ANALYSIS OF REPORTED ERROR IN MONTE CARLO RENDERED IMAGES

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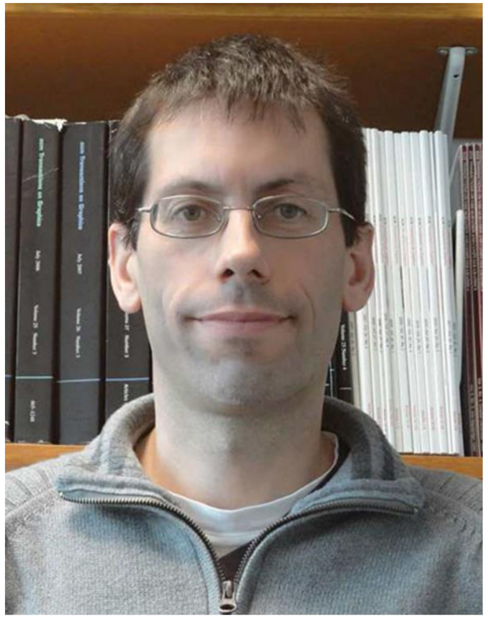
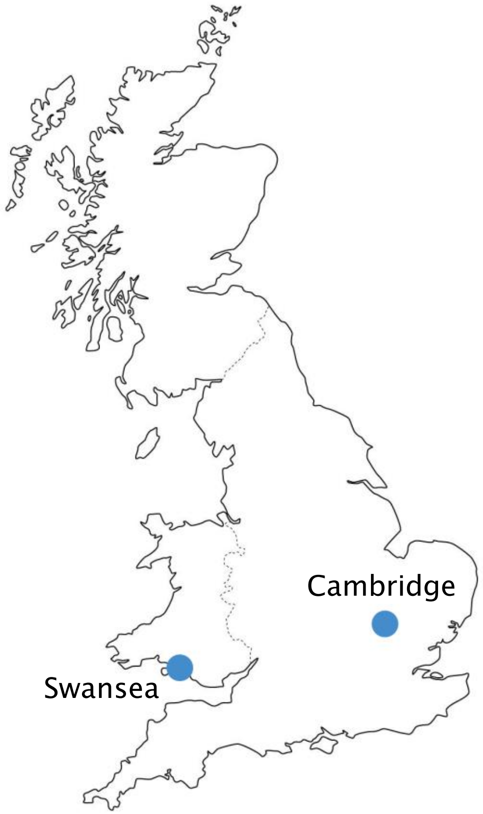




ANALYSIS OF REPORTED ERROR IN MONTE CARLO RENDERED IMAGES

Need to evaluate the quality of novel rendering algorithms w.r.t to existing ones

- Common methodology is to compare images made by different algorithms to a common reference image
- Requires the availability of a ground truth image which is noise free which may not be available
- What effect does the quality of the reference image have on reported results?

MONTE CARLO RENDERING

Physical simulation of light interactions within an environment

Pros

- Photorealistic images and animations
- Camera lens models
  - Depth of field
  - Chromatic Aberration
- Physical materials
- Spectral Rendering – Dispersion
- Temporal Rendering – Motion Blur

Cons

- Expensive to compute
  - Stochastic process that converges in the limit
- Distorted images before convergence
  - Impulse noise – Salt & Pepper
  - Missing illumination contribution

IMAGE QUALITY ASSESSMENT (IQA)

$$Image \in \mathbb{R}^{WHC}$$

- Full Reference (FR-IQA)
  - Requires that the reference is a ground truth image
  - Distance metric between images in high dimensional space

$$\mathcal{Q} = \mathcal{E}\left(Reference,\ Image\right)$$

- Reduced Reference (RR-IQA)
  - Reference image is representative of the ground truth
  - Distance metric between statistical distributions of images

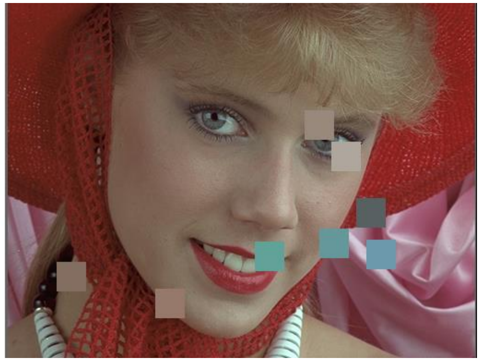
- No Reference (NR-IQA)

$$\mathcal{Q} = \mathcal{E}\left(Image\right)$$

  - Requires the test image is a distorted version of an image with expected statistics
  - Comparison between statistical distribution of the image and expected statistics learnt during model creation from representative images







NATURAL IMAGE DATABASES

TID 2008/13
Live Image Database

NATURAL IMAGE DATABASES

TID 2008/13

Live Image Database

- Natural images (photographs) under synthetically added distortions
- Human observers asked to give opinion scores (0-9) for image quality
- Mean opinion scores (MOS) used to fit parameters of IQA models

Nikolay Ponomarenko, Vladimir Lukin, Alexander Zelensky, et al. "TID2008-a database for evaluation of full-reference visual quality assessment metrics". In: Advances of Modern Radioelectronics 10.4 (2009), pp. 30-45.

N. Ponomarenko, O. Ieremeiev, V. Lukin, et al. "Color image database TID2013: Peculiarities and preliminary results". In: European Workshop on Visual Information Processing (EUVIP). 2013, pp. 106-111.

H. R. Sheikh, Z. Wang, L. Cormack, and A. C. Bovik. LIVE Image Quality Assessment Database Release 2. 2014.

MONTE CARLO IMAGE DATABASE

Ground Truth Images

MONTE CARLO IMAGE DATABASE

- Synthetic images under naturally occurring distortions
- 5 scenes

$$\mathcal{S} \in \mathbb{S} : \{Cornell\ Box,\ \ Torus,\ \ Veach\ Bidir,\ \ Veach\ Door,\ \ Sponza\}$$

- 7 rendering algorithms

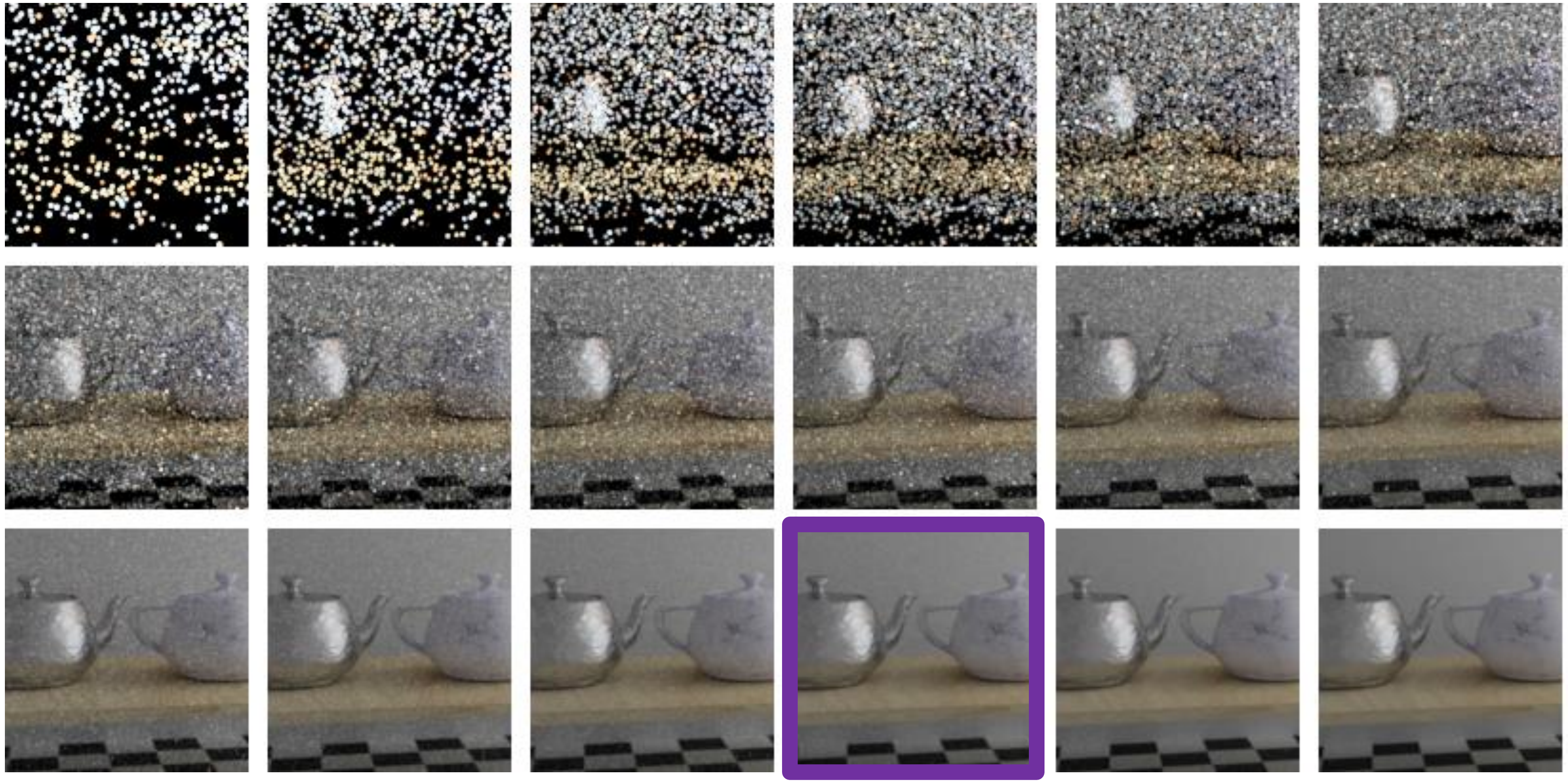
$$\mathcal{A} \in \mathbb{A} : \{PT,\ BDPT,\ PSSMLT,\ MLT,\ Manifold\text{-}MLT,\ ERPT,\ Manifold\text{-}ERPT\}$$

- Images rendered to 2, 4, 8, 16, …, 524288 independent s.p.p.

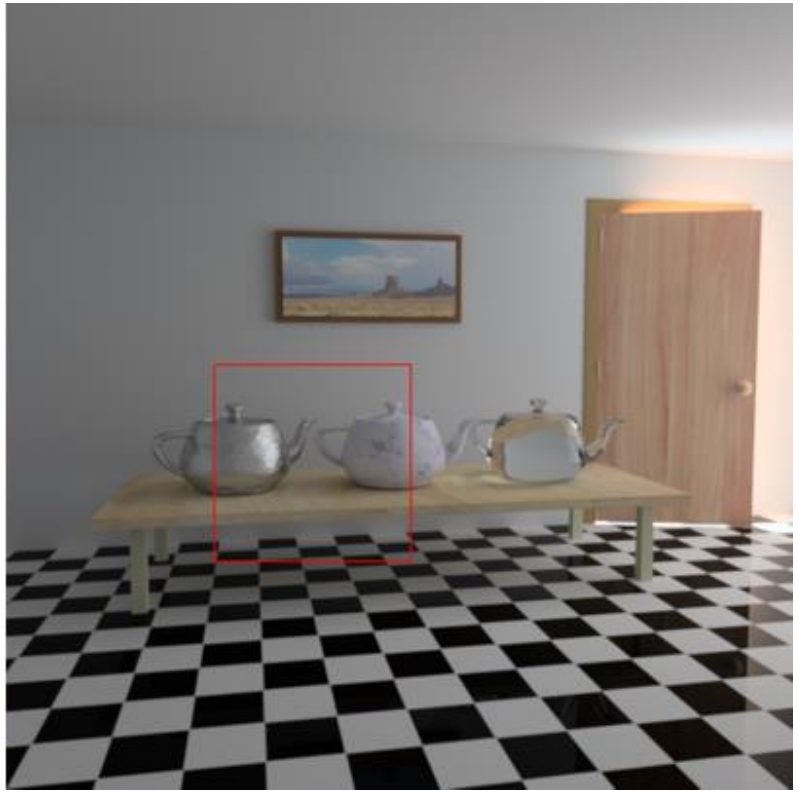
$$\mathcal{N} \in \mathbb{N} : \{2^n | 2 \leq n \leq \ldots\}$$

- 590 images in total, rendered with Mitsuba Renderer

Wenzel Jakob. Mitsuba renderer. http://www.mitsuba-renderer.org. 2010.



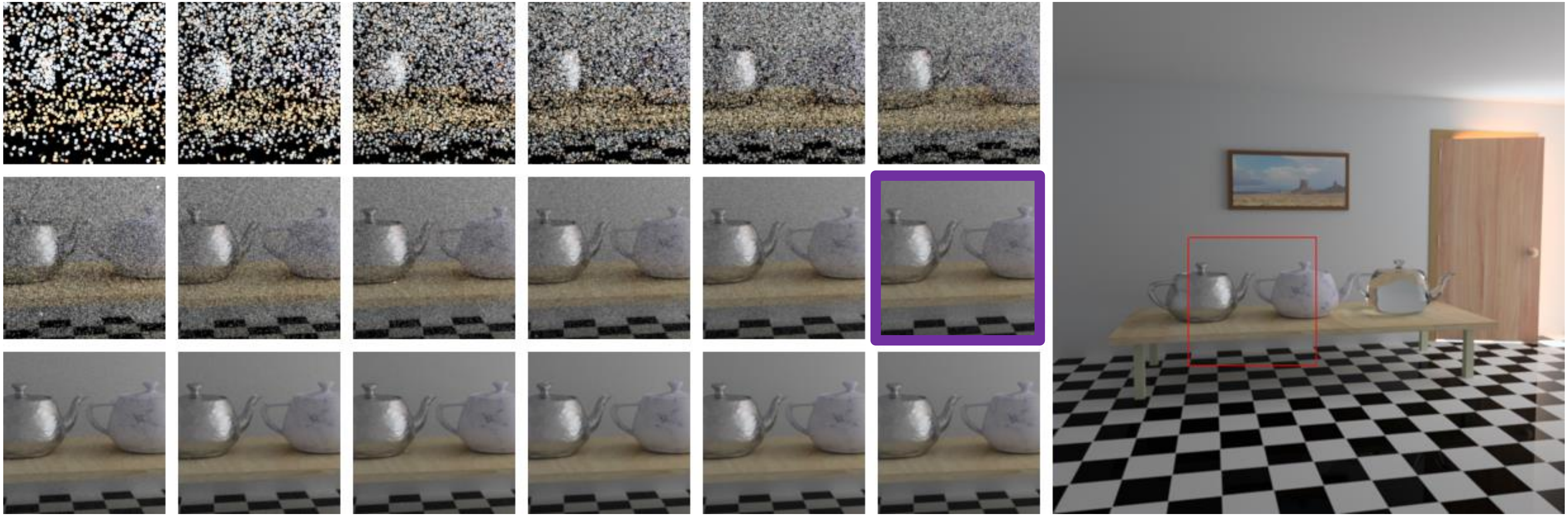
2 – 262144 s.p.p.



GT – BDPT 524228 s.p.p.

PATH TRACING

Veach Door



2 – 262144 s.p.p.

GT – BDPT 524228 s.p.p.

BIDIRECTIONAL PATH TRACING

Veach Door

EXPERIMENTAL DESIGN

$$\ln \mathcal{Q} = \ln\left(\frac{Observed}{Expected}\right)$$

$$\mathcal{E} \in \mathbb{E} : \{MSE,\ RMSE,\ MAE,\ PSNR,\ UQI,\ SSIM,\ MS\text{-}SSIM, IW\text{-}SSIM,\ IW\text{-}MSE,\ IW\text{-}PSNR,\ VSNR,\ Contourlet,\ WBCT,\ NQM,\ VIF,\ IFC,\ FSIM,\ FSIMc,\ HDR\text{-}VDP\text{-}2,\ SC\text{-}QI,\ SC\text{-}DM\}$$

- $\mathcal{M}^{\mathcal{C}}$ yields a triangular matrix for configuration $\mathcal{C}$ of the error metric on a test image with $\mathcal{N}_j$ s.p.p. evaluated using a reference image with $\mathcal{N}_i$ s.p.p.

$$\mathcal{M}^{\mathcal{C}}_{i,j} = \mathcal{E}\left(\mathcal{I}_{\mathcal{S}\mathcal{A}^G\mathcal{N}_i}, \mathcal{I}_{\mathcal{S}\mathcal{A}\mathcal{N}_j}\right)$$

- The bottom row of $\mathcal{M}^{\mathcal{C}}$ represents the use of the true GT image as the reference

$$\mathcal{P}^{\mathcal{C}}_{i,j} = \ln\left(\frac{\mathcal{M}^{\mathcal{C}}_{i,j}}{\mathcal{M}^{\mathcal{C}}_{|\mathbb{N}|,j}}\right)$$

- $\mathcal{P}^{\mathcal{C}}$ is a matrix with the same size as where each element is the $\ln \mathcal{Q}$ of how much error is misreported by due to the error contained in the reference image used

$$\text{where } i > j \text{ and } \mathcal{C} = (\mathcal{E}\mathcal{S}\mathcal{A})$$

$$\forall \mathcal{C} \in (\mathbb{E} \times \mathbb{S} \times \mathbb{A})$$

BDPT	2	4	8	16	32	64	128	256	512	1024	2048	4096	8192
GT (PT)													
16384	0.00021	0.00044	0.00035	0.00146	0.00250	0.00604	0.01123	0.01857	0.03963	0.06006	0.10249	0.14676	0.20907
8192	0.00082	0.00089	0.00228	0.00439	0.00790	0.01515	0.03214	0.05903	0.10703	0.17634	0.27113	0.38223	
4096	0.00067	0.00301	0.00481	0.00984	0.01821	0.03760	0.07164	0.13536	0.23000	0.37515	0.54666		
2048	0.00206	0.00420	0.01003	0.01965	0.04178	0.08150	0.14686	0.26415	0.44191	0.66779			
1024	0.00577	0.01141	0.02103	0.04097	0.08008	0.14905	0.27787	0.48703	0.75710				
512	0.01046	0.02234	0.04352	0.08472	0.15813	0.29235	0.50361	0.81414					
256	0.02121	0.04110	0.08476	0.16638	0.30385	0.52198	0.85770						
128	0.04228	0.08528	0.16436	0.30002	0.54550	0.87442							
64	0.08224	0.16066	0.30742	0.53591	0.88474								
32	0.15806	0.29905	0.53027	0.87775									
16	0.29062	0.52153	0.86325										
8	0.50545	0.84654											
4	0.81929												

$\mathcal{P}^{\mathcal{C}}$ for Scene: [**Cornell Box**] Algorithm: [**BDPT**] Metric: [**MSE**] True GT: [**PT @ 32768 spp**].

EXPERIMENTAL RESULTS

Scene: Cornell Box
Algorithm: BDPT
Metric: MSE

BDPT	2	4	8	16	32	64	128	256	512	1024	2048	4096	8192
GT (PT)													
16384	-0.00010	-0.00000	-0.00003	-0.00006	-0.00003	-0.00008	-0.00005	-0.00005	-0.00006	-0.00005	-0.00005	-0.00005	-0.00006
8192	-0.00012	-0.00004	-0.00015	-0.00014	-0.00013	-0.00012	-0.00015	-0.00016	-0.00015	-0.00015	-0.00016	-0.00016	
4096	-0.00007	-0.00025	-0.00025	-0.00027	-0.00026	-0.00035	-0.00034	-0.00036	-0.00035	-0.00037	-0.00037		
2048	-0.00010	-0.00033	-0.00059	-0.00063	-0.00069	-0.00076	-0.00073	-0.00076	-0.00075	-0.00076			
1024	-0.00104	-0.00105	-0.00119	-0.00120	-0.00141	-0.00133	-0.00148	-0.00155	-0.00152				
512	-0.00179	-0.00159	-0.00252	-0.00266	-0.00279	-0.00294	-0.00305	-0.00310					
256	-0.00306	-0.00351	-0.00468	-0.00539	-0.00561	-0.00583	-0.00620						
128	-0.00628	-0.00800	-0.00909	-0.01011	-0.01146	-0.01181							
64	-0.01118	-0.01467	-0.01825	-0.02007	-0.02134								
32	-0.02254	-0.02859	-0.03358	-0.03739									
16	-0.04154	-0.05122	-0.05902										
8	-0.07407	-0.08862											
4	-0.12584												

$\mathcal{P}^{\mathcal{C}}$ for Scene: [**Cornell Box**] Algorithm: [**BDPT**] Metric: [**MS-SSIM**] True GT: [**PT @ 32768 spp**].

EXPERIMENTAL RESULTS

Scene: Cornell Box
Algorithm: BDPT
Metric: MS-SSIM

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		VIF	IFC	UQI	PSNR	IW-PSNR	SSIM	NQM	IW-SSIM	MS-SSIM	SC-QI	HDR-VDP-2	FSIMc	FSIM	VSNR	SC-DM	RMSE	MAE	IW-MSE	MSE	Contourlet	WBCT
Cornell Box	PT	-0.03370	-0.08914	-0.03688	-0.02483	-0.02508	-0.00175	-0.02421	-0.00299	-0.00038	0.00004	-0.02242	0.00829	0.00830	-0.02707	-0.09727	0.14771	0.16635	0.31313	0.29542	0.19501	0.24858
GT (PT)	BDPT	-0.03766	-0.16721	-0.05302	-0.04385	-0.05098	-0.00187	-0.03961	-0.00198	-0.00037	0.00003	-0.03381	0.00747	0.00747	-0.02998	0.45376	0.27333	0.35324	0.67251	0.54666	0.08481	-0.36078
	PSSMLT	-0.03556	-0.08665	-0.04487	-0.01529	-0.01522	-0.00181	-0.01222	-0.00250	-0.00037	0.00002	-0.01098	0.00694	0.00694	-0.02383	0.07454	0.08651	0.16461	0.18188	0.17301	0.15779	0.07700
	MLT	-0.03221	-0.06861	-0.03109	-0.01000	-0.00561	-0.00176	-0.00550	-0.00266	-0.00038	0.00003	-0.00911	0.00835	0.00837	-0.01501	-0.05995	0.05437	0.07013	0.06195	0.10875	-0.05600	0.06757
	Manifold-MLT	-0.03270	-0.08660	-0.03258	-0.01017	-0.00606	-0.00177	-0.00814	-0.00255	-0.00036	0.00003	-0.00505	0.00838	0.00840	-0.01564	-0.06605	0.05548	0.07346	0.06705	0.11096	0.06355	0.06738
	ERPT	-0.02270	-0.02777	-0.01161	-0.00209	-0.00177	-0.00164	-0.00217	-0.00093	-0.00035	0.00001	0.00135	0.00307	0.00306	-0.00459	-0.05302	0.00947	0.01039	0.01547	0.01894	0.04870	0.03389
	Manifold-ERPT	-0.02187	-0.02349	-0.01002	-0.00181	-0.00157	-0.00156	-0.00200	-0.00094	-0.00034	0.00001	0.00162	0.00305	0.00305	-0.00511	-0.05370	0.00812	0.00894	0.01362	0.01624	0.04506	0.03296
Torus	PT	-0.25696	-0.11270	-0.09195	-0.04573	-0.03921	-0.02489	-0.06889	-0.01844	-0.00672	0.00020	0.05888	0.05853	0.05892	-0.11038	-0.21958	0.19842	0.16418	0.32761	0.39684	0.65864	0.54952
GT (BDPT)	BDPT	-0.24771	-0.10768	-0.09545	-0.04234	-0.03724	-0.02300	-0.05962	-0.01684	-0.00625	0.00021	0.06461	0.05934	0.05977	-0.10721	-0.23365	0.18291	0.14665	0.31065	0.36581	0.65733	0.57969
	PSSMLT	-0.32934	-0.20121	-0.18467	-0.04048	-0.01267	-0.03565	-0.04632	-0.01518	-0.00748	0.00018	0.06946	0.01822	0.01833	-0.09096	0.29185	0.17438	0.18690	0.09537	0.34876	0.61894	1.10642
	MLT	-0.33488	-0.21295	-0.20203	-0.01372	0.00515	-0.03606	0.09016	-0.01120	-0.00756	0.00020	0.05198	0.01144	0.01169	-0.07703	0.08907	0.05004	0.07799	-0.01348	0.10008	0.38458	0.84635
	Manifold-MLT	-0.35628	-0.25590	-0.25184	-0.02246	0.00560	-0.03818	0.11864	-0.01310	-0.00847	0.00015	0.03651	0.01484	0.01525	-0.33361	0.16379	0.08771	0.12577	0.02145	0.17542	0.49481	0.88657
	ERPT	-0.26809	-0.10343	-0.12235	-0.03366	-0.01447	-0.03133	-0.04850	-0.01580	-0.00740	0.00003	0.06267	0.01360	0.01367	-0.08538	-0.05514	0.14077	0.13070	0.11061	0.28155	0.58266	0.77866
	Manifold-ERPT	-0.26922	-0.10264	-0.12673	-0.03137	-0.01457	-0.03111	-0.04444	-0.01593	-0.00755	0.00002	0.02725	0.01280	0.01289	-0.08659	-0.05230	0.12942	0.12117	0.10828	0.25885	0.61998	0.83238
Veach Bidir	PT	-0.01659	-0.04894	-0.00333	-0.00107	0.00227	-0.00148	0.16618	0.00274	0.00089	0.00009	0.00748	0.01231	0.01231	0.01058	-0.03357	0.00399	0.00178	-0.01441	0.00798	0.03948	0.02995
GT (BDPT)	BDPT	-0.03412	-0.08898	-0.04388	-0.04562	-0.07197	-0.00234	-0.04159	0.00196	-0.00063	0.00006	-0.08495	0.00817	0.00817	-0.09721	0.37055	0.25648	0.18924	0.76863	0.51296	-0.20462	0.42495
	PSSMLT	-0.03463	-0.06634	-0.04196	-0.02015	-0.02454	-0.00242	-0.01531	0.00176	-0.00060	0.00005	-0.05244	0.00832	0.00832	-0.04186	-0.07394	0.10093	0.09001	0.23824	0.20186	0.18517	0.14017
	MLT	-0.02697	0.03898	-0.01720	-0.00637	0.00964	-0.00211	0.01242	0.00212	0.00064	0.00006	0.07547	0.01050	0.01049	0.01921	-0.05900	0.02815	0.02496	-0.06739	0.05631	0.06778	0.10887
	Manifold-MLT	-0.02796	0.05100	-0.02065	-0.00642	0.00935	-0.00226	0.01560	0.00233	0.00109	0.00006	-0.02304	0.01030	0.01030	-0.02151	-0.05647	0.02839	0.02692	-0.06480	0.05679	0.15042	0.09750
	ERPT	-0.02107	-0.03051	-0.00509	-0.00366	0.00636	-0.00216	0.00674	0.00090	-0.00061	0.00002	0.00834	0.00438	0.00438	-0.00904	-0.03695	0.01429	0.00472	-0.04387	0.02858	0.07840	0.03530
	Manifold-ERPT	-0.02088	-0.03062	-0.00466	-0.00298	0.00571	-0.00202	0.00641	-0.00098	-0.00062	0.00002	-0.00631	0.00440	0.00441	-0.00922	-0.03737	0.01150	0.00477	-0.03731	0.02301	0.07422	0.03457
Veach Door	PT	-0.02103	-0.05344	-0.00593	-0.00573	-0.00518	-0.00263	-0.00632	-0.00454	-0.00053	0.00011	-0.04776	0.00492	0.00491	0.18706	-0.07075	0.02645	0.02691	0.04978	0.05291	0.14363	-0.17180
GT (BDPT)	BDPT	-0.03288	-0.05916	-0.03910	-0.02856	-0.02913	-0.00301	-0.02221	-0.00458	-0.00058	0.00011	-0.08349	0.00473	0.00473	2.02713	0.12240	0.15684	0.16258	0.33436	0.31368	-0.13587	0.24808
	PSSMLT	-0.03248	-0.05987	-0.04727	-0.02185	-0.01861	-0.00295	-0.01608	-0.00409	-0.00056	0.00008	-0.05149	0.00392	0.00392	0.02342	0.14725	0.11636	0.16274	0.20014	0.23272	0.10445	-0.42433
	MLT	-0.03410	-0.07112	-0.06547	-0.02261	-0.00967	-0.00298	-0.01709	-0.00404	-0.00056	0.00009	-0.08106	0.00401	0.00401	-0.02349	0.21519	0.12090	0.21554	0.10119	0.24180	0.14322	-0.36902
	Manifold-MLT	-0.03438	-0.07323	-0.06571	-0.02045	-0.00787	-0.00301	-0.01439	-0.00424	-0.00057	0.00009	-0.02645	0.00395	0.00395	-0.03055	0.21065	0.10804	0.20825	0.07769	0.21608	0.15131	-0.31213
	ERPT	-0.01619	-0.00649	-0.00410	-0.00122	0.00049	-0.00227	-0.00140	-0.00176	-0.00056	0.00002	0.00753	0.00303	0.00303	-0.00389	-0.02886	0.00441	0.00467	-0.00301	0.00882	0.04275	-0.00764
	Manifold-ERPT	-0.01563	-0.00862	-0.00327	-0.00121	-0.00047	-0.00218	-0.00172	-0.00203	-0.00058	0.00002	0.00702	0.00314	0.00314	-0.00388	-0.02996	0.00430	0.00415	0.00314	0.00860	0.04368	0.00666
Sponza	PT	-0.11977	-0.08352	-0.05734	-0.03651	-0.03375	-0.01970	-0.03707	-0.00850	-0.00427	0.00021	0.05730	0.02183	0.02187	-0.05280	0.16746	0.17109	0.17006	0.33750	0.34219	0.22184	0.39590
GT (PT)	BDPT	-0.11455	-0.07631	-0.05407	-0.03133	-0.02826	-0.01951	-0.03274	-0.00838	-0.00444	0.00022	0.05653	0.02157	0.02160	-0.04809	0.13580	0.14373	0.14427	0.27357	0.28747	0.21191	0.42433
	PSSMLT	-0.10372	-0.04370	-0.04225	-0.01021	-0.00640	-0.01793	-0.01145	-0.00762	-0.00397	0.00016	0.06167	0.02050	0.02054	-0.01744	-0.04242	0.04062	0.06704	0.05275	0.08123	0.16550	0.09456
	MLT	-0.12948	-0.09366	-0.07845	-0.01209	-0.00628	-0.01992	-0.01219	-0.00856	-0.00431	0.00016	0.04427	0.02080	0.02075	-0.01973	-0.03910	0.04906	0.11132	0.05216	0.09811	0.15318	0.10647
	Manifold-MLT	-0.13087	-0.09648	-0.08093	-0.01190	-0.00723	-0.01953	-0.01410	-0.00716	-0.00435	0.00016	0.04745	0.02090	0.02094	-0.01777	-0.03696	0.04823	0.11457	0.06079	0.09647	0.18738	0.11788
	ERPT	-0.08035	-0.01056	-0.02362	-0.00702	-0.00439	-0.01611	-0.00797	-0.00516	-0.00391	0.00003	0.01427	0.00583	0.00583	-0.01411	-0.03573	0.02614	0.03129	0.03308	0.05229	0.14768	0.08338
	Manifold-ERPT	-0.07951	-0.01462	-0.02092	-0.00671	-0.00428	-0.01557	-0.00713	-0.00545	-0.00388	0.00003	0.01591	0.00569	0.00570	-0.01438	-0.03634	0.02488	0.02913	0.03204	0.04976	0.14297	0.08400
	Average	-0.09731	-0.07349	-0.05772	-0.01833	-0.01251	-0.01127	-0.00584	-0.00532	-0.00248	0.00009	0.00683	0.01250	0.01255	0.02372	0.02669	0.08810	0.10273	0.13344	0.17620	0.19058	0.19697
	Average Absolute Magnitude	0.09731	0.07863	0.05772	0.01833	0.01506	0.01127	0.02962	0.00600	0.00263	0.00009	0.03760	0.01250	0.01255	0.10585	0.11287	0.08810	0.10273	0.14740	0.17620	0.21324	0.29101
	Maximum Magnitude	-0.35628	-0.25590	-0.25184	-0.04573	-0.07197	-0.03818	0.16618	-0.01844	-0.00847	0.00022	-0.08495	0.05934	0.05977	2.02713	0.45376	0.27333	0.35324	0.76863	0.54666	0.65864	1.10642

CONCLUSIONS & RECOMMENDATIONS

What properties make for a good error metric for Monte Carlo Images?

- Monotonicity w.r.t. numerical divergence
  - Reported quality should not worsen as numerical quality improves
- Per-pixel or neighbourhood statistics preferable to image-wide statistics
  - Monte Carlo noise and illumination under-sampling is inherently spatially varying
- Multi-scale Geometric Analysis (MGA) helps isolate impulse noise
  - Gaussian / Laplacian / Steerable Pyramids, Wavelet / Contourlet Decompositions
- Simple models of the Human Visual System (HVS)
  - More advanced HVS models seem to be easily distracted by noise in reference images

CONCLUSIONS & RECOMMENDATIONS

What should we do when evaluating new algorithms?

- Render reference images to **a few orders of magnitude** more s.p.p. than test images
- Prefer **uniform sampling strategies** for reference images to avoid introducing structural distortions
  - Path Tracing
  - Bidirectional Path Tracing
- Use **robust IQA** to minimize error misreporting from noise in reference images
  - Multi-Scale Structural Similarity Index (MS-SSIM)
  - Structural Contrast Quality Index (SC-QI)

Wang, Z., Simoncelli, E.P., Bovik, A.C.: Multiscale structural similarity for image quality assessment. In: Conference Record of the Thirty-Seventh Asilomar Conference on Signals, Systems and Computers, 2004, vol. 2, pp. 1398–1402. IEEE (2003)

Bae, S.H., Kim, M.: A novel image quality assessment with globally and locally consilient visual quality perception. IEEE Trans. Image Process. 25(5), 2392–2406 (2016). doi:10.1109/TIP.2016.2545863

THANK YOU

Questions?