Adaptive BRDF-Oriented Multiple Importance Sampling of Many Lights

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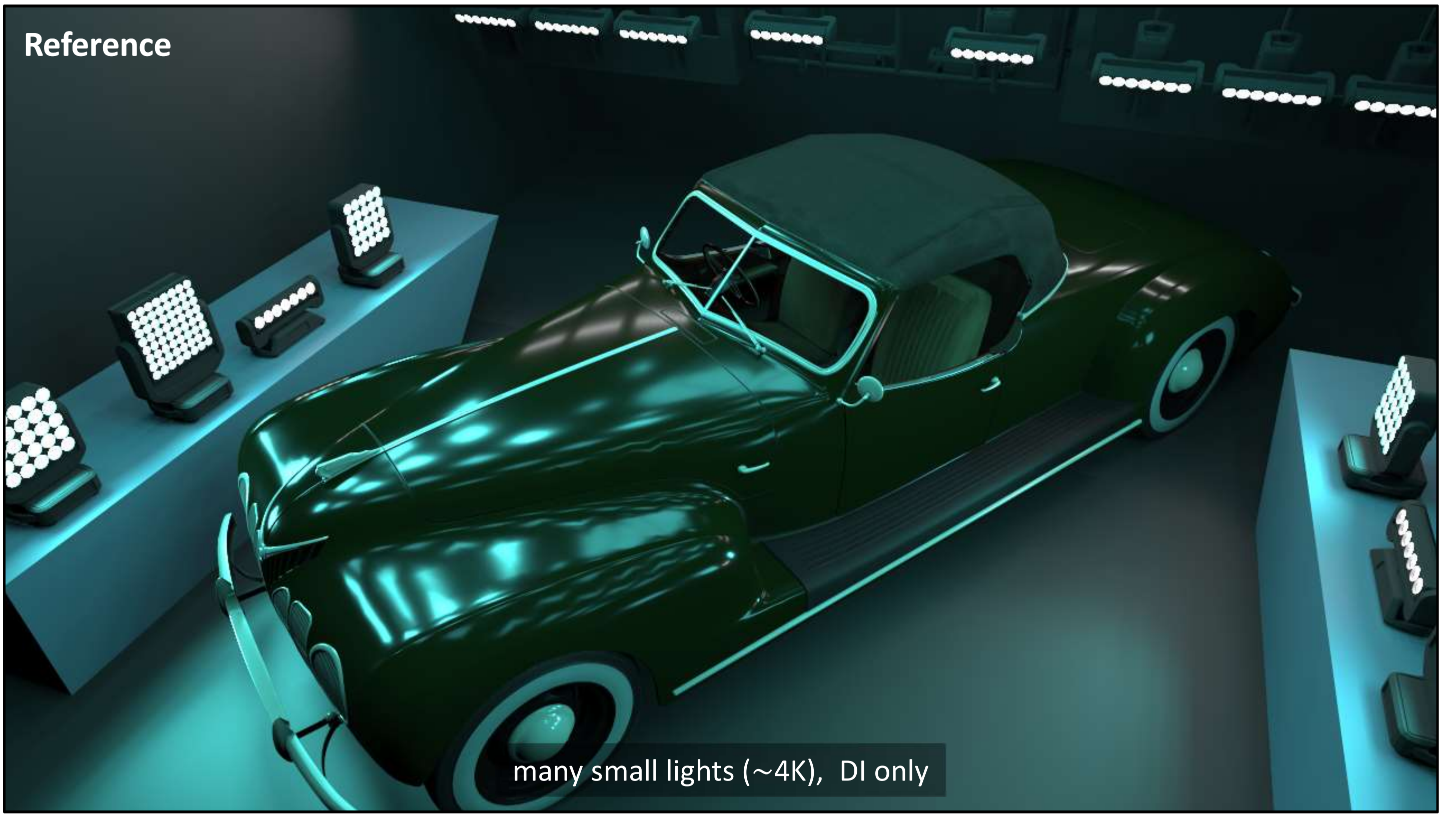
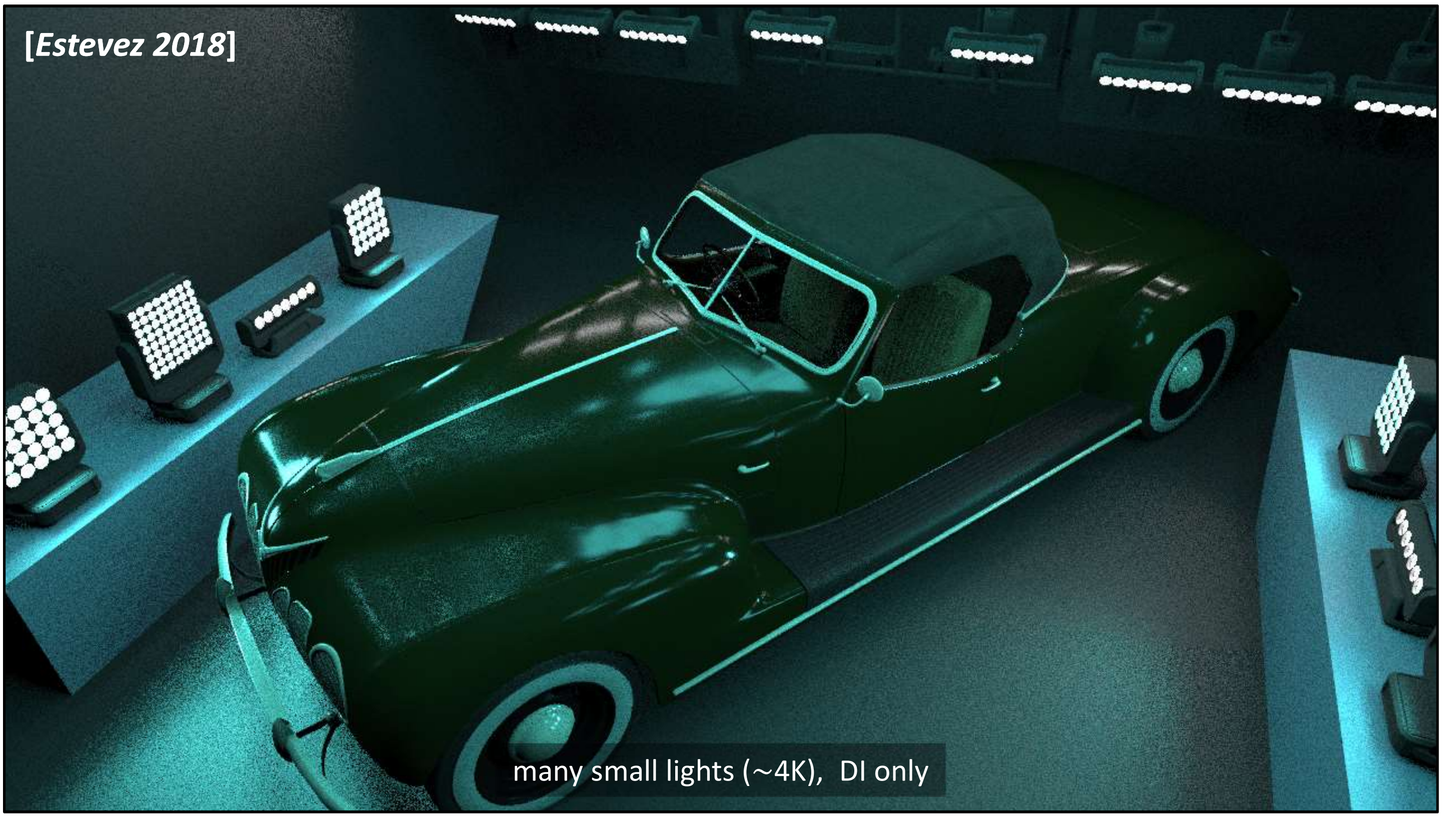
Thanks for the introduction.
In this talk, I will present a technique for direct illumination importance sampling in scenes with many lights.

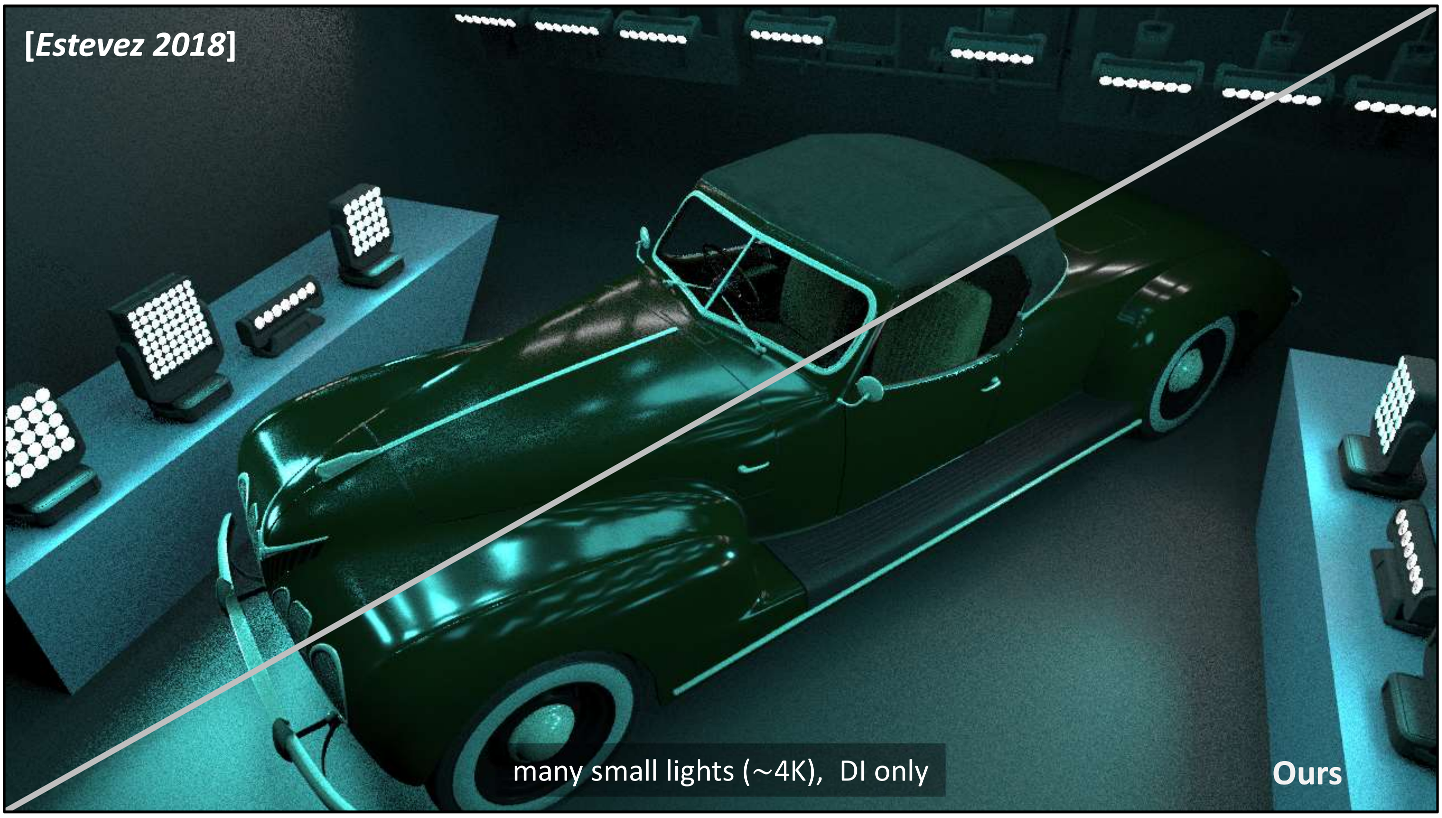


This is a scene containing many small lights. The car and the ground have glossy materials.

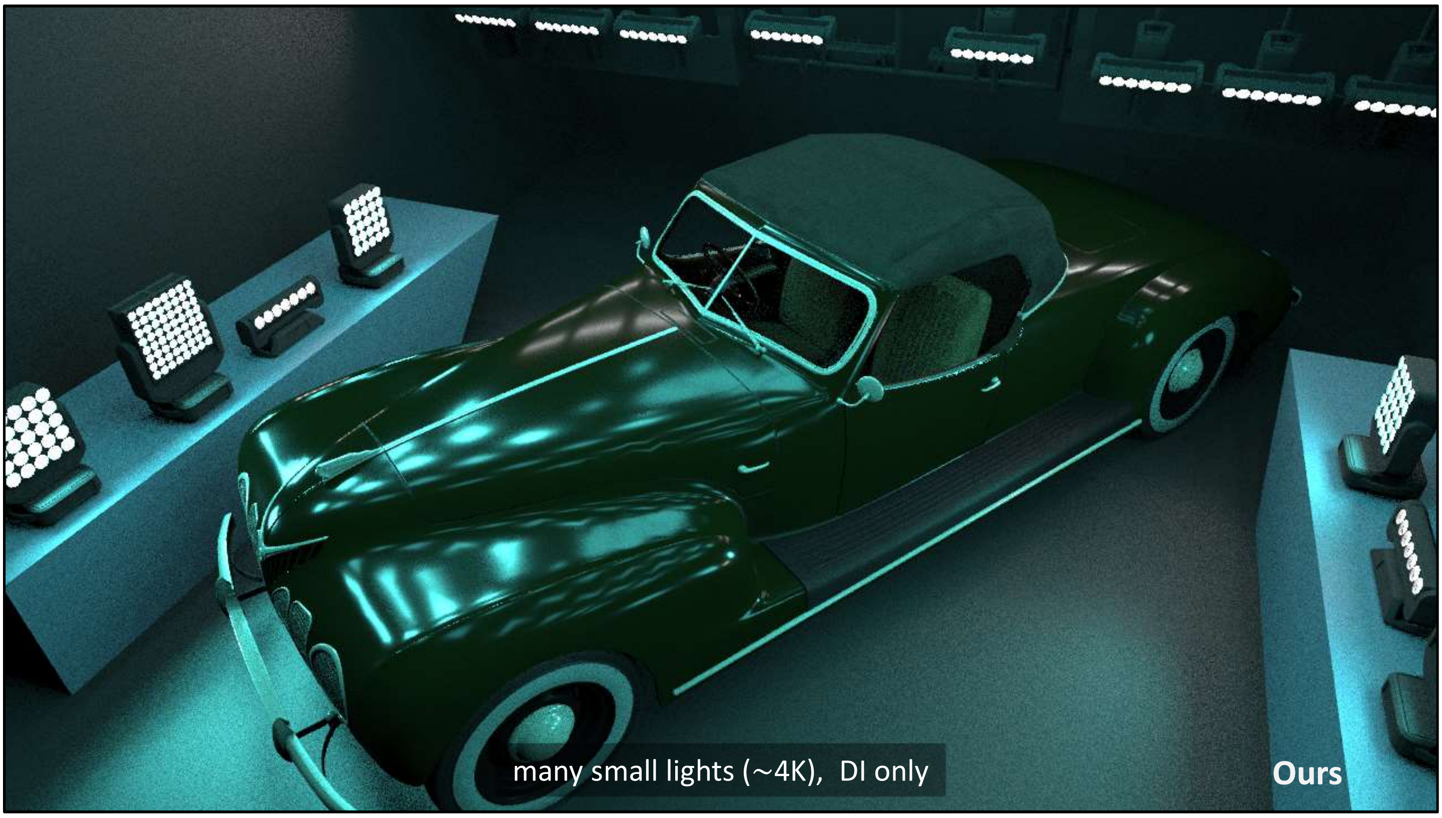
We only consider ***direct illumination*** here. We can see the reflections of small area lights.



Usually previous methods have difficulties in rendering this scene, we can see that small reflections have gone and the ground has much noise.



While using our algorithm, we get great improvements, especially on the reflections of small area lights.



This is a full image of our result.

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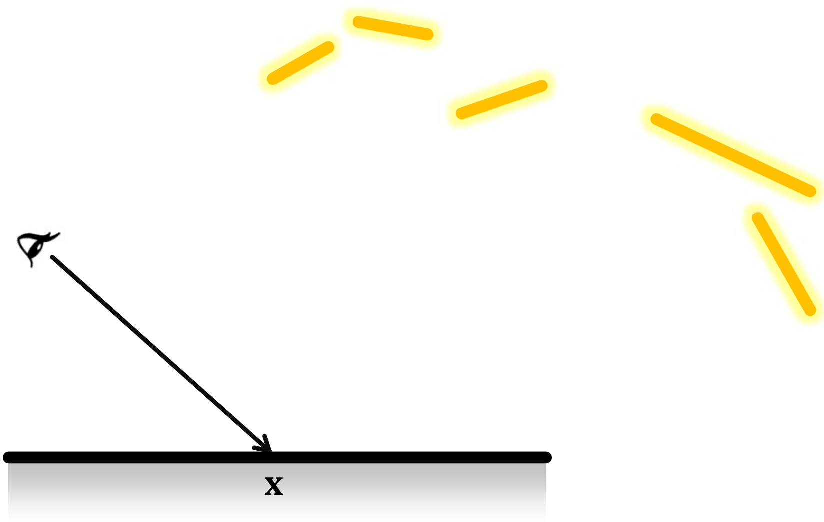
Background

Adaptive BRDF-Oriented Multiple Importance Sampling of Many Lights

First, let me give you some background related to direct illumination of many lights

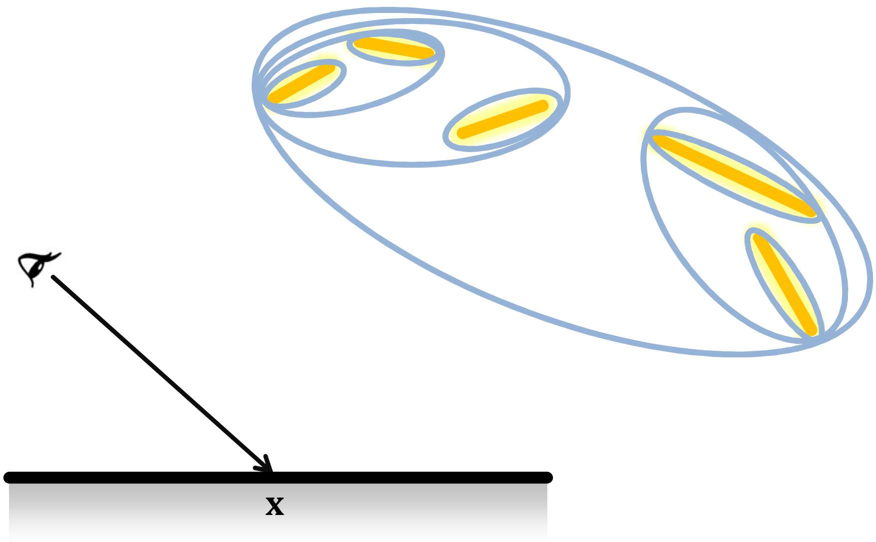
Direct illumination



In the context of direct illumination, we should estimate the contribution of each light directly at each shading point.

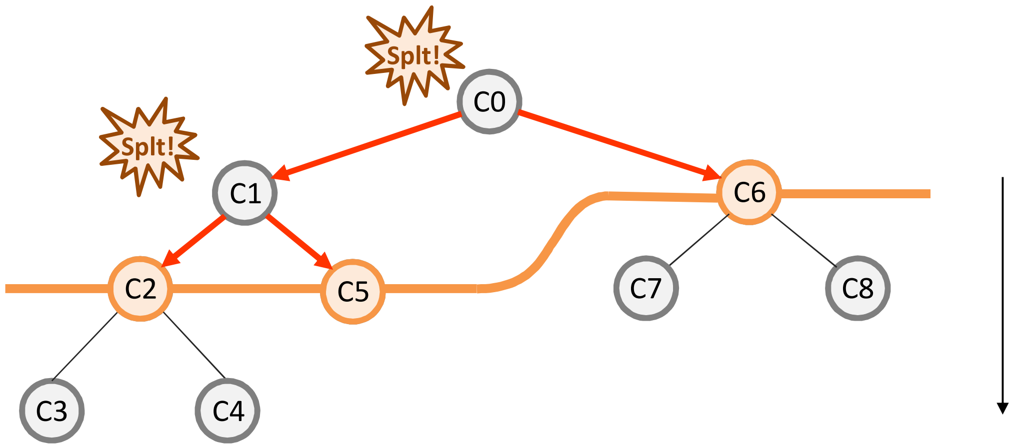
Light tree & Light cut

- Lightcuts [*Walter 2005*]
- SAOH heuristic [*Estevez 2018*]



For a scene filled with many lights, we usually construct a hierarchy of lights to improve scalability. **[click]**
And then for each shading point, we search a light cut via certain light node splitting metric.

Light tree & Light cut



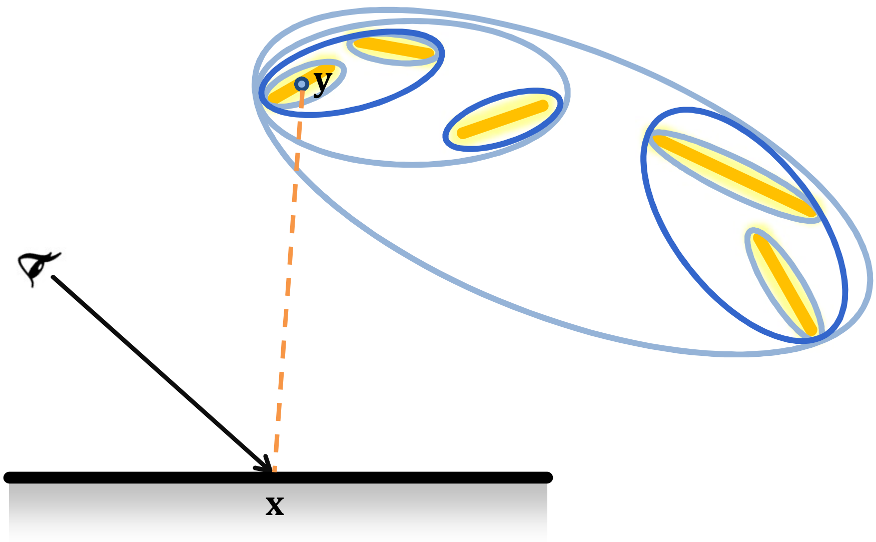
Light tree

A light cut is a collection of clusters of lights. For example, we may find a cut consists of light node C2, C5, and C6.

Light sampling

- Consider BRDF [*Wang 2009*]
- Consider visibility [*Wu 2013*]
- Consider visibility [*Vévoda 2018*]

For diffuse surfaces,
it is good…



Once finding a light cut, we can perform light sampling. It usually consists of three steps: **[click]** choose a light cluster, **[click]** choose a light within the selected cluster, **[click]** and choose a point on the selected light. At last the lighting contribution of that light point is evaluated.

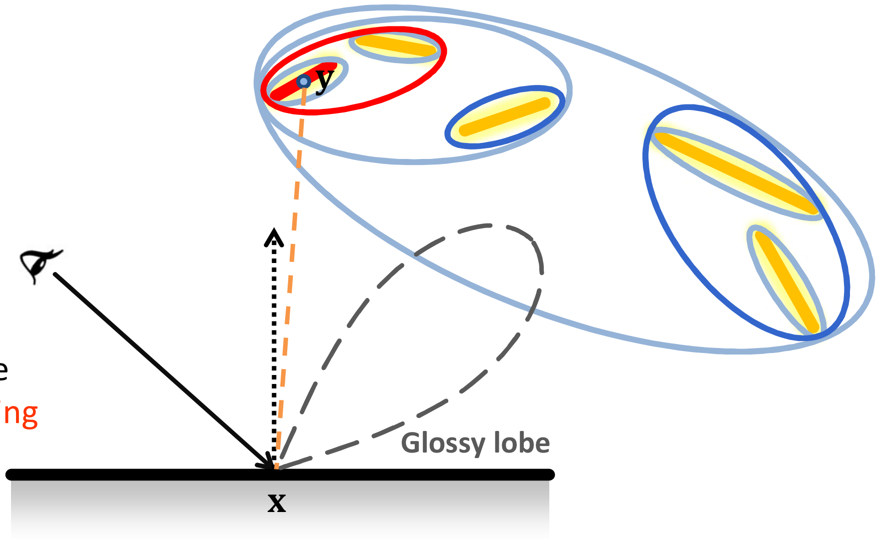
[click]
For diffuse surface, light sampling performs quite well.

Light sampling

- Consider BRDF [*Wang 2009*]
- Consider visibility [*Wu 2013*]
- Consider visibility [*Vévoda 2018*]

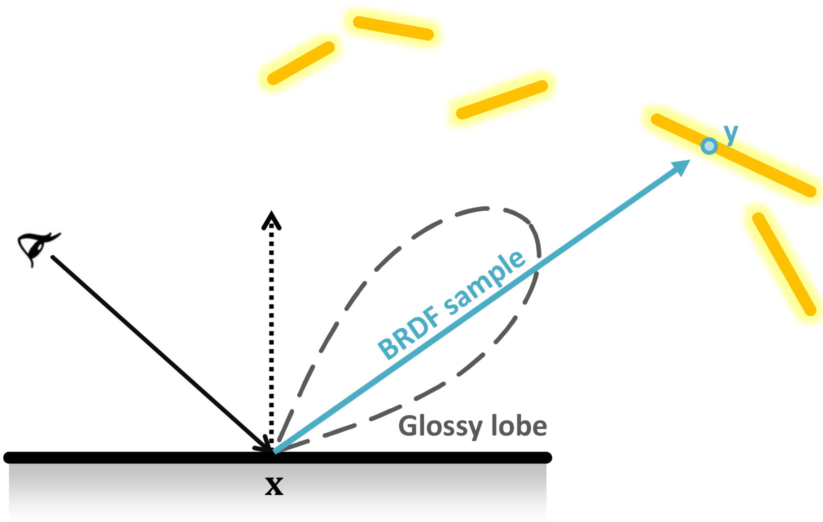
For glossy surfaces,

- Light sampling becomes inefficient
- All previous works rely on the performance of BRDF sampling



However, for glossy surfaces light sampling may become very inefficient. For example, the selected point y is outside the glossy lobe thus has little lighting contribution. The reason is that most previous methods doesn't consider BRDF during light sampling and they choose a combination with BRDF sampling to remedy it. *Wang et al. takes BRDF into account by counting the hit number between BRDF samples and light clusters. However, it still rely on the performance of BRDF sampling.*

BRDF sampling

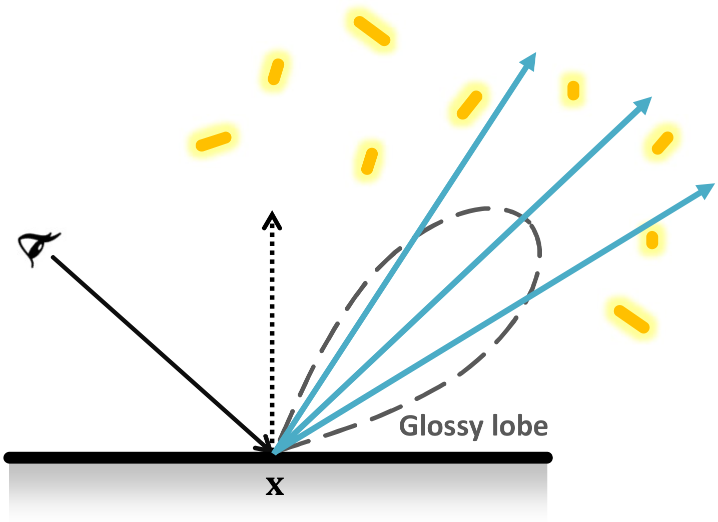


BRDF sampling, is to sample a ray from the shading point according to the distribution of BRDF. It calculates the intersection point of the sampled ray with lights and then it evaluates lighting contribution of that intersection point.

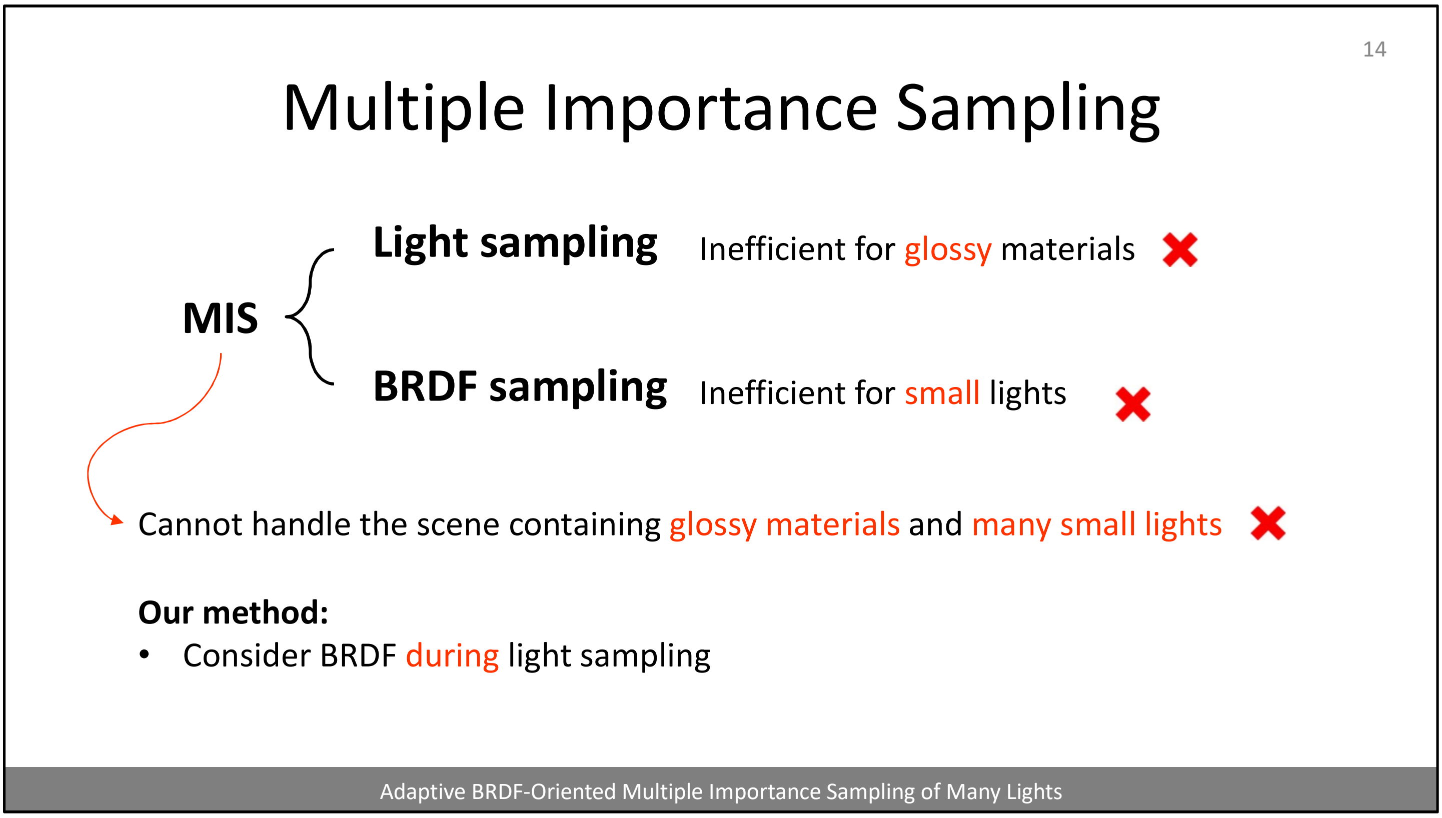
BRDF sampling

However…

BRDF sampling may hardly work for scene with many small lights!



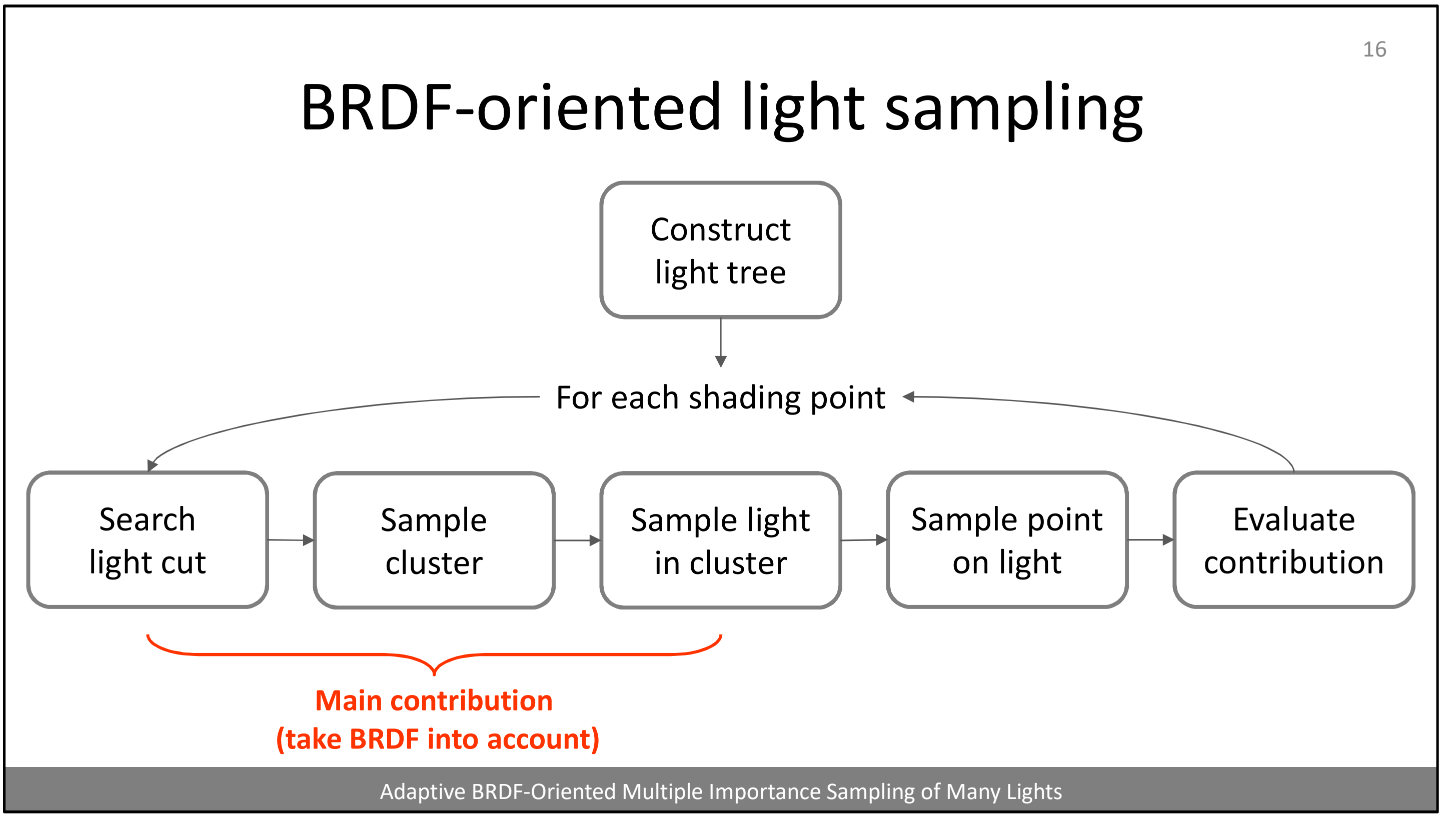
However, there is a problem that the sampled direction cannot always hit lights. As you might have probably guessed, the smaller the surface area of lights is, the more likely BRDF sampling fails. Under extreme situations, the BRDF sampling might not work at all!!!



A typical multiple importance sampling usually consists of light sampling and BRDF sampling. It works only if at least one of the two sampling techniques is efficient. **[click]** However, light sampling is not efficient for glossy materials, **[click]** and BRDF sampling is not efficient for small area lights. **[click]** Thus, the traditional MIS cannot handle the scene containing both glossy materials and many small lights. **[click]** In view of this, our method considers BRDF during light sampling and can solve the problem described above.

Our approach

Now let me introduce our approach…

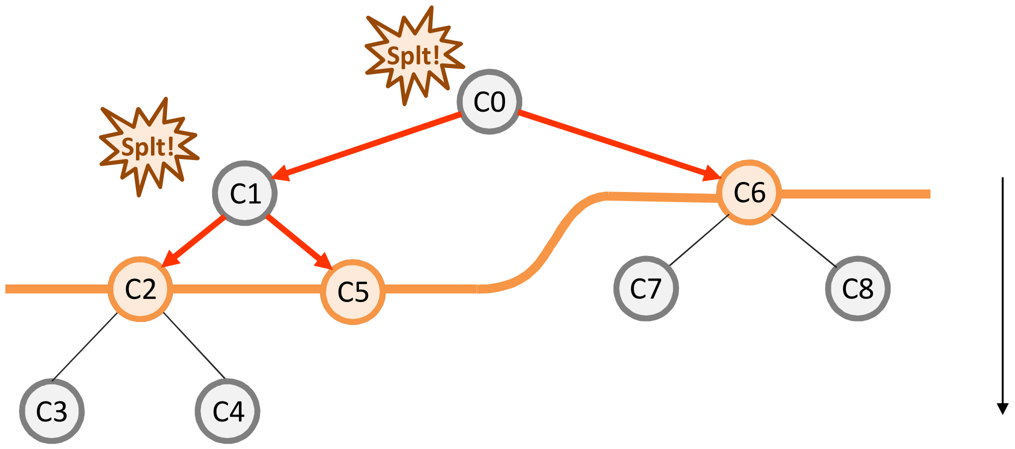


As the name implies, our BRDF-oriented light sampling takes BRDF into account. **[click]** Similar to other many light sampling methods, we first construct a light tree in a preprocessing step. A light tree is a hierarchy that organizes all the lights in the scene and it's fixed after the preprocessing step. **[click]** During rendering, for each shading point **[click]** we search for a light cut. **[click]** sample a cluster, **[click]** sample a light in the cluster, **[click]** and sample a point on the light, **[click]** and evaluate the lighting contribution of the light point. **[click]**

The main contribution of our sampling technique lies in the steps of searching light cut, sampling cluster and sampling light within the cluster.**[click]**

First let we look at the step of light cut search.

Light cut search



Light tree

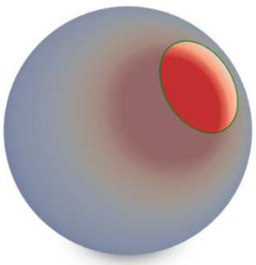
The process of searching a light cut, is to start from the root node of the light tree. We recursively split the light node when some metric is met.

Light cut search

Split a light node when:

- Shading point lies in the light node's bounding sphere
- The light node covers a large proportion of shading point's glossy lobe:

$$\int_{\Omega_C} B(\mathbf{x}, \omega_i, \omega_o) \cos\theta_{\mathbf{x}} \mathrm{d}\omega_i > \delta \text{ (threshold parameter)}$$

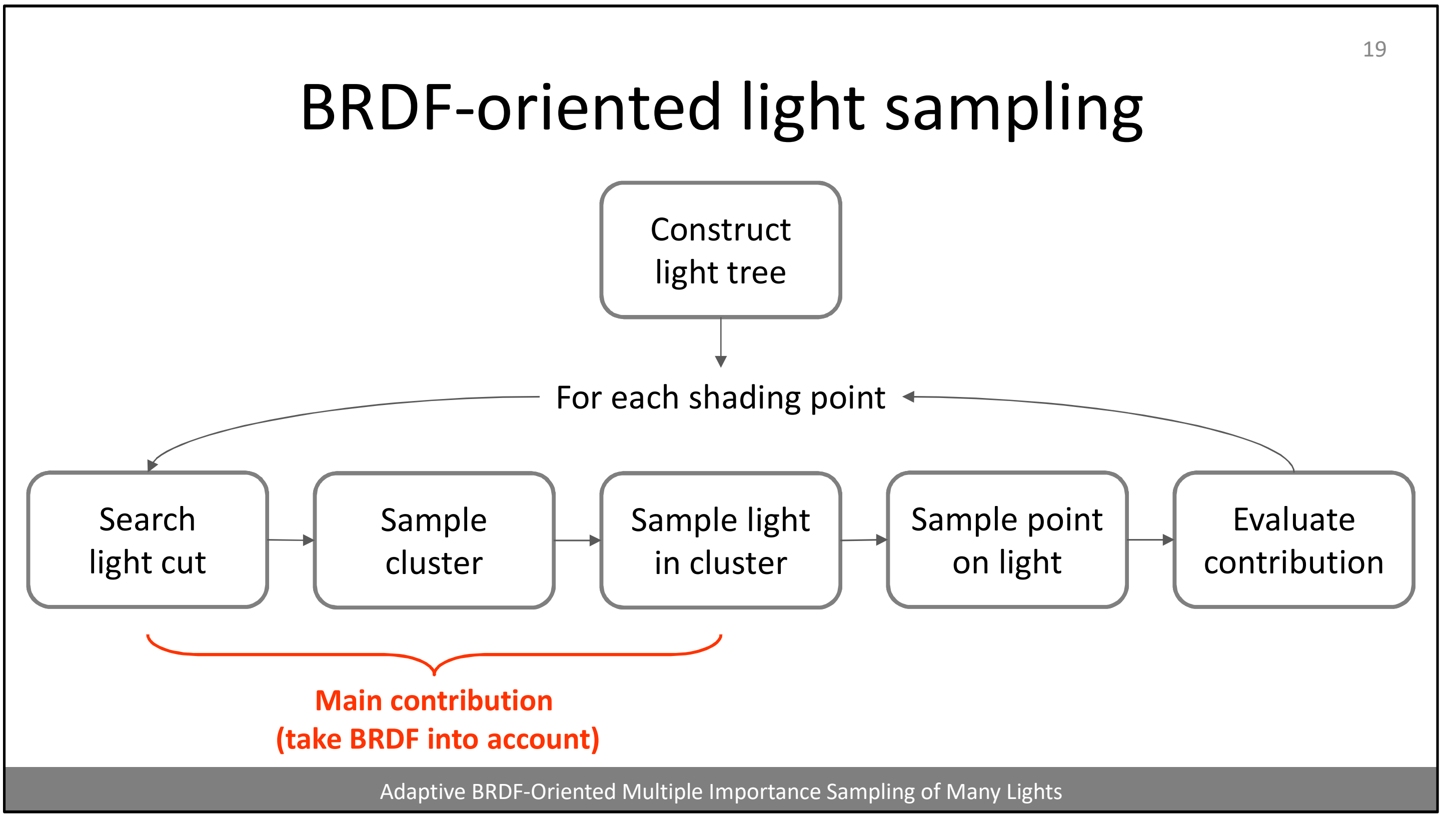


Analytic area light shading methods:

- Linearly Transformed Cosines (LTCs) [*Heitz 2016*]
- Spherical Pivot Transformed Distributions (SPTDs) [*Dupuy 2017*] ✔

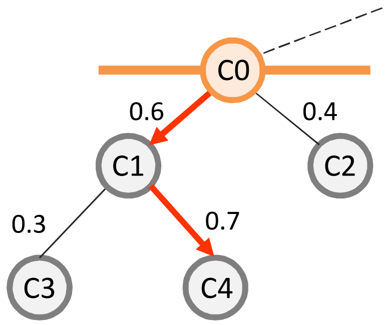
Our light node splitting metric is that: First, when the shading point lies in the light node's bounding sphere, the importance measure will have a large error and thus we need to split this node. Second, When the light node covers a large proportion of shading point's glossy lobe, we should further refine this light node. See in the formula, we compare the cosine weighted BRDF integral with a predefined parameter \delta. If it's larger than this parameter, we split this node. **[click]**

For estimating the cosine weighted BRDF integral, we choose to use state of art methods on analytic area light shading, such as LTCs and SPTDs. **[click]** In our implementation, we use SPTDs for efficiency. In other words, we approximate the cosine weighted BRDF as pivot transformation distributions and fetch the integral over a sphere's solid angle from a pre-generated table.



Once a light cut has been selected, we move on to the steps of cluster sampling, and light sampling in a cluster. Actually, both of them can be regarded as light node sampling.

Light node sampling



Light tree

Cluster sampling
- Build discrete distribution over clusters and sample one
- → C0

Light sampling in cluster
- Recursively sample one child until leaf node [*Estevez 2018*]
- → C1 → C4

We need to evaluate the importance of a light node!

For cluster sampling, we build a discrete distribution over clusters and sample one. **[click]** For example, we sample C0 here.
[click]
After selecting a cluster, we need to sample a light in it. We follow Estevez's, recursively compare importance of children and sample one of them until leaf node. **[click]** Here we may sample C1 first and then sample C4. **[click]**

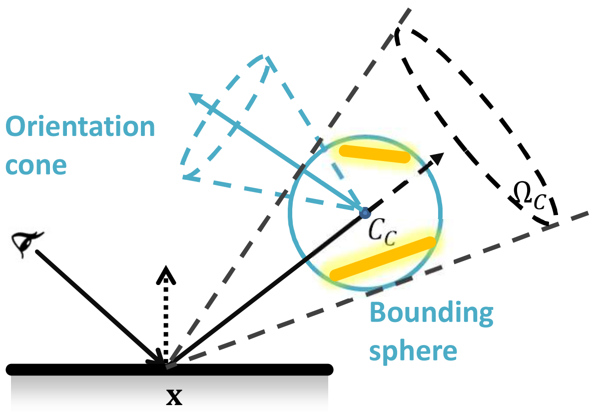
Both in the two sampling procedures, we need to evaluate the importance of a light node. So how we compute the importance?

Importance of a light node

Importance of light node C is a product of three factors:

- E_C: Total energy of the light node
- G_C: The geometry term
- B_C: BRDF term

$$I_C(\mathbf{x}) = E_C G_C B_C$$



The importance of a light node C is a product of three factors: the total energy of the light node E_C, the geometry term G_C, and the BRDF term B_C.

To make this formula practical to calculate, we need to perform some formula transformation.

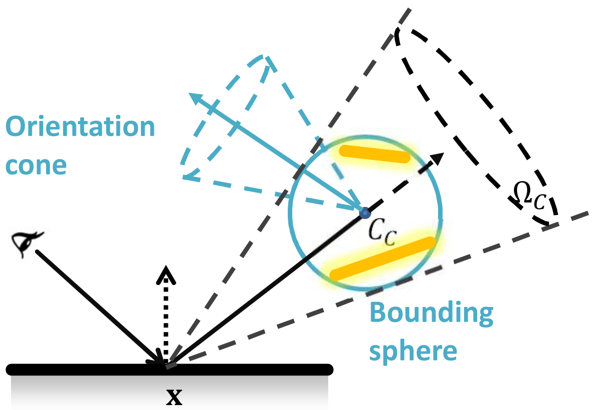
Importance of a light node

Importance of light node C is a product of three factors:

- E_C: Total energy of the light node
- G_C: The geometry term
- B_C: BRDF term

$$I_C(\mathbf{x}) = E_C G_C B_C$$

$$\approx E_C G_C \frac{1}{\Omega_C} \int_{\Omega_C} B(\mathbf{x}, \omega_i, \omega_o) \mathrm{d}\omega_i$$



We first approximate the BRDF term using the average of it. That is, we integrate BRDF over the solid angle of the light node's bounding sphere, and then divide it by the solid angle.

Importance of a light node

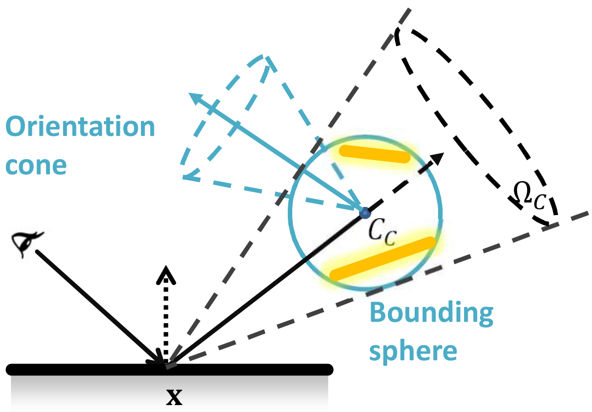
Importance of light node *C* is a product of three factors:

- E_C: Total energy of the light node
- G_C: The geometry term
- B_C: BRDF term

$$I_C(\mathbf{x}) = E_C G_C B_C$$

$$\approx E_C G_C \frac{1}{\Omega_C} \int_{\Omega_C} B(\mathbf{x}, \omega_i, \omega_o) \mathrm{d}\omega_i$$

$$\approx E_C \frac{\cos\theta_C \cos\theta_{\mathbf{x}}}{d(\mathbf{x}, \mathrm{ctr}(C))^2} \frac{1}{\Omega_C} \int_{\Omega_C} B(\mathbf{x}, \omega_i, \omega_o) \mathrm{d}\omega_i$$



We replace the G_C term with its expanded form, *where ctr function returns the center point of the light node's bounding sphere. \theta_C stands for the angle between light direction and normal of surface of lights and \theta_x stands for the angle between light direction and normal of shading point.*

Importance of a light node

Importance of light node C is a product of three factors:

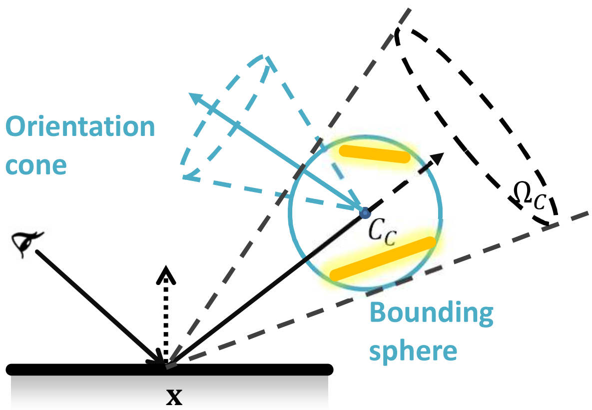
- E_C: Total energy of the light node
- G_C: The geometry term
- B_C: BRDF term

$$I_C(\mathbf{x}) = E_C G_C B_C$$

$$\approx E_C G_C \frac{1}{\Omega_C} \int_{\Omega_C} B(\mathbf{x}, \omega_i, \omega_o) \mathrm{d}\omega_i$$

$$\approx E_C \frac{\cos\theta_C \cos\theta_{\mathbf{x}}}{d(\mathbf{x}, \mathrm{ctr}(C))^2} \frac{1}{\Omega_C} \int_{\Omega_C} B(\mathbf{x}, \omega_i, \omega_o) \mathrm{d}\omega_i$$

$$\approx E_C \frac{\overline{\cos\theta_C}}{d(\mathbf{x}, \mathrm{ctr}(C))^2} \frac{1}{\Omega_C} \int_{\Omega_C} B(\mathbf{x}, \omega_i, \omega_o) \cos\theta_{\mathbf{x}} \mathrm{d}\omega_i$$



At last, put the cos\theta_x into the integral and use the upper bound of cos\theta_C to approximate the original one.

Importance of a light node

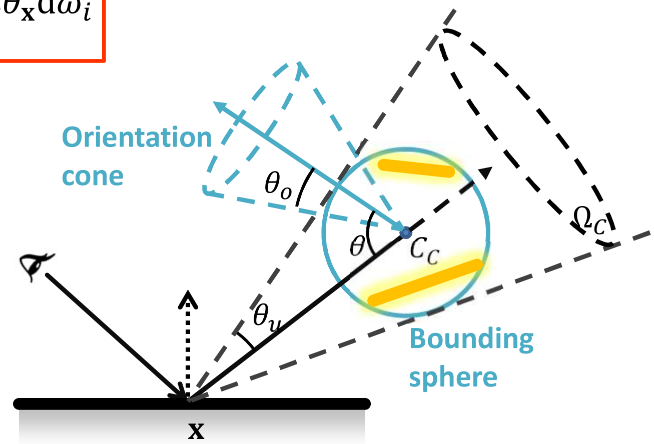
$$I_C(\mathbf{x}) \approx E_C \frac{\overline{\cos\theta_C}}{d(\mathbf{x}, \mathrm{ctr}(C))^2} \frac{1}{\Omega_C} \int_{\Omega_C} B(\mathbf{x}, \omega_i, \omega_o) \cos\theta_{\mathbf{x}} \mathrm{d}\omega_i$$

$$\overline{\cos\theta_C} = \cos(\max(\theta - \theta_o - \theta_u, 0))$$

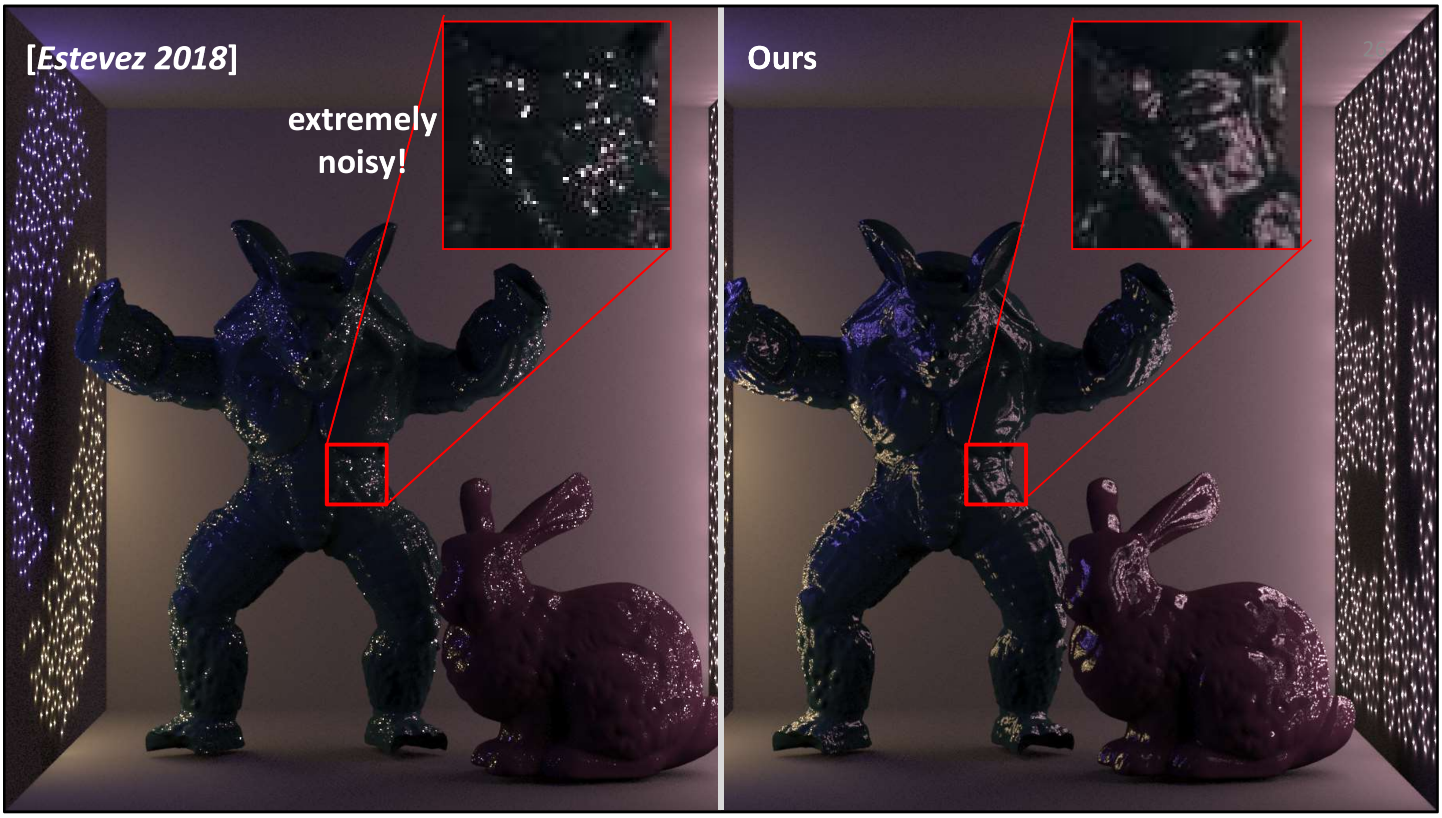
[*Estevez 2018*]

Analytic area light shading (SPTDs)

[*Dupuy 2017*]



Even though most terms of this formula are trivial to calculate, there are two terms I need to explain a little more here. The first is the upper bound of cos\theta_C. **[click]** We use the work of Estevez et al. *and it can be evaluated by the following formula on the screen.* **[click]** And the second is the cosine weighted BRDF integral, we estimate it using an exit analytic area light shading method, SPTDs, as what we do during light cut search.



Here is a result of our BRDF-oriented light sampling compared to Estevez et al.'s method. They use a combination with BRDF sampling for taking BRDF into account. The improvement is huge because of BRDF sampling scarcely works in this scene which contains many tiny sphere lights.

Multiple Importance Sampling

To be more robust…

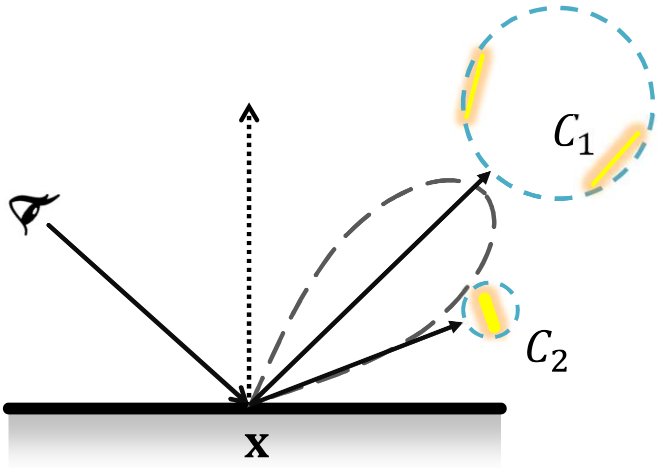
- BRDF-oriented light sampling
- Traditional light sampling [*Estevez 2018*]
- Traditional BRDF sampling

} Our MIS algorithm
(consist of 3 sampling techniques)

To further improve the robustness, we combine our BRDF-oriented light sampling with other two traditional sampling techniques —— traditional light sampling and BRDF sampling. Let me demonstrate the reasons one by one.

MIS: + traditional light sampling

- Our BRDF-oriented light sampling is affected by Error(B_C)
- Error(B_C) may be large because the high dynamic range



Tend to overestimate!

First let me show the need of combination with traditional light sampling. Our BRDF-oriented light sampling can be affected by the evaluation error of B_C, which may be very large because BRDF has a high dynamic range.

For example here, when we estimate the contribution of the lights within C1, we can only assume that the lights distribute uniformly in this circle. However, as you can see in this specific case, the lights within C1 completely miss the peak of the BRDF. This indicates that our BRDF-oriented light sampling will overestimate the contribution thus is not accurate.

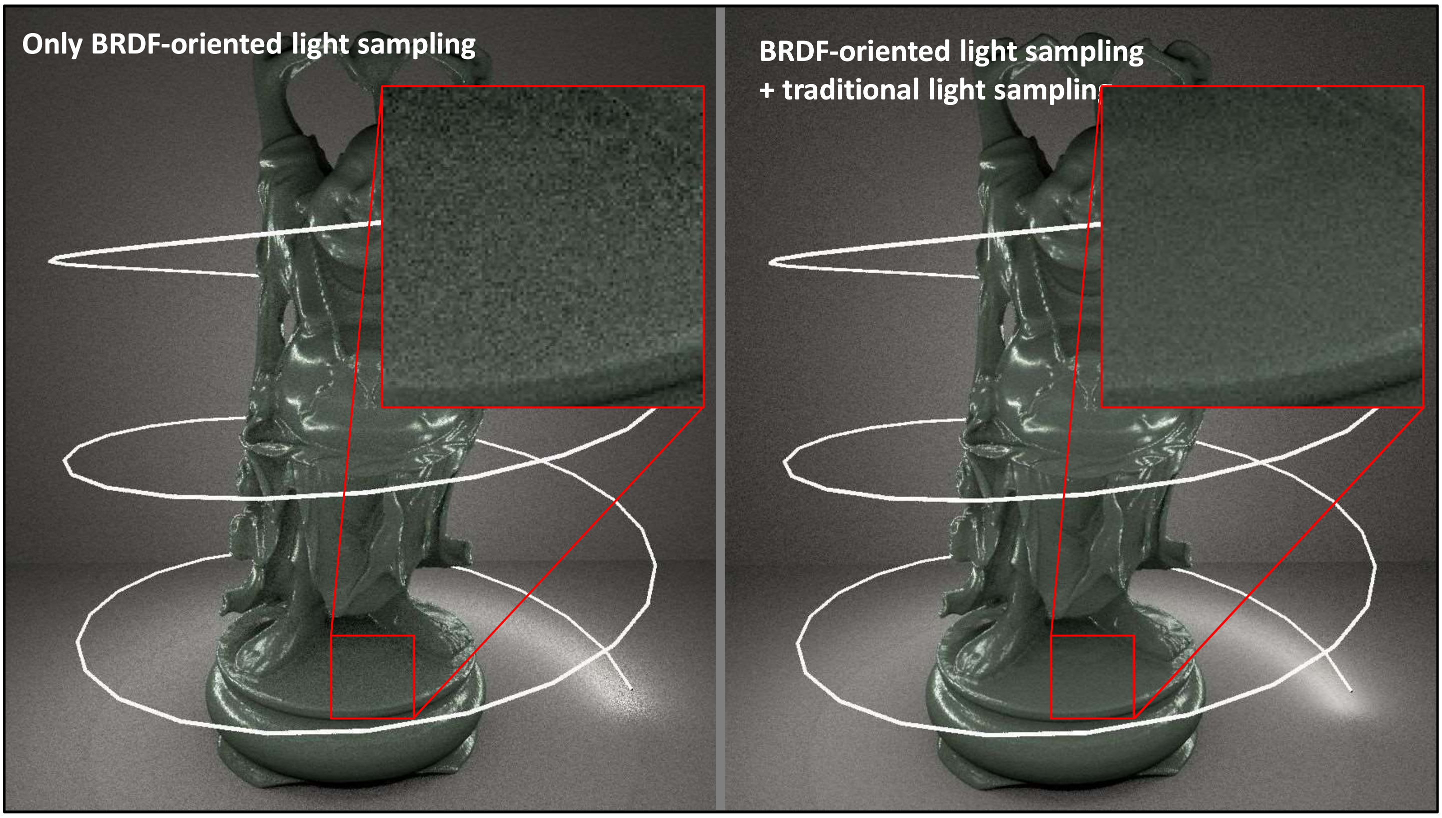
For example here, the estimate of B_C1 might be overlarge because the bounding sphere of C1 covers the peak of glossy lobe. This overestimate could result in large error on light node importance.

MIS: + traditional light sampling

Combine with a defensive light sampling (not considered BRDF)

- [*Estevez 2018*] ✔
- [Vévoda 2018]
- ……

To alleviates the dependence on BRDF, we combine our BRDF-oriented light sampling with a ***defensive*** light sampling technique. The “defensive” means it doen’t take BRDF into account. In our implementation, it is actually the method proposed by Estevez et al. And in principle, any other defensive light sampling techniques would achieve similar effects.



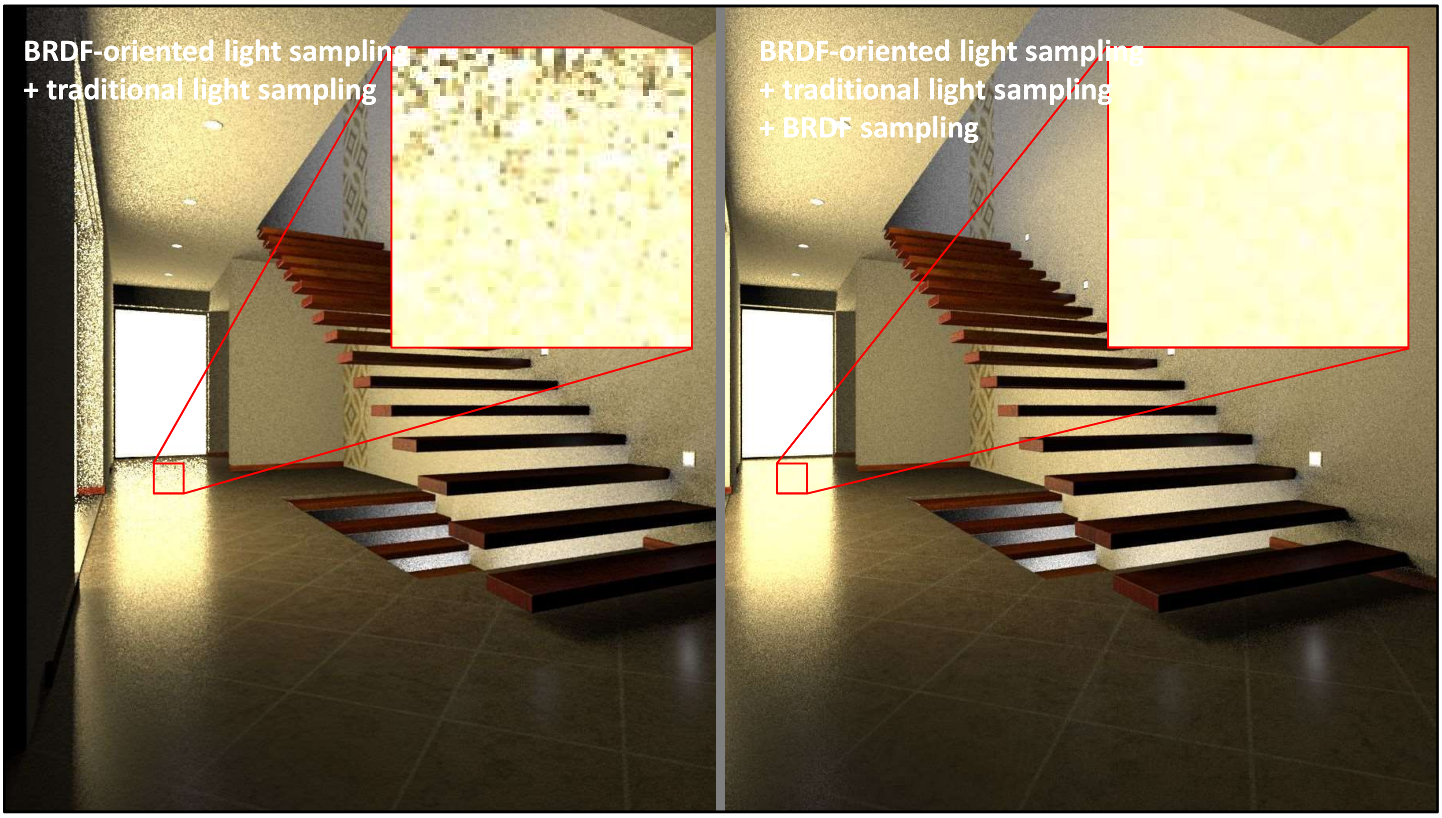
In this scene where the buddha has BRDFs with both diffuse and glossy terms, we can see that, **[click]** after combining with a defensive light sampling technique, the noise of result is further reduced, especially in the regions without highlights.

MIS: + classic BRDF sampling

It is difficult to consider BRDFs when sampling a point on a light

We make a combination with BRDF sampling

Secondly, it’s difficult to consider BRDF when sampling a point on a light, and in our BRDF-oriented light sampling, we uniformly sample a point according to the light’s shape like all previous methods. When a scene contains large area lights, this naïve uniform sampling method could be very inefficient, so we make a combination with BRDF sampling to ameliorate this problem.



We can see that, after combining with BRDF sampling, **[click]** the noise of reflection from large area lights is reduced further

Adaptive sample allocation

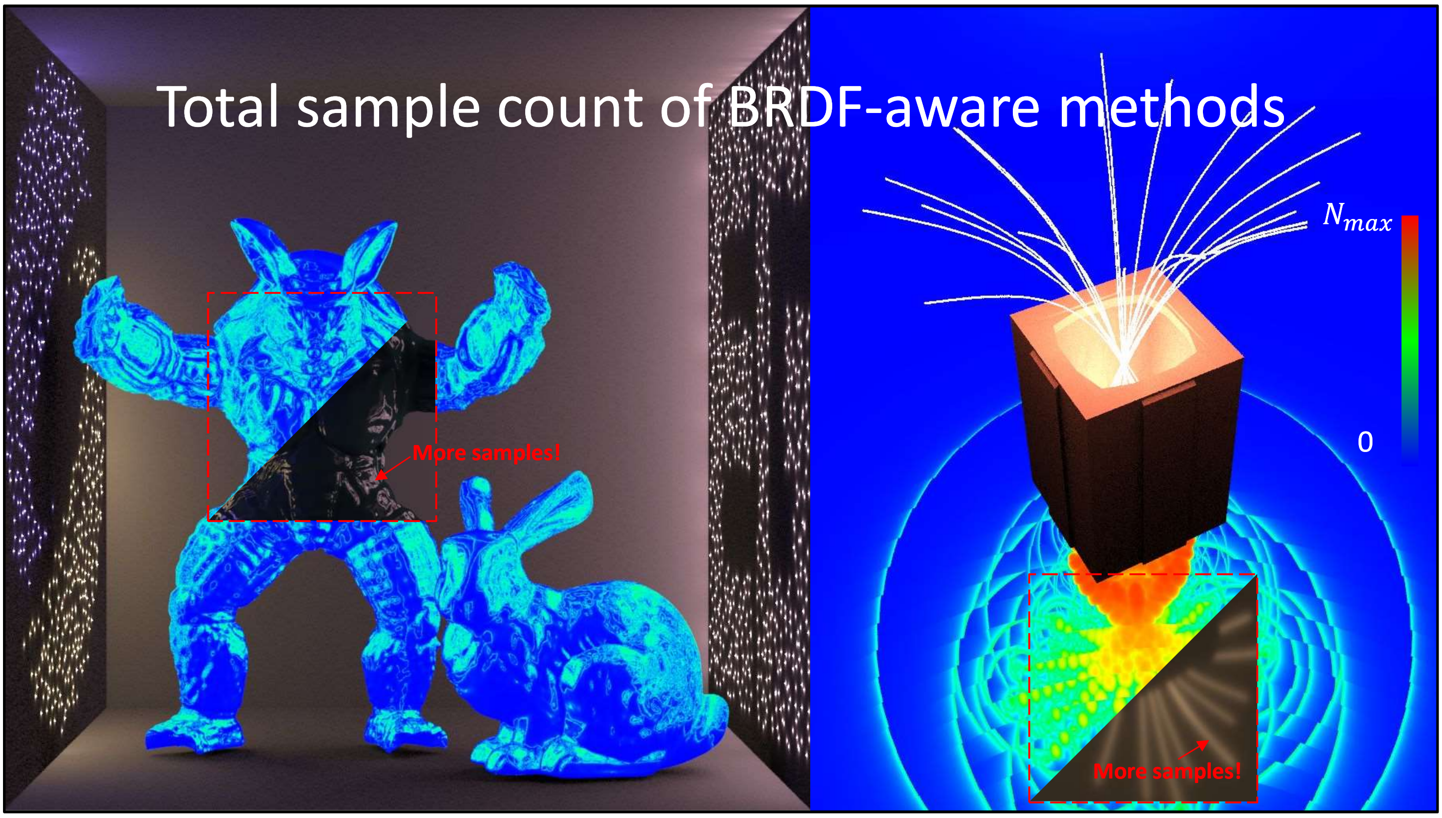
Our final MIS
- Traditional light sampling [*Estevez 2018*]
- BRDF-oriented light sampling
- BRDF sampling

BRDF-aware methods! (BRDF-oriented light sampling, BRDF sampling)

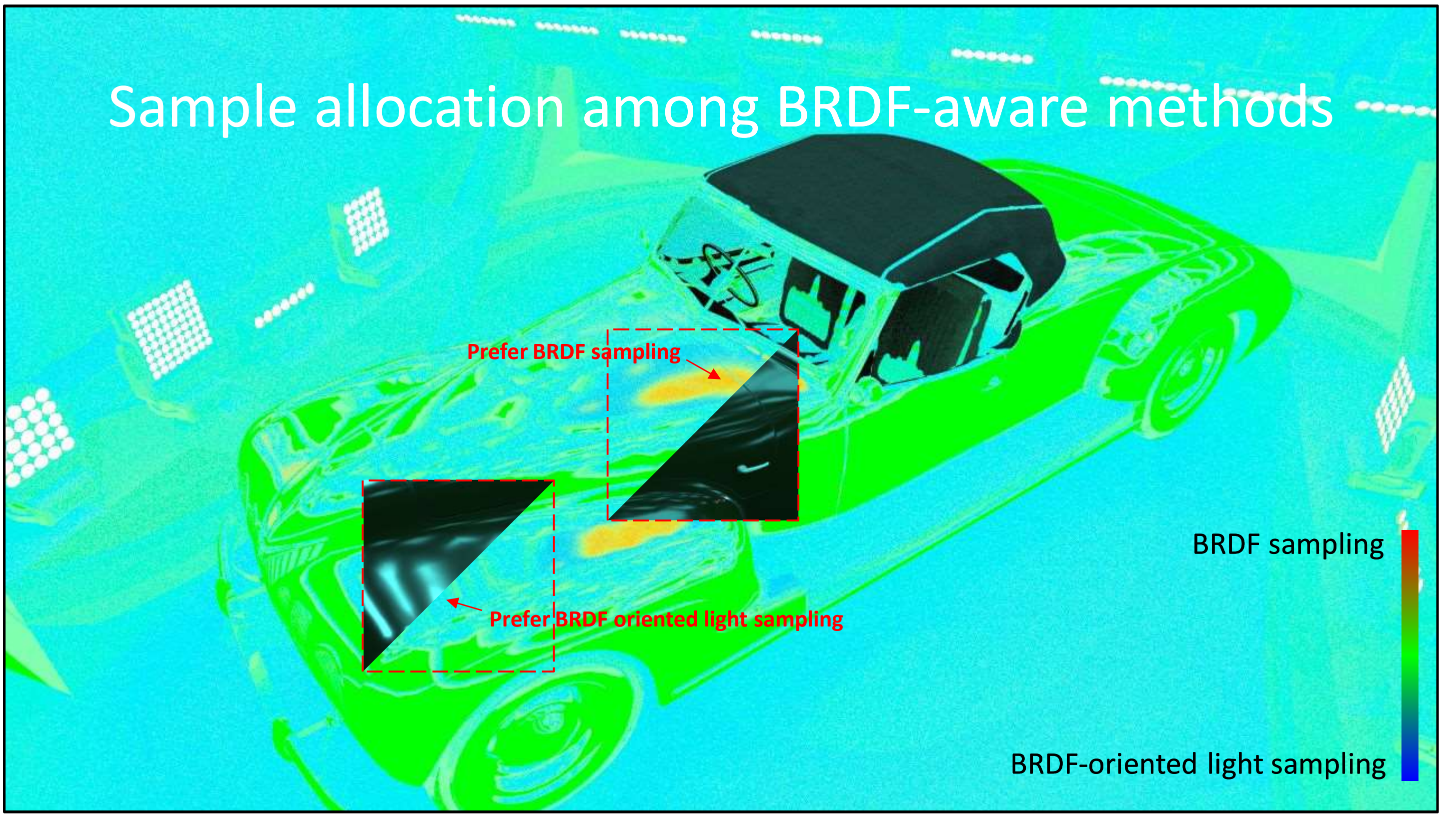
How to allocate samples?

heuristic!

Now, we get our MIS strategy. **[click]**
It is found that both the last two sampling techniques take the BRDF into account, for convenience we call them as BRDF-aware methods. **[click]**
Then, how we allocate samples among these sampling techniques? Making all samples equal is simple, but far from good. **[click]** As the number of samples for direct illumination calculation is usually small, we propose two heuristic methods instead of ones based on variance.



Our first heuristic considers the total sample count of BRDF-aware methods. Here is a visualization of sample count after using our heuristic. **[click]** It can be seen that the regions corresponding to reflections have larger values. Note that N_max is a predefined maximum sample count.



Our second heuristic considers sample allocation among the two BRDF-aware methods, namely, BRDF-oriented light sampling and BRDF sampling.

For the car scene from the beginning of the presentation, we make a visualization for the ratio of sample count after using our heuristic. Red means totally BRDF sampling and blue means totally BRDF-oriented light sampling. **[click]**

We can see the reflections from large area lights are redder and reflections from small area lights are bluer.

Summary

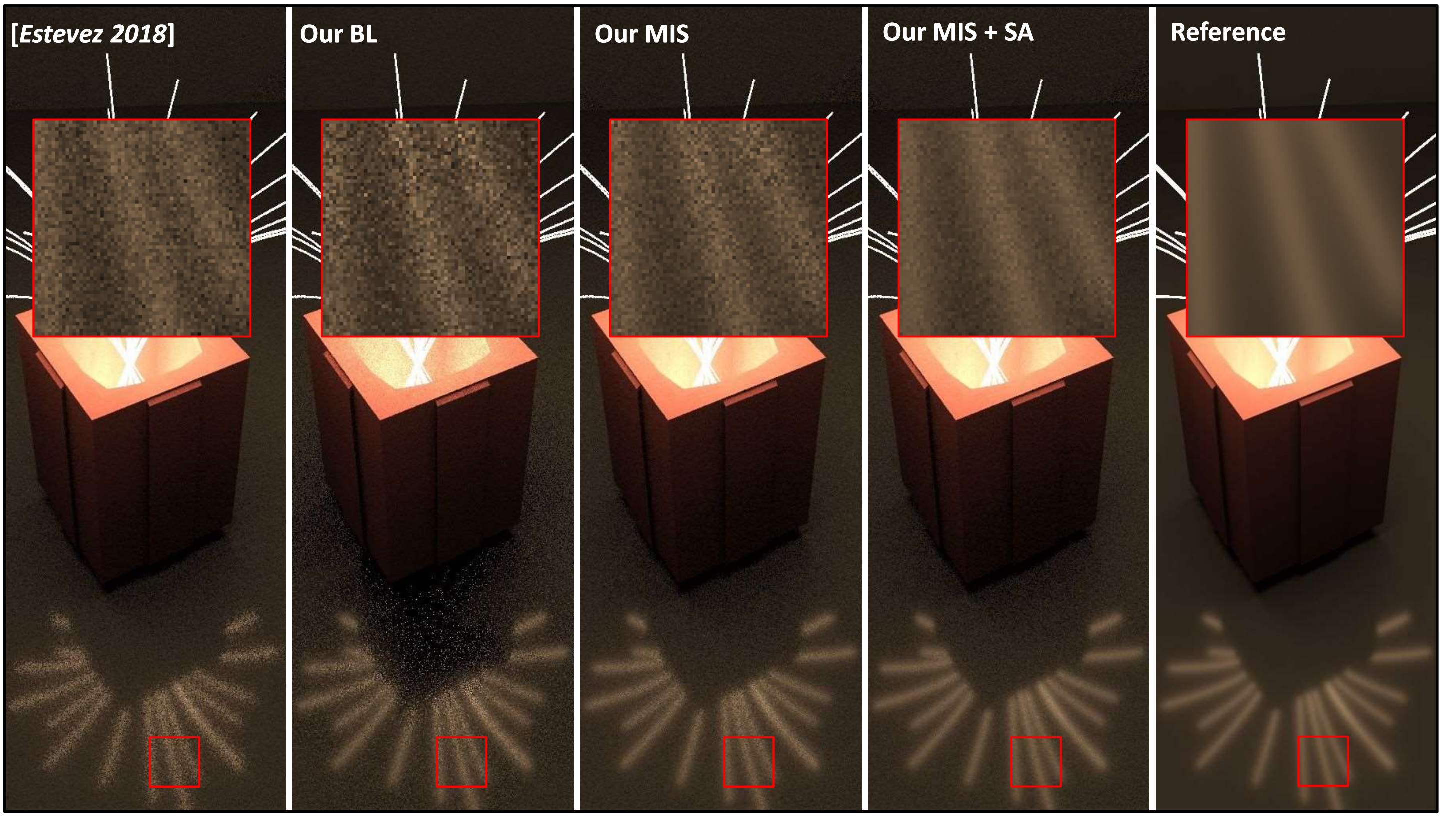
- Our MIS algorithm contains three sampling techniques.
  - Traditional light sampling
  - BRDF-oriented light sampling
  - BRDF sampling
- Adaptive sample allocation occurs in:
  - Allocate total samples for BRDF-aware methods
  - Allocate samples among the two BRDF-aware methods

In summary, our MIS algorithm contains three sampling techniques: traditional light sampling, BRDF-oriented light sampling, and BRDF sampling. *Note that we omit BRDF-oriented light sampling for pure diffuse surfaces as it will degrade to traditional light sampling because of the constant Lambert term.*

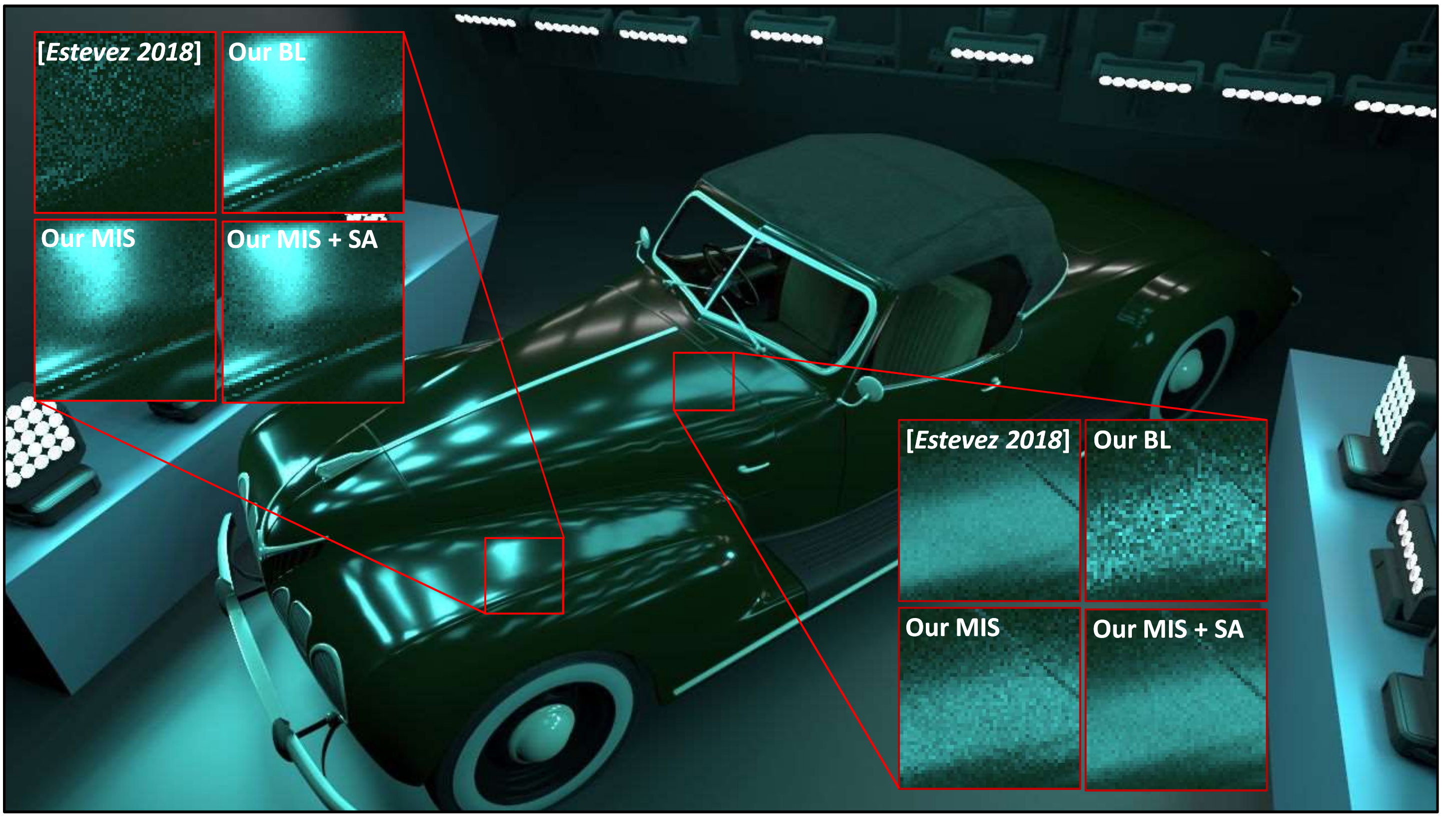
And we also propose two heuristic to guide the sample allocation: calculate the total number of samples for BRDF-aware methods and allocate samples among the two BRDF-aware methods.

Results

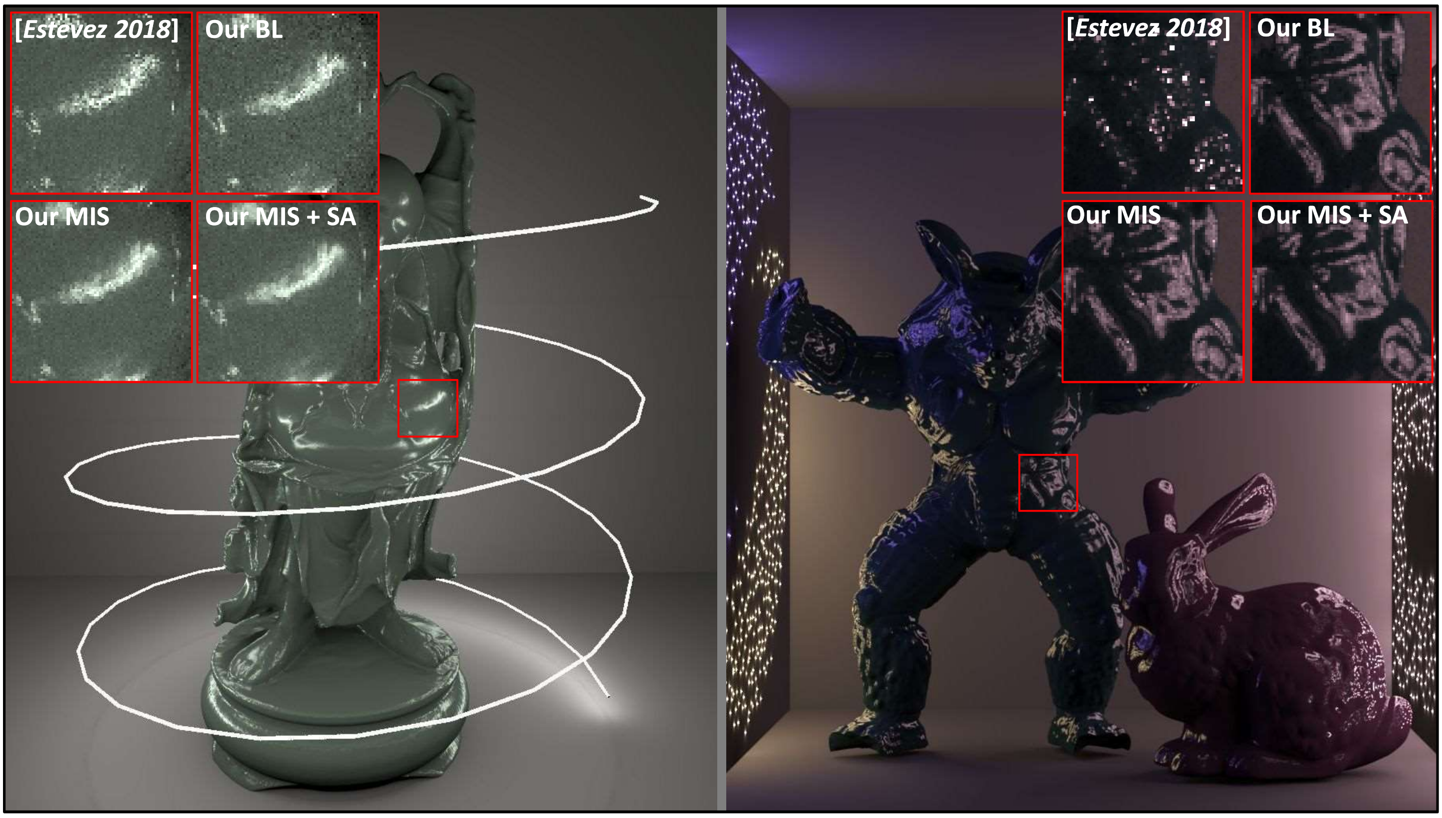
Let me demonstrate more results.



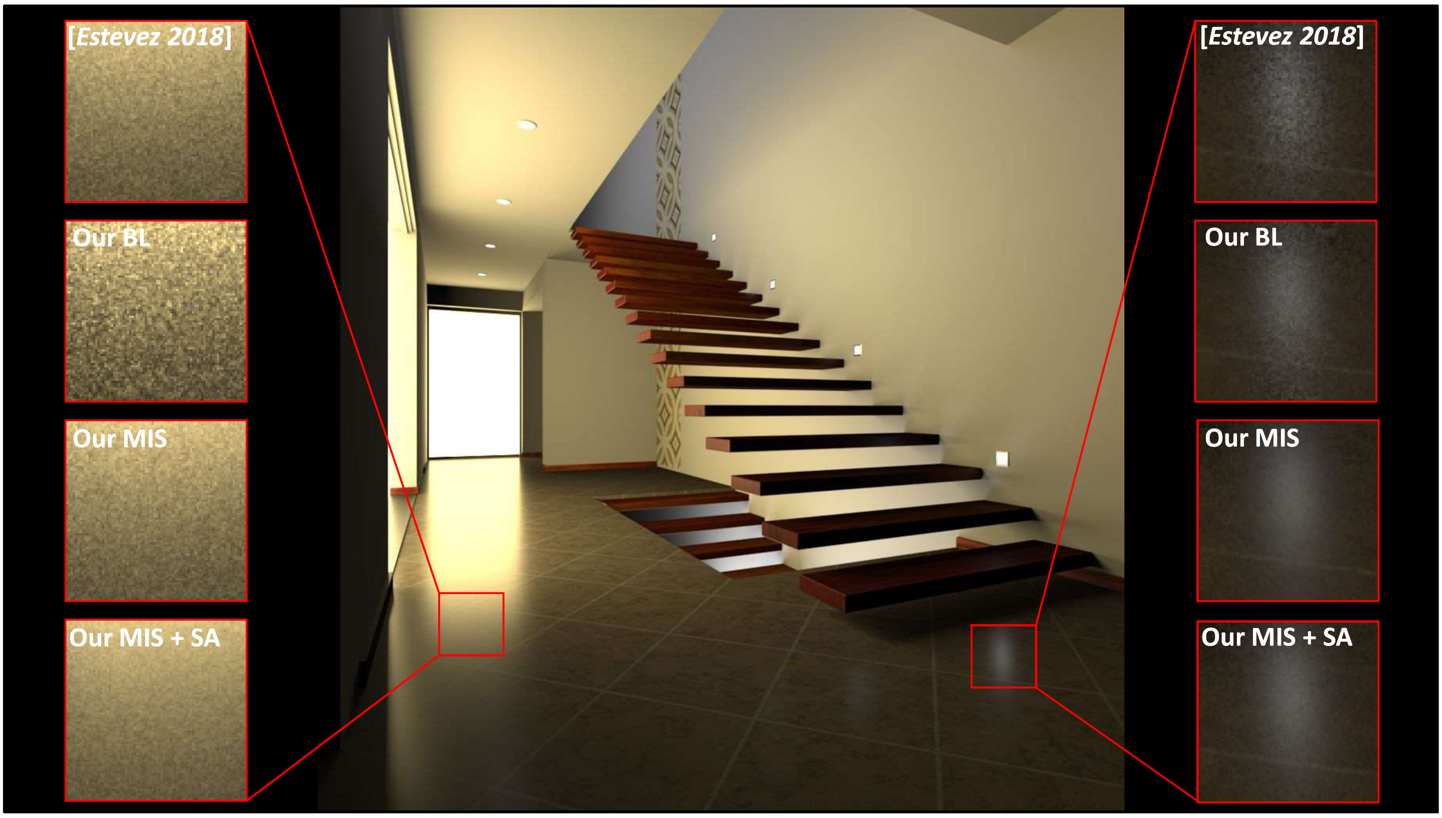
This is a lamp scene. From the left to right, we compare the method of Estevez et al.'s, the method of our BRDF-oriented light sampling, our MIS strategy with naive equal sample allocation, our MIS strategy with our sample allocation heuristic, and reference. **[click]** We can see the noise becomes smaller and smaller from left to right, which shows our BRDF-oriented light sampling is better than Estevez et al.'s, our MIS strategy is more robust then only one sampling technique, and our adaptive sample allocation is better than simply setting each sample count equal.



For other scenes, the results are similar. **[click]** We can see our method always outperforms on the reflections of small lights. And it achieves similar result on reflections of large area lights thanks to our adaptive sample allocation heuristic.`



These are two another results. The left is a buddha scene and the right is a modified cornell-box scene.



And this is a typical staircase scene.

Conclusion

The last is the conclusion.

Contribution

- Light sampling technique taking BRDFs into account
- Heuristic for adaptive sample allocation when MIS

⇩

- Achieve great improvements for the scene containing glossy materials and many small lights
- Keep similar performance in other cases

Our contribution is proposing a light sampling technique taking BRDFs into account and a heuristic for adaptive sample allocation when MIS. In result, we can achieve great improvements for the scene containing glossy material and many small lights while keeping similar performance in other cases.

Future work

- Better BRDF integral methods (improve LTCs and SPTDs)
- Take BRDF into account when sampling points on a light
- More optimal sample allocation strategy
- Generalize BRDFs to BSDFs
- Also take visibility into account [*Vévoda 2018*]

There still remains some possible topics for a future work.

- Our evaluation of BRDFs relies on exist area light shading methods, which could be improved further.
- It is potential to take BRDF into account when sampling points on a light so that we can totally omit traditional BRDF sampling.
- Our sample allocation heuristic is far from optimal and could be investigated in the future.
- And it is straightforward to extend our algorithm to general BSDFs.
- Taking visibility into account is also worth thinking, for example, the on-line learning method from Vévoda et al.

THANKS FOR LISTENING!

Questions?

Sample allocation among BRDF-aware methods

Insight:

- Prefer BRDF-oriented light sampling if BRDF sampling is more likely to fail

Method:

- Adaptively determine which sampling technique to use, based on the probability:

$$P(\text{BRDF-oriented light sampling}) = \frac{n_{nohit}}{n_{nohit}+\lambda \cdot n_{hit}}$$

- λ = 10 in our implementation

We first consider sample allocation among the two BRDF-aware methods, namely, BRDF-oriented light sampling and BRDF sampling. Our insight is that: we should prefer our BRDF-oriented light sampling when BRDF sampling is more likely to fail. **[click]**

We propose to adaptively determine which sampling technique to use based on the probability of choosing BRDF-oriented light sampling, which equals the ratio of the failure of BRDF sampling. The n_nohit and n_hit records the number of failure and success of BRDF sampling during sampling process, respectively.

As BRDF sampling may still miss lights frequently even in cases when it is better than BRDF-oriented light sampling, we make \lambda great than 1, and a value of 10 is practical in our implementation.

Total sample number of BRDF-aware methods

Traditional light sampling [*Estevez 2018*] → Set as 1

- How to measure?
- **BRDF integral!**

BRDF-aware methods

Insight:

- Should allocate more samples when the BRDF is at least **important** to one light

Measure (brute-fore):

- Traverse each **light** and compute an upper bound of BRDF integral ✗

Measure (efficient):

- Traverse each **light cluster** and compute an upper bound of BRDF integral ✓

Sample count:

$$N = N_{max} \cdot UPPER\_BOUND$$

Next, we should balance the samples allocated between BRDF-aware methods and traditional light sampling. Our traditional light sampling is identical to Estevez's, which summing up samples from each cluster and is thus using quite a lot samples already, so we leave its sample count as 1. **[click]**

Then we need to find a proper number of sample count for BRDF-aware methods. **[click]** The insight is that, we should allocate more samples when the BRDF is at least important to one light. **[click]** How to measure the importance? One way is to calculate the BRDF integral. **[click]**

It is simple to get a brute-force importance measure method: traverse each light and compute an upper bound of BRDF integral. However, the linear time with regard to the number of lights is unaffordable. **[click]**

What we choose is to traverse light clusters instead of all lights. Though the upper bound becomes not tight, this method is quite efficient and the compute overhead is negligible. **[click]**

At last, we simply linearly scale the upper bound and get the total sample count of BRDF-aware methods N. In the formula, N_max is a pre-defined maximum number of samples.