3

Path Tracing

This chapter describes the origins of path tracing, and gives a simple overview of path tracing and how it has been used in movies.

3.1 Origins of path tracing

The very first Monte Carlo simulations were done by Enrico Fermi using a small mechanical adding machine in the 1930s [84], but Monte Carlo only became more widely used as the first electronic computers were developed. Monte Carlo simulations were especially useful for neutron transport simulation in the development of nuclear bombs and reactors in the 1940s. Much inspiration can be found in classic texts such as Spanier and Gelbard [114], and Kalos and Whitlock [59].

Photons are governed by the same equations as neutrons (they are both electrically neutral—each particle neither attracts nor repels others of the same kind), so the same mathematical simulation methods can be used. Path tracing is a variation of Monte Carlo simulation that was introduced to computer graphics by Kajiya [57] in 1986, and the connection to particle transport was later solidified by Arvo and Kirk [5].

3.2 Simple path tracing

Path tracing is a simple recursive method. To calculate the color of an image pixel, a number of rays are traced from the eye point through that pixel. When a ray intersects a surface, the direct illumination from the light sources is calculated for the intersection point (which includes tracing shadow rays between the light sources and intersection point—referred to as "next-event estimation" in the particle transport field). In addition, a new ray is spawned to calculate indirect illumination. The direction of the new ray is stochastically chosen based on the light scattering properties of the surface material: specular or matte, reflective or refractive. When such a ray hits another surface the direct illumination is calculated there (including tracing more shadow rays), a new ray are spawned, and so on. The colors from all rays at all depths contribute to the color of the pixel of their originating eye ray. The recursion stops when the new ray does not hit a surface, or it is probabilistically terminated using Russian roulette [5], or when a pre-determined maximum recursion depth has been reached.

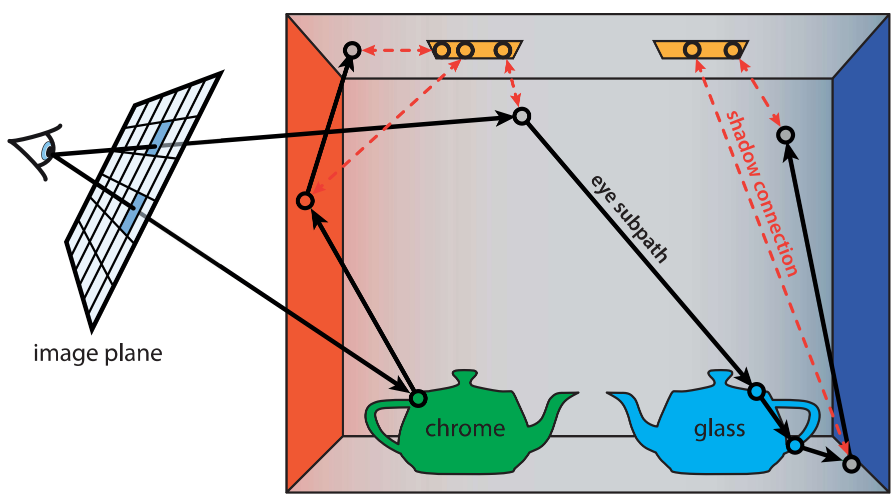

Figure 3.1: An illustration of tracing paths from the eye to the light sources in a Cornell box scene with two teapots.

Figure 3.1 illustrates this process in a variation of the classic Cornell box with two teapots and two light sources. One path originating from the eye hits the chrome teapot. Chrome exhibits specular reflection so a reflection ray is generated (in the mirror direction), which subsequently hits the diffuse red wall. At that point a random position on one of the light sources is chosen, a shadow ray (shown in red) is shot to determine visibility, and the direct illumination from that light source point is calculated. The path continues as a new random diffuse reflection ray is chosen, which this time hits the ceiling. A new shadow ray is shot, and the path is stochastically terminated. The other path from the eye first hits the diffuse back wall, direct illumination is calculated using a shadow ray to determine visibility, and a new reflection direction is chosen. That ray hits the glass teapot, where a choice is made between specular reflection or refraction, and refraction is chosen. After one more refraction the path hits the diffuse floor, a shadow ray is traced, and a new ray direction is stochastically chosen. The new ray hits the back wall, another shadow ray is traced, and this path is terminated.

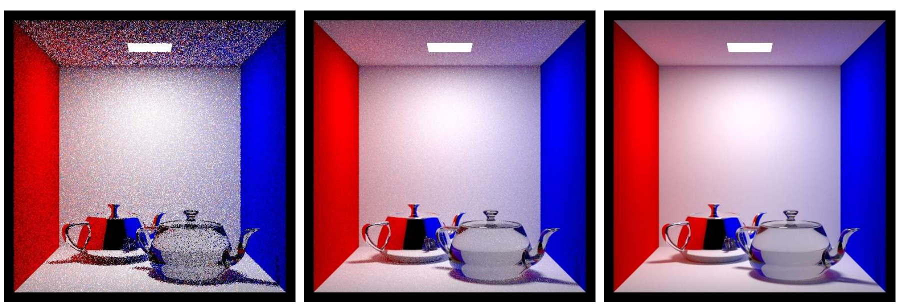

Figure 3.2: Path-traced images rendered with 1, 16, and 256 samples per pixel.

Figure 3.2 shows path-traced images with 1, 16, and 256 samples per pixel in the box scene from figures 2.1 and 2.2. The image on the left was rendered very quickly, but is very noisy; the other images took longer to render but are much less noisy. Despite the noise, an artist can form an opinion about the illumination and materials in the scene even with only a few samples per pixel, i.e. after a few iterations in an interactive session.

When shadows, reflections, refractions, and indirect diffuse are computed in a single pass, *all* geometry needs to be accessible during the entirety of rendering. This is very different from Reyes, and puts a harder constraint on scene size (or requires a computer with more memory).

3.3 Depth of field and motion blur

Real cameras have finite aperture openings and the shutter is open for a finite amount of time. Hence real images have limited depth of field and contain motion blur. In fields such as architectural visualization these effects are not important, but movie audiences expect these effects in CG and VFX images. Figure 3.3 shows examples of these effects: in the left image the front teapot is in focus while the back teapot is out of focus; in the right image both teapots are moving and blurry while the checkered plane is static and sharp.

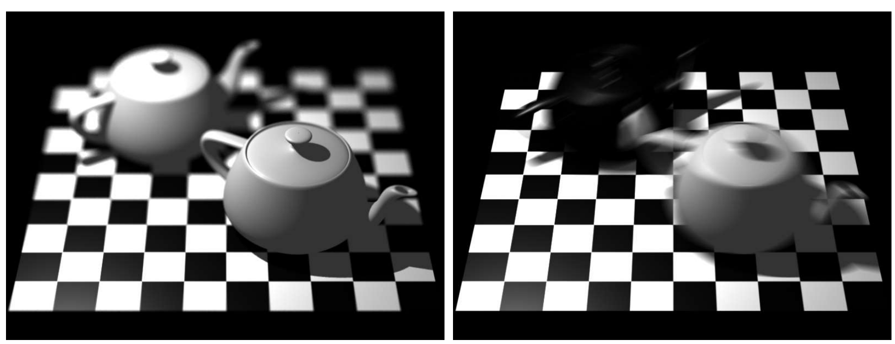

Figure 3.3: (a) Depth of field. (b) Motion blur.

Depth of field can be simulated in path tracing by—instead of shooting eye rays from a single viewpoint—shooting camera rays with small variations in origins and directions [24, 67]. Motion blur can be simulated by assigning each camera ray a random time within the time interval the shutter is open [24] (spawned rays inherit the time of their parent ray). For ray intersection tests, moving or deforming objects have to be transformed to the position and shape corresponding to the ray's time.

3.4 Path tracing in movies

Figure 3.4(a) shows a frame from the short film *Bunny* from Blue Sky Studios, released in 1998. This was an early ground-breaking use of path tracing, proving that effects like indirect diffuse illumination, depth of field, and motion blur can successfully be rendered at film quality using path tracing.

Figure 3.4(b) shows a frame from the movie *Monster House* from 2006. This was the first feature-length movie to be rendered with path tracing; it used the Arnold renderer. The movie was rendered without motion blur—partially as an artistic choice to mimic the look of classic stop-motion films, and partially to avoid noise from sampling the motion. Depth of field (as seen in the image) was added in a separate post-process. For a long time Arnold was the only production-strength renderer based on path tracing, but recently at least a dozen other commercial and in-house renderers have been written or re-written to use path tracing.

Figure 3.4: Path-traced images from *Bunny* and *Monster House*. (Bunny: © 1998 Twentieth Century Fox. All rights reserved. Courtesy of Twentieth Century Fox. Monster House: © 2006 Columbia Pictures Industries, Inc. and GH One LLC. All rights reserved. Courtesy of Columbia Pictures.)