing paths from lights
2. Render image by tracing paths from camera

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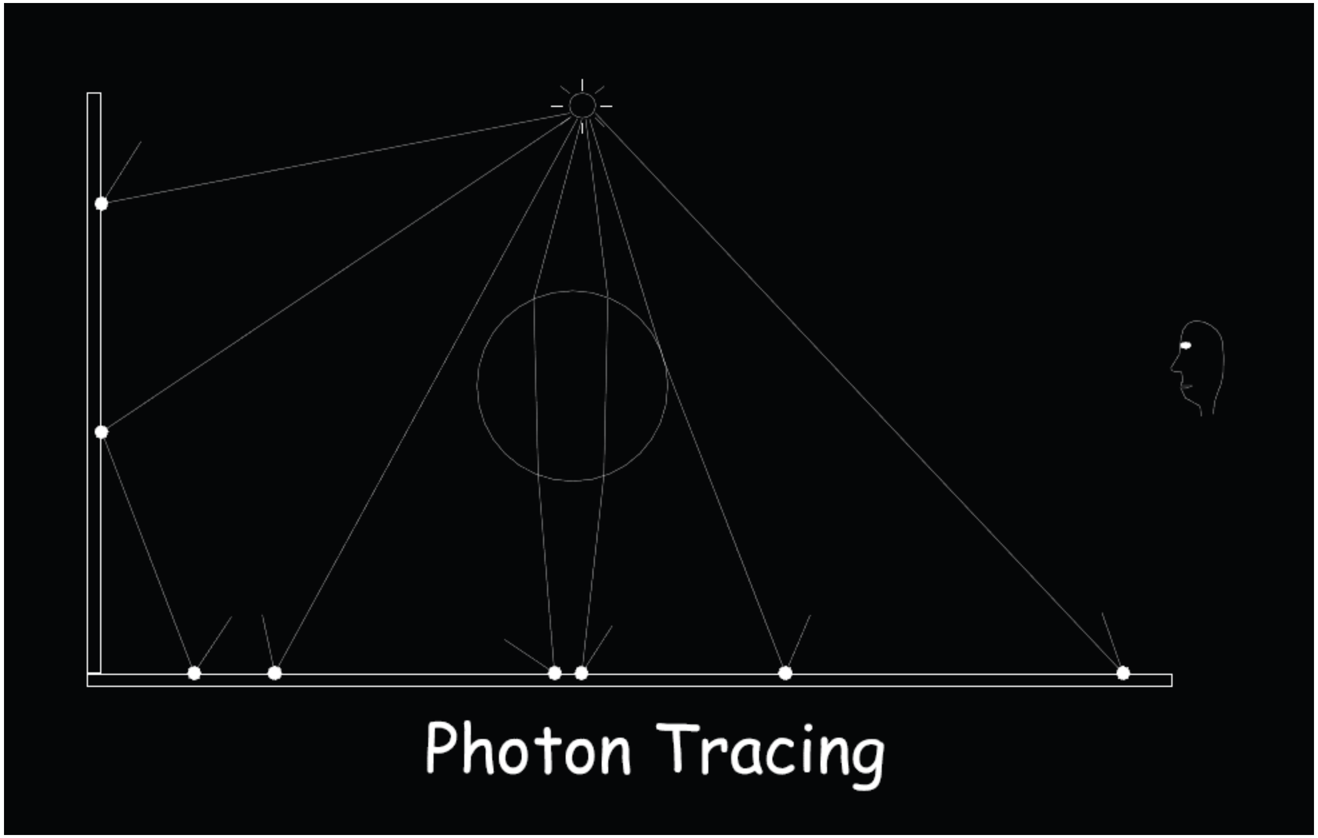
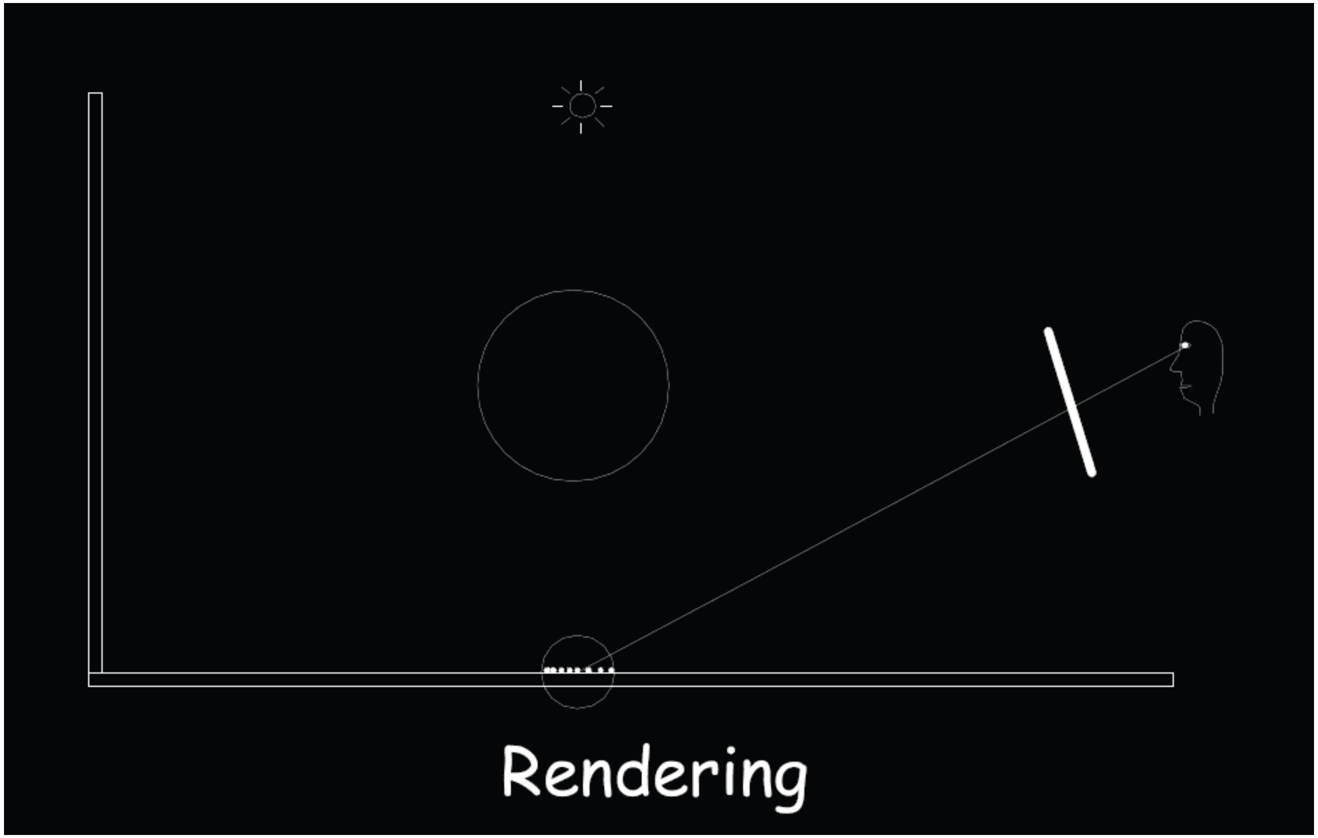


Photon Mapping

Two pass method:

1. Build photon map by tracing paths from lights
2. Render image by tracing paths from camera



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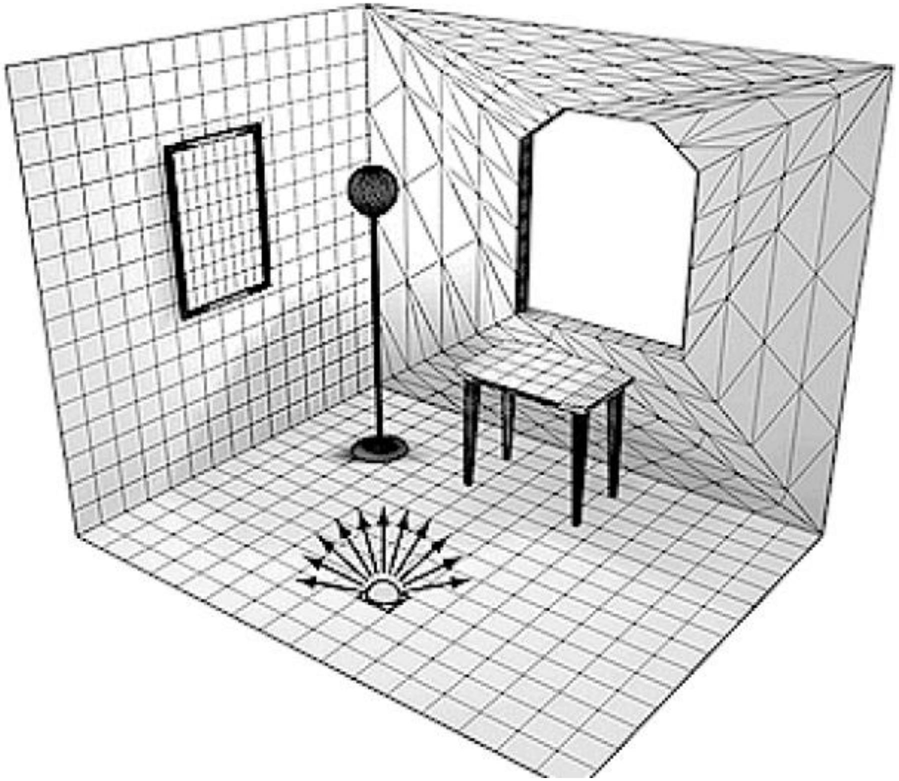
Radiosity

Discretize surfaces into small patches

Baum

Radiosity

Assume simple function (constant) is good approximation for radiosity (sum of all energy leaving a point) within a patch



Thadani

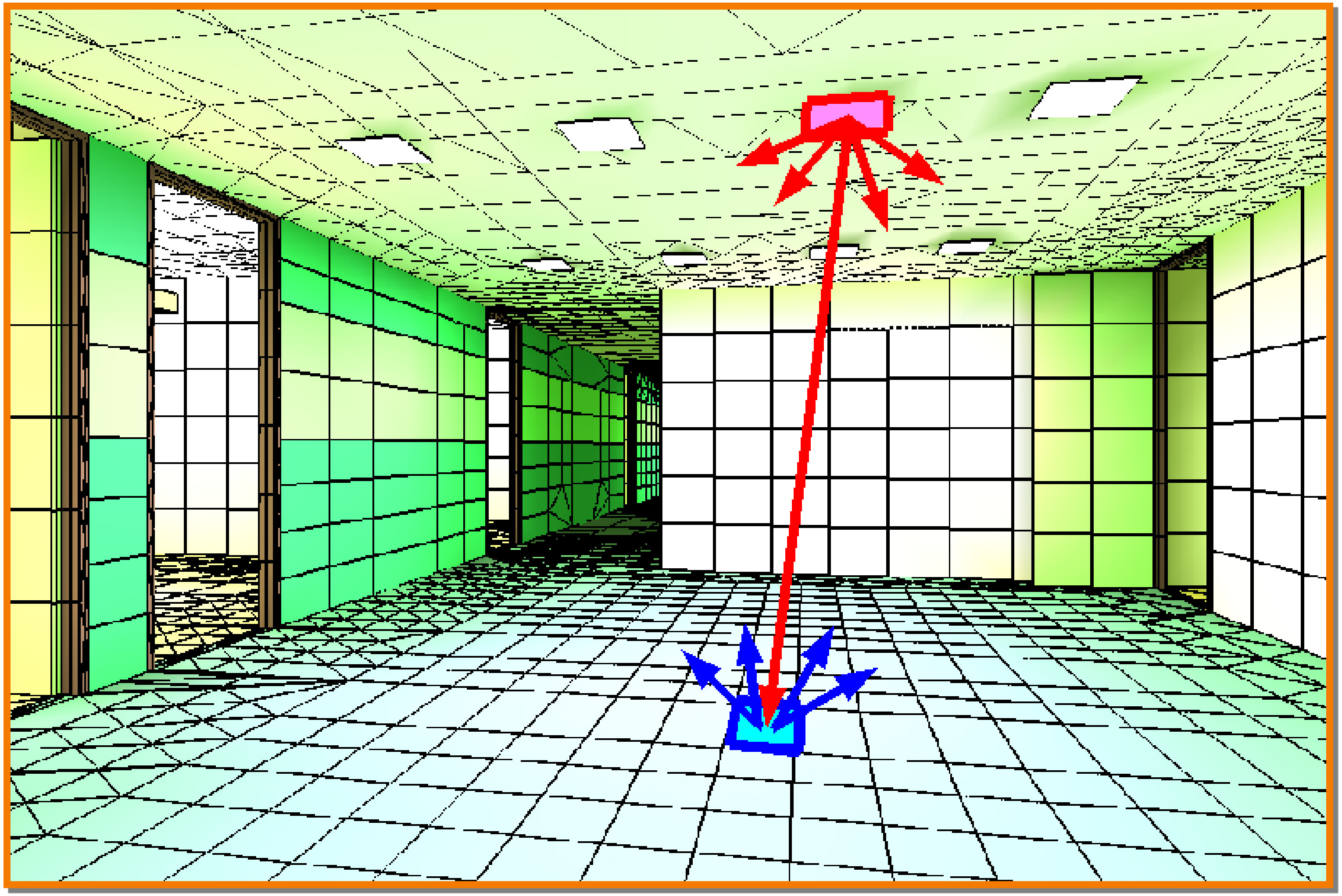
Radiosity

Leads to sparse linear system of equations

$$B_i A_i = E_i A_i + \rho_i \sum_{j=1}^{N} F_{ji} B_j A_j$$

$$\begin{bmatrix} 1-\rho_1 F_{1,1} & . & . & . & -\rho_1 F_{1,n} \\ -\rho_2 F_{2,1} & 1-\rho_2 F_{2,2} & . & . & -\rho_2 F_{2,n} \\ . & . & . & . & . \\ . & . & . & . & . \\ -\rho_{n-1} F_{n-1,1} & . & . & . & -\rho_{n-1} F_{n-1,n} \\ -\rho_n F_{n,1} & . & . & . & 1-\rho_n F_{n,n} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ . \\ . \\ . \\ B_n \end{bmatrix} = \begin{bmatrix} E_1 \\ E_2 \\ . \\ . \\ . \\ E_n \end{bmatrix}$$

Radiosity



Outline

Rendering equation

- Explanation of terms

Solution methods

- Direct illumination
- Recursive ray tracing
- Distribution ray tracing
- Path tracing
- Photon Mapping
- Radiosity
- etc.

Which method is best?

Summary

Rendering equation

- Rendering is integration

Different solution methods are best for different types of scenes (depending on path types)

- Direct illumination - LDE
- Recursive ray tracing - LDS*E
- Distribution ray tracing – L(SD)*E
- Path tracing– L(SD)*E
- Photon Mapping– L(SD)*E (biased)
- Radiosity – LD*E
- etc.

Radiometric and Photometric Units

Radiant energy Joule (J)	Luminous energy Talbot
Radiant flux or power (F) Watt (W) = J / sec	Luminous power Lumen (lm) = talbot / sec = cd · sr
Radiant intensity (I) W / sr	Luminous intensity Candela (cd)
Irradiance (E) W / m^2	Illuminance Lux = lm / m^2
Radiance (L) W / m^2 / sr	Luminance Nit = lm / m^2 / sr
Radiosity (B) W / m^2	Luminosity Lux = lm / m^2