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Importance Sampling for Video Environment Maps

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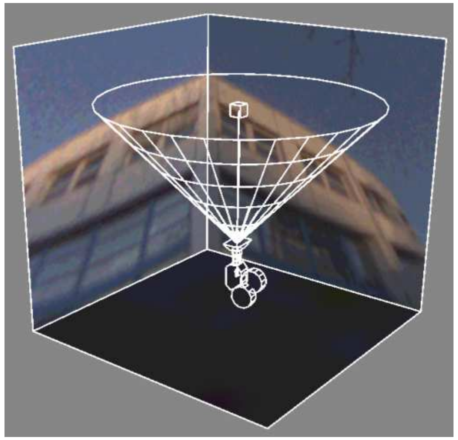
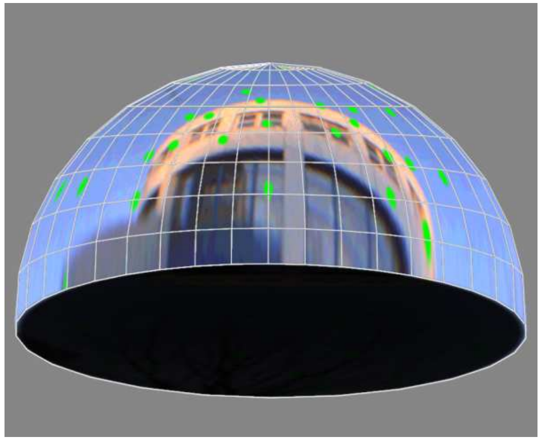
- Motivation, overview, and previous work.
- Introduction: video environment maps and importance sampling.
- Algorithm description.
- Results and conclusion.

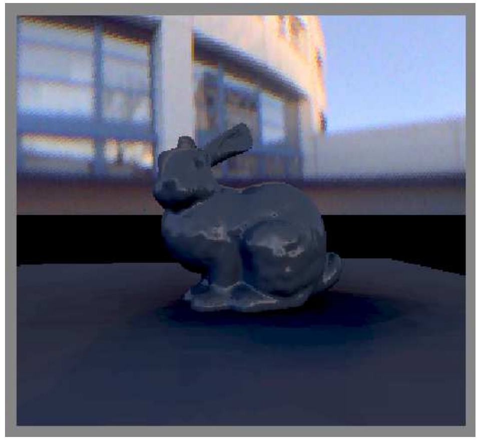
System Motivation



Illumination Acquisition



Light Source Generation



Rendering (GPU) (+Compositing)

Goal: acquire HDR video ⇒ light sources ⇒ interactive rendering

Illumination Acquisition

1 2 **3** 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27

HDR Camera

- Basic info
  - Resolution 640×480
  - 12bits logarithmic response
  - 8 orders of magnitude dynamic range
  - 22 frames per second
  - RGB channels
  - IMS Chips, cca 6,000 USD `http://www.ims-chips.de`
- Fish-eye lens
- Photometric calibration necessary

Goals for Light Source Generation

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Input: HDR environment map or video stream in RGB.

Required Properties for Output Light Sources:

- A - Arbitrary number of light sources.
- E - Equal power of all light sources (small variance).
- P - Progressiveness of light source sequence.
- B - Blue noise of the sampling pattern.
- D - Dependence on the surface normal.
- M - Small memory requirements.
- R - Real-time performance.
- T - Temporal coherence (flickering).

Previous Work

1 2 3 4 **5** 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27

Previous Work (for static HDR environment map):

- Agarwal + Ramamoorthi + Belogne + Jensen: Structured Importance Sampling, SIGGRAPH'03.
- Kollig + Keller: Efficient Illumination by High Dynamic Range Images, EGSR'03.
- Ostromoukhov + Donuhue + Jodoin: Fast Hierarchical Importance Sampling, SIGGRAPH'04.
- Burke + Heidrich: Bidirectional Importance Sampling for Illumination from Environment Maps, University of British Columbia, October 2004.
- Pharr + Humphreys: Infinite Area Light Source with Importance Sampling, October 2004.

Previous Work - Overview Table

A - arbitrary number of light sources
E - equal power of all light sources
P - progressiveness of light sources
B - blue noise of the sampling pattern
D - dependence on the surface normal
M - small memory requirements
R - real-time performance
T - temporal coherence (flickering)

Algorithm	**A**	**E**	**P**	**B**	**D**	**M**	**R**	**T**
Agarwal et al. 2003	Y	Y	P			Y		
Kollig+Keller 2003	Y	Y				Y		
Ostromoukhov et al. 2004		Y		Y		Y	Y	P
Burke + Heidrich 2004	Y	Y	(Y)			Y	Y	
Pharr + Humphreys 2004	Y	Y	(Y)			Y	Y	
Havran et al. 2003-5	Y	Y	Y	P	Y	Y	Y	Y

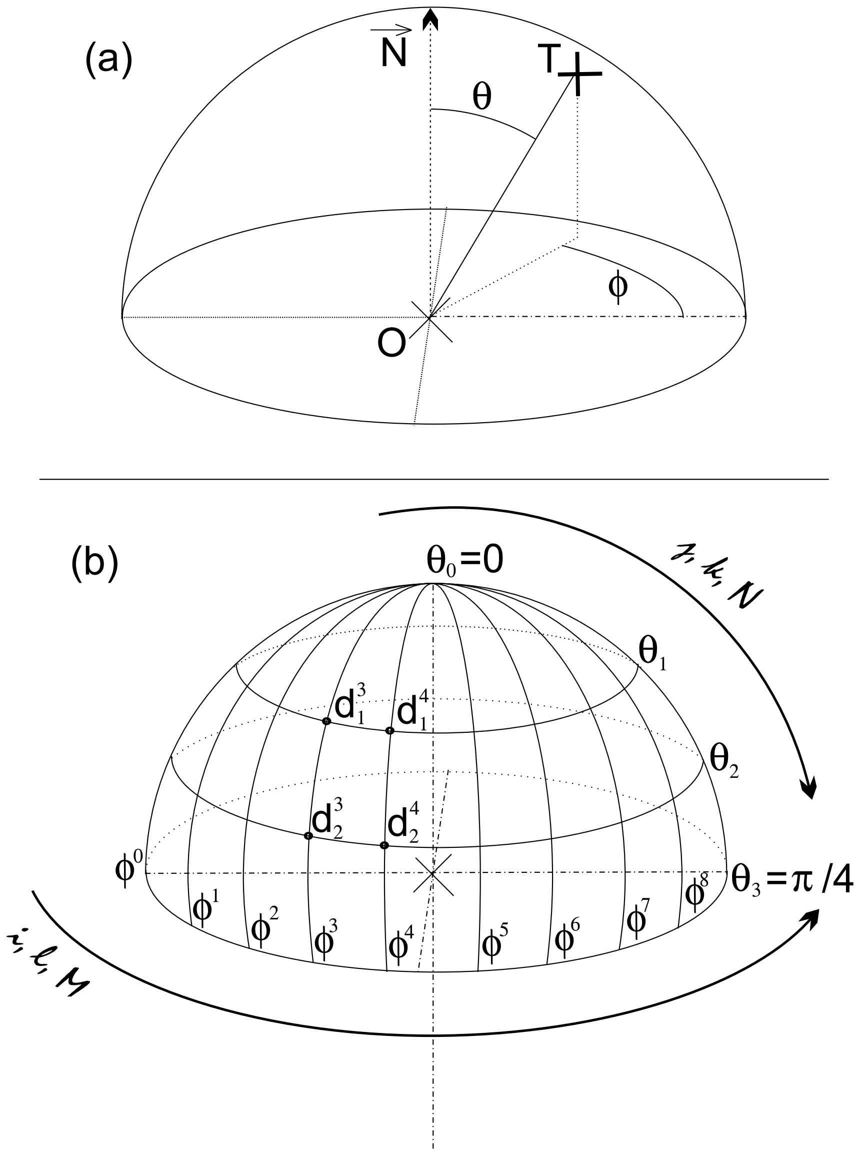
- Y . . . yes.
- P . . . partially.
- . . . no.

HDR Image on Hemisphere

- N parallels ($\phi = const$) and M meridians ($\theta = const$)
- Pixel luminances at grid points are used as a probability density function.

(Video) Environment Map (VEM)

- An image taken for a sphere or hemisphere (fish-heye lens)
- Extension to time domain: video environment map.

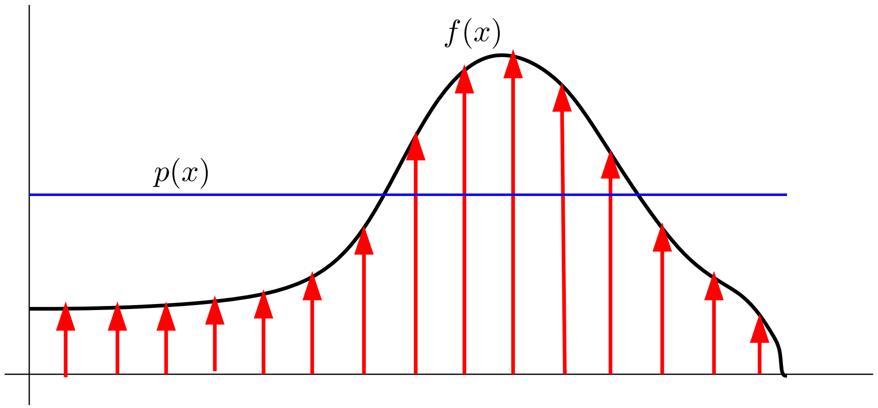


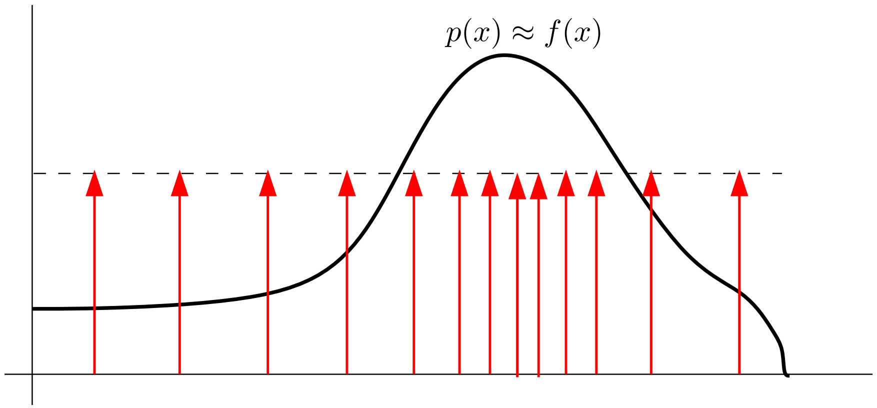
Introduction - Importance Sampling

Probability Density Function (PDF) in 1D and 2D

PDF properties for continuous random variable $p(x)$:

- $p(X) \geq 0 \quad \forall X$
- $\int p(X) = 1$
- Estimator for integration of $f(x)$: $\langle I \rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{f(x_i)}{p(x_i)}$
- Uniform sampling versus Importance sampling





Mapping 2D Square → 3D Hemisphere

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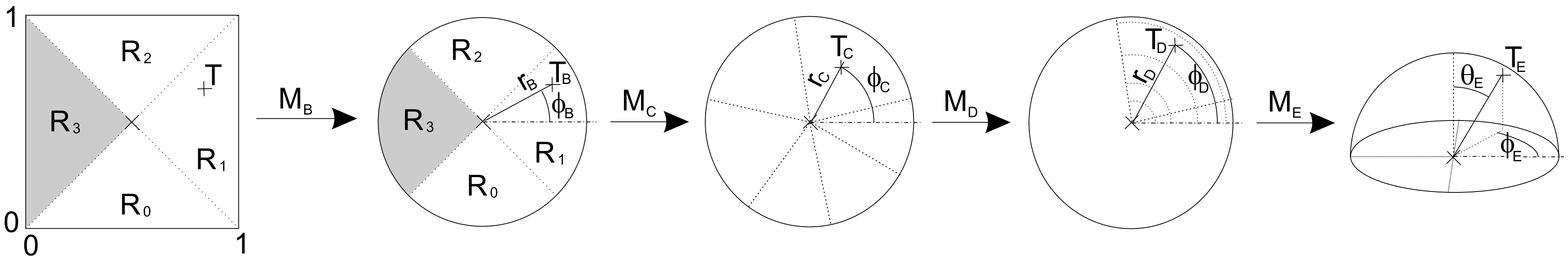
Hemigon mapping algorithm - Havran et al. 2003
(Eurographics Short Presentations)



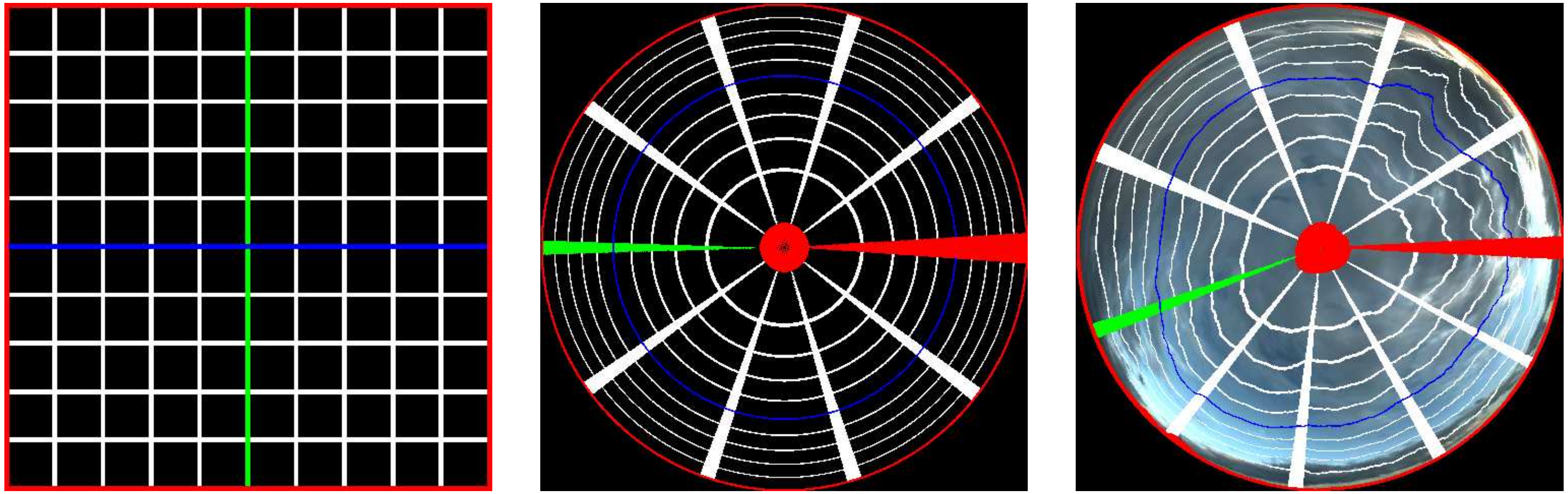
T=(u,v)	$T_B=(r_B,\phi_B)$	$T_C=(r_C,\phi_C)$	$T_D=(r_D,\phi_D)$	$T_E=(\theta_E,\phi_E)$
u in <0, 1>	r_B in <0, 1>	r_C in <0, 1>	r_D in <0, 1>	θ_E in <0, π/2 >
v in <0, 1>	ϕ_B in <0, 2.π >	ϕ_C in <0, 2.π >	ϕ_D in <0, 2.π >	ϕ_E in <0, 2.π >

Important properties of "Hemigon mapping":

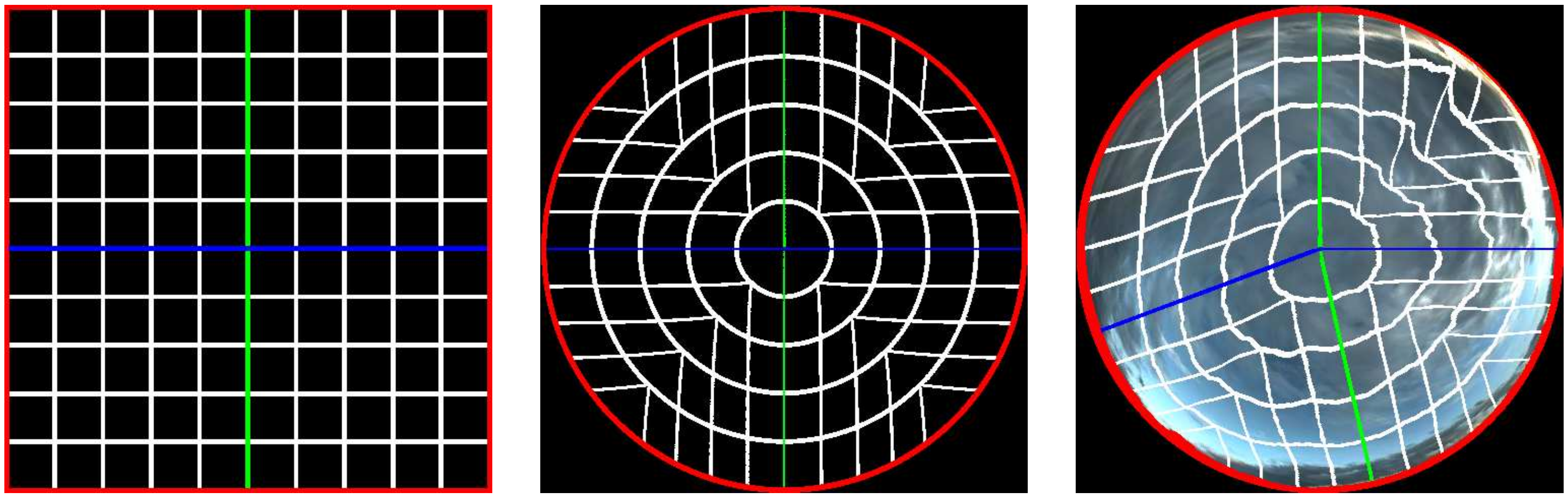
- Bijectivity, continuity in both directions, and low distortion.
- Implementation of fast importance sampling for EM and VEM.
- Preprocessing time and space $\mathcal{O}(M \cdot N)$.
- Drawing of samples in $\mathcal{O}(\log M + \log N)$, achieving maximum performance $\approx 600 \times 10^3$ samples per second on a single CPU.

Inverse Transform Method: (CDF) Twice

2D square | Constant PDF | Real-World PDF



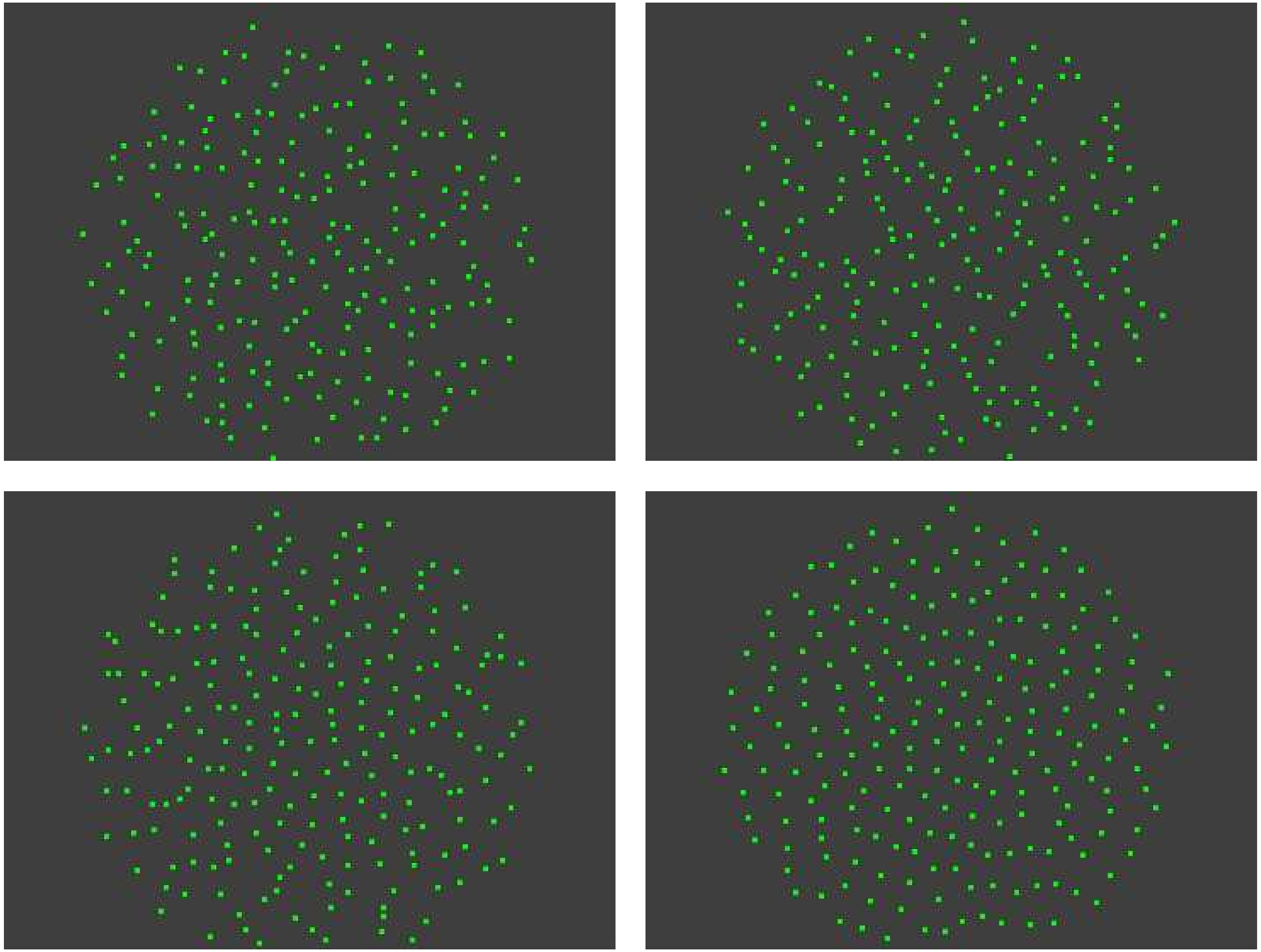
Top: Standard (Pharr + Humphreys 2004, Burke + Heidrich 2004)



Bottom: Hemigon (Havran et al. 2003)

Sampling Pattern Properties

Constant PDF



Halton sequence

Halton sequence after Lloyd's relaxation

Standard

Hemigon(Havran et al. 2003)

Light Source Generation

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Progressiveness: using Halton sequence base 2 and 3.

Blue noise: relaxing Halton sequence using Lloyd's relaxation, only once in precomputation (time consuming $\approx$ 10 hours).

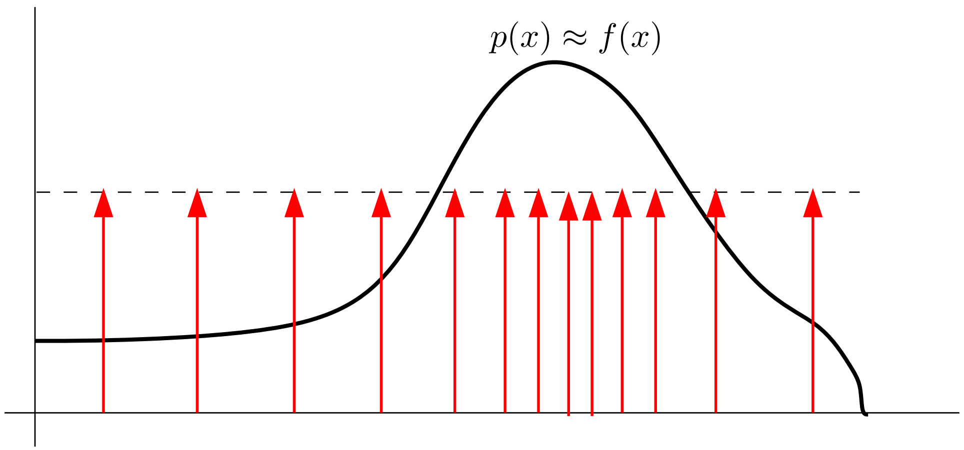
Required memory: $N \times M \times (3 + 1 + 1)$ floats (RGB channels + luminance + CDF) + memory to store computed light sources

Other properties: arbitrary number of light sources, equal power of light sources, real-time performance $\rightarrow$ given by hemigon mapping.

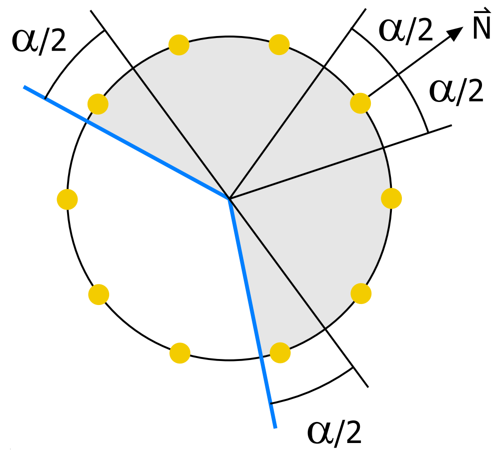
Achieving Required Properties

Dependence on the surface normal: progressiveness is desirable.

Observation: The samples drawn progressively according to the importance function F in a domain D are also drawn progressively in any continuous subdomain of the domain D.



1D function



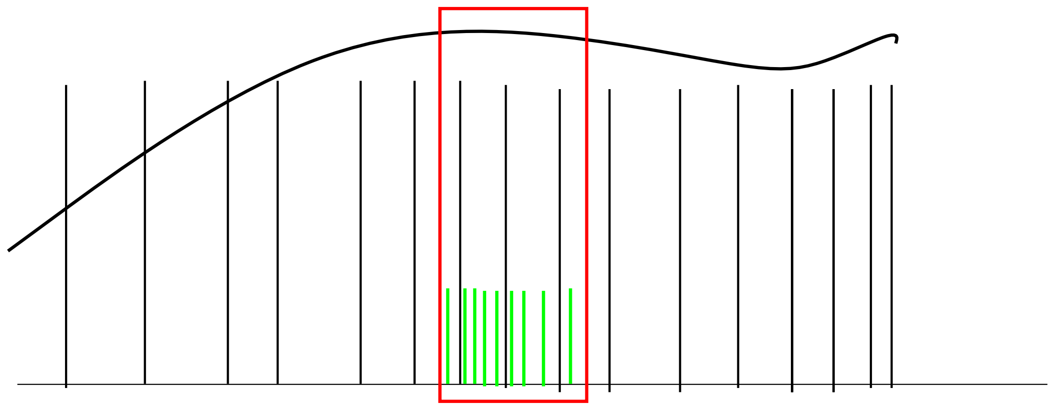
Application: from base sampling sequence many sampling subsequences over angular cuts.

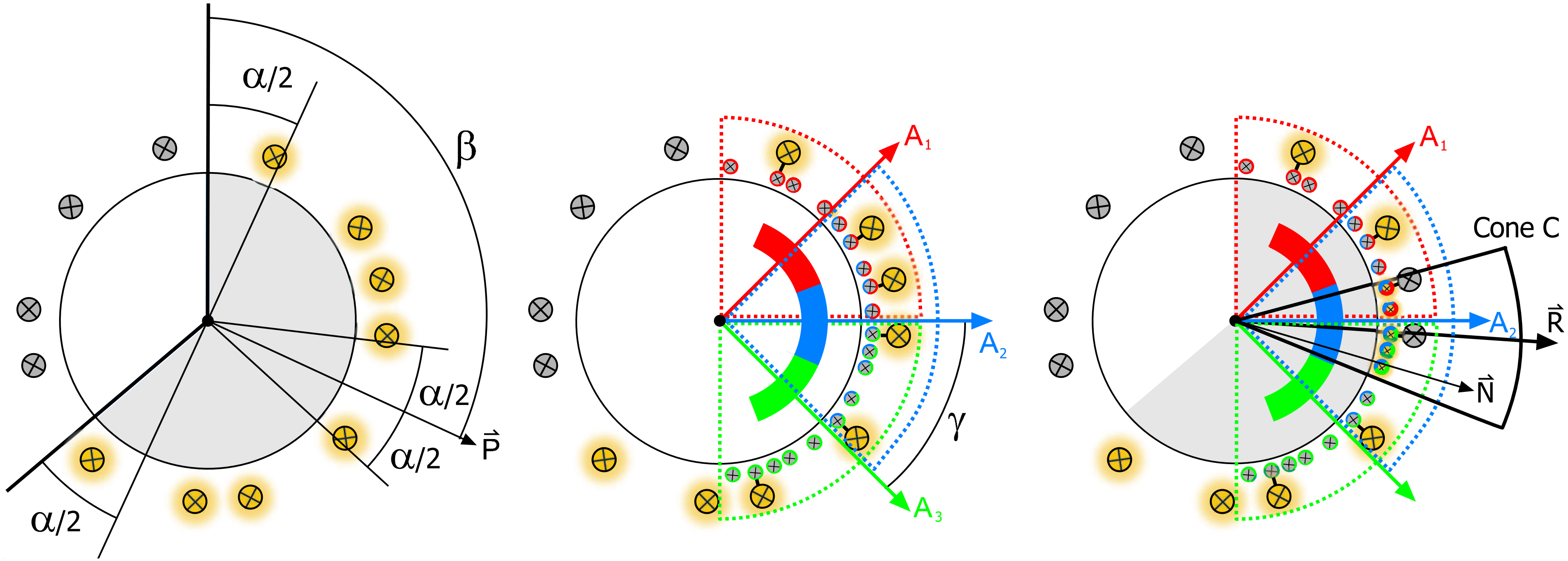
Covering: Hemisphere covered by overlapping angular cuts identified by LUT for rendering based on normal. Efficiency improvement up to 60-80%.

Handling Glossy Surfaces

Domain stratification:

- high intensity light sources
- low intensity light sources (red box - lobe of BRDF)





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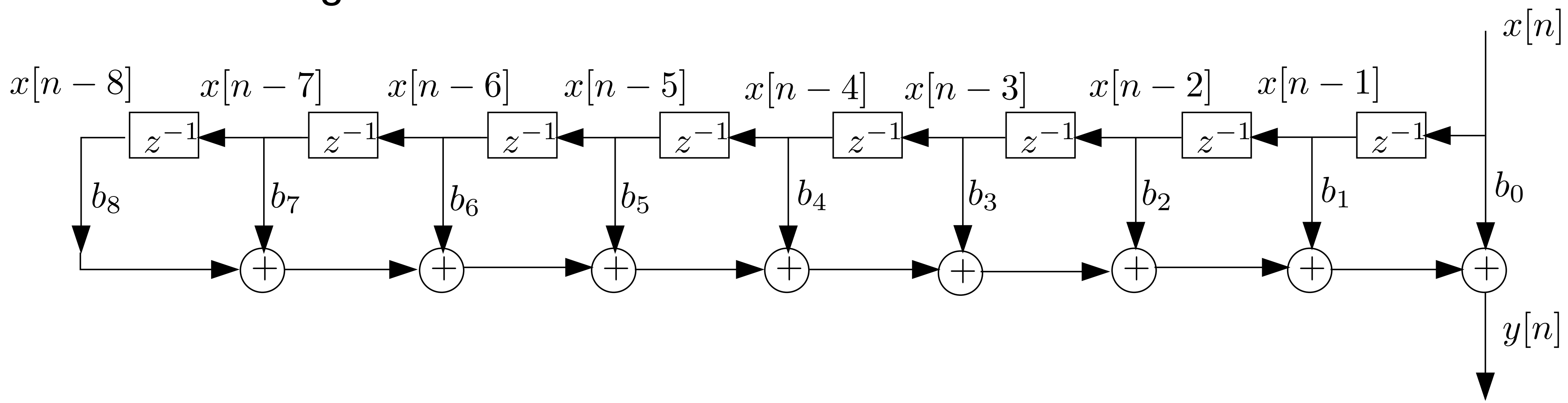
Achieving Temporal Coherence

1 2 3 4 5 6 7 8 9 10 11 12 13 14 **15** 16 17 18 19 20 21 22 23 24 25 26 27

Problematic for existing approaches, excluding Ostromoukhov (only local changes).

Temporal filtering using FIR or IIR filters - both light source position and power to avoid flickering.



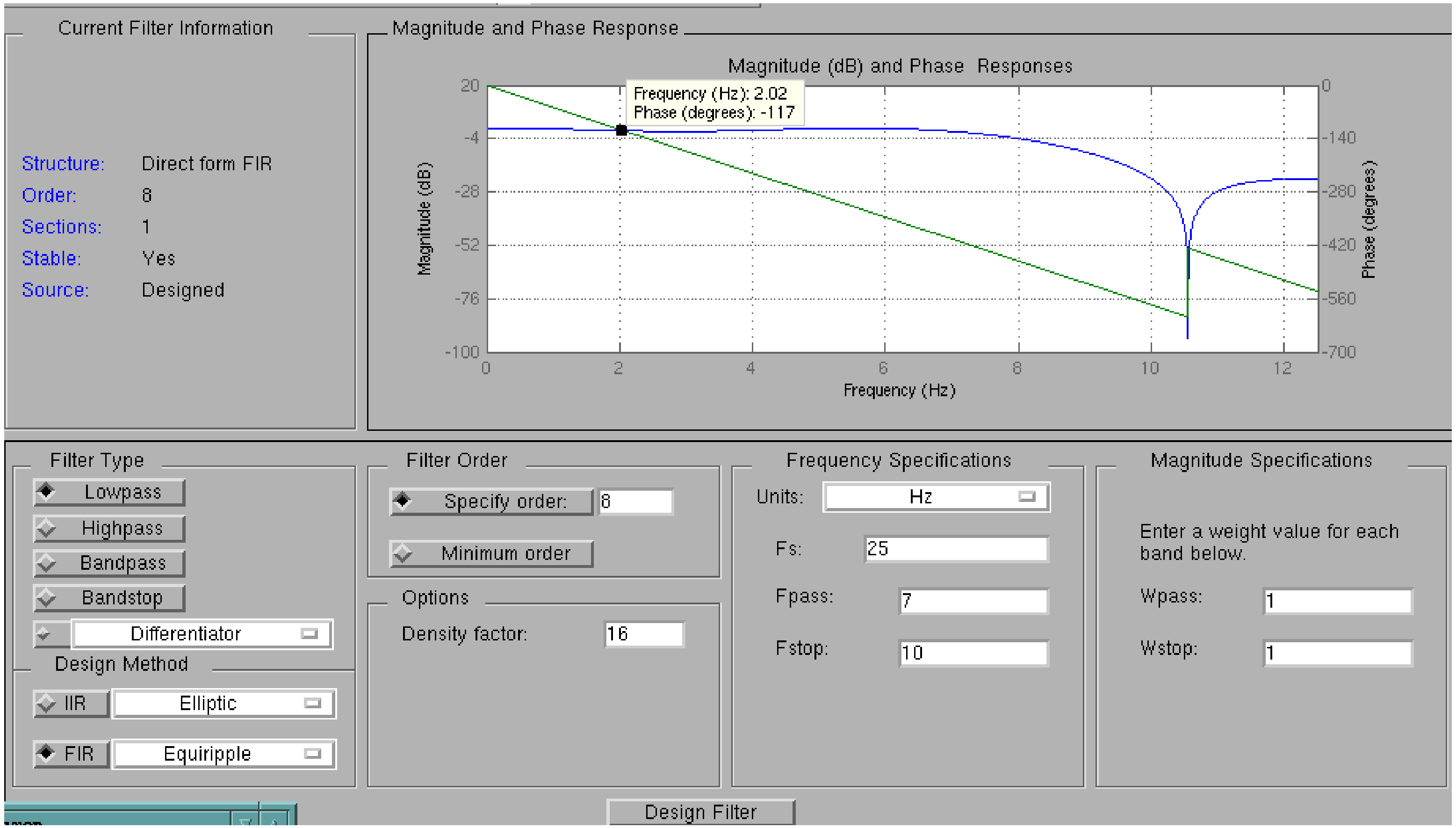
FIR filter equation: $y[n] = \sum_{k=0}^{M-1} b_k \cdot x[n-k]$

FIR filtering introduces the delay M/2 frames.

See the book Oppenheim et al.: Discrete Time Signal Processing, Prentice Hall, 1999, for more details on FIR design.

FIR example

FIR filter, sampling frequency = $22\ Hz$, pass frequency = $7\ Hz$, stop frequency = $9\ Hz$: Coefficients $b_0 = b_8 = 0.06216$, $b_1 = b_7 = 0.01296$, $b_2 = b_6 = -0.13816$, $b_3 = b_5 = 0.28315$, $b_4 = 0.65223$



MATLAB, using fdatool.

Other Issues

Clustering - for very non-uniform lighting (bright sunlight).

- Using fixed-distance search, radius given in advance.
- Data structure based on bounding box decomposition (BBD) tree [Arya94].
- Clustering not compliant with progressiveness.
- Achieving real-time performance, time complexity $\mathcal{O}(N \cdot \log N)$ for N initial light sources.

Color estimation of light sources - three methods implemented and tested.

- Simple method - taking pixel color at the sample direction.
- Two integration methods - taking samples on a sphere and add the color to the closest neighbors (BBD-tree search) - approximating Voronoi diagram.

Rendering with many shadow maps - shadow maps packing into a single large texture (similarly to Knuth and Fuhrman's paper, WSCG 2005)

One Really Important Issue

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 **18** 19 20 21 22 23 24 25 26 27

FULLY DYNAMIC SYSTEM:

- direct lighting
- camera
- geometry
- BRDF

NO PRECOMPUTATION NECESSARY

(However, no interreflection supported.)

System Pipeline

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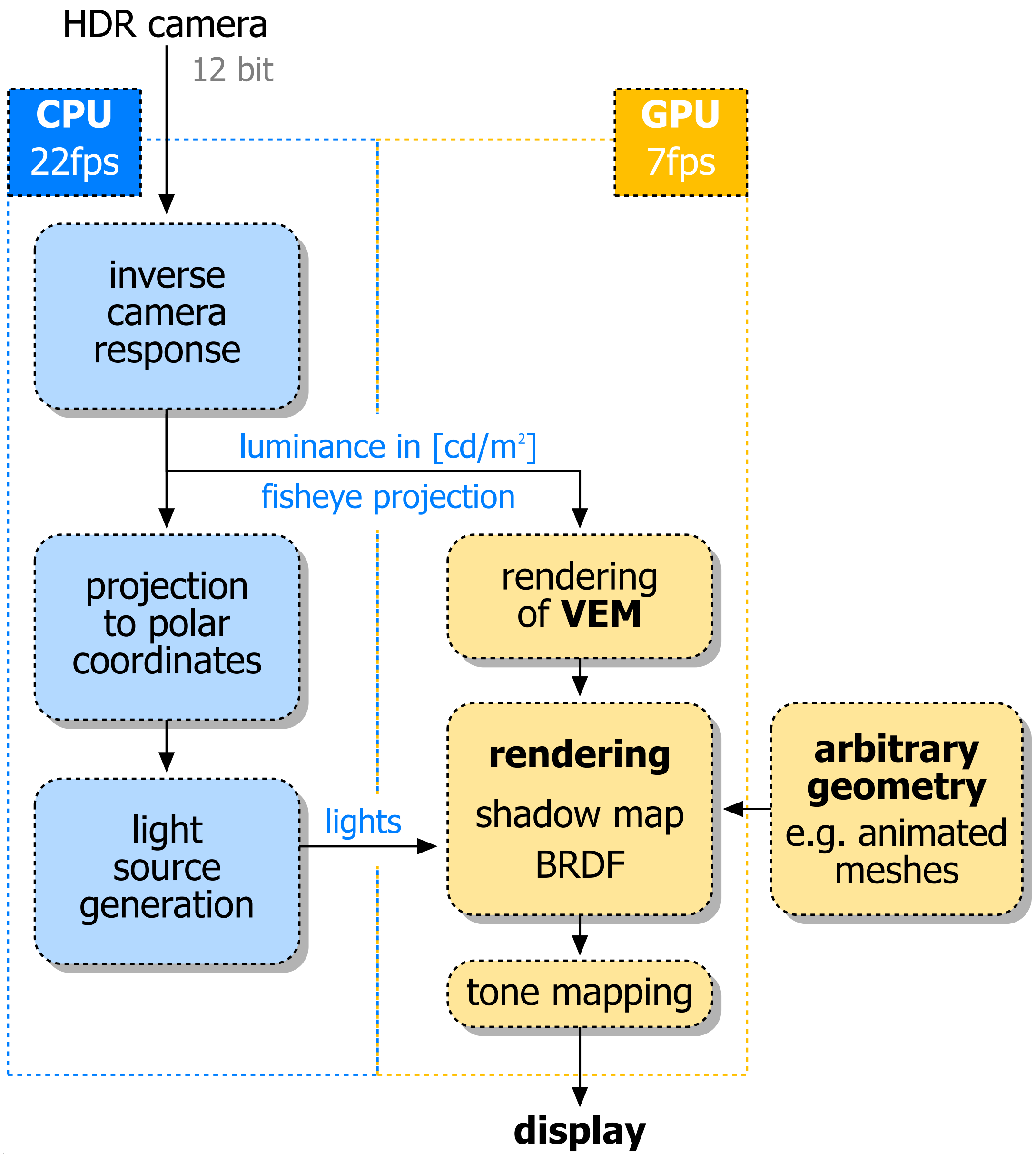

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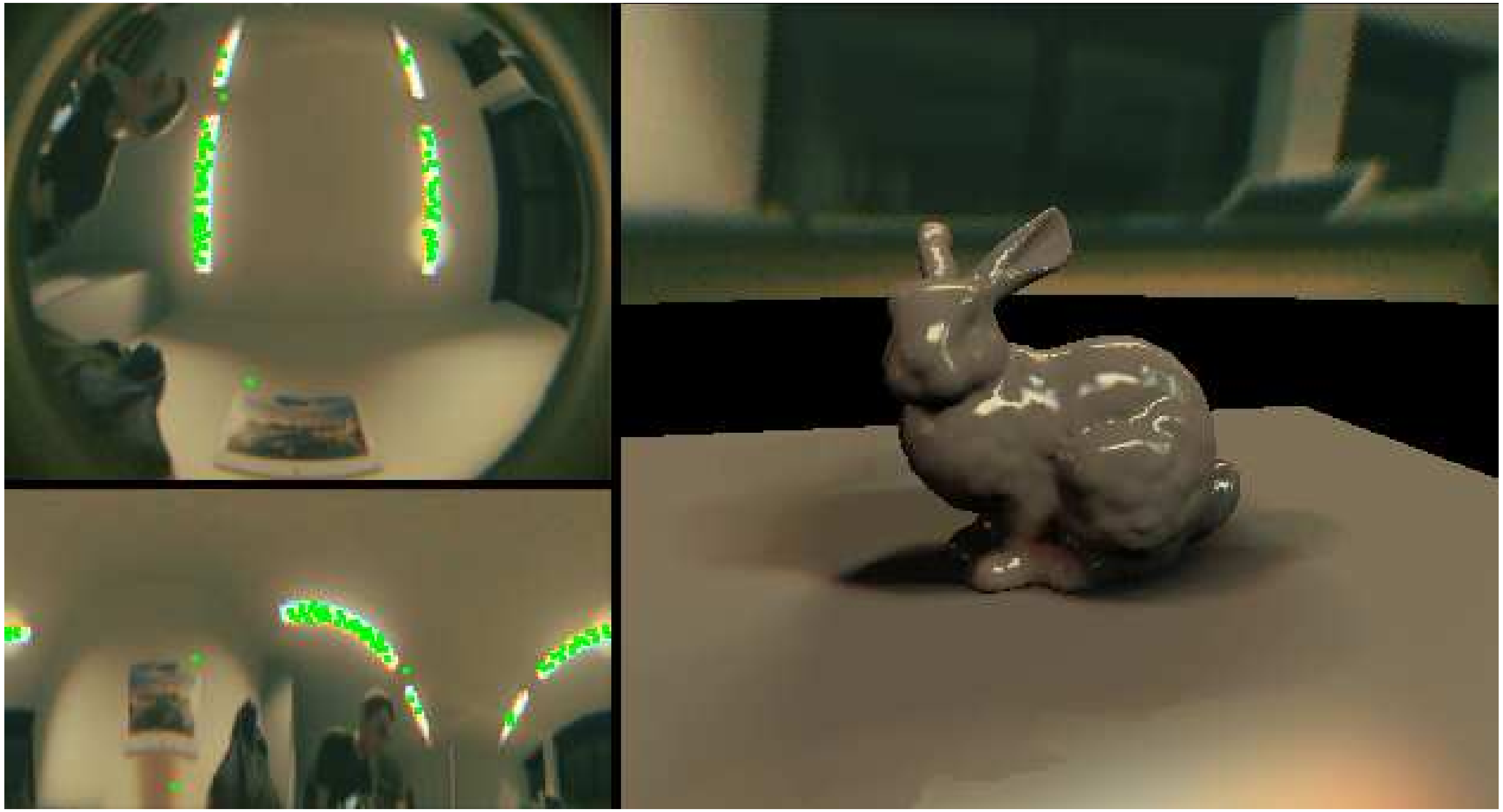
Some Numbers and Facts

- Acquisition 22 FPS, $640 \times 480 \rightarrow 320 \times 240$ RGB pixels, 12 Bits.
- CDF created over 360×90 float pixels (luminance).
- Computation time to generate ≈ 100 light sources 5 milliseconds.
- Computation time to generate ≈ 5000 light sources for glossy surfaces and creating $100 - 200$ sampling subsequences takes 20 milliseconds.
- FIR filter of order 8 with pass frequency 7 Hz, stop frequency 9 Hz requires delay of 4 VEM frames.
- Rendering speed $2.6 - 8$ FPS on NVidia GeForce 6800GT for 72 light sources, up to 216 light sources for glossy surfaces enhancements, and 320×240 resolution: performance bottleneck is pixel shader.
- Shadow maps packed in 9×9 grid in a single texture 2304×2304, a single shadow map of resolution 256×256.

Results – “office night” lighting



$16,200$ **triangles,** 72 **shadow maps,** 5.3 **FPS.**

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Results – “office window” illumination

$16,200$ **triangles,** $72 + 5,000$ **light sources,** 2.6 **FPS**

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Results – outdoor illumination

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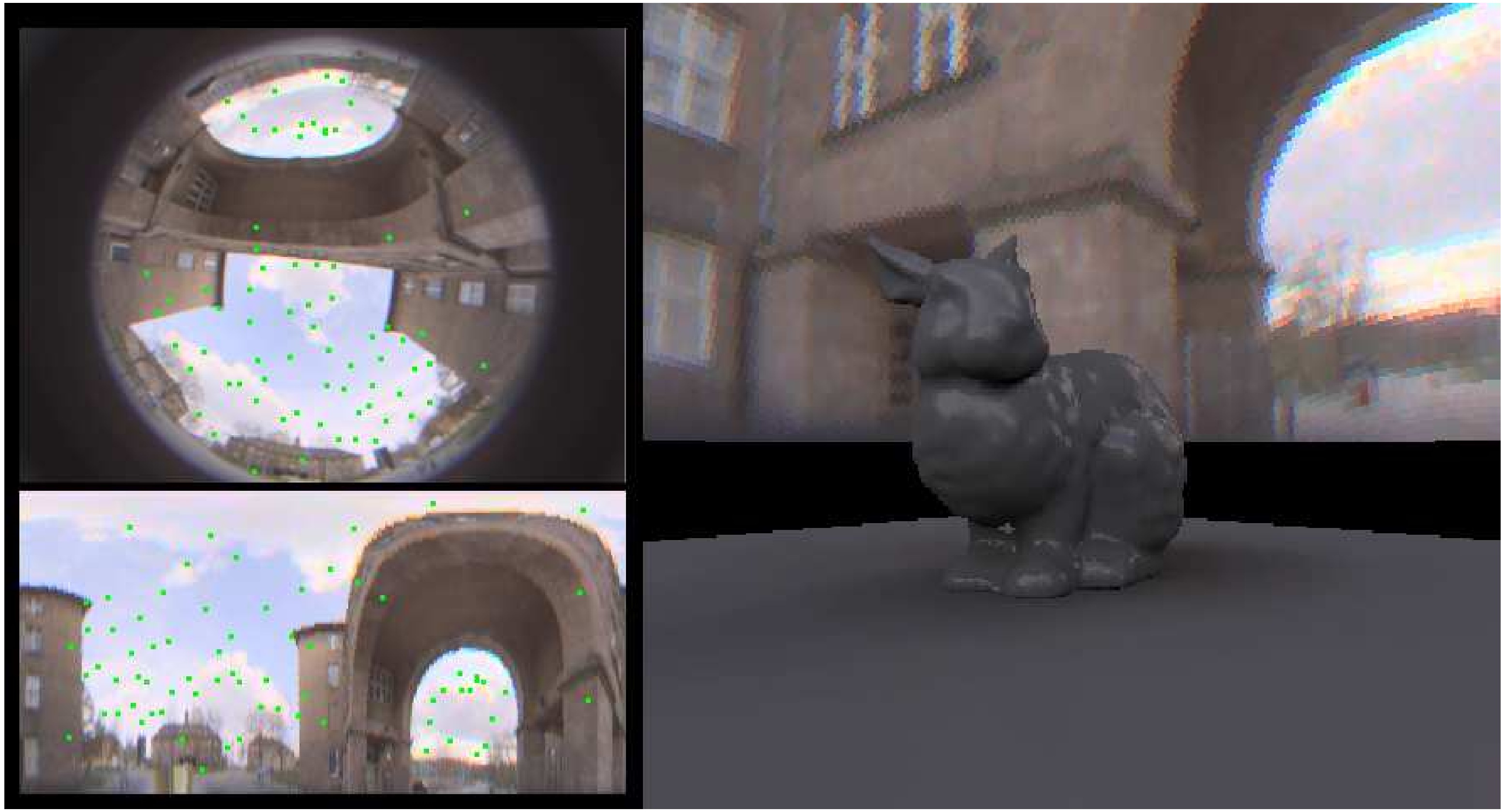

$16,200$ **triangles,** $72 + 5,000$ **light sources,** 2.6 **FPS**

Results – video

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Conclusion and Future Work

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Summary

- Acquiring HDR VEM, computing light sources, rendering.
- To our best knowledge the first system and solution of this kind.
- Quality comparable to published offline techniques.
- Achieving progressiveness, efficiency (normals), low variance, blue noise for uniform subregions, small memory requirements, and real-time performance.
- The algorithmic improvements useful for CPU-based rendering systems.

Applications

- Mixed reality, virtual studio systems (reportage) etc.
- More cameras and correct shadows from synthetic objects.

Acknowledgements

- Paul Debevec and Andrew Jones for providing us with a sequence of HDR images of the sky for case study.
- Partial Support of IST-2001-34744, “Realtime Visualization of Complex Reflectance Behaviour in Virtual Prototyping” (RealReflect).
- IMS Chips company for lending us HDR camera.
  `http://www.ims-chips.de`
- Kristina Scherbaum and Josef Zajac for their help with illustrations.

Demo of the system at the booth 1419,
’BrightSide Technologies’

Job Search Announcement

- I am looking for
  - Post-Doc Researcher, or
  - Research Fellow, or
  - Visiting Assistant Professor
- Period: one or two years.
- More than 20 referred conference + journal papers.
- More details on my home page:

  `http://www.mpi-inf.mpg.de/˜havran`
- E-mail:

  `havran@mpi-inf.mpg.de`
- Do not hesitate to contact me during conference.

Thank you for your attention.

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