Light Transport Simulation with Vertex Connection and Merging (supplemental document)

Iliyan Georgiev
Saarland University
Intel VCI, Saarbrücken

Jaroslav Křivánek
Charles University in Prague
Faculty of Mathematics and Physics

Tomáš Davidovič
Saarland University
Intel VCI, Saarbrücken

Philipp Slusallek
Saarland University
Intel VCI & DFKI, Saarbrücken

Abstract

In this document, we provide additional experimental data that we generated during the preparation of our paper, as well as a derivation of the radius reduction scheme that we use in our combined progressive vertex connection and merging algorithm.

1 Results

We provide a comprehensive set of results for the four scenes discussed in the results section of the paper. For each scene, we provide two sets of images and statistics, taken after 4 and 30 minutes of progressive rendering, respectively. These results are assembled in the eight pages at the end of this document.

Readers of the electronic version are encouraged to zoom in the document for closer inspection of the images.

Benchmarked algorithms. For each scene we show images rendered with (1) path tracing (PT), (2) bidirectional path tracing (BPT), (3) stochastic progressive photon mapping (PPM), (4) a combination of BPT and PPM based on a heuristic caustic path classification (BPT-PPM), two variants of Metropolis light transport: (5) MLT-Veach [Veach and Guibas 1997]) and (6) MLT-Kelemen [Kelemen et al. 2002], as well as (7) our progressive vertex connection and merging (VCM) algorithm. The numbers in parentheses for each algorithm denote the number of rendering iterations, proportional to the total number of samples, taken in the given time.

On each page, we additionally include a reference image, as well as color-coded relative error between the reference and BPT, PPM, and our VCM, respectively. All images have a resolution of 1024×768 and have been gamma-corrected with $\gamma = 2.2$ for display.

All rendering algorithms have been implemented in the same CPU-based single-ray rendering framework, with the exception of MLT-Kelemen and MLT-Veach, for which we used the Mitsuba renderer [Jakob 2010]. To improve the fairness of the comparison, we let Mitsuba run $3\times$ longer than the algorithms implemented in our slightly faster framework. Even with a rendering budget of 90 minutes, the MLT algorithms cannot handle well the complex light interactions resulting from the various configurations of specular and highly glossy objects in the scenes.

The BPT-PPM algorithm handles caustic paths with PPM and all other paths with BPT. We classify a path as caustic if it either contains an SDS segment or ends with an SDE segment (see [Heckbert 1990] for an explanation of the notation), i.e. if it is a caustic directly visible from the camera. While such classification based combination can often produce better results than BPT and PPM alone, it can be far from optimal, as can be seen when comparing the BPT-PPM images to the results achieved by our VCM algorithm. We also experimented with different classification strategies, but none could deliver quality similar to our VCM, which employs more path sampling techniques than BPT and PPM together, and also often mixes vertex connection (VC) and vertex merging (VM) techniques with roughly equal weights. Such combinations appear in green in the relative VC-VM false-color contribution images.

Image quality metrics. The bottom row on each page shows statistics from two image quality metrics: (1) the structural similarity (SSIM) index [Wang et al. 2004] and (2) the visual difference predictor of Mantiuk et al. [2011] (HDR-VDP-2). We used the authors' MatLab implementations with the default, recommended parameters, and ran them w.r.t. the reference images in the middle.

Overall, our VCM algorithm gets highest visual quality scores from both metrics. There are some slight inconsistencies between the two metrics, due to SSIM operating on the gamma-corrected low dynamic range images, and HDR-VDP-2 operating on the raw high dynamic range images, also taking into account the observer's luminance adaptation. The resulting differences are noticeable for PPM on the **Car** scene and for BPT-PPM on the **Mirror balls** scene.

Running the image quality metrics on the MLT images would require separate reference images, due to the slight differences in the materials between the Mitsuba renderer and our framework. Unfortunately, we were not able to obtain such references in reasonable time with the algorithms available in Mitsuba, so as to provide these results.

2 A Simple Radius Reduction Scheme

Knaus and Zwicker [2011] compute the the radius r_i at iteration i in progressive photon mapping as

$$r_i = r_1 \sqrt{\left(\prod_{k=1}^{i-1} \frac{k+\alpha}{k}\right)\frac{1}{i}},$$

where r_1 is the initial radius and $\alpha \in (0;1)$ is a user parameter. From Appendix E in their paper it follows that $r_i = O\big(i^{\frac{\alpha-1}{2}}\big)$. From this we derive our simpler radius reduction scheme

$$r_i = r_1 \sqrt{i^{\alpha-1}}$$

to have the same asymptotic behavior while being easier to compute. We demonstrate the asymptotic equivalence of the two schemes experimentally in Figure 1.

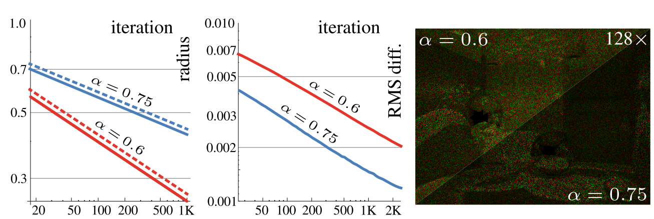


Figure 1: *A comparison of our new radius reduction scheme against that of Knaus and Zwicker [2011] (dashed lines), tested in a PPM implementation for two α values.* ***Left:*** *Log-log plots of the radii computed by the two schemes.* ***Middle:*** *A relative RMS image difference log-log plot of the two schemes, showing that the two schemes converge to the same solution for both α values.* ***Right:*** *A $128\times$ scaled difference image taken after 2500 rendering iterations.*

Acknowledgements

We would like to thank the reviewers for their insightful comments, Miloš Hašan and Wenzel Jakob for the fruitful discussions, and Ondřej Karlík and Jiří Vorba for proofreading the paper. The Mirror balls scene has been modeled by Toshiya Hachisuka. Chaos Group kindly provided the Bathroom scene.

References

HECKBERT, P. S. 1990. Adaptive radiosity textures for bidirectional ray tracing. In *SIGGRAPH '90*, ACM, New York, NY, USA.

JAKOB, W., 2010. Mitsuba renderer. http://www.mitsuba-renderer.org.

KELEMEN, C., SZIRMAY-KALOS, L., ANTAL, G., AND CSONKA, F. 2002. A simple and robust mutation strategy for the Metropolis light transport algorithm. *Computer Graphics Forum 21*, 3.

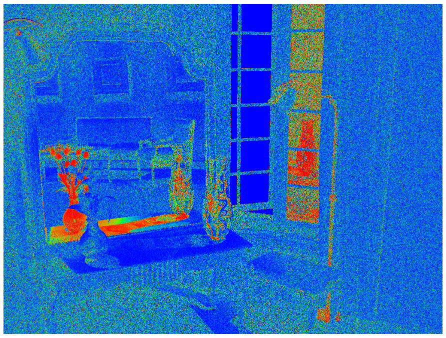
KNAUS, C., AND ZWICKER, M. 2011. Progressive photon mapping: A probabilistic approach. *ACM Trans. Graph. 30* (May).

MANTIUK, R., KIM, K. J., REMPEL, A. G., AND HEIDRICH, W. 2011. HDR-VDP-2: A calibrated visual metric for visibility and quality predictions in all luminance conditions. *ACM Trans. Graph. 30*, 4 (July), 40:1–40:14.

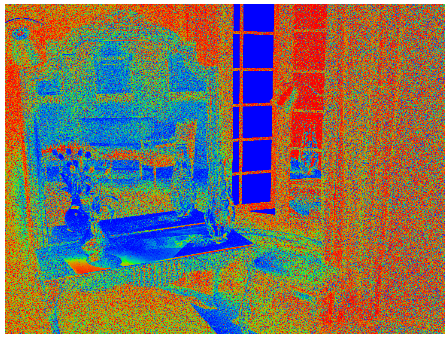
VEACH, E., AND GUIBAS, L. J. 1997. Metropolis light transport. In *SIGGRAPH '97*.

WANG, Z., BOVIK, A. C., SHEIKH, H. R., AND SIMONCELLI, E. P. 2004. Image quality assessment: From error visibility to structural similarity. *IEEE Trans. on Image Processing 13*, 4.

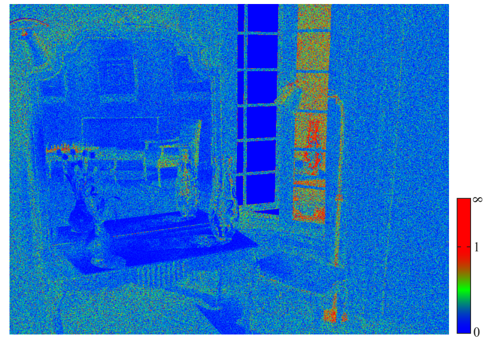
Living room (4 min)



Relative error of BPT w.r.t. reference



Relative error of PPM w.r.t. reference



Relative error of our VCM w.r.t. reference

Bidirectional path tracing (BPT) (96 iterations)

Progressive photon mapping (PPM) (187 iterations)

Our vertex connection and merging (VCM) (93 iter.)

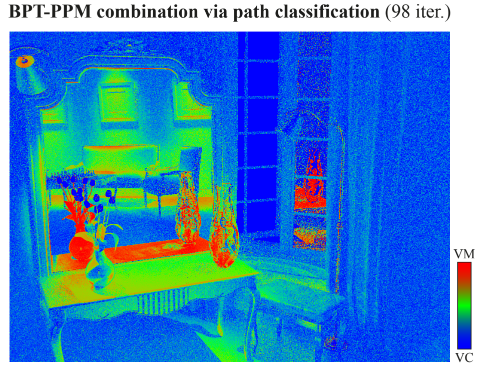
Path tracing (PT) (280 iterations)

Reference

BPT-PPM combination via path classification (98 iter.)

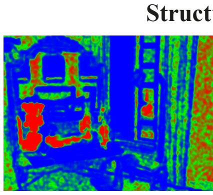
Metropolis light transport (MLT-Kelemen) (12 min)

Metropolis light transport (MLT-Veach) (12 min)

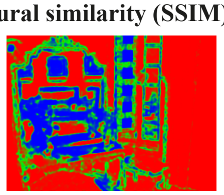


Relative contributions of vertex connection (VC) and vertex merging (VM) in the VCM image above

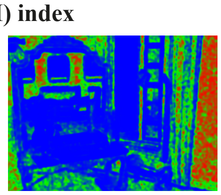
Structural similarity (SSIM) index



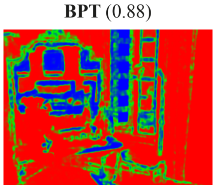
BPT (0.88)



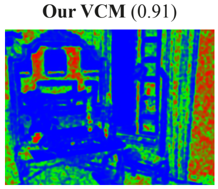
PPM (0.57)



Our VCM (0.91)

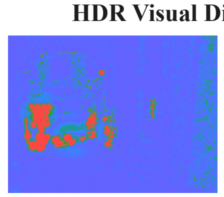


PT (0.56)



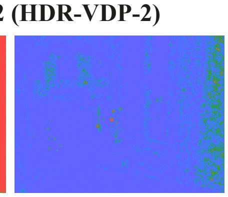
BPT-PPM (0.90)

HDR Visual Difference Predictor 2 (HDR-VDP-2)

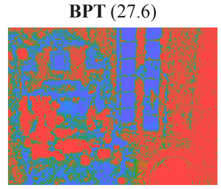


BPT (27.6)

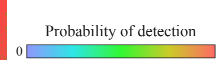
PPM (23.3)

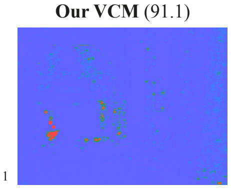


Our VCM (91.1)



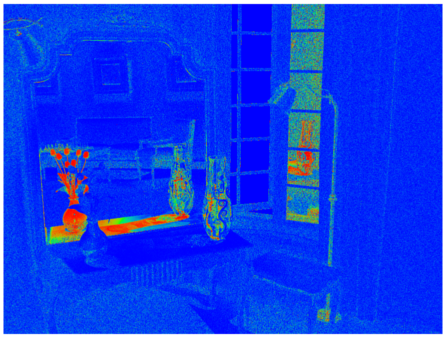
PT (4.5)



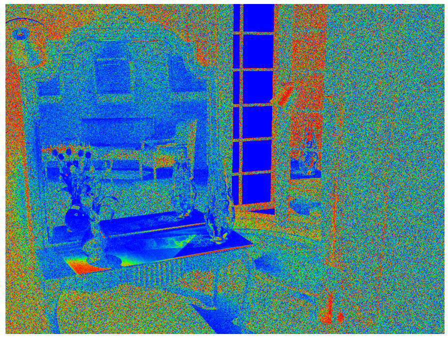


BPT-PPM (78.4)

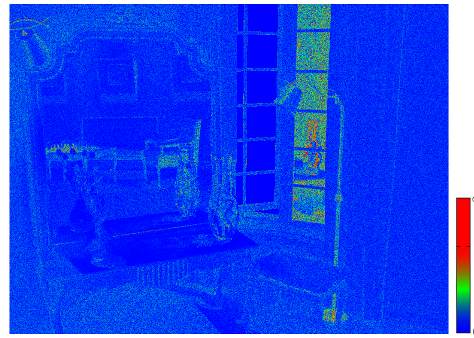
Living room (30 min)



Relative error of BPT w.r.t. reference



Relative error of PPM w.r.t. reference



Relative error of our VCM w.r.t. reference

Bidirectional path tracing (BPT) (771 iterations)

Progressive photon mapping (PPM) (1267 iterations)

Our vertex connection and merging (VCM) (646 iter.)

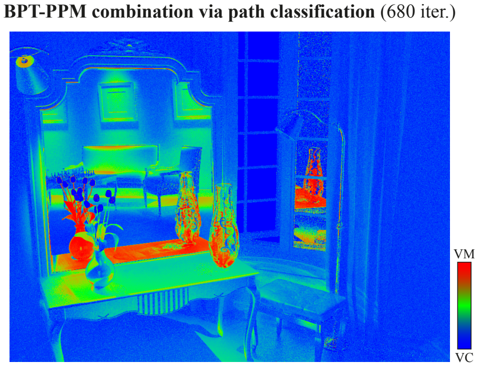
Path tracing (PT) (1961 iterations)

Reference

BPT-PPM combination via path classification (680 iter.)

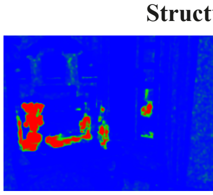
Metropolis light transport (MLT-Kelemen) (90 min)

Metropolis light transport (MLT-Veach) (90 min)

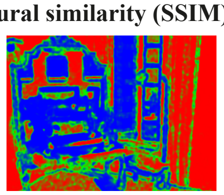


Relative contributions of vertex connection (VC) and vertex merging (VM) in the VCM image above

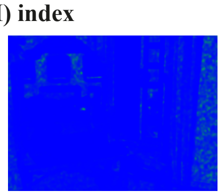
Structural similarity (SSIM) index



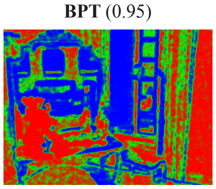
BPT (0.95)



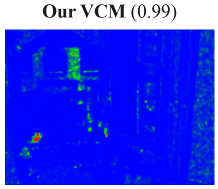
PPM (0.75)



Our VCM (0.99)

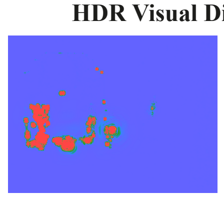


PT (0.77)

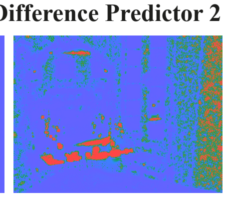


BPT-PPM (0.98)

HDR Visual Difference Predictor 2 (HDR-VDP-2)

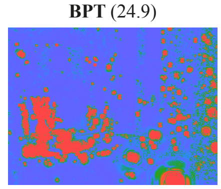


BPT (24.9)

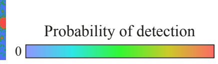


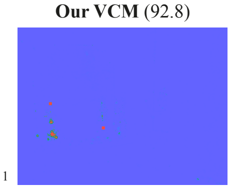
PPM (33.7)

Our VCM (92.8)



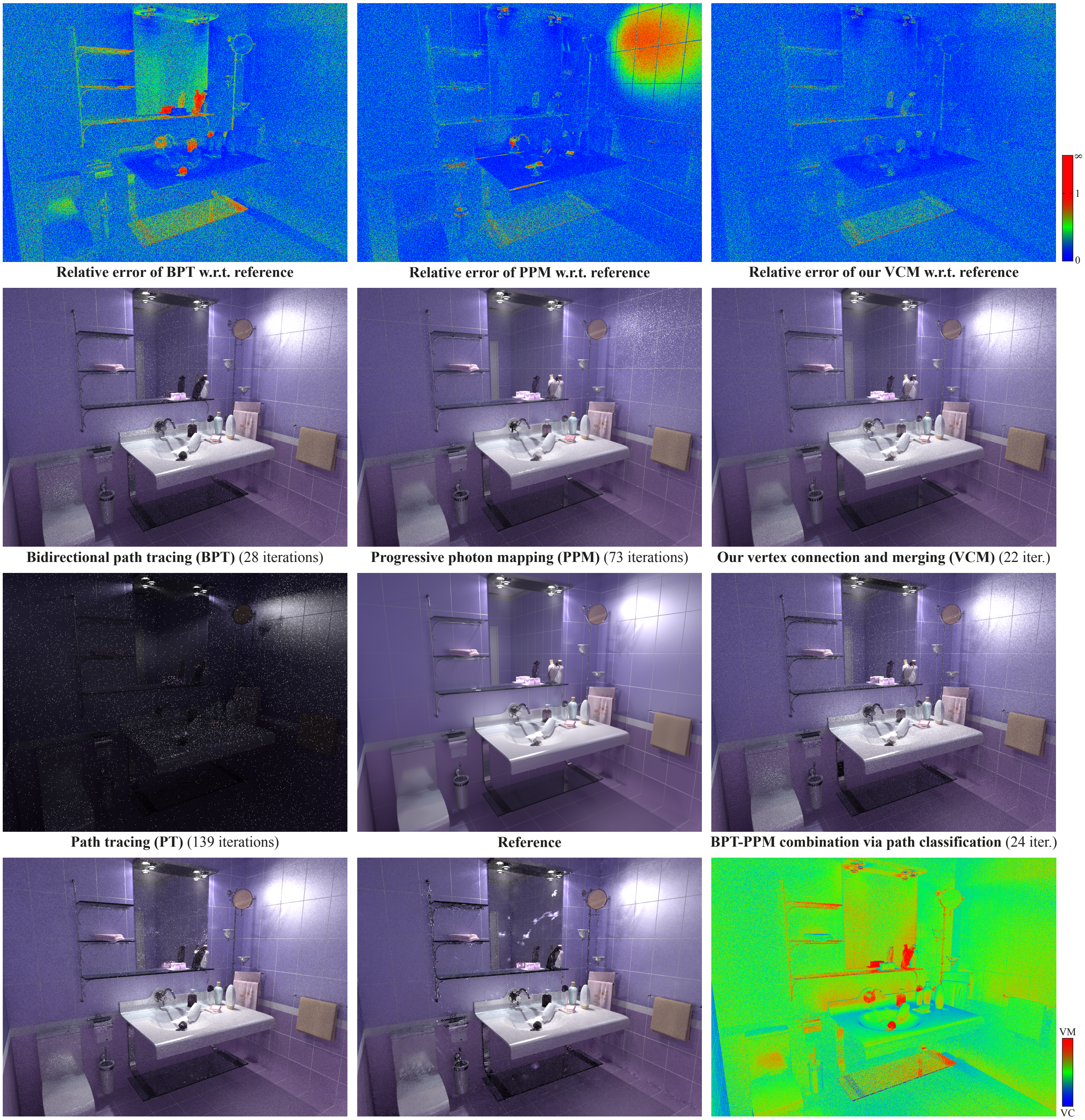
PT (9.0)



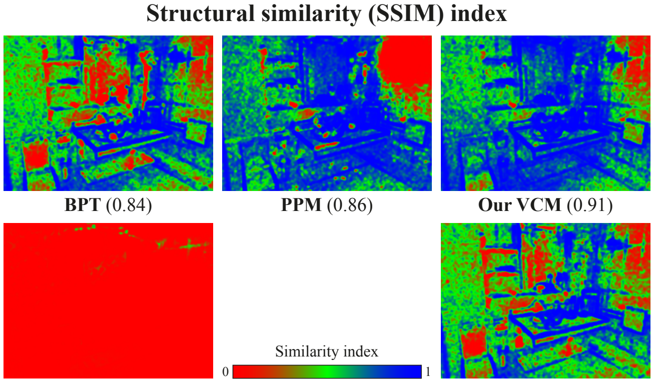


BPT-PPM (86.3)

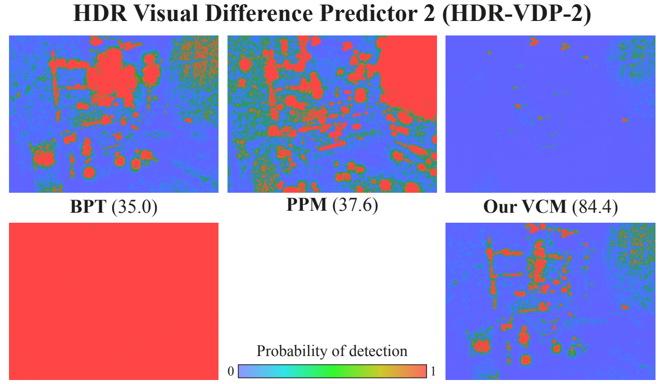
Bathroom (4 min)



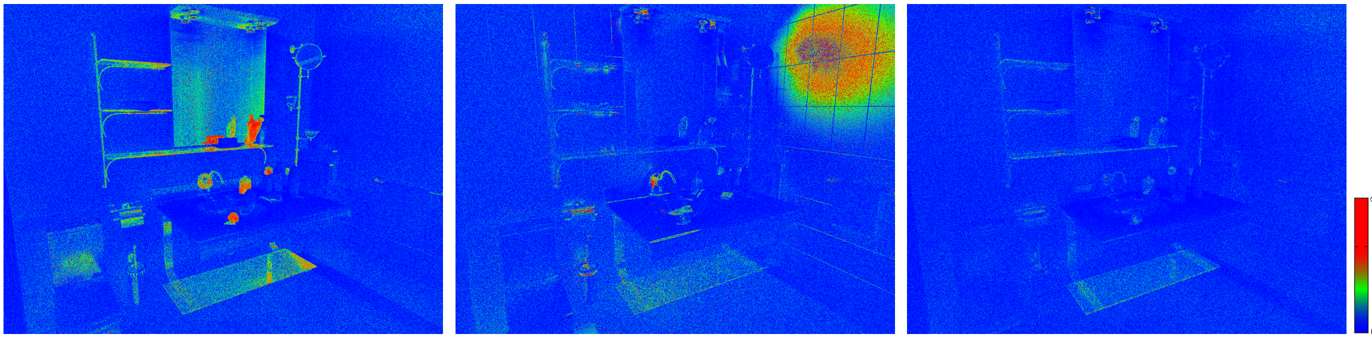
Structural similarity (SSIM) index



HDR Visual Difference Predictor 2 (HDR-VDP-2)



Bathroom (30 min)



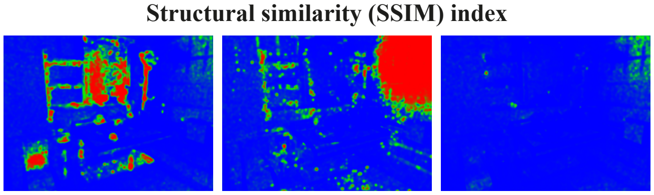
Relative error of BPT w.r.t. reference | **Relative error of PPM w.r.t. reference** | **Relative error of our VCM w.r.t. reference**

Bidirectional path tracing (BPT) (211 iterations) | **Progressive photon mapping (PPM)** (589 iterations) | **Our vertex connection and merging (VCM)** (165 iter.)

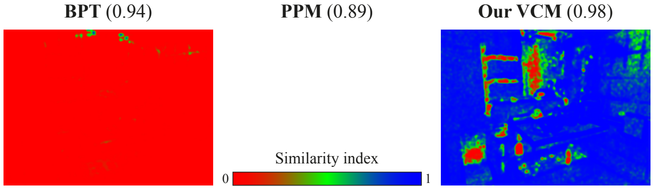
Path tracing (PT) (1117 iterations) | **Reference** | **BPT-PPM combination via path classification** (190 iter.)

Metropolis light transport (MLT-Kelemen) (90 min) | **Metropolis light transport (MLT-Veach)** (90 min) | **Relative contributions of vertex connection (VC) and vertex merging (VM) in the VCM image above**

Structural similarity (SSIM) index



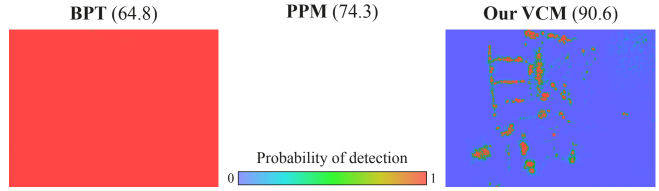
BPT (0.94) | **PPM** (0.89) | **Our VCM** (0.98)



PT (0.18) | **BPT-PPM** (0.95)

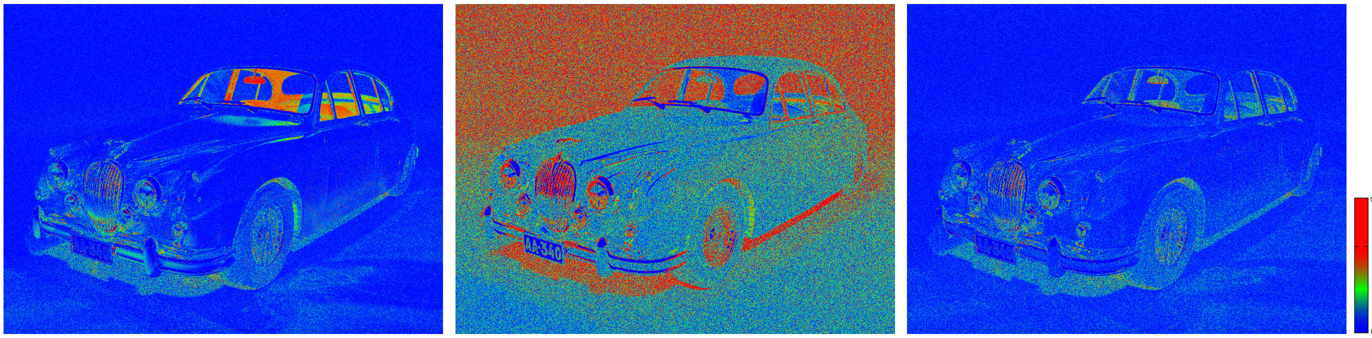
HDR Visual Difference Predictor 2 (HDR-VDP-2)

BPT (64.8) | **PPM** (74.3) | **Our VCM** (90.6)



PT (28.5) | **BPT-PPM** (83.2)

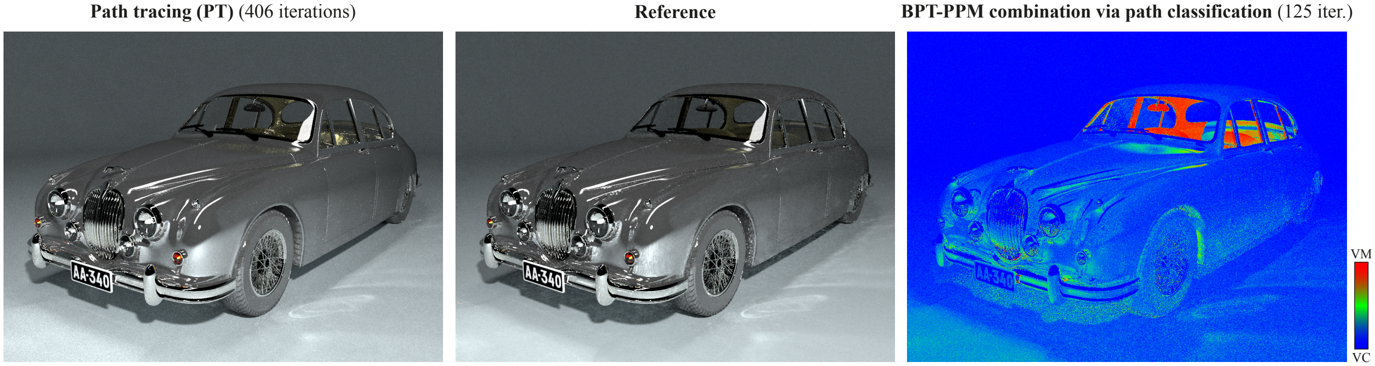
Car (4 min)



Relative error of BPT w.r.t. reference | **Relative error of PPM w.r.t. reference** | **Relative error of our VCM w.r.t. reference**

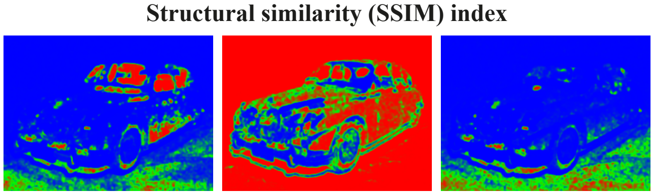
Bidirectional path tracing (BPT) (134 iterations) | **Progressive photon mapping (PPM)** (184 iterations) | **Our vertex connection and merging (VCM)** (117 iter.)

Path tracing (PT) (406 iterations) | **Reference** | **BPT-PPM combination via path classification** (125 iter.)

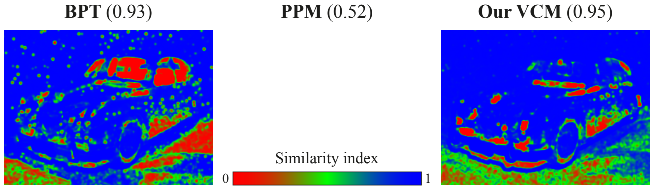


Metropolis light transport (MLT-Kelemen) (12 min) | **Metropolis light transport (MLT-Veach)** (12 min) | **Relative contributions of vertex connection (VC) and vertex merging (VM) in the VCM image above**

Structural similarity (SSIM) index

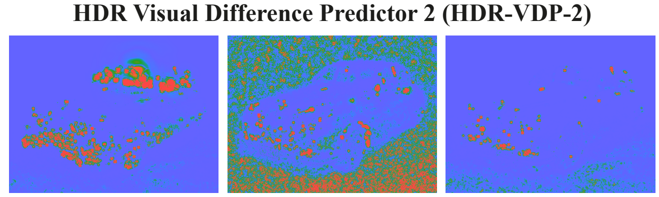


BPT (0.93) | **PPM** (0.52) | **Our VCM** (0.95)

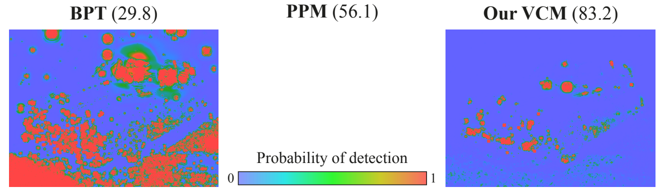


PT (0.90) | **BPT-PPM** (0.92)

HDR Visual Difference Predictor 2 (HDR-VDP-2)



BPT (29.8) | **PPM** (56.1) | **Our VCM** (83.2)



PT (17.0) | **BPT-PPM** (56.7)

Car (30 min)

Relative error of BPT w.r.t. reference

Relative error of PPM w.r.t. reference

Relative error of our VCM w.r.t. reference

Bidirectional path tracing (BPT) (929 iterations)

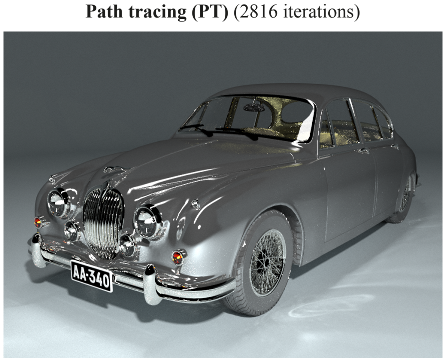
Progressive photon mapping (PPM) (1265 iterations)

Our vertex connection and merging (VCM) (805 iter.)

Path tracing (PT) (2816 iterations)

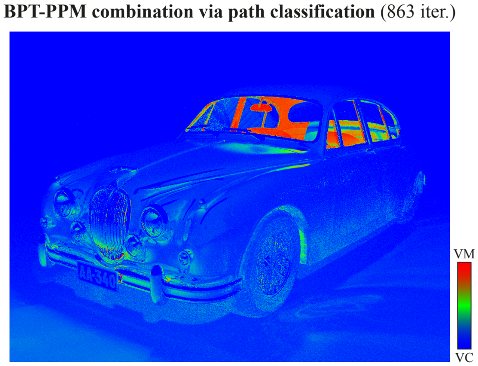
Reference

BPT-PPM combination via path classification (863 iter.)



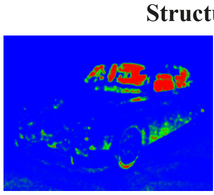
Metropolis light transport (MLT-Kelemen) (90 min)

Metropolis light transport (MLT-Veach) (90 min)

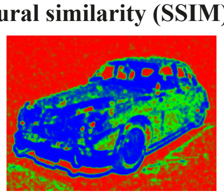


Relative contributions of vertex connection (VC) and vertex merging (VM) in the VCM image above

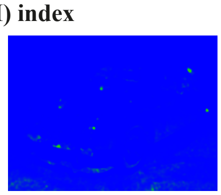
Structural similarity (SSIM) index



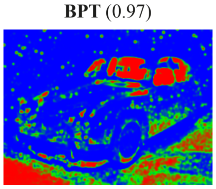
BPT (0.97)



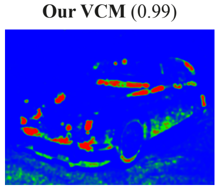
PPM (0.75)



Our VCM (0.99)

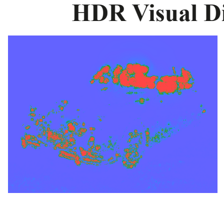


PT (0.90)

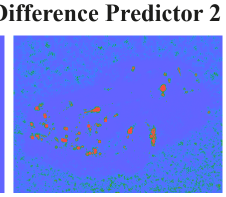


BPT-PPM (0.96)

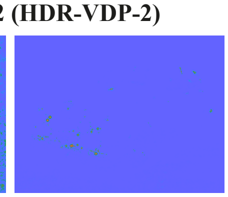
HDR Visual Difference Predictor 2 (HDR-VDP-2)



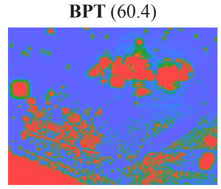
BPT (60.4)



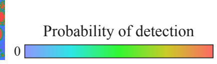
PPM (66.1)

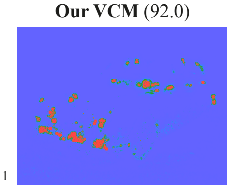


Our VCM (92.0)



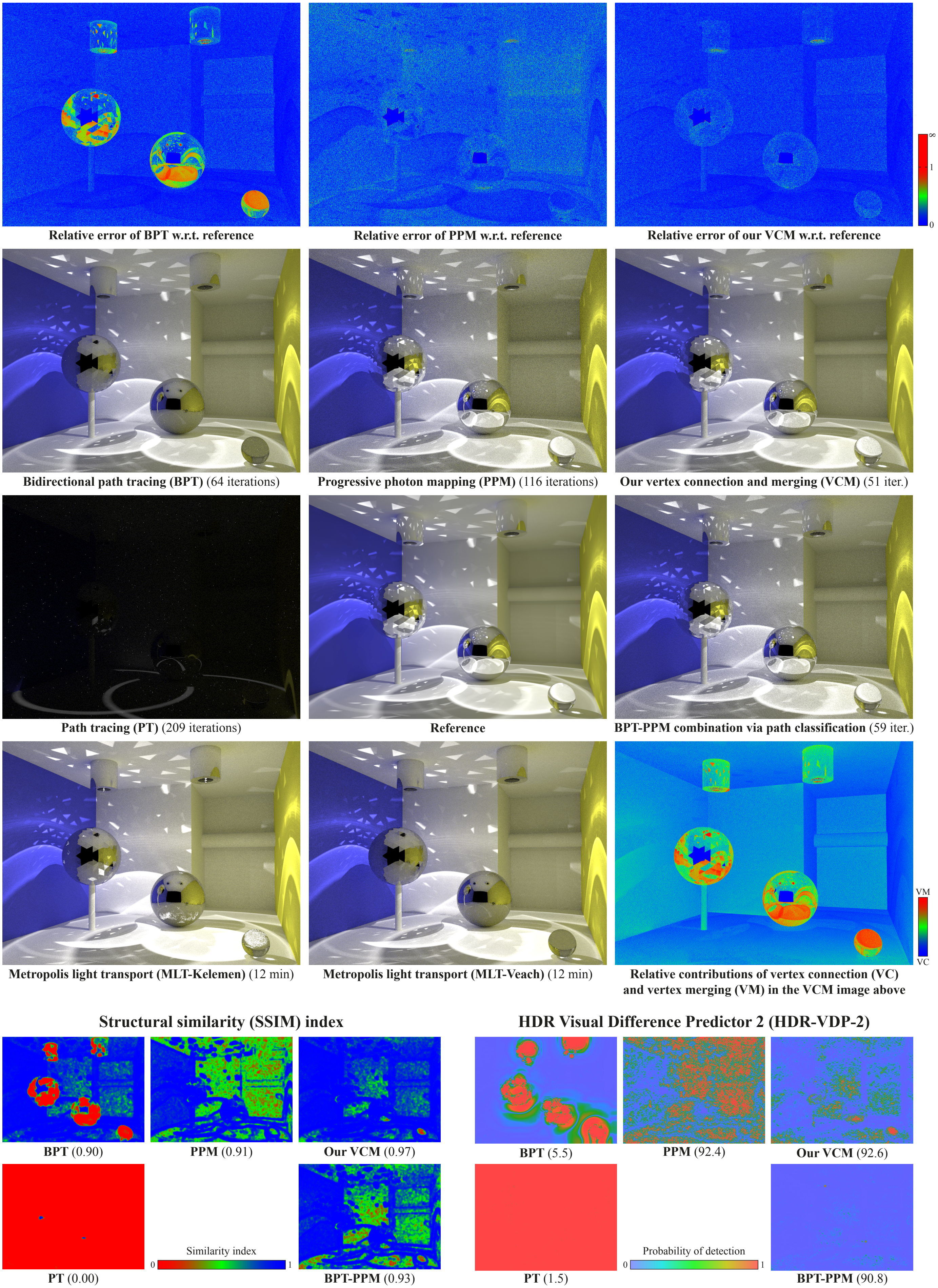
PT (38.6)



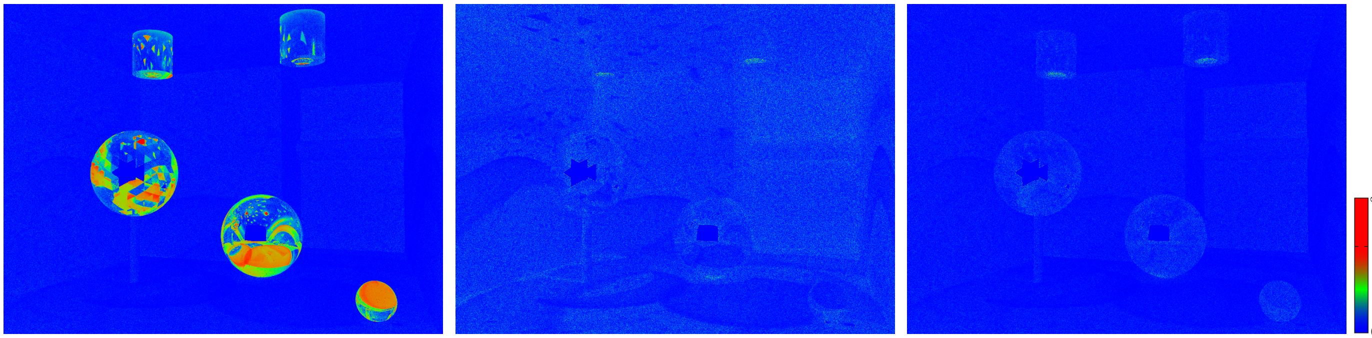


BPT-PPM (65.3)

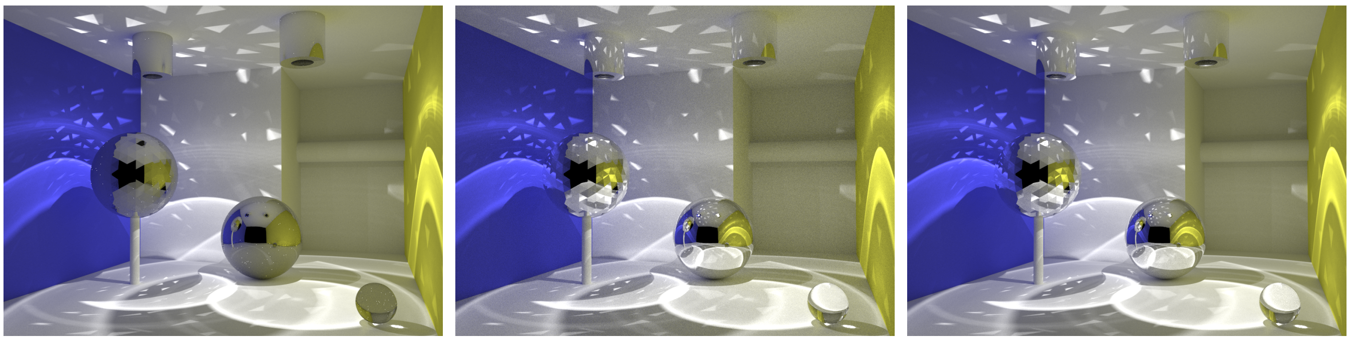
Mirror balls (4 min)



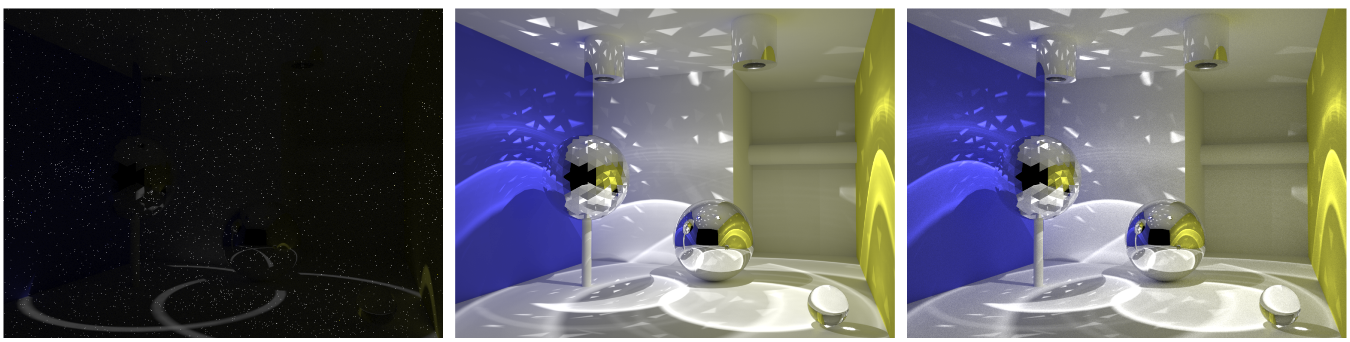
Mirror balls (30 min)



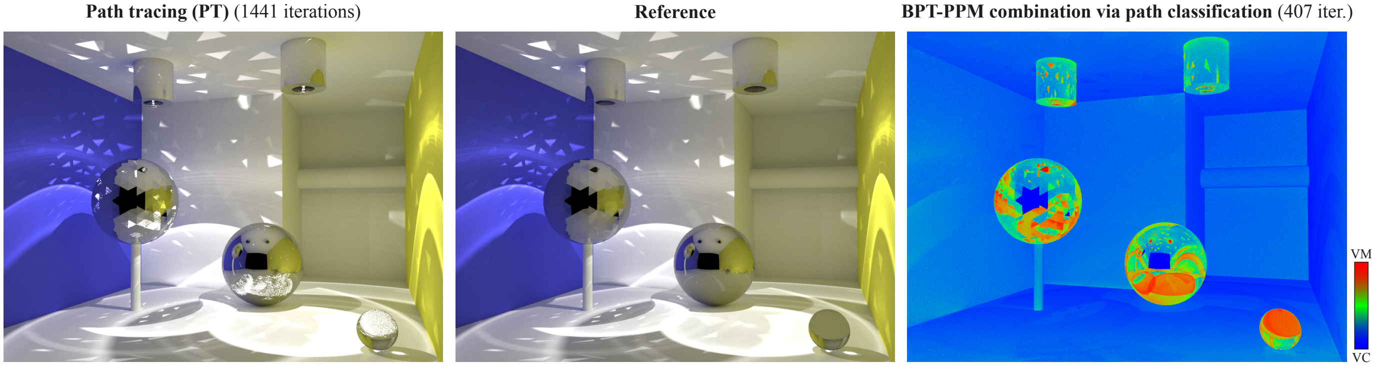
Relative error of BPT w.r.t. reference | **Relative error of PPM w.r.t. reference** | **Relative error of our VCM w.r.t. reference**



Bidirectional path tracing (BPT) (434 iterations) | **Progressive photon mapping (PPM)** (811 iterations) | **Our vertex connection and merging (VCM)** (356 iter.)

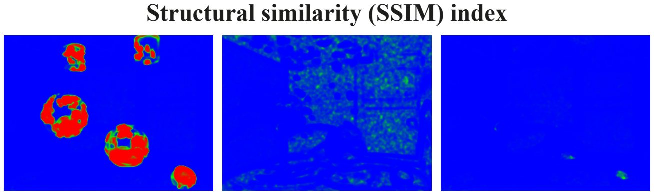


Path tracing (PT) (1441 iterations) | **Reference** | **BPT-PPM combination via path classification** (407 iter.)

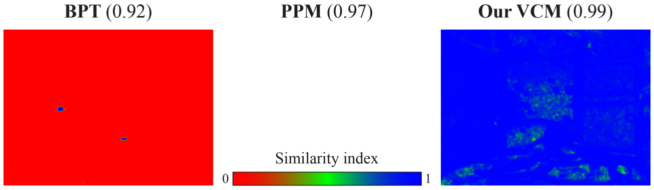


Metropolis light transport (MLT-Kelemen) (90 min) | **Metropolis light transport (MLT-Veach)** (90 min) | **Relative contributions of vertex connection (VC) and vertex merging (VM) in the VCM image above**

Structural similarity (SSIM) index

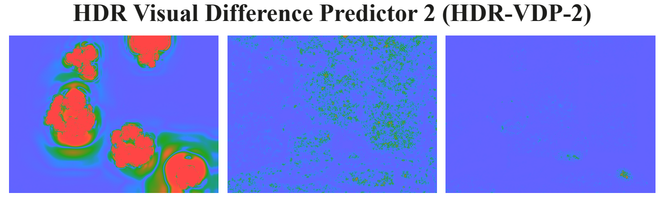


BPT (0.92) | **PPM** (0.97) | **Our VCM** (0.99)

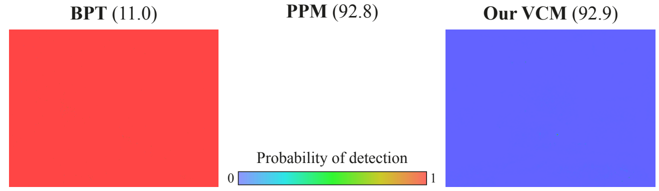


PT (0.01) | **BPT-PPM** (0.98)

HDR Visual Difference Predictor 2 (HDR-VDP-2)



BPT (11.0) | **PPM** (92.8) | **Our VCM** (92.9)



PT (3.8) | **BPT-PPM** (92.6)