Ray Tracing in Entertainment Industry

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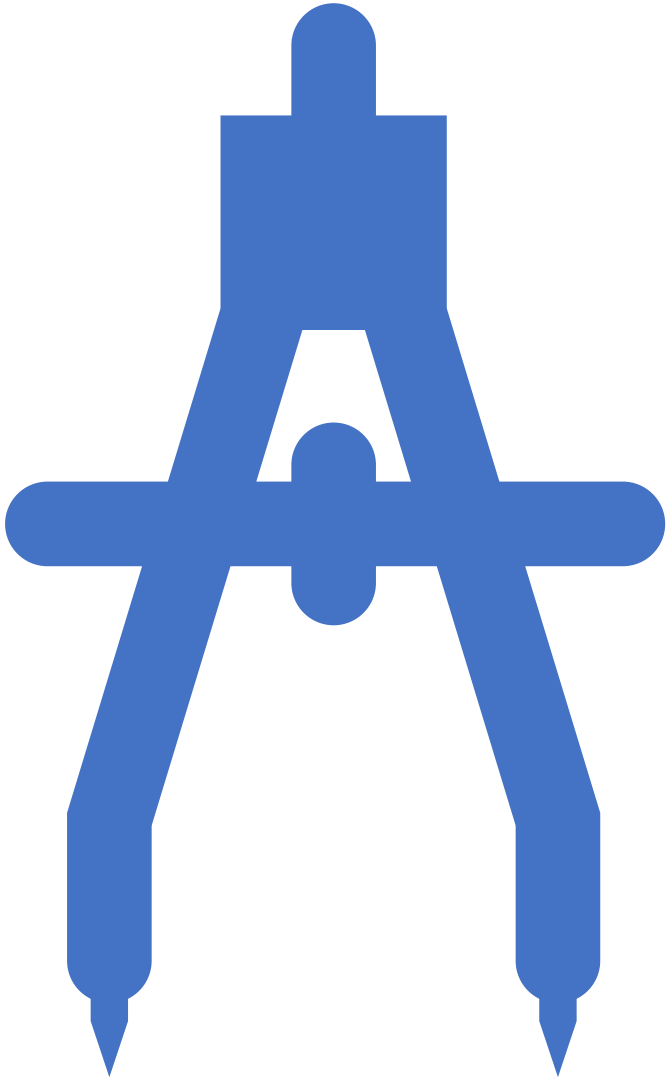
Week 1

Course outline

- First half
  - Week 1 - Ray tracing overview
  - Week 2 - Ray tracing components
  - Week 3 - Image formation and rays
  - Week 4 - Basic shapes and intersections
  - Week 5 - Lighting and shadows
  - Week 6 - Geometric optics
  - Week 7 – Texture and reflection models



Course outline

- Second half
  - Week 8 – Reflection models and indirect illuminations
  - Week 9 - Sampling techniques and reconstruction
  - Week 10 - Simple visual effects
  - Week 11 - Path tracing and Monte Carlo sampling
  - Week 12 - Variance reduction
  - Week 13 - Reflectance measurement
  - Week 14,15 - Advanced techniques in photo-realistic image synthesis

Course materials

- Reading
  - Ray Tracing in One Weekend Series - raytracing.github.io – codes available
  - Lecture notes from https://ocw.mit.edu/courses/6-837-computer-graphics-fall-2012/pages/lecture-notes/
  - Introduction to Real-Time Ray Tracing (realtimerendering.com) - http://rtintro.realtimerendering.com/
  - Physically Based Rendering: From Theory to Implementation (pbr-book.org)
  - Ray tracing gem - www.realtimerendering.com/raytracinggems/
  - Data-driven approaches for sparse reflectance modeling and acquisition, Ph.d. thesis
- Watching
  - Introduction to Ray tracing (Siggraph Frontier course)
    - Videos - https://youtube.com/playlist?list=PLUPhVMQuDB_a7ODdVCKj3C6-63PCE6ekm&si=qB2KTD6KolS15Tbq
    - Slides - https://drive.google.com/drive/folders/11cQDkO0fPLakZO0WaK2zrhxzUxm7F_e2

Grading

- Participation – 10%
  - Presence in class
  - Being able to discuss
- Assignment – 40%
  - 8 class assignments
  - Submit before the next lecture
- Presentation – 20 %
- Project – 30%
  - Submit 2 rendered scenes
  - Resolution : width 3840 pixels
  - Aspect ratio : 16 : 9
  - Submission – 5% each
  - Good work – 5% each
  - Scene complexity and/or special effects – 2.5% each
  - New feature (not shown in the teaching codes) – 2.5% each

Course schedule

- Lecture hour
  - Thursday, 10.00 – 13.00
  - Room 704
- Midterm
  - No
- Final
  - No

Week 1 – Ray tracing overview

- Photo-realistic image synthesis
- Light transport problem
- Radiometry
- Rendering equation

Photo-realistic image synthesis

- Alternative terminlogy
  - Photo-realistic image generation
  - Realistic image synthesis
  - Physically-based image synthesis
  - Synthetic image generation

- Definition of “Photo-realistic image synthesis” : A computer-generated algorithm aiming to produce synthetic images that are indistinguishable from photographs.

Applications of Photo-realistic image synthesis

Applicable to various industries that require

- 3D digital contents
- Immersive experience
- Product visualization, simulation

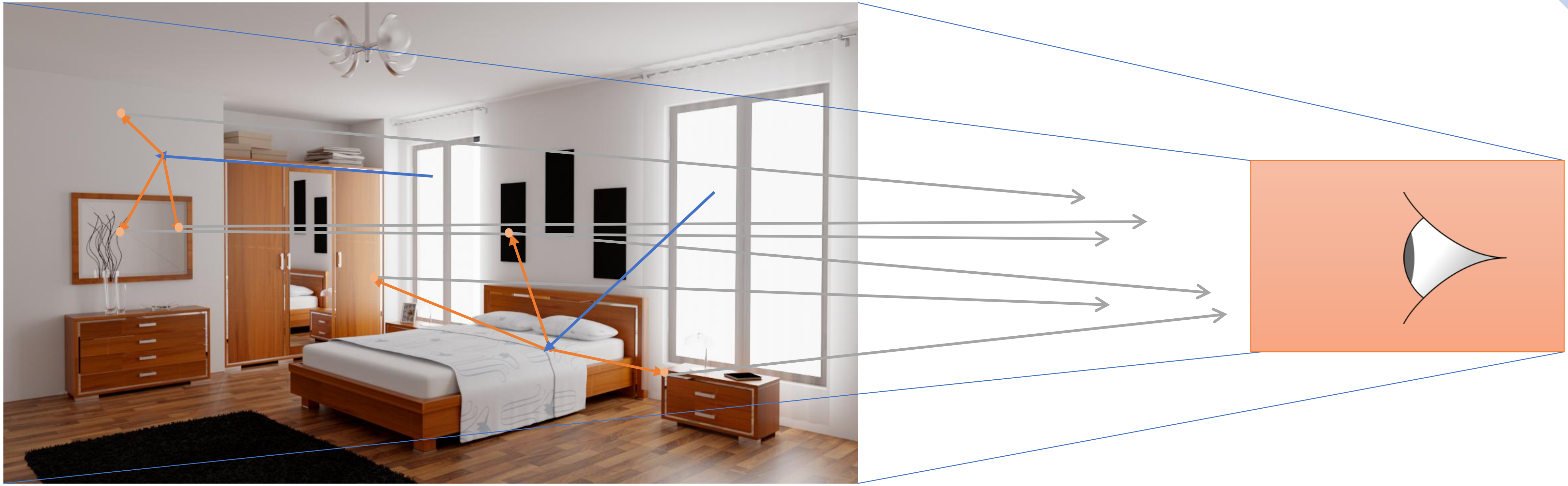
Examples …

- Movies and Films
- VR games
- Furniture catalog

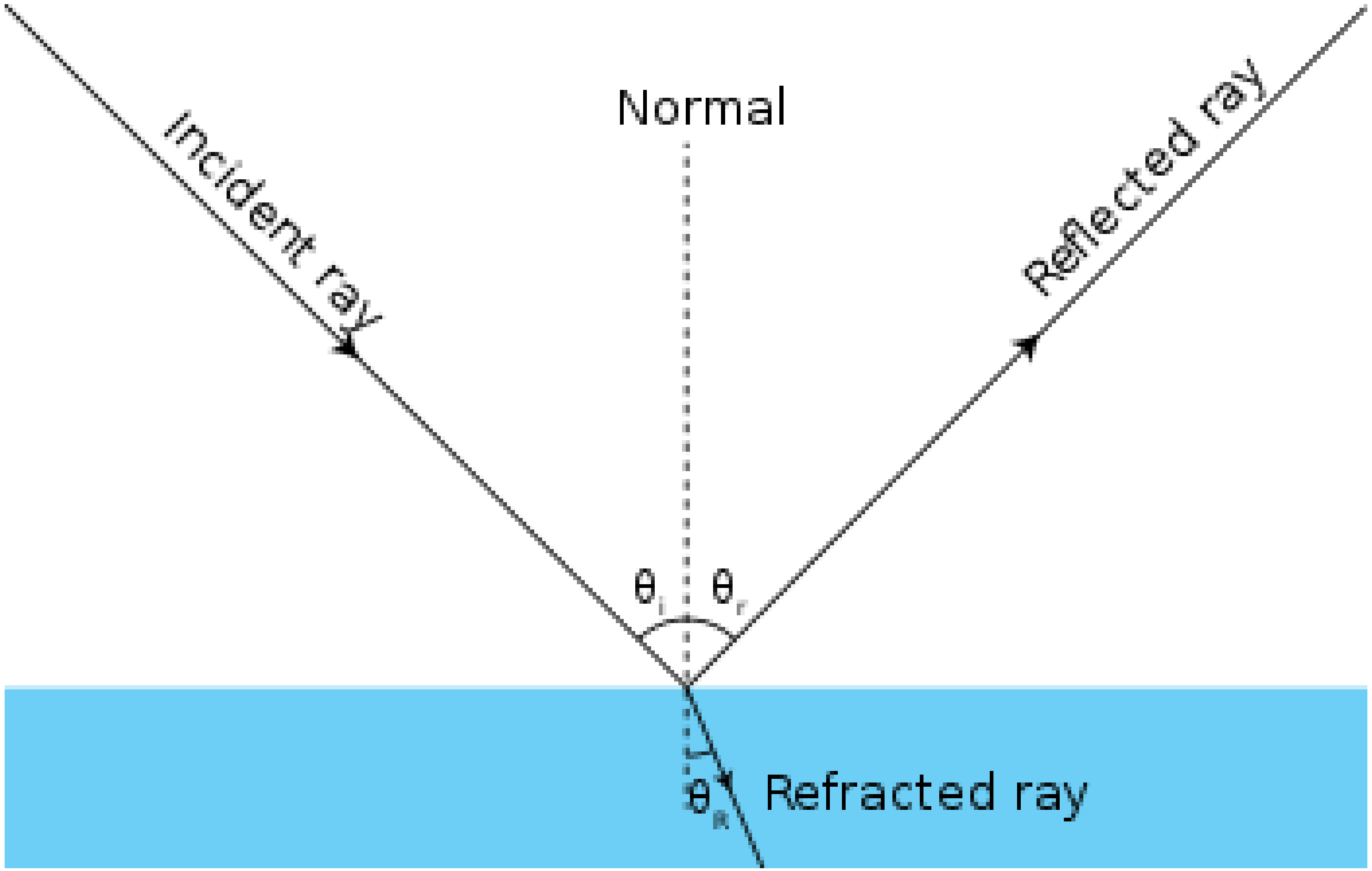
What problem are we going to solve for the photo-realistic image synthesis ?

- Light transport problem
  - We seek to solve the light transport problem that given a scene at a particular time we would like to find the equilibrium of photons (radiance) in the scene.
  - Photons contributed to the given scene is the solution of the light transport problem.
  - Light can be modelled by following :
    - Geometric optics
    - Wave optics
    - Quantum optics

Light scattering around environment before reaching our eyes.



Light scattering with "Geometric optics"



Retrieved from https://en.wikipedia.org/wiki/Ray_%28optics%29.

Wave optics

Interference

White light interference in a soap bubble.
(https://en.wikipedia.org/wiki/Wave_interference)

https://studiousguy.com/light-interference-examples/

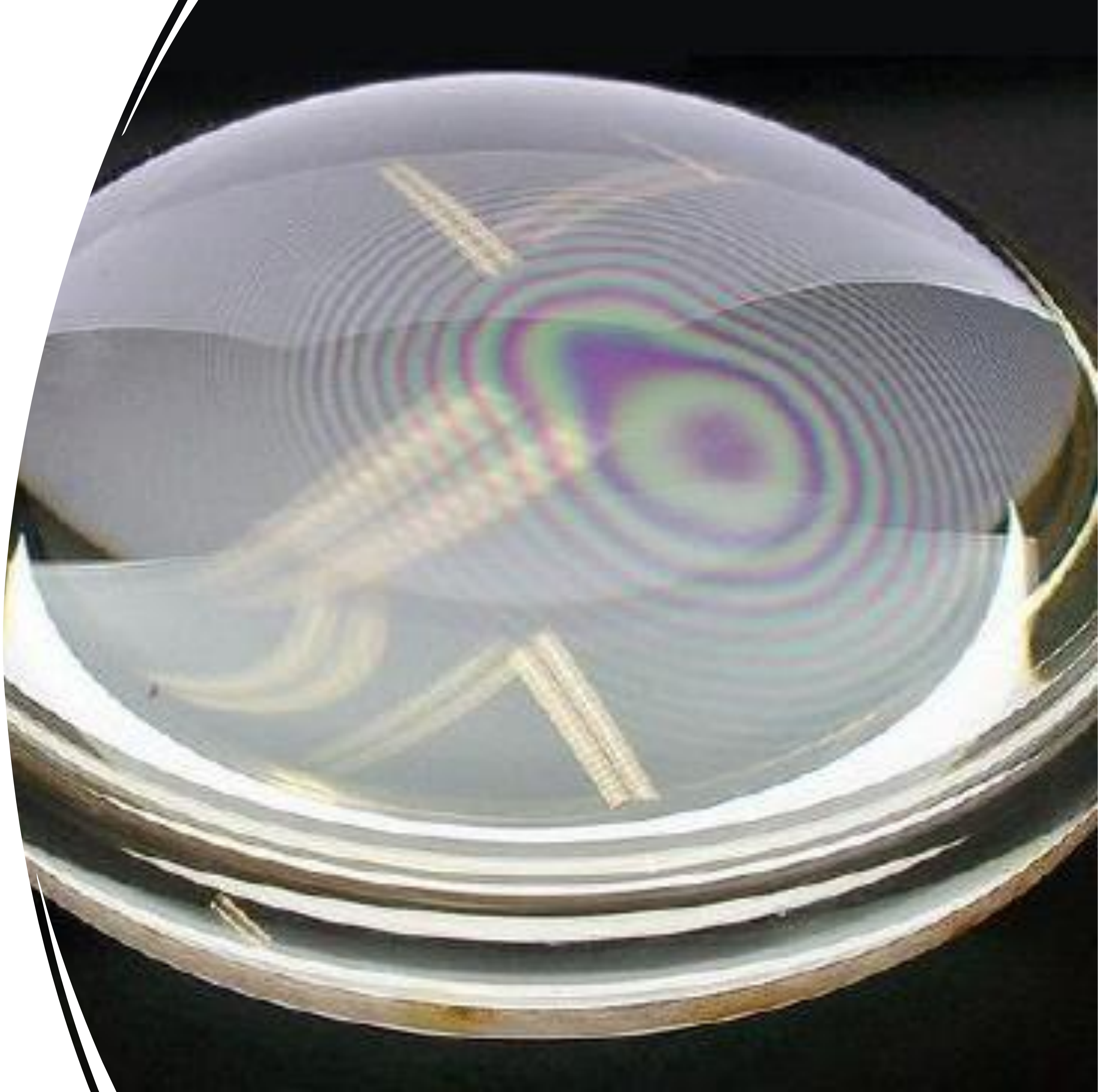
Diffraction

Data is written on CDs as pits and lands; the pits on the surface act as diffracting elements. (https://en.wikipedia.org/wiki/Diffraction)

https://studiousguy.com/diffraction-examples/

Interference (Physics)

- **Newton's Rings in a drop of water:** Newton's rings seen in two plano-convex lenses with their flat surfaces in contact. One surface is slightly convex, creating the rings. In white light, the rings are rainbow-colored, because the different wavelengths of each color interfere at different locations.



LibreTexts, Physics, Lesson 26.1: Superpositioon and Interference, https://phys.libretexts.org/Bookshelves/University_Physics/Physics_(Boundless)/26%3A_Wave_Optics/26.1%3A_Superposition_and_Interference. Accessed Nov 2025.

Diffraction (Physics)

- Readable Surface of a CD: The readable surface of a Compact Disc includes a spiral track wound tightly enough to cause light to diffract into a full visible spectrum.

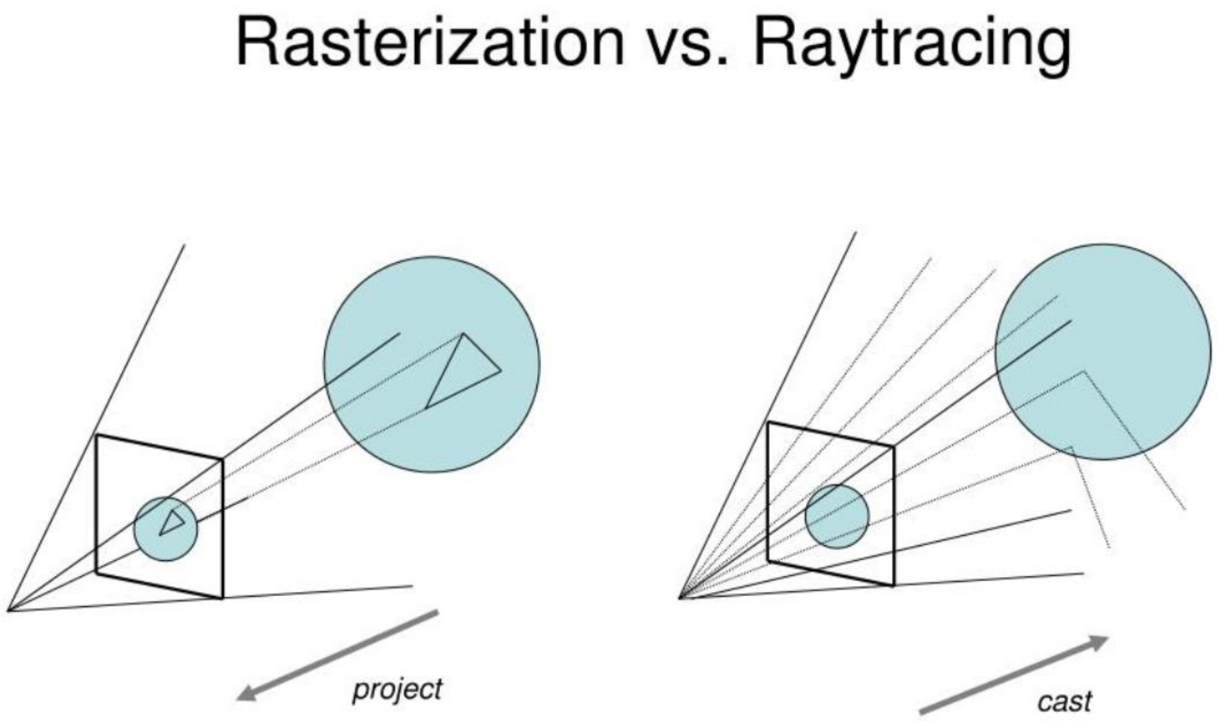
LibreTexts, Physics, Lesson 26.2: Diffraction, https://phys.libretexts.org/Bookshelves/University_Physics/Physics_(Boundless)/26%3A_Wave_Optics/26.2%3A_Diffraction. Accessed Nov 2025.

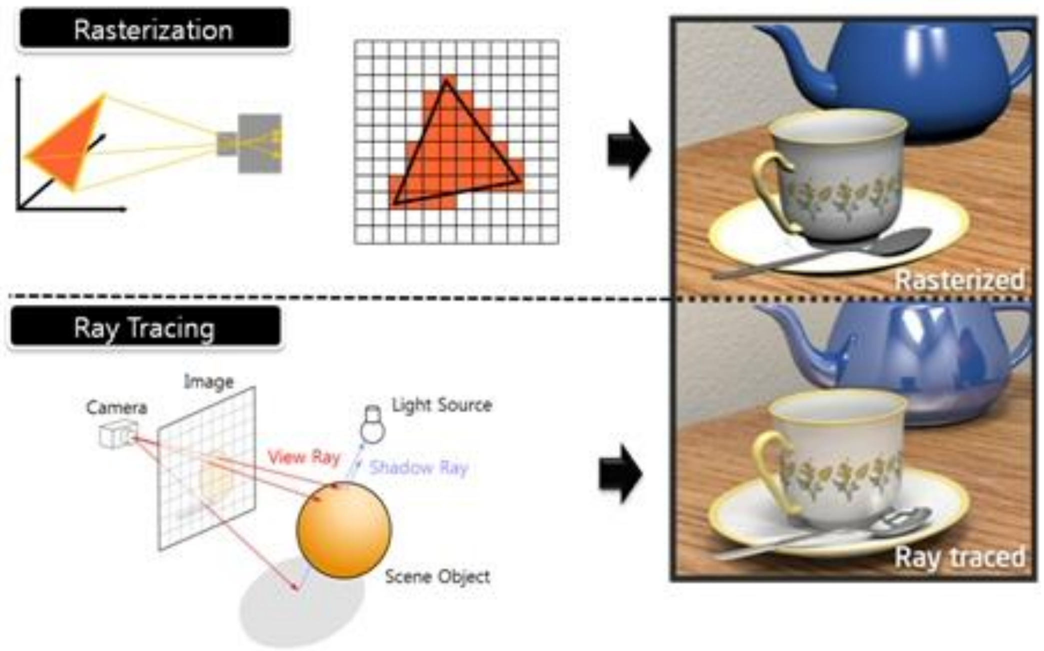
Solutions to solving the light transport problem

- Rasterization
  - https://en.wikipedia.org/wiki/Reyes_rendering
  - Less memory and computations required
  - Physically-plausible rendering
  - Fast and high quality at the time
- Ray tracing
- Radiosity
- Photon mapping

These algorithms are categorized as "Global Illumination".

Comparisons

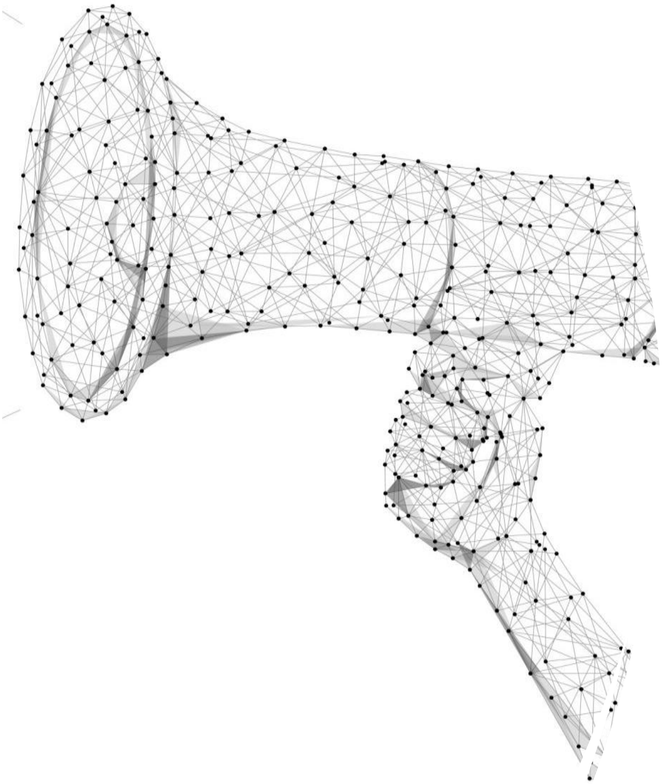




Rasterization projects objects onto the image plane while Raytracing casts multiple rays to objects.

https://www.pixelsham.com/2019/10/24/whats-the-difference-between-ray-tracing-and-rasterization/

Ray Tracing Essentials Part 2: Rasterization versus Ray Tracing

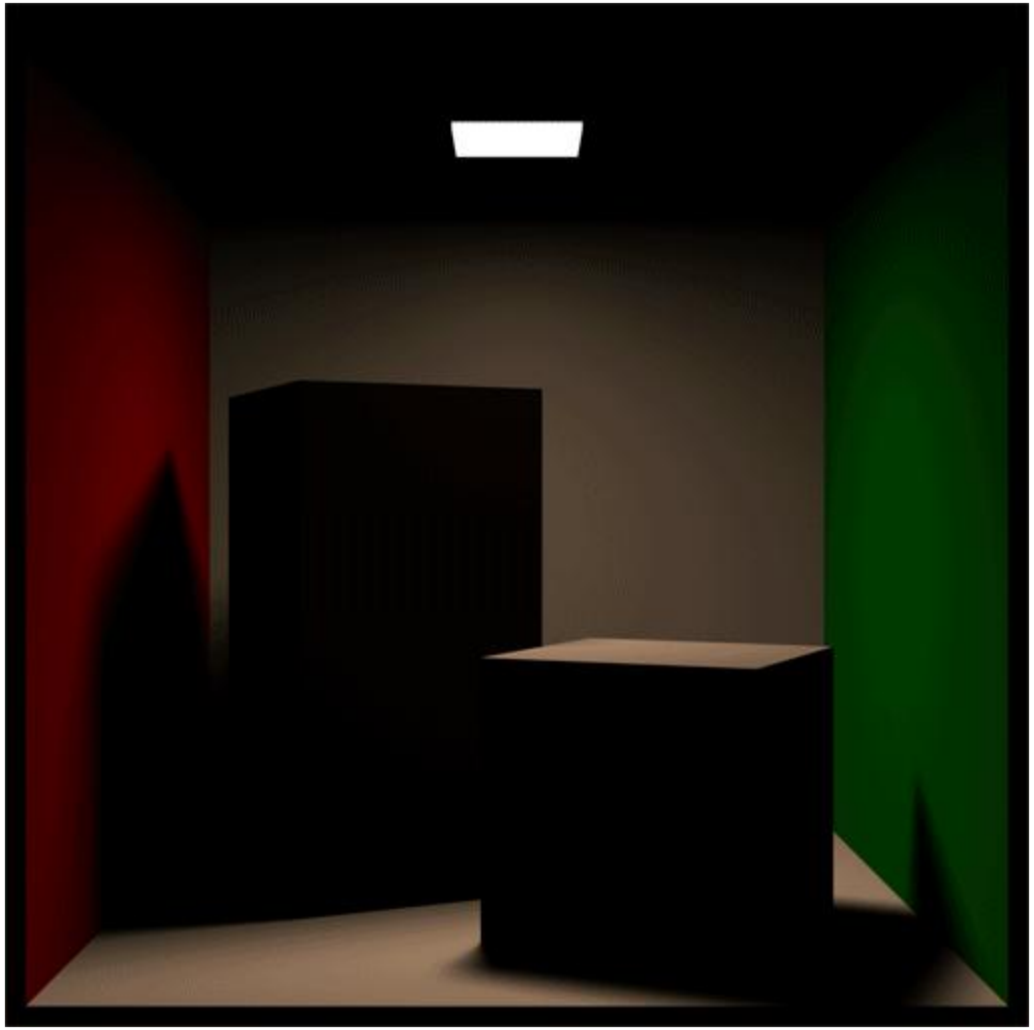


Rasterization and Ray Tracing

Key Concept	Rasterization	Ray Tracing
Fundamental question	What pixels does geometry cover?	What is visible along this ray?
Key operation	Test if pixel is inside triangle	Ray-triangle intersection
How streaming works	Stream triangles (each tests pixels)	Stream rays (each tests intersections)
Inefficiencies	Shade many tris per pixel (overdraw)	Test many intersections per ray
Acceleration structure	(Hierarchical) Z-buffering	Bounding volume hierarchies
Drawbacks	Incoherent queries difficult to make	Traverses memory incoherently

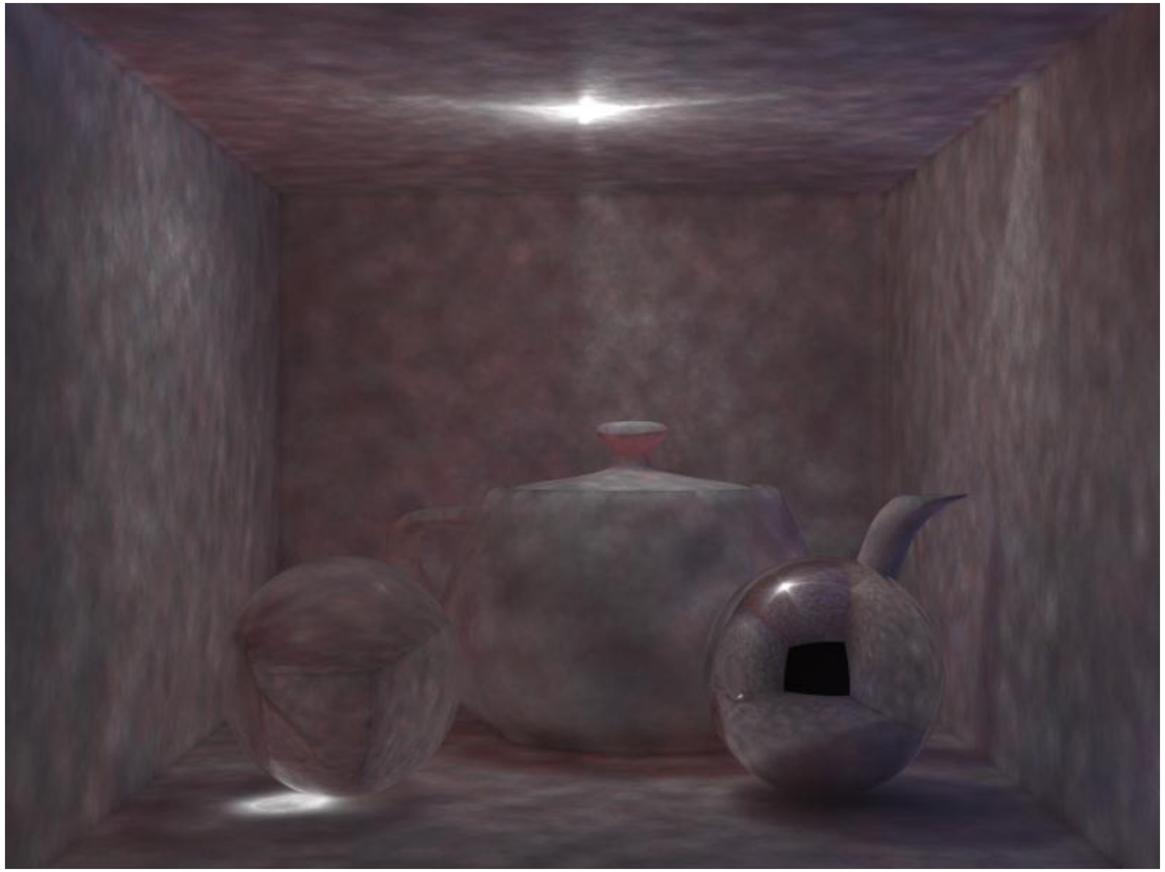
Table from www.youtube.com/watch?v=ynCxnR1i0QY.

Radiosity



A cornel box image rendered by using Radiosity.
Image from https://iwantthatcake.wordpress.com/2012/02/22/real-time-radiosity-geometrics-enlighten/

Photon mapping



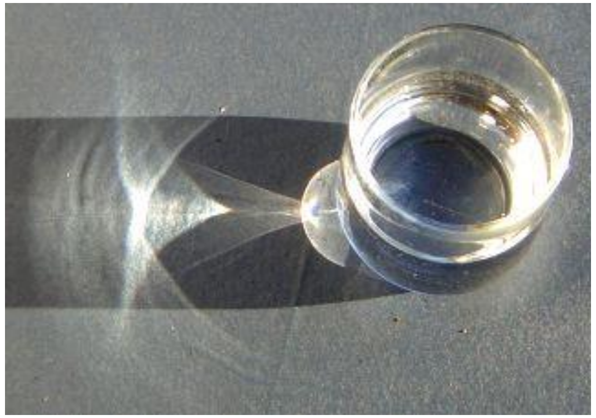
First pass : photons are deposited throughout the entire scene by precomputation.

Second pass : The scene is rendered by raytracing technique using precomputed photons.

http://sci.utah.edu/~mavinm/school/cs6620/index.php?prj=13

Global Illumination

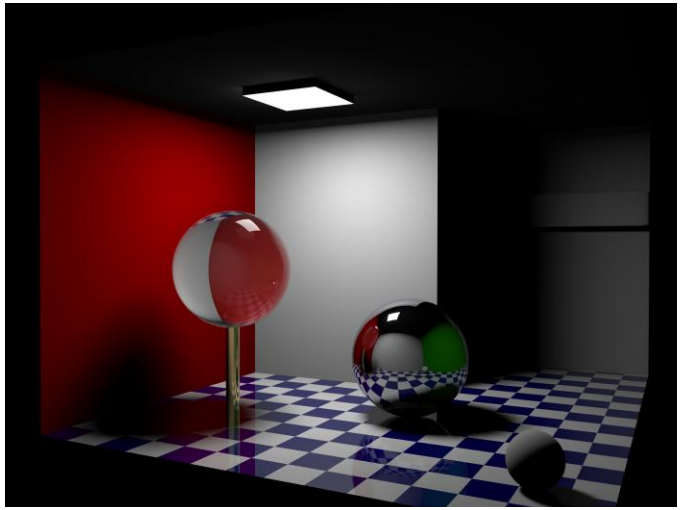
- Definition
  - Global illumination is the process of computing the color and quantity of all light — both direct and indirect — that is on visible surfaces in a scene.[1]
- Indirect illumination solves the following phenomenon :
  - Inter reflection, color bleeding
  - Soft shadows
  - Caustic effects
  - Etc. ?

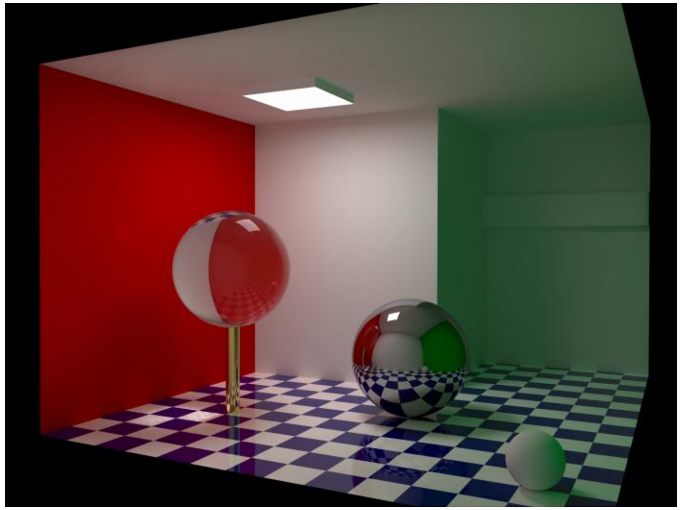


[1] https://blogs.nvidia.com/blog/2022/08/04/direct-indirect-lighting/

Global Illumination

- Global illumination is a key aspect to the realism of a 3D scene. Naive 3D lighting will only take into account direct light, meaning any light which radiates off a light source and bounces directly into the virtual camera. (https://en.wikipedia.org/wiki/Global_illumination)

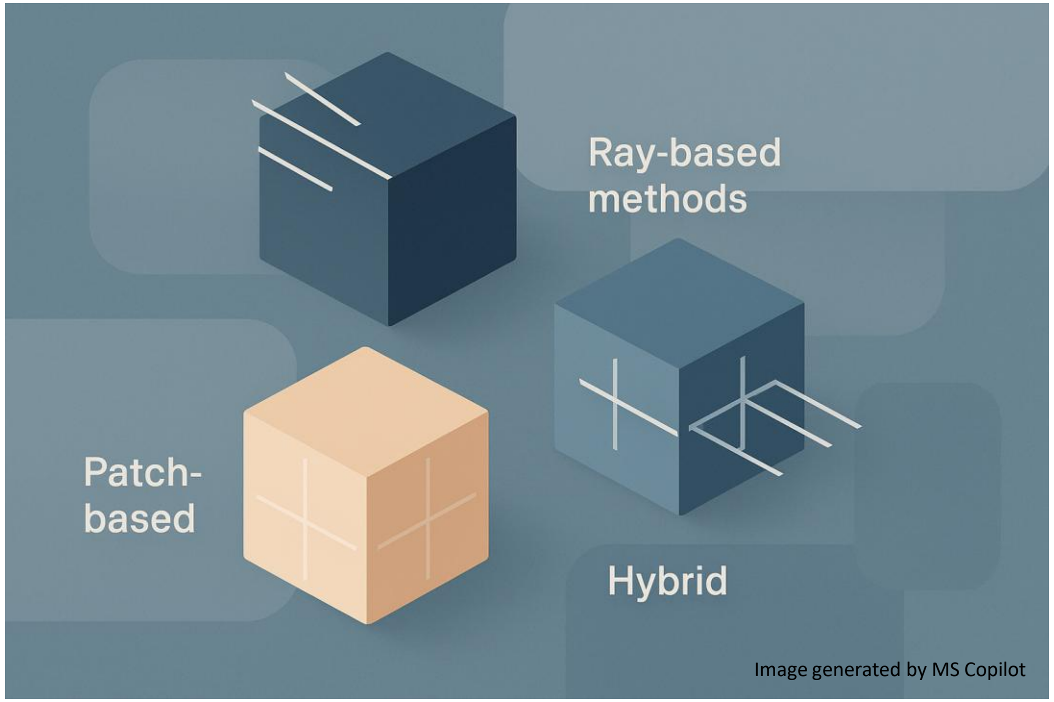




Which one is rendered by using a global illumination method ?

Global Illumination methods (classified by techniques)

- Ray-based methods (Monte Carlo methods)
- Patch-based methods (Finite element methods)
- Hybrid (Multi-pass methods)



Global Illumination methods (classified by estimators)

- Biased rendering
  - **Focuses on Speed and Visual Appeal -** Prioritizes rendering images quickly while achieving visually pleasing results.
  - **Uses Shortcuts -** Employs optimizations and algorithms to accelerate the rendering process. These shortcuts might introduce slight inaccuracies in the final image compared to a perfect simulation of light.
  - **Good for Animations and Games -** Due to its speed, biased rendering is well-suited for creating animations and real-time graphics in games.
- Unbiased rendering
  - **Prioritizes Accuracy and Realism -** Aims to achieve the most physically accurate simulation of light possible, replicating how light interacts with surfaces in the real world.
  - **No Shortcuts -** Doesn't employ optimizations and calculates every light bounce to create a highly realistic image.
  - **Slower Rendering Times -** Because of the meticulous calculations, unbiased rendering can be significantly slower than biased rendering.

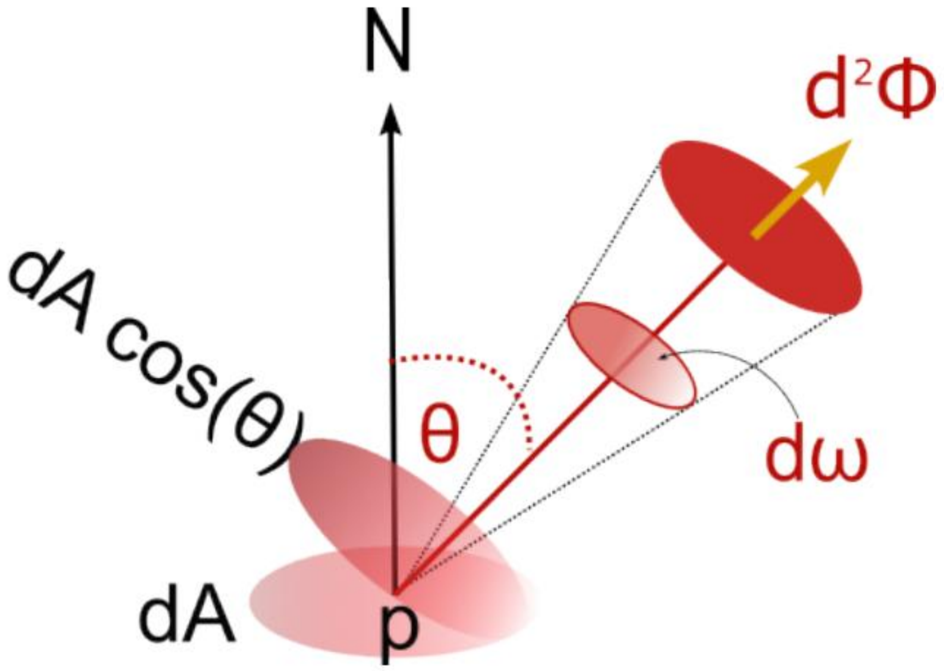
https://www.chaos.com/blog/the-truth-about-unbiased-rendering

Basic radiometry

Radiometric quantity	**Definition**	**Unit**
Radiant energy, Q	$\frac{h\ c}{\lambda}$	Joule (J)
Radiant flux, Φ	$\frac{dQ}{dt}$	$J \cdot s^{-1}$ or Watt (W)
Irradiance, E	$\frac{d\Phi}{dA}$	$W \cdot m^{-2}$
Intensity, I	$\frac{d\Phi}{d\omega}$	$W \cdot sr^{-1}$
Radiance, L	$\frac{d^2\Phi}{d\omega\ dA\ cos(\theta)}$	$W \cdot m^{-2} \cdot sr^{-1}$

Tongbuasirilai, T. (2023). Data-Driven Approaches for Sparse Reflectance Modeling and Acquisition (PhD dissertation, Linköping University Electronic Press). https://doi.org/10.3384/9789179295585

Radiometric quantities



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Rendering Equation

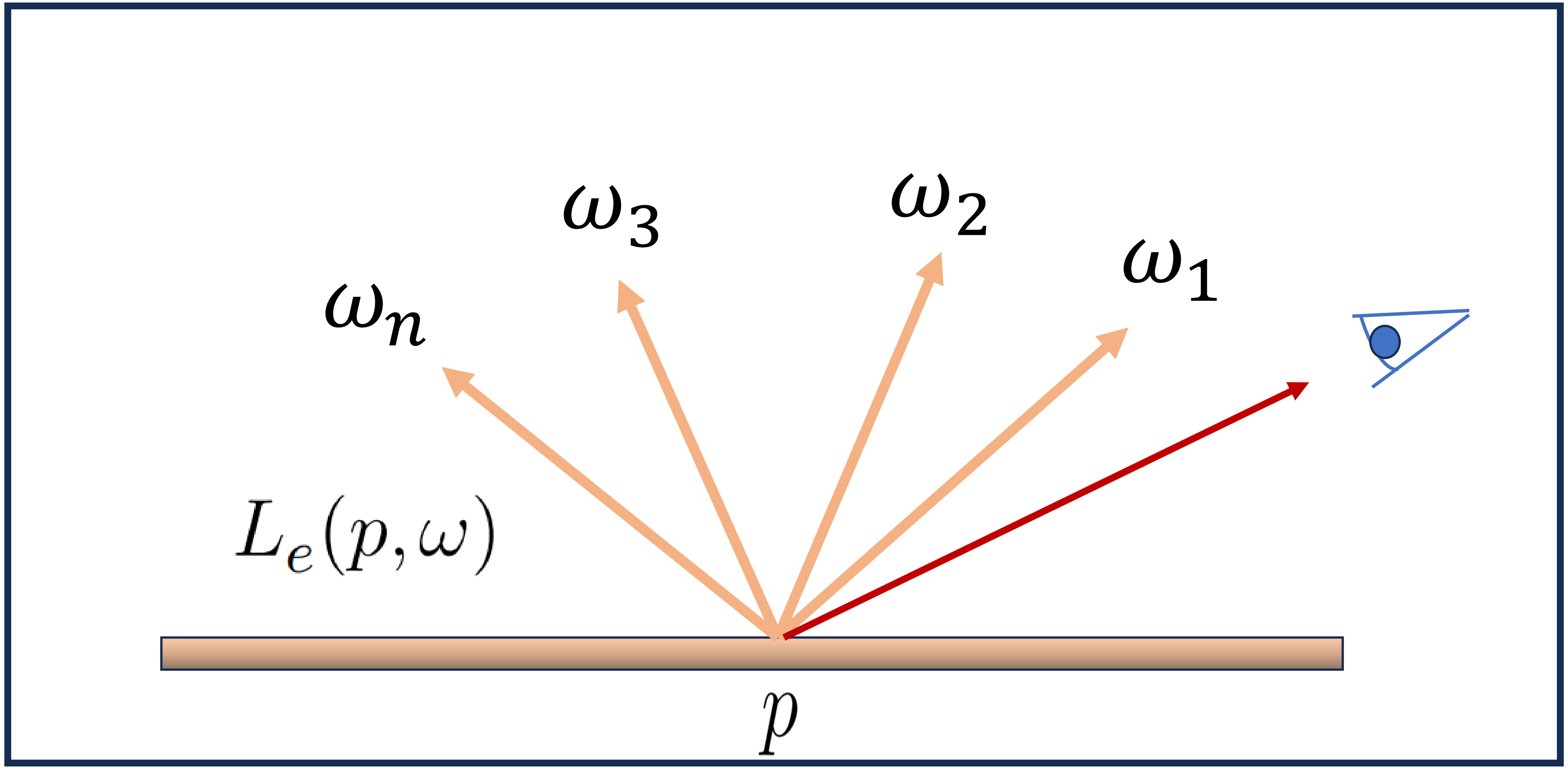
$$L_o(p,\omega) = L_e(p,\omega) + L_r(p,\omega)$$

Expanding the reflection contribution term.

$$L_o(p,\omega_o) = L_e(p,\omega_o) + \int_\Omega \underbrace{\rho(p,\omega_o,\omega_i)}_{reflectance} \underbrace{L_i(p,\omega_i) \mid cos(\theta_i) \mid d\omega_i}_{irradiance}$$

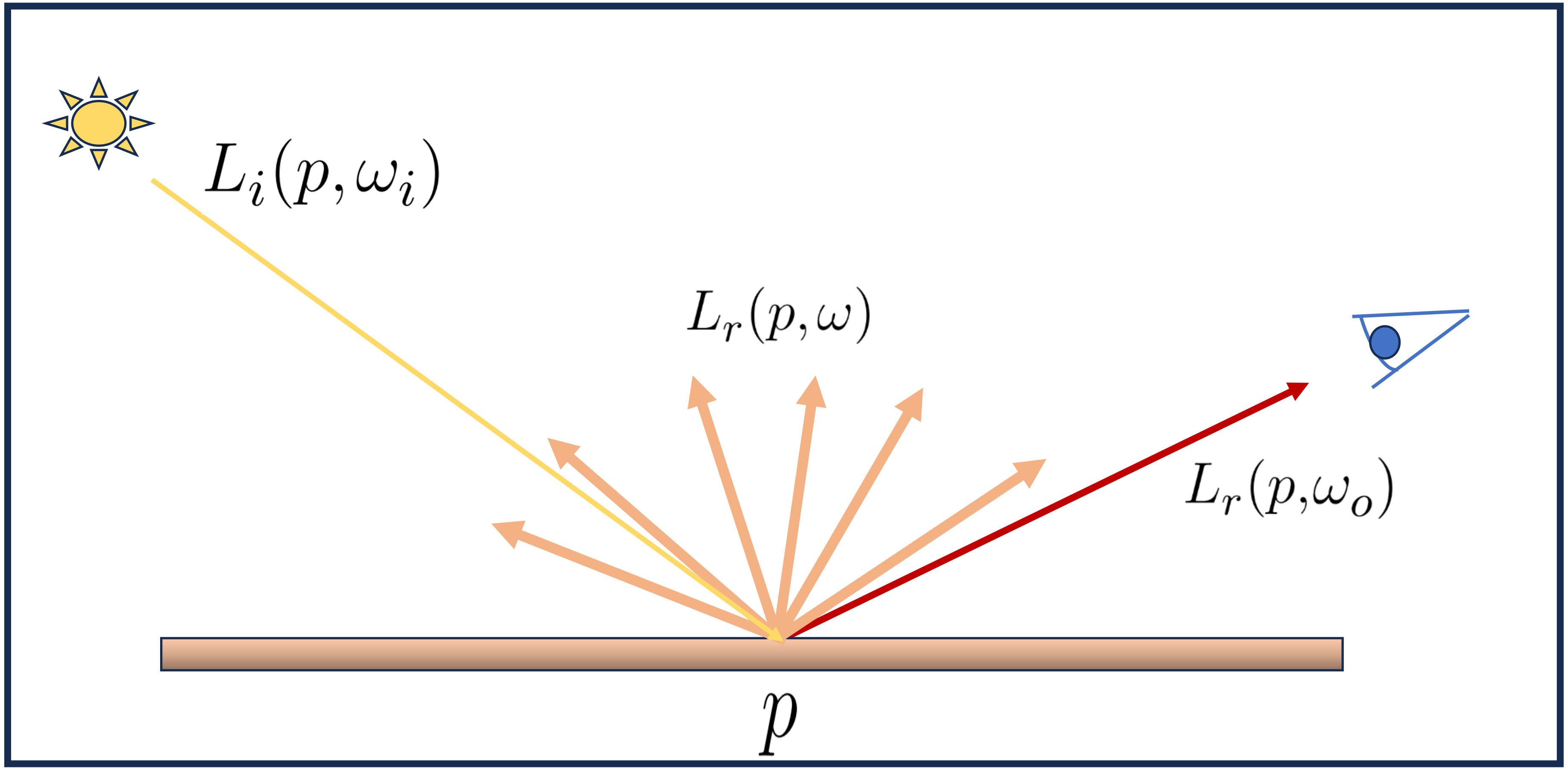
Kajiya, James T. (1986). "The rendering equation" (PDF). In David C. Evans; RussellJ. Athay (eds.). SIGGRAPH '86. Proceedings of the 13th annual conference on Computer graphics and interactive techniques. pp. 143–150. doi:10.1145/15922.15902. ISBN 978-0-89791-196-2. S2CID 9226468.

Illustration of the rendering equation



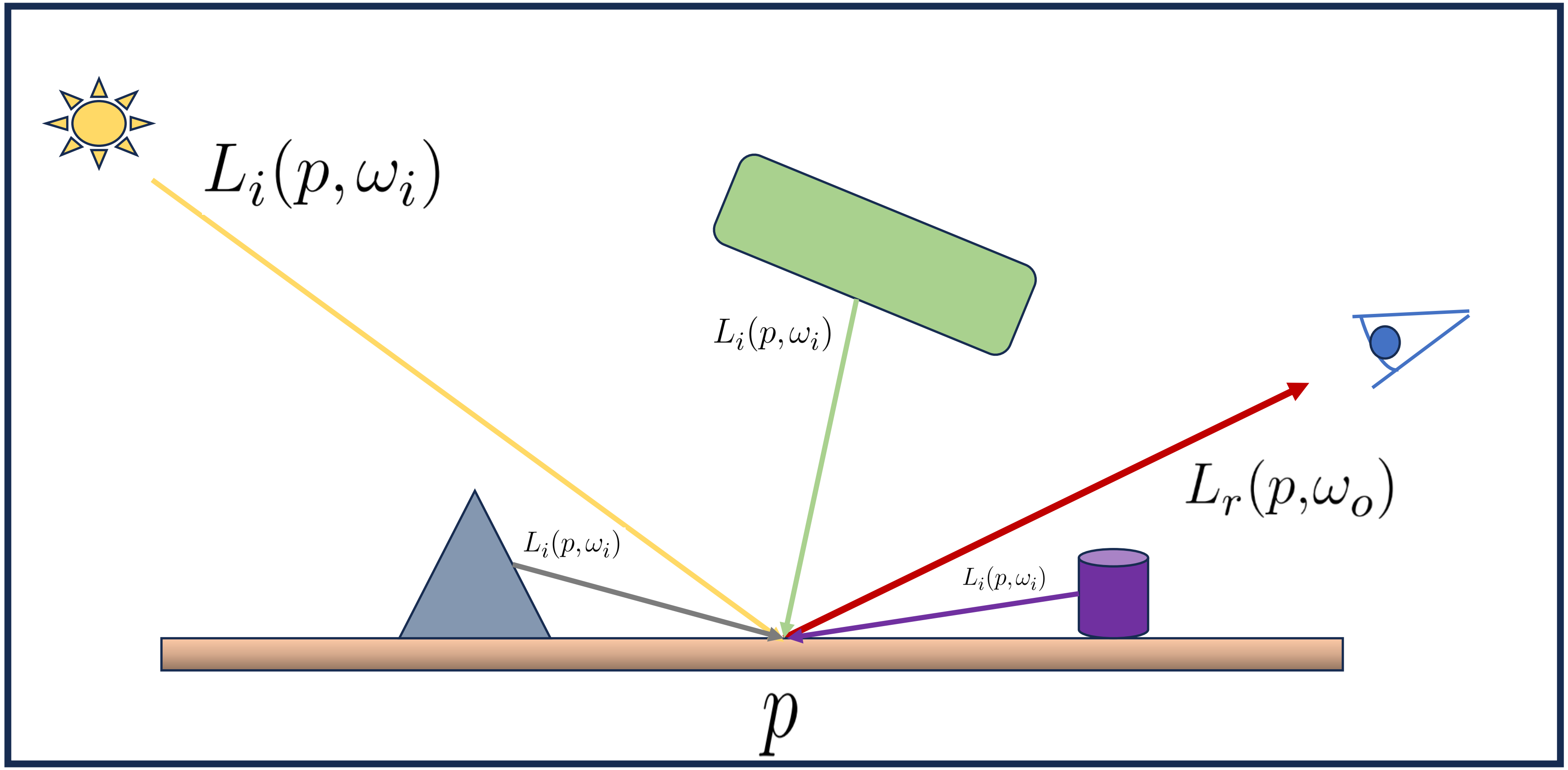
The term Le represents the emitted radiance scattering at a point p. It might reach the observation point (eye).

$$L_r(p,\omega_o) = \int_\Omega \underbrace{\rho(p,\omega_o,\omega_i)}_{reflectance} \underbrace{L_i(p,\omega_i)\ |\ cos(\theta_i)\ |\ d\omega_i}_{irradiance}$$



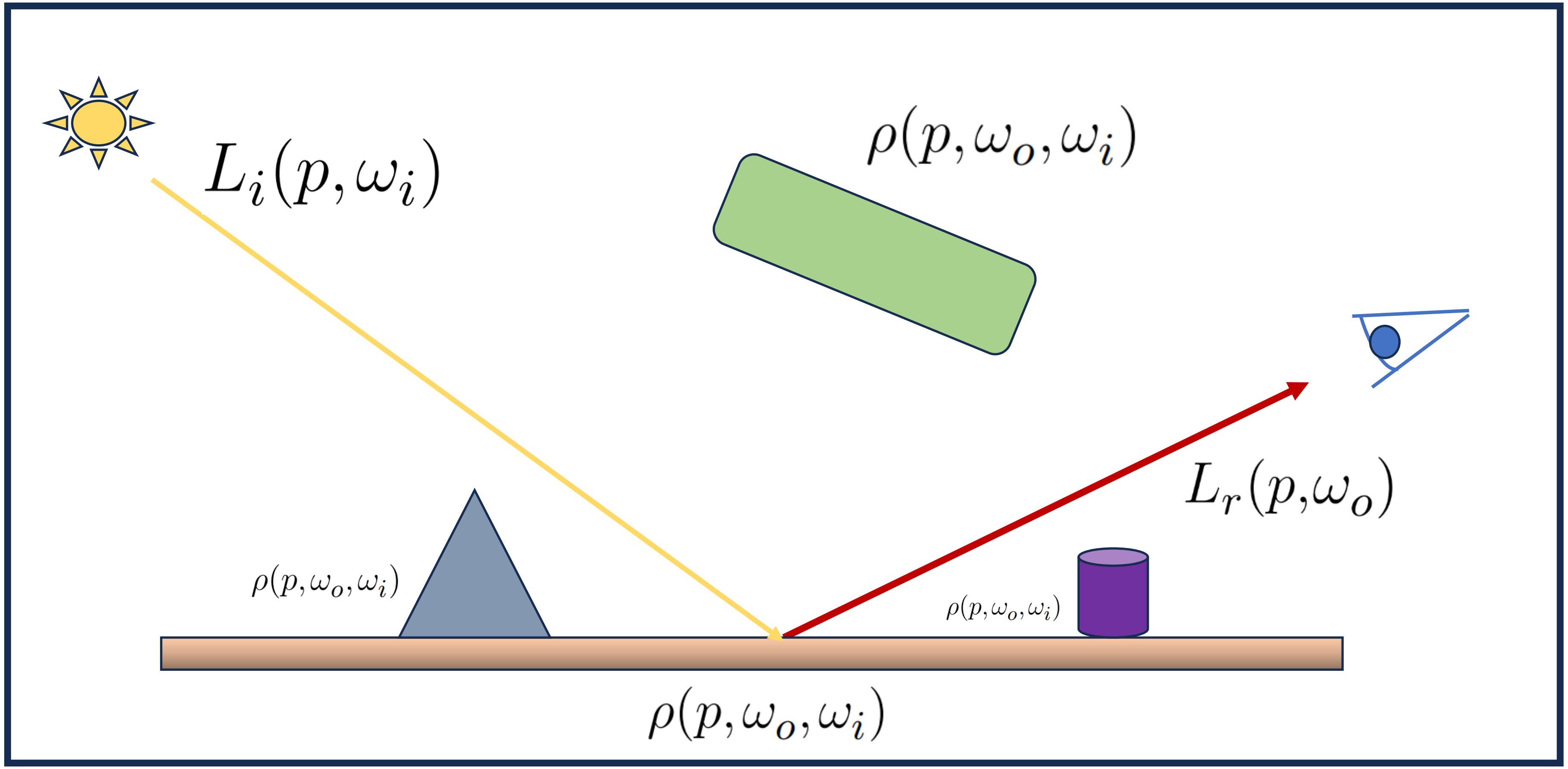
The reflected radiance Lr is caused by an incoming radiance quantity from a light source. The photons are scattered at a point p.

$$\int_{\Omega} \underbrace{\rho(p, \omega_o, \omega_i)}_{reflectance} \underbrace{L_i(p, \omega_i) \mid cos(\theta_i) \mid d\omega_i}_{irradiance}$$



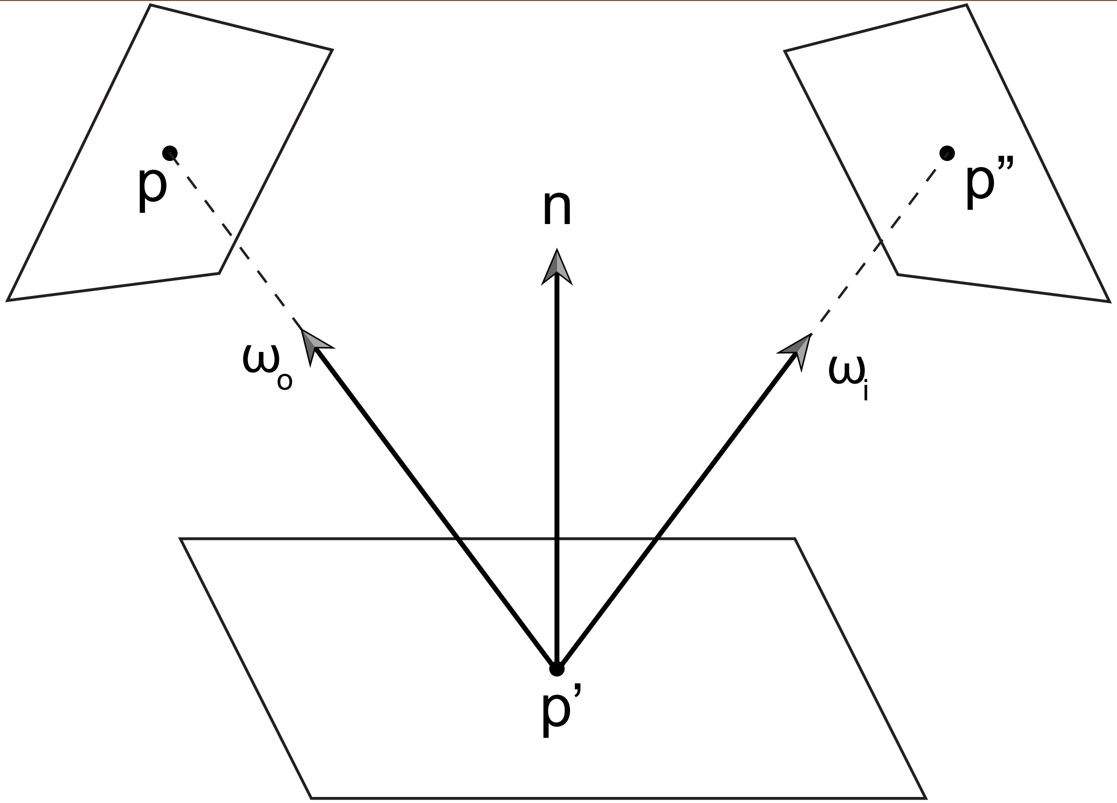
The integration comes from having incoming radiance complexity from the rendered scene. In this case, 3D objects may contribute to radiance at point p.

$$\int_{\Omega} \underbrace{\rho(p,\omega_o,\omega_i)}_{reflectance} \underbrace{L_i(p,\omega_i) \mid cos(\theta_i) \mid d\omega_i}_{irradiance}$$



Note that each 3D object has its own reflectance property, this is a major cause of radiance contribution from environment.

Analytical solution of the LTE (Light Transport Equation)



To illustrate the LTE, we shows a simple light transport path with 3 patches.

There is an outgoing direction (wo) and an incoming direction (wi) from a point p’.

In this case, we are discussing the radiance from p’ to p.

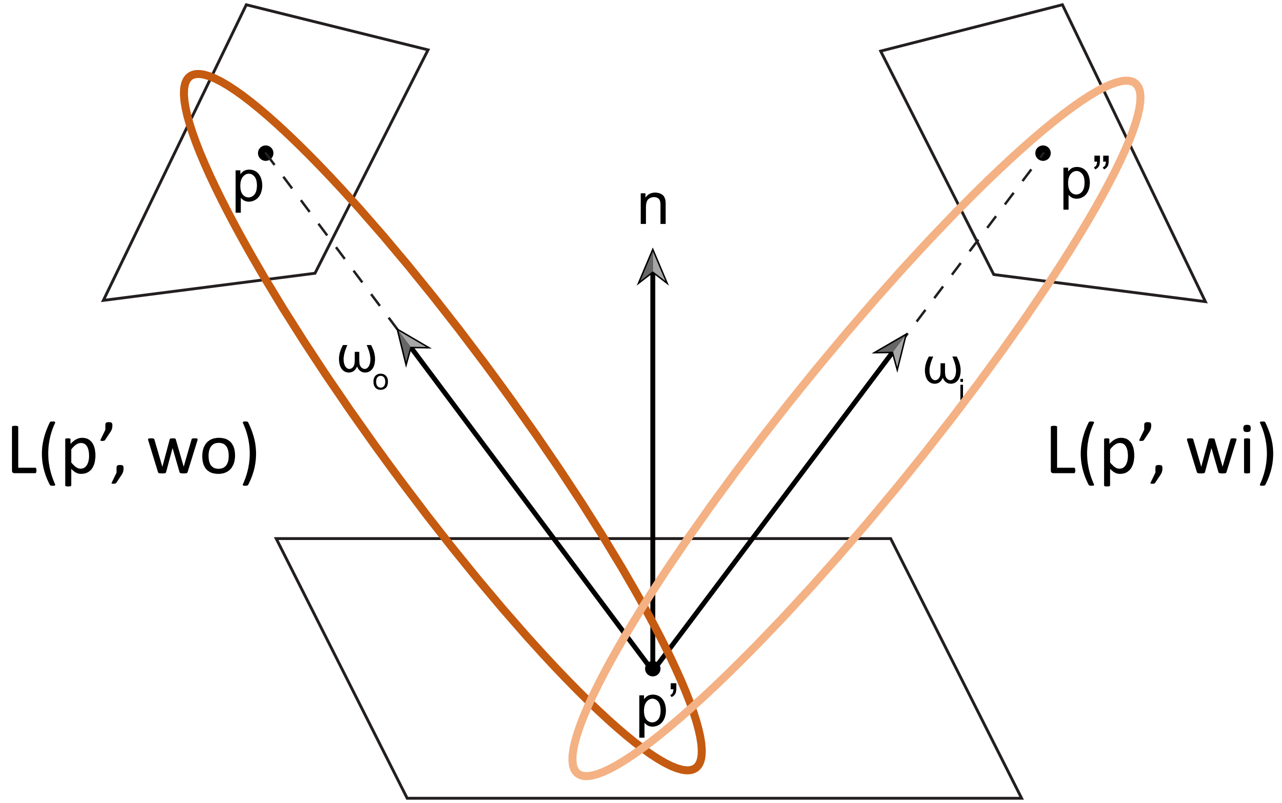
$$L(\mathrm{p}' \to \mathrm{p}) = L_{\mathrm{e}}(\mathrm{p}' \to \mathrm{p}) + \int_A f\,(\mathrm{p}'' \to \mathrm{p}' \to \mathrm{p})\, L(\mathrm{p}'' \to \mathrm{p}')\, G(\mathrm{p}'' \leftrightarrow \mathrm{p}')\ \mathrm{d}A(\mathrm{p}'')$$

Notations

$$L(\mathrm{p}' \to \mathrm{p}) = L_{\mathrm{e}}(\mathrm{p}' \to \mathrm{p}) + \int_A f(\mathrm{p}'' \to \mathrm{p}' \to \mathrm{p})\, L(\mathrm{p}'' \to \mathrm{p}')\, G(\mathrm{p}'' \leftrightarrow \mathrm{p}')\; \mathrm{d}A(\mathrm{p}'')$$

$$\boxed{L(\mathrm{p}' \to \mathrm{p}) = L(\mathrm{p}', \omega)}$$

Radiance from point p’ to point p. The term is denoted by L(p’, w).

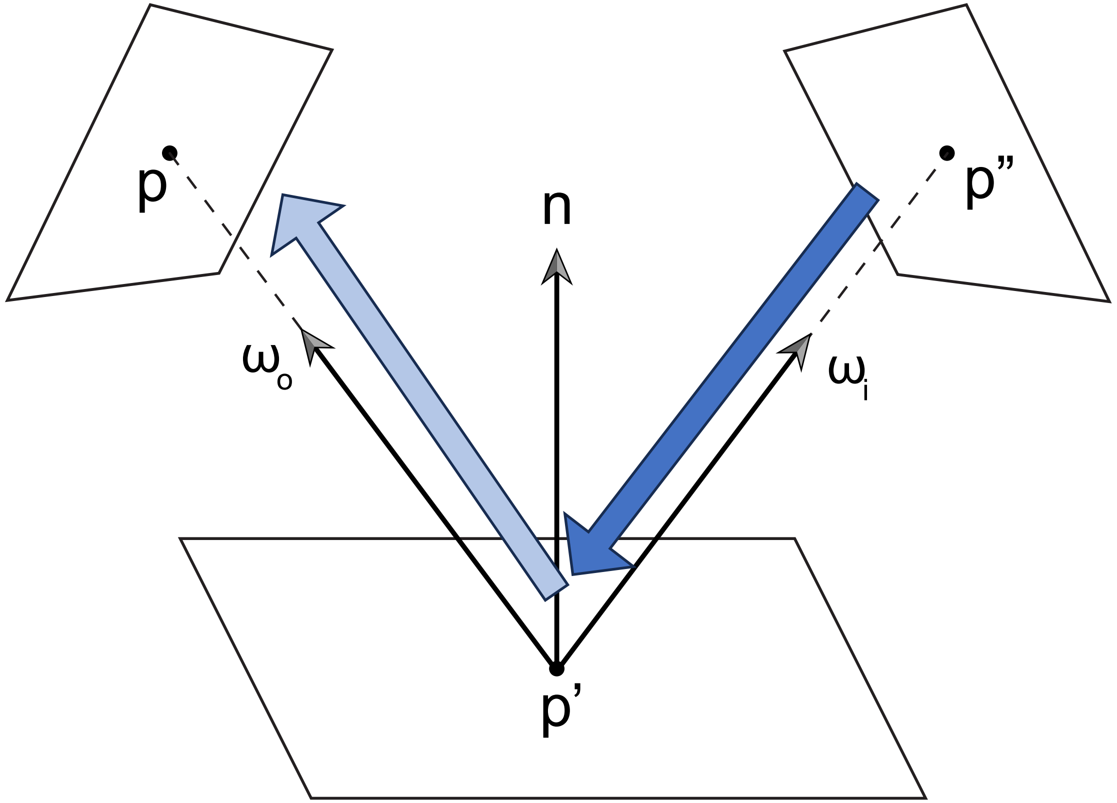


Notations

$$L(\mathrm{p}' \to \mathrm{p}) = L_{\mathrm{e}}(\mathrm{p}' \to \mathrm{p}) + \int_A f(\mathrm{p}'' \to \mathrm{p}' \to \mathrm{p})\, L(\mathrm{p}'' \to \mathrm{p}')\, G(\mathrm{p}'' \leftrightarrow \mathrm{p}')\, \mathrm{d}A(\mathrm{p}'')$$

$$\boxed{f(\mathrm{p}'' \to \mathrm{p}' \to \mathrm{p}) = f(\mathrm{p}', \omega_{\mathrm{o}}, \omega_{\mathrm{i}})}$$

Reflectance from point p’’ to point p’ then point p.
This term is denoted by f(p’, wo, wi).



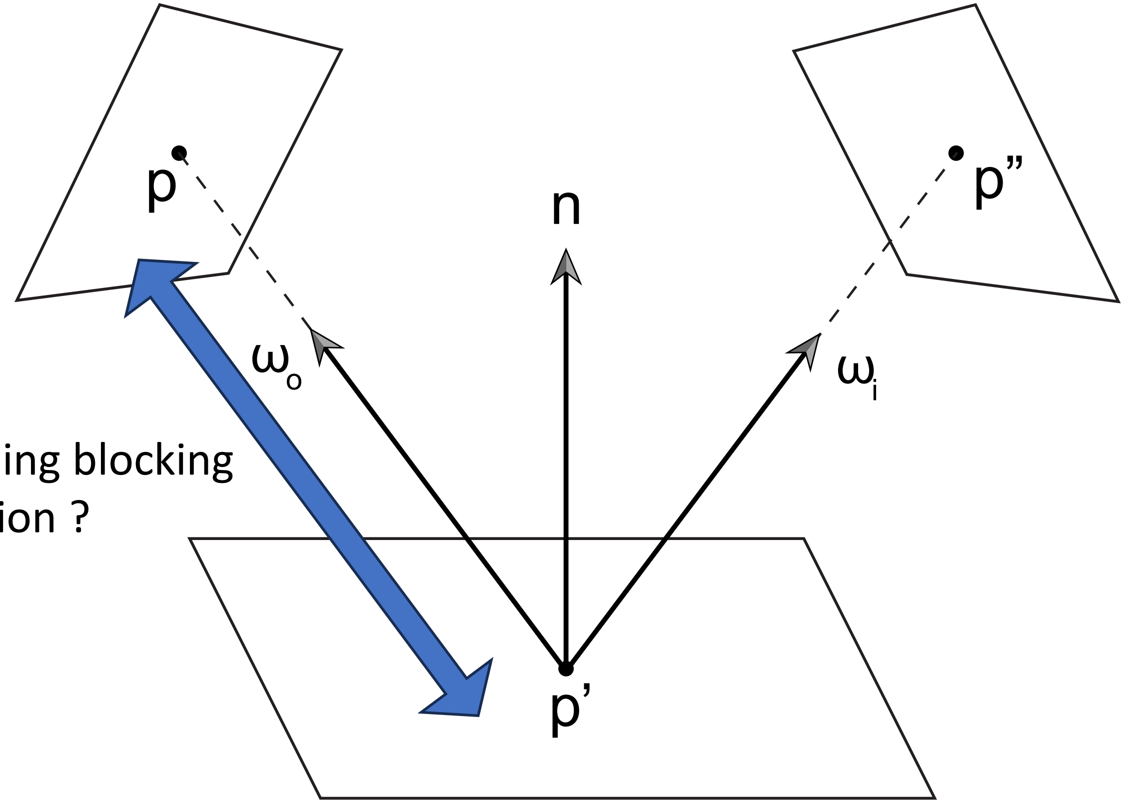
Notice that even if point p’’ might not fully refer to a light source, it might also contribute radiance to point p.

Notations

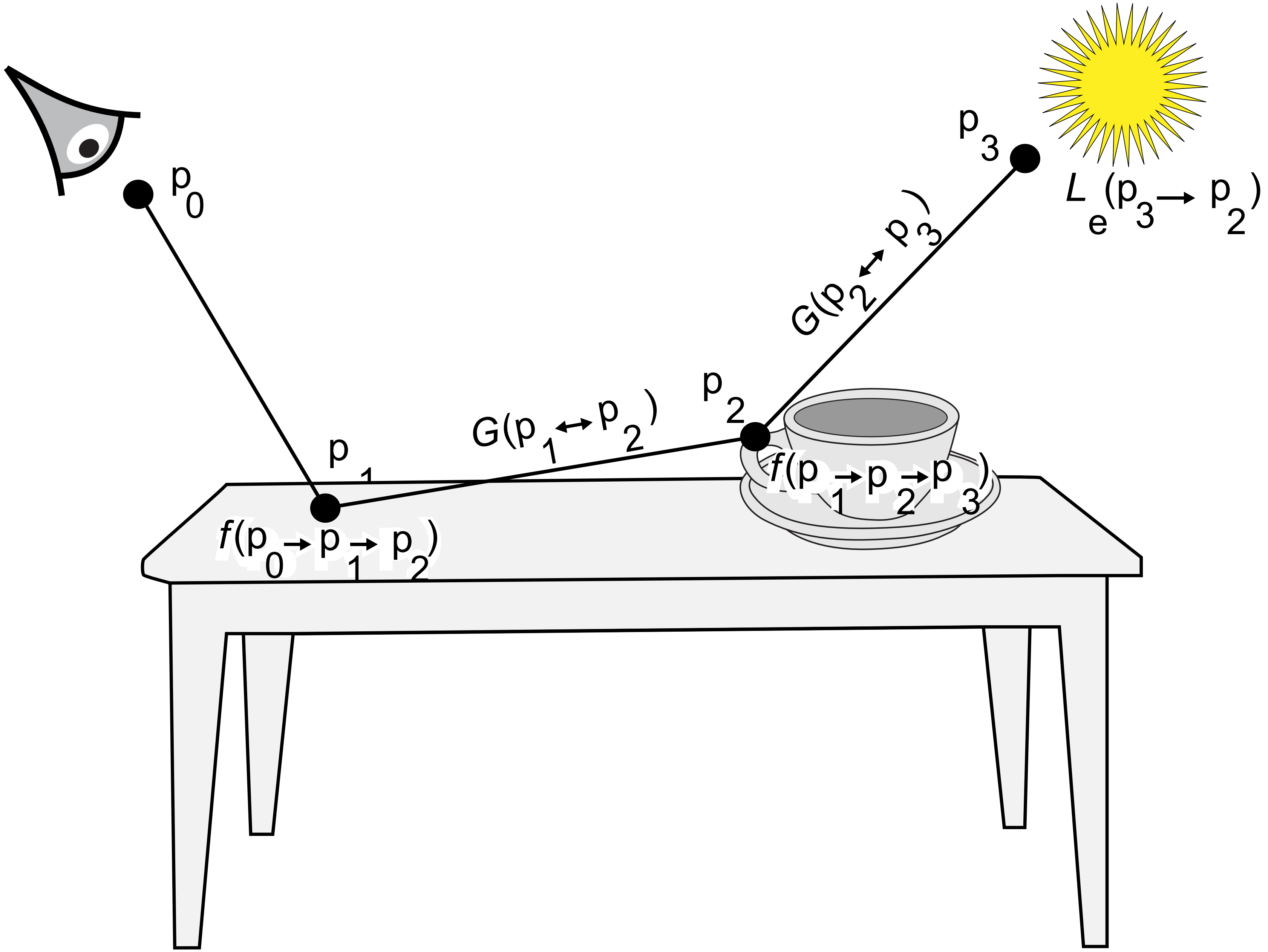
$$L(\mathrm{p}' \to \mathrm{p}) = L_{\mathrm{e}}(\mathrm{p}' \to \mathrm{p}) + \int_A f(\mathrm{p}'' \to \mathrm{p}' \to \mathrm{p})\, L(\mathrm{p}'' \to \mathrm{p}')\, G(\mathrm{p}'' \leftrightarrow \mathrm{p}')\, \mathrm{d}A(\mathrm{p}'')$$

$$\boxed{G(\mathrm{p} \leftrightarrow \mathrm{p}') = V(\mathrm{p} \leftrightarrow \mathrm{p}') \frac{|\cos\theta|\, |\cos\theta'|}{\|\mathrm{p} - \mathrm{p}'\|^2}}$$

The geometrical term is denoted by G. However this term can be interpreted as a visibility term.



Is there anything blocking this contribution ?



p_0
p_1
p_2
p_3
$f(p_0 \rightarrow p_1 \rightarrow p_2)$
$G(p_1 \leftrightarrow p_2)$
$f(p_1 \rightarrow p_2 \rightarrow p_3)$
$G(p_2 \leftrightarrow p_3)$
$L_e(p_3 \rightarrow p_2)$

The integral over paths of length four

$$
\begin{aligned}
L(\mathrm{p}_1 \to \mathrm{p}_0) = L_{\mathrm{e}}(\mathrm{p}_1 \to \mathrm{p}_0) \\
&+ \int_A L_{\mathrm{e}}(\mathrm{p}_2 \to \mathrm{p}_1) f(\mathrm{p}_2 \to \mathrm{p}_1 \to \mathrm{p}_0)\, G(\mathrm{p}_2 \leftrightarrow \mathrm{p}_1) \mathrm{d}A(\mathrm{p}_2) \\
&+ \int_A \int_A L_{\mathrm{e}}(\mathrm{p}_3 \to \mathrm{p}_2) f(\mathrm{p}_3 \to \mathrm{p}_2 \to \mathrm{p}_1)\, G(\mathrm{p}_3 \leftrightarrow \mathrm{p}_2) \\
&\quad \times f(\mathrm{p}_2 \to \mathrm{p}_1 \to \mathrm{p}_0)\, G(\mathrm{p}_2 \leftrightarrow \mathrm{p}_1)\, \mathrm{d}A(\mathrm{p}_3)\, \mathrm{d}A(\mathrm{p}_2) + \cdots
\end{aligned}
$$

Fredholm integral equation of the second kind

A Fredholm integral equation of the second kind

$$\phi(x) = f(x) + \lambda \int_a^b K(x,t)\,\phi(t)\,dt$$

may be solved as follows. Take

$$\phi_0(x) \equiv f(x)$$

$$\phi_1(x) = f(x) + \lambda \int_a^b K(x,t)\,f(t)\,dt$$

$$\phi_2(x) = f(x) + \lambda \int_a^b K(x,t_1)\,f(t_1)\,dt_1 + \lambda^2 \int_a^b \int_a^b K(x,t_1)\,K(t_1,t_2)\,f(t_2)\,dt_2\,dt_1$$

$$\phi_n(x) = \sum_{i=0}^{n} \lambda^i\,u_i(x),$$

https://mathworld.wolfram.com/IntegralEquationNeumannSeries.htmlb

A solution

$$\boxed{\begin{aligned}&+\int_A\int_A L_{\mathrm{e}}(\mathrm{p}_3 \to \mathrm{p}_2) f(\mathrm{p}_3 \to \mathrm{p}_2 \to \mathrm{p}_1)\, G(\mathrm{p}_3 \leftrightarrow \mathrm{p}_2)\\ &\qquad \times f(\mathrm{p}_2 \to \mathrm{p}_1 \to \mathrm{p}_0)\, G(\mathrm{p}_2 \leftrightarrow \mathrm{p}_1)\, \mathrm{d}A(\mathrm{p}_3)\, \mathrm{d}A(\mathrm{p}_2)\end{aligned}}$$

$$\begin{aligned}P(\bar{\mathrm{p}}_n) = &\underbrace{\int_A\int_A \cdots \int_A}_{n-1} L_{\mathrm{e}}(\mathrm{p}_n \to \mathrm{p}_{n-1})\\ &\times \left(\prod_{i=1}^{n-1} f(\mathrm{p}_{i+1} \to \mathrm{p}_i \to \mathrm{p}_{i-1})\, G(\mathrm{p}_{i+1} \leftrightarrow \mathrm{p}_i)\right) \mathrm{d}A(\mathrm{p}_2) \cdots \mathrm{d}A(\mathrm{p}_n)\end{aligned}$$

$$\boxed{L(\mathrm{p}_1 \to \mathrm{p}_0) = \sum_{n=1}^{\infty} P(\bar{\mathrm{p}}_n)}$$

Path sampling

$$L(\mathrm{p}_1 \rightarrow \mathrm{p}_0) = \sum_{n=1}^{\infty} P(\bar{\mathrm{p}}_n)$$

$$L(\mathrm{p}_1 \rightarrow \mathrm{p}_0) = P(\bar{\mathrm{p}}_1) + P(\bar{\mathrm{p}}_2) + \sum_{i=3}^{\infty} P(\bar{\mathrm{p}}_i)$$

Emitted radiance

Direct lighting

Indirect lighting

Monte Carlo integration