Efficient direct lighting calculation for area lights with light portals

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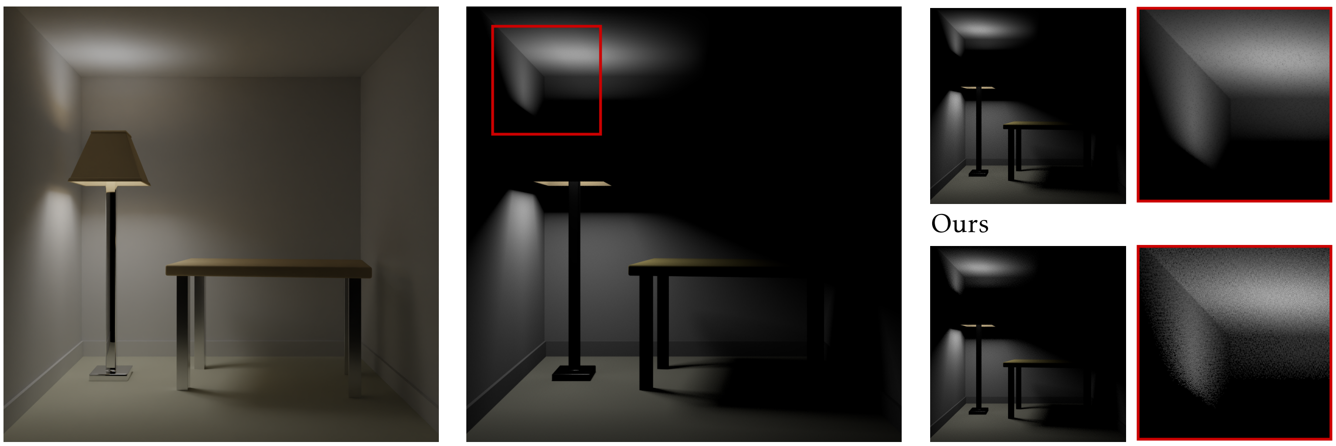


Path traced: Reference **Direct Lighting:** Reference Ours Baseline

Figure 1: *Direct lighting for a simple indoor scene where the light source is occluded by the lampshade. Our method works by manually specifying the locations of the openings to the light as portals, and then focusing sampling to the directions facing the portal.*

Abstract. Direct lighting calculation is an essential part of photorealistic rendering. Standard importance sampling techniques converge slowly in scenes where a light source is only visible through small openings as visibility is not considered. This problem is often addressed by manually placing *light portals*, marking the openings to the light. However, existing portal sampling techniques are not suitable for area lights since the portal is often times larger than the light itself. We present a novel portal sampling technique inspired by shadow volumes, which considers the light geometry to efficiently choose the optimal sampling strategy, depending on the location of the shading point. Our technique is unbiased, robust, applicable to many scenes, and easy to integrate into an existing renderer.

1 Introduction

Physically-based Monte Carlo light transport algorithms create photorealistic imagery with applications ranging from videogames to architecture visualization. While they can deliver accurate illumination, their most significant limitation is their high computational demands.

Direct lighting is often one of the most significant components, so most rendering algorithms compute direct illumination separately, allowing for more effective light sampling. Direct lighting is computed by explicitly casting shadow rays from the shading point to the light sources. The probability distribution function (PDF) from which the shadow ray directions are sampled can have a high impact on the convergence rate of the scene. For example, consider a scene with a lamp occluded by a lampshade, all of the shadow rays blocked by the lampshade will have no contribution to the final image and are thus wasted sampling effort.

One widely used technique for sampling direct lighting from environment lights is *light portals*. These are artist-specified regions which indicate an opening to the environment light. This information is then used during rendering to prioritize sampling the directions that go through the portal. Our contribution is extending the idea of light portals to accelerate the sampling of partially occluded area lights by repurposing concepts from shadow volume calculations.

We begin by reviewing Monte Carlo techniques for direct lighting calculations and provide an overview of existing use cases and sampling strategies for light portals (Section 2). Next, we expand on the details of our method (Section 3) and its implementation into an existing path tracer (Section 4). Lastly, we evaluate our portal sampling strategy against light sampling (Section 5), and discuss the results (Section 6) before concluding and giving final remarks (Section 7).

2 Background and related work

The Light Transport Equation The light transport equation (LTE) [Kaj86] is a recursive integral over radiometric quantities, which governs our approximation of light transport.

$$L_o(p,\omega_o) = L_e(p,\omega_o) + \int_\Omega f(p,\omega_o,\omega_i) L_o(p,\omega_o,\omega_i)\cos\theta_i d\omega_i, \tag{1}$$

The equation states that the outgoing radiance at point p in direction ω_o is equal to the emitted radiance at that point and direction plus the portion of the incident light on p that gets reflected towards ω_o.

The direct lighting integral The LTE can be reformulated into an infinite sum where each term represents the contribution of a given path length [Vea]. In doing so, we can separate the calculation of direct and indirect lighting. The term accounting for direct light is the one we are concerned with evaluating, and is given by the integral:

$$\int_\Omega f(p,\omega_o,\omega_i) L_d(p,\omega_i)\cos\theta_i d\omega_i, \tag{2}$$

where p is the *shading point* we are evaluating direct light on, L_d is the *direct* incident radiance from direction ω_i to the shading point, and f is the Bidirectional Scattering Function (BSDF) at the shading point.

Monte Carlo Integration This integral cannot be solved analytically in general, so an unbiased estimate is obtained with *Monte Carlo integration*. To compute this estimate, we need to sample N directions ω_i with a probability density function (PDF) p and apply the Monte Carlo estimator [Laf96]:

$$\frac{1}{N}\sum_{i=1}^{N} \frac{f(p,\omega_o,\omega_i) L_d(p,\omega_i)\cos\theta_i}{p(\omega_i)} \tag{3}$$

To reduce the variance of Monte Carlo, we can use *importance sampling* to choose the directions ω_i from a probability density function (PDF) similar to the integrand. When deciding on a distribution to sample from, it is worth clarifying that we are *not* after the distribution with the lowest variance for a given number of samples, but instead the one with the lowest variance for a given amount of *execution time* [SWZ96]. Thus, an effective sampling strategy may be worse than an ineffective one if the latter can be sampled more efficiently.

Returning to direct lighting, Equation 2 is usually reformulated into a sum over the contributions of each light source in the scene [SWZ96], and each term is estimated separately. To estimate direct light from a single emitter, we sample directions according to the emitters area or solid angle [SWZ96] and then combined with BSDF sampling using Multiple Importance Sampling (MIS) [Vea]. However, this approach ignores the light source's visibility when drawing the samples, which can lead to high variance in scenes where the light is partially occluded.

Light portals *Light portals* are artist-specified regions in the scene which indicate an opening to an environment light, such as a window in an interior scene. During rendering, the portal is then used to focus the environment light sampling to those directions visible through the portal. They are highly effective for accelerating convergence in many scenes and are implemented in several production renderers such as Cycles [BF] and Renderman [PAS].

The portal area is typically sampled uniformly, although more advanced portal sampling strategies exist [Oga20][BNJ15]. Nonetheless, these sampling strategies are designed for sampling *environment lights*, and several challenges and opportunities are presented when applying the same technique to area lights. Unlike area lights, environment lights extend across the whole scene, so any direction sampled through the portal will also be directed to the environment. For this reason, existing portal sampling strategies are unsuitable for area lights.

3 Method

We now present our method. We begin by explaining how the portal is represented and sampled for a scene with a single emitter and a single portal. Next, we give an effective yet potentially slow sampling strategy and show how it can be made more efficient by repurposing ideas from shadow calculations. Lastly, we generalize the provided method to multiple portals and show how the portal data can be incorporated into a spatial emitter distribution.

3.1 Sampling a single light portal

Consider a simple scene containing a single light source covered by a lampshade (Figure 2). The core idea behind our method is to have the artist include the geometry of the opening to the light source as a "portal" in the scene description. During rendering, if the shading point is in front of the portal, instead of sampling the light, we sample the portal using the method explained in (sampling the portal, thinking in terms of shadows).

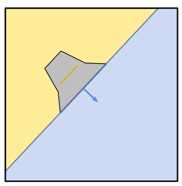


Figure 2: *Simple scene with a single light and single portal. Light is sampled in the region behind the portal (yellow), and the portal is sampled in the region in front of it (blue)*

3.2 Ensuring an unbiased estimate

By sampling the portal, we only consider the directions to the light that also go through the portal. If the portal is well-placed, the light is only visible through the portal if the shading point is in front of it. Thus this method remains unbiased. However, if the portal is slightly misplaced, there may be directions facing the light which do not go through the portal Figure 3. Ignoring these directions makes the sampling technique biased.

There is one issue with this approach, for the estimate to be unbiased there needs to be a nonzero probability of sampling every light carrying distribution.

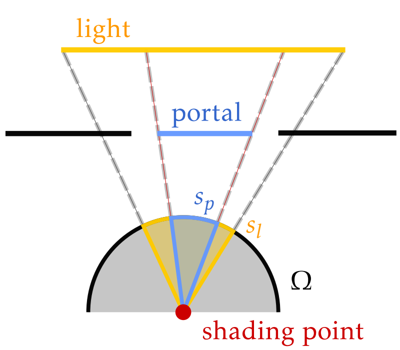


Figure 3: *Illustration of how, part of the integration domain is ignored when sampling directions from a misplaced portal. If samples are instead drawn from a linear combination of the solid angles of the light and portal we ensure the entire integration domain is covered.*

To resolve this, when sampling a portal, instead of only drawing samples according to the portal's solid angle, we sample from a linear combination of the portal's PDF and the target light's solid angle, ensuring the full integration is covered with a nonzero probability. We use MIS with the single sample model, and the balance heuristic [Vea] to weigh the linear combination optimally. We opt for the single sample model as, in most cases, sampling the light over the portal gives a higher variance. The probability of sampling the light instead of the portal is an artist-specified parameter, defaulting to a low value such as 0.1.

3.3 Effectively sampling the portal

In Section 2, we explained why uniformly sampling the portal area is not a suitable strategy when applying light portals to area lights. If we want to only sample those directions that go through the portal and face the light, then the region that needs to be sampled is the intersection of the solid angles subtended by the emitter and the portal.

This region can be computed by first perspective-projecting the light area, from the perspective of the shading point, onto the portal and then clipping the projected region to the portal bounds. We then sample the solid angle subtended by the clipped region (Figure 4).

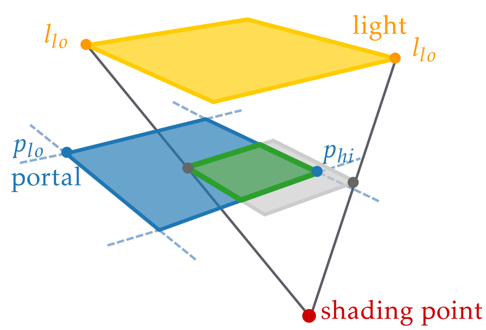


Figure 4: *Projecion sampling. The light (yellow) is projected onto the portal-plane (blue) and clipped to the portal bounds. Samples are then drawn from the clipped region (green).*

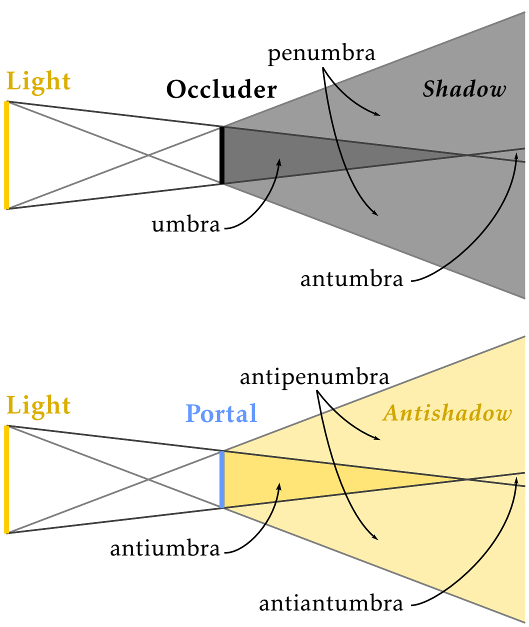
This sampling strategy is effective per sample but can be considerably slower than light or uniform portal sampling, introducing runtime overhead. In the next section, we show how some additional geometric calculations allow us to restrict the use of this sampling strategy to points where it provides the most significant advantage over more efficient alternatives.

3.4 Thinking in terms of shadows

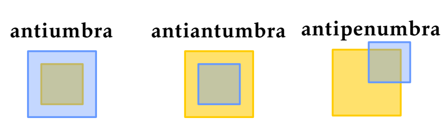
An interesting way to think about light portals is to consider the shadow that the portal would cast if we were to replace it with an occluder. The area in front of the occluder can then be separated into four regions. These regions are called the *umbra*, *penumbra antumbra* and the *region out of shadow* [Has+03].

These regions are relevant because the portal represents the precise opposite of an occluder, an *opening* to the light. We call the imaginary shadow volume cast by the portal the *antishadow*. The regions of the antishadow then take on a new meaning when we treat them from the portal's perspective. The portal-equivalent regions are shown in figure 3.4 and represent:

- The **antiumbra** is the region where all direct paths to the light go through the portal.
- The **antipenumbra** is the region where some but not all paths to the light go through the portal.
- The **antiantumbra** is the region where the portal is directly in front of the light but does not fully cover it.
- The region **outside of the antishadow** is the area where none of the paths from the shading point to the light to the light pass through the portal



(a) *2D representation of shadow and antishadow regions.*



(b) *View of the light and portal from the point of view of the shading point, in different regions of the portal antishadow.*

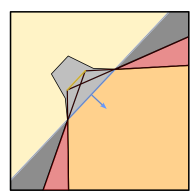
Figure 5: *Two-dimensional representation of the regions of a shadow. If we replace the occluder with a light portal, the same geometric volumes take different roles.*

Returning to our problem of sampling the light going through a portal, having an idea of which region of the antishadow the shading point is in can be used to choose the optimal sampling strategy. If the shading point is **outside of the antishadow**, then there is no light carrying directions through the portal to the light, so there is no need to sample.

If the shading point is in the portals **antiumbra**, then all direct paths from the shading point to the light go through the portal. Thus, the optimal sampling strategy is to ignore the portal and sample the light source itself. Conversely, when the shading point is in the **antiantumbra**, all directions to the portal also face the light. Hence, the optimal strategy is to ignore the light and sample the portal uniformly. Figure (antishadow b) gives a good intuition on why this works.

Lastly, if the shading point is in the **antipenumbra** then some but not all directions to the light go through the portal. In this case, we resort to using the effective, but slow projection sampling method explained in Subsection 3.3.

Returning to the simple scene from figure Figure 2, we can now partition the volume in front of the portal further by including the antishadow volumes.



Out of antishadow: Dont sample
Antipenumbra: Sample projection
Antiumbra: Sample light
Behind portal: sample light

Figure 6: *Simple scene employing antishadow volumes to weight the choice of sampling strategy depending on the location of the shading point.*

By doing this, we restrict the use of the slow projection sampling technique to only the points in the antipenumbra and use faster strategies when there is no benefit to performing the projection.

3.5 Computing antishadow volumes

In Subsection 3.4, we explained the concept of a light portal ”antishadow” and how information about which region of the antishadow the shading point is in can be used to sample the portal efficiently. This section discusses how these antishadow volumes are computed and used to weigh sapling strategies.

For arbitrary polygonal objects, the shape of the umbra and penumbra regions can be embedded in a discontinuity mesh constructed from the edges and vertices of the light, and the portal [DF94]. However, for simplicity, we implement a version of this algorithm limited to rectangular aligned light and portal.

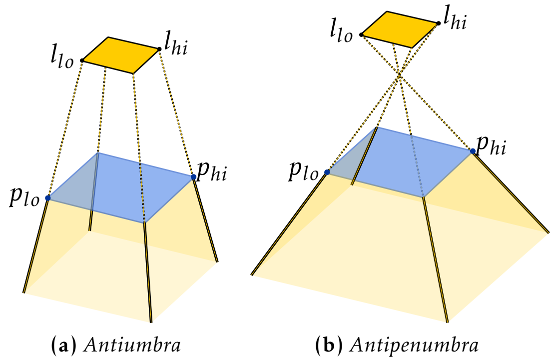


Figure 7: *Computing the antiumbra and antipenumbra for aligned rectangles. The antiantumbra can be derived from the antiumbra.*

The antiumbra is the frustum produced by connecting the adjacent vertices from the portal and the light (7a). Likewise, the antipenumbra is the frustum produced by connecting the *opposite* vertices from the light to the portal (7b). The antiantumbra does not need to be explicitly computed, as it is defined by the same planes that make up the antiumbra, but with their normals inverted.

3.6 Multiple portals per light

To generalize the method presented above to multiple lights per portal, we separately include each portal in the emitter distribution. This way, if a spatial emitter distribution is used we can prioritize portals facing the shading point. To maintain an unbiased estimate, one minor adjustment needs to be made. By including each portal separately, the contribution of the light needs to be scaled down accordingly. Instead of dividing by the probability of the portal being selected, we divide by the target emitter being selected.

4 Implementation

We implement our method within the PBRT-V3 renderer described in [PJH16]. We create a `LightPortal` class by extending the the `Light` interface. The light portal class contains the portal geometry and a reference to its target area light. The class implements uniform portal area sampling and projection sampling (Subsection 3.3). Lastly, the class implements routines to efficiently determine which antishadow volume the shading point is located. Each light portal is then included in the light distribution, and the probability of sampling it is weighed spatially.

5 Results

We evaluate the method presented in 3 similar *Suzanne* scenes, differing in the shapes of the portal and the light (8).

- Scene 8a has a small portal with a comparatively large source behind it. The monkey is in the monkey is then in the antiantumbra of the portal, making uniform portal sampling the best approach.
- Scene 8b has a large portal with a small light behind it. The monkey is in the antiumbra, making Light sampling the optimal approach.
- Scene 8c has a similarly sized light and portal, arranged so that they don't fully overlap. The monkey is then located in the antipenumbra, making projection sampling optimal.

For each scene, we compare against the four sampling approaches presented in the paper. Each sampling strategy is then combined with BSDF sampling using MIS.

- **Light (baseline):** Sampling the target lights area uniformly.
- **Portal:** Sampling the portal area uniformly .
- **Projection:** Sampling the lights projection onto the portal.
- **Antishadow:** First we determine in which region of the portal's antishadow the shading point resides in, then choose the least expensive, optimal strategy from the above three.

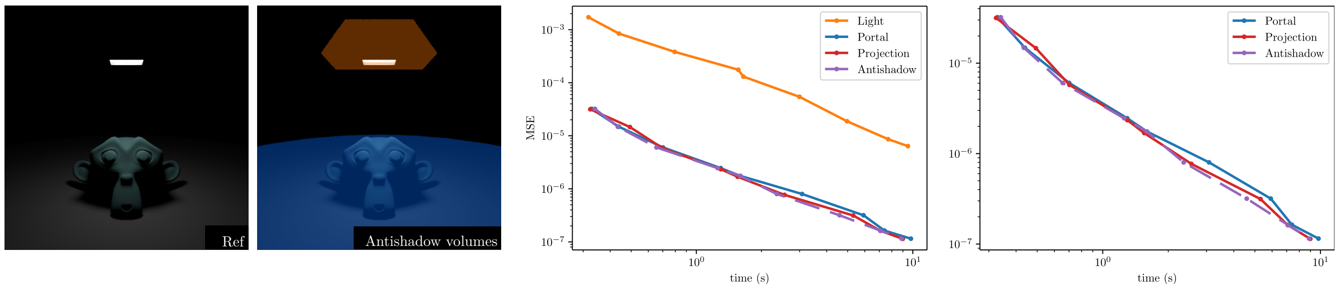
We provide the measured MSE over time for each sampling strategy. The results indicate that light and portal sampling are not robust as each strategy only works well in one of the three scenes. Projection is robust as it works adequately in all scenes, but at a minor runtime overhead, due to projecting and clipping the portal. Lastly, antishadow-based sampling gives the best of both worlds, as it works well in all scenes and has a lower runtime overhead than projection sampling.

6 Discussion

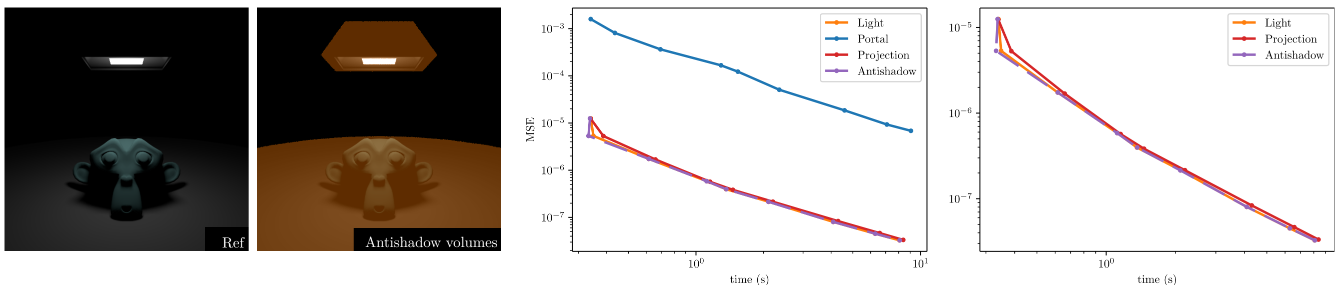
We have shown that our method generally increases the convergence of direct lighting calculations at the expense of some additional artist input in specifying the portal location. However, we believe this burden on the artist is not too significant. Since light portals for environment lights are already widely adopted. The only additional change in artist workflow would be optionally allowing to change the target of a light portal to an area light.

6.1 Responsible research

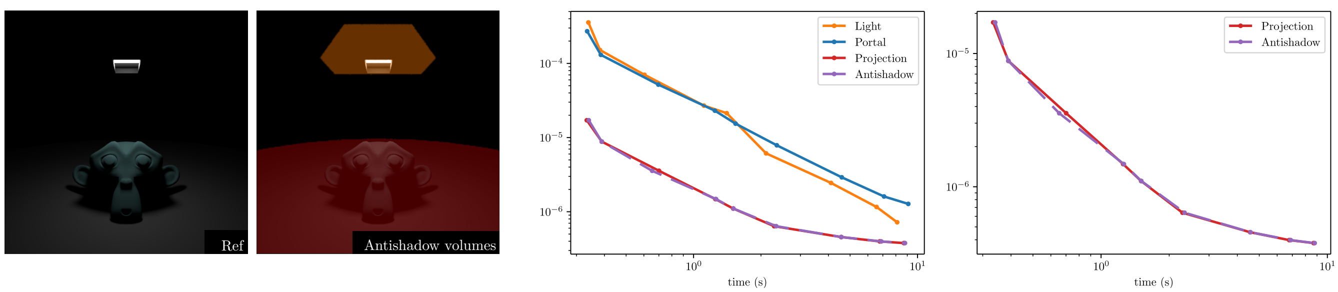
Reproducibility in computer graphics is crucial, as it enables verifying and improving existing techniques. To ensure that our method is reproducible, we include implementation details in Section 4 and chose to implement our method in the publically available and open-source renderer PBRT-v3 [PJH16], and use simple



(a) ***Large light, small portal:*** *Optimal sampling strategy is portal.*



(b) ***Small light, large portal:*** *Optimal sampling strategy is light sampling.*



(c) ***Balanced light and portal:*** *Optimal sampling strategy is projection.*

Figure 8: *We compare light sampling (baseline), portal sampling, projection sampling and antishadow-based sampling for three* Suzanne *scenes, differing in the portal-light solid angle ratios. Light and portal sampling are not robust as they fail in all scenes but one. Projection sampling works well in all scenes at a small runtime cost, and antishadow-based sampling works as well as projection sampling but at a decreased runtime cost.*

scenes with a publicly available model. This work follows the research integrity principles from the *Netherlands code of conduct* [KNA+18].

6.2 Limitations and Future work

Arbitrary geomertry For arbitrary polygonal objects, the shape of the umbra and penumbra regions can be embedded in a discontinuity mesh constructed from the edges and vertices of the light, and the portal [DF94]. However, for simplicity, we implement a version of this algorithm limited to rectangular aligned light and portal.

Throughout the paper, we assumed that the portal and light are aligned, rectangular planes. While this restriction simplifies some calculations, it can be quite restrictive. However, generalizing to arbitrary geometry is, in principle, straightforward. The antishadow umbra and penumbra can be calculated for arbitrary polygonal light and portal by using existing efficient shadow algorithms [DF94]. While the more general algorithm may introduce substantial overhead, this could be alleviated by caching the shadow volume data in a spatial data structure.

Projection sampling can also be generalized to arbitrary polygonal geometry by using a general clipping algorithm [GH98] and then sampling the clipped triangle mesh. While this would also introduce overhead, it is decreased by using shadow volumes.

Light portals for point lights Throughout this paper, we have focused on applying light portals to area lights. However, the method provided is general enough to be applied to other kinds of lights, such as point lights. In this case, the antishadow is significantly simplified as it is made up only of the umbra.

7 Conclusion

We have extended the concept of light portals to be efficiently used with area lights. Our technique relies on geometric shadow volumes algorithms to determine the most effective sampling strategy depending on the location of the point being shaded. We demonstrated that this approach is more robust and efficient than alternatives for a variety of portal-light arrangements. Our method handles several lights and several portals and requires relatively low artist input.

8 Acknowledgements

We would like to thank the authors of Physically Based Rendering From Theory to Implementation [PJH16] for making the book and its corresponding code base publicly available. Additionally, we thank the Blander foundation for providing open-source 3D modelling tooling. Lastly, we thank Pavlos Makridis, Mathanrajan Sundarajan, Tan Dao and Piyush Deshmukh for their numerous helpful suggestions spanning the entire project.

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