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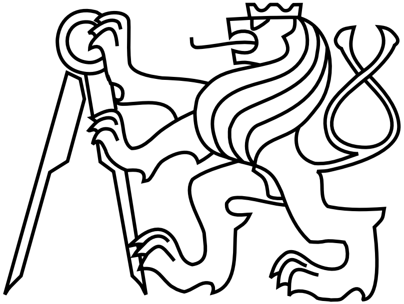

Doctoral Thesis Statement

Czech Technical University in Prague

Faculty of Electrical Engineering
Department of Computer Graphics and Interaction

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Illumination Coherence for Light Transport Simulation

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Abstrakt

Při syntéze obrazu na počítači je nutné simulovat transport světla ve scéně. Simulace transportu světla je však časově velmi náročná. Jak naznačují nedávno publikované teoretické práce, klíčem k urychlení této simulace je využití koherentních vlastností světla, které prochází scénou. V této dizertační práci se zabýváme návrhem efektivních algoritmů pro syntézu obrazu, které odhalují a používají právě zmíněné koherence transportu světla.

Navrhujeme nový algoritmus nazvaný *prostorově-směrová úschova radiance* (SDRC) pro urychlení simulace transportu světla ve scénách s lesklými povrchy. Algoritmus SDRC využívá toho, že nepřímé osvětlení se v reálných scénách mění spojitě a relativně pomalu vzhledem k pozici. To nám dovoluje vypočítávat nepřímé osvětlení pouze v některých, vhodně zvolených místech ve 3D scéně, a v ostatních místech jej následně zrekonstruovat z okolních dříve vypočtených kešovaných záznamů radiance. V práci ukazujeme, že SDRC překonává nejen původní algoritmus kešování radiance navržený Křivánkem a kol. [KGPB05], ale i obecné numerické metody Monte Carlo založené na vzorkování s důležitostí podle odrazivé funkce (BRDF).

V další části práce navrhujeme efektivní a přesnější algoritmus pro *lokální analýzu hlavních komponent* (LPCA), který se používá pro redukci dimenzionality a komprese rozsáhlých datových souborů. Efektivity algoritmu dosahujeme předáváním některých výsledků mezi jednotlivými iteracemi LPCA algoritmu. K zlepšení přesnosti algoritmu slouží lepší inicializace LPCA, která předchází uváznutí LPCA ve špatném lokálním minimu. Navržený algoritmus použijeme pro kompresy matic přenosu osvětlení používané v metodách souhrnně označovaných jako metody s předpočítaným přenosem radiance.

V poslední části dizertace popisujeme návrh algoritmu pro interaktivní nasvětlování animovaných sekvencí s globálním osvětlením. Problém nasvětlování formulujeme pomocí 3D tenzoru, který popisuje propagaci světla ve scéně napříč animovanou sekvencí. Pro urychlení před-výpočtu tenzoru navrhujeme adaptivní algoritmus, který využívá koherenci obsaženou v transportu světla. Návrh našeho algoritmu dosud nebyl implementačně ověřen a tuto úlohu ponecháváme jako námět pro budoucí práci.

Klíčová slova. Počítačová grafika, rendering, koherence, globální osvětlení, simulace transportu světla, klování radiance, analýza hlavních komponent, PCA, k-means, předpočítaný přenos radiance, kinematografické znovu nasvětlování.

Abstract

Simulation of light transport in a scene is an essential task in realistic image synthesis. However, an accurate simulation of light as it bounces in the scene is time consuming. It has been shown that a key to speeding up light transport simulation algorithms is to take advantage of the high degree of spatial, angular, and temporal coherence. In this thesis we make three contributions in this area.

First, we propose *spatial directional radiance caching* (SDRC) for accelerating the light transport simulation in scenes with glossy surfaces. The SDRC algorithm takes advantage of the smoothness of shading on glossy surfaces by interpolating the indirect illumination from a set of sparsely distributed radiance samples that are both spatially and directionally close. We show that SDRC outperforms the original radiance caching proposed by Křivánek et al. [KGPB05] and also the Monte Carlo-based methods based on BRDF importance sampling.

In the next part of the thesis, we propose an efficient and accurate *local principal component analysis* (LPCA) algorithm for dimensionality reduction and data compression of large data sets. To achieve efficiency our new algorithm, called SortCluster-LPCA, passes various information from previous iteration to the next, showing a speed up of up to 20. Improved accuracy is achieved through better initial seeding of cluster centroids in LPCA, producing substantially better data approximation.

Finally, we describe a work in progress focusing on the development of an algorithm for interactive relighting of animation sequences with indirect illumination. We formulate the relighting problem as a large 3D array expressing light propagation in a scene over multiple frames. We suggest an adaptive algorithm to make the pre-computation tractable exploiting coherence in light transport. Since our approach has not been implemented yet we leave its practical verification as a future work.

Keywords. Computer graphics, rendering, coherence, global illumination, light transport simulation, radiance caching, principal component analysis, PCA, k-means, precomputed radiance transfer, cinematic relighting.

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[GK08] Gassenbauer V., Křivánek J.: Spatial directional radiance caching. In *Siggraph Asia 2008 NEW HORIZONS, Sketches and Posters* (Singapore, 2008).

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Publication has been cited in [LWDB10, PGSP10, NJH11].

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Authorship of Ph.D. student in each publication is 70%.

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Résumé

One of the important problems in the field of computer graphics is to generate an image of a scene in such a way that the difference between a photograph of a real scene and the computer-generated image of the corresponding virtual scene is not noticeable. Generating such photorealistic images is called *Realistic Image Synthesis* and has a number of applications in the film industry, architecture, lighting design, etc.

1 Global Illumination Problem

The input of any realistic image synthesis system is a complete description of a virtual world. It consists of the objects' geometry, the material properties of those objects, and the geometry and emission characteristics of light sources. In order to create an image of the virtual world we need to calculate the amount of light entering a virtual camera which is positioned in the scene. Light enters the camera directly from the light sources and also indirectly as it is reflected or refracted off the objects in the scene. The effects of light as it bounces in the scene are referred to as *global illumination* (GI); this is the main objective of realistic image synthesis. Some examples of global illuminated scenes are given in Figure 1.

The fundamental mathematical foundation for realistic image synthesis is the rendering equation [Kaj86]. The rendering equation describes the energy balance in the scene. One approach to solve the rendering equation is the finite element method that the radiosity algorithms are based on [CW93, SP94]. The radiosity algorithms have been shown to be very efficient, especially for relatively simple scenes with diffuse surfaces. For complex environments with a lot of materials with different reflectance functions, however, radiosity algorithms are impractical in terms of memory space and computation time.

Other approaches to solve the rendering equation are based on Monte Carlo methods. Instead of solving the rendering equation directly they calculate it in an explicit form: they expand the equation into an infinite series of finite-dimensional integrals that can be evaluated numerically. The pioneering work in solving the finite-dimensional integrals using Monte Carlo was distributed ray

(a) Refraction **(b)** Color bleeding **(c)** Caustic

Figure 1 – Global illumination effects. Images courtesy were borrowed from [KG09].

tracing [CPC84] and path tracing [Kaj86], as well as the follow-up algorithms like bi-directional path tracing [LW93, VG97], etc. Such methods are general and robust. But it can take hours to generate artifact-free images.

The main source of inefficiency of above Monte Carlo algorithms is that they reuse no (or just very little) information about the contributions of previously calculated light paths, essentially ignoring any coherence of light transport in the scene. To speed up the global illumination calculation other algorithms trade generality of provided solution for restrictions imposed on the scene configuration and/or make use the coherence of light transfer in the scene [WRC88, KGPB05, GBP07, HPB07]. Irradiance and radiance caching algorithms [WRC88, KGPB05] are efficient methods for solving global illumination in scenes with diffuse and low-gloss surfaces, respectively, using the observation that indirect lighting changes slowly over surfaces. Another observation is that lighting changes smoothly whenever the camera and/or objects in the scene move slowly [GBP07, HPB07].

Mathematical foundation for light transport coherence was presented in [DHS+05, MSRB07, PML+09]. These works show that light transport has a high degree of coherence over directional, spatial, and temporal domains. As suggested in these works, the use of light transfer coherence can play the key role in further acceleration of global illumination algorithms. In the thesis we focus on the very goal of speeding-up global illumination algorithms by exploiting the coherence of light transfer in the scene.

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2 Contributions

A huge amount of calculation must be performed to provide a high-quality image with global illumination. To reduce the amount of calculation it is customary to simplify the problem in an application-specific manner. In the thesis we develop three algorithms of different applications making use of light transfer coherence for efficient calculation of GI: one for general computation of GI on glossy surfaces, another for the acceleration of *local principal component analysis* (LPCA) used for compression of large data matrices in *precomputed radiance transfer* (PRT) [SKS02, SHHS03] and image databases of *Bi-directional texture function* (BTF) [FH09], and the last one which is a work in progress extending PRT for animation sequences. In the following, we shortly introduce these three algorithms.

2.1 Spatial Directional Radiance Caching

As we mentioned above, computing full global illumination in virtual scenes is very time-consuming. Monte Carlo importance sampling [Coo86, LF97, LRR04], Metropolis light transport [VG97] or photon mapping [Jen01] are examples of very general techniques for solving GI. Irradiance caching [WRC88] delivers fast GI solution in scenes with diffuse surfaces. Radiance caching [KGPB05] includes the support for caching in the scenes with low-glossy surfaces. But effective algorithms for computing GI on shiny surfaces are missing. We focus on generalizing caching approaches to shiny surfaces. We propose a novel efficient algorithm that we call *spatial directional radiance caching* (SDRC), for computing GI effects on these surfaces. We use both spatial and angular coherence of light transport in the scene to make our algorithm efficient.

2.1.1 Algorithm Overview

Our algorithm is built on the fundamental idea behind the original irradiance caching, the "lazy evaluation procedure": query the cache, perform interpolation if possible, otherwise compute a new illumination value and store it in the cache for later reuse.

When we evaluate a new record (if none is available for interpolation), we generate random directions using BRDF importance sampling and compute incoming radiance for each direction by ray tracing. We then map such directions to a phi-theta space and build a kd-tree over them. The whole L-tree (how we called the kd-tree) is then stored in the cache as a single spatial record. The cached L-trees may later be selectively updated during the interpolation as described in

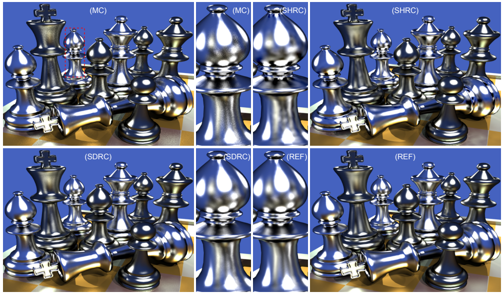

Figure 2 – Renderings of the chess scene. Images were rendered at a resolution of 1024 × 768 in approximately the same time, 468 seconds. The indirect term computation on glossy surfaces took 365 seconds. Note the sharper glossy reflection of black pieces on the white chess piece in the details. Chess pieces courtesy of T. Hachisuka.

the following paragraph. To determine the area over which the new record can be reused, we estimate the upper bound on the illumination gradient from the radiance samples. The gradient formula takes the BRDF into account, hence the record spacing is automatically adapted to the surface reflectance properties.

The major novelty of our caching algorithm consists in performing the "lazy evaluation procedure" not only in the spatial but also in the directional domain: To compute indirect illumination at a point, we first collect existing nearby cache records, or L-trees, (in space) and we attempt to use them for interpolation. However, for each sample *direction* (generated by BRDF importance sampling at the point of interpolation), we check if there is a nearby radiance sample stored in the L-tree and possibly reuse it. If not, we shoot a ray to obtain a new radiance sample and update the L-tree. The process is applied to all contributing L-trees separately. Finally, outgoing radiance is computed as a weighted average of the contributions from individual L-trees. The major benefit of the *directional caching* is that it ensures a smooth integration of the *view-dependent* BRDF importance sampling with the *view-independent* overall caching algorithm.

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2.1.2 Results

We compare our algorithm (spatial directional radiance caching, SDRC) with the original radiance caching algorithm as described in [KBPv06] (spherical harmonics radiance caching, SHRC) and Monte Carlo importance sampling (MC). Our new caching algorithm outperforms the original radiance caching for scenes with shiny surfaces, where radiance caching produces blurring of reflections or banding artifacts. Compared to Monte Carlo importance sampling, our algorithm produces less noisy images in the same time. The main disadvantages of our algorithm are a higher memory demand and potentially difficult parallelization due to the continual updates of cache records. Equal-time comparison of the rendering quality achieved using the MC, SHRC and SDRC is in Figure 2.

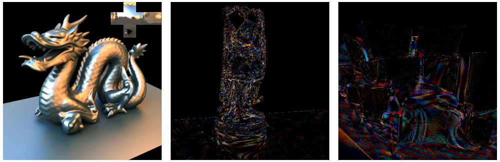
2.2 Improving Performance and Accuracy of Local PCA

Precomputed radiance transfer (PRT) [SKS02] and image databases of Bidirectional texture function (BTF) [MMK03, FH09] are the main applications in computer graphics where the local principal component analysis (LPCA) [KL97] is largely used. PRT refers to a group of methods used for interactive relighting of a virtual scene with GI effects while dynamically changing some parameters of the scene. The original PRT application was used for image relighting of a scene lit by an environment map. In the many follow-up papers [SHHS03, LSSS04, NRH03, FPJY07, HR10] the PRT has been improved, lifting some restrictions on the scene configuration. The PRT methods have been shown to be very popular for lighting design in cinematography [KAMJ05, HPB06]. They have also been used in computer games because of their ability to deliver GI effects at real-time frame rates. To achieve these goals, PRT techniques precompute and compress light transfer in the scene expressed as a large transfer matrix. Precomputation and compression of the light transfer matrix, however, is very time-consuming and is a serious bottlenecks of PRT methods. Huang and Ramamoorthi [HR10] address the slow precomputation of light transfer matrix by exploiting spatial and angular coherence of the light transfer. Nevertheless they still use the slow LPCA for the light transfer matrix compression. Our goal is to accelerate the LPCA by exploiting the coherence in the compressed data.

2.2.1 Algorithm Overview

Having a set of high-dimensional data vectors and a number of clusters k, the goal of LPCA is to find an approximation of these vectors in k low-dimensional affine subspaces minimizing an error criterion. The original LPCA starts with

(a) Horse **(b)** Happy Buddha **(c)** Walt Disney



(d) Dragon **(e)** Happy: 16× Err-img **(f)** Disney: 16× Err-img

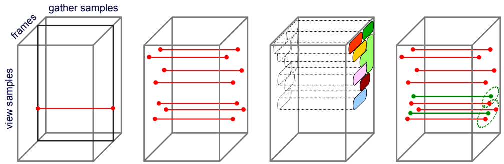
Figure 3 – Scenes used in our experiments. We tested our SortClusters LPCA (SC-LPCA) for compression of transfer matrices for these scenes. The models in 3a, 3b, and 3d are made of glossy materials represented using Phong's BRDF with exponent from 10 to 30. The model in 3c is represented using Ward's BRDF with the roughness of 0.1. Compared to LPCA, we achieve a 5× to 20× speed-up using SC-LPCA, while providing identical output. For the sake of completeness, Figure 3e and 3f show a 16× amplified difference between images rendered using the original and compressed transfer matrix.

a random initialization of affine subspaces. After that it alternately performs classification of the data vectors into nearest clusters as well as clusters' update. But there are serious bottlenecks with this simple LPCA algorithm. First it is inefficient: When classifying a data vector to the nearest cluster, distances to all clusters must be computed. The data vector is then assigned to the cluster for which the distance is minimal. A second problem is low accuracy since the LPCA is prone to get stuck in a local minimum of the objective function that guides the clustering.

To improve the efficiency of the LPCA we propose to use a very fast test which allows us to eliminate unnecessary distance calculations in the classification stage. Before calculating the true distance of a data vector to a tested cluster (represented by affine subspace) we check, whether the data vector can be closer to

In Contribution 1 we developed *spatial directional radiance caching* (SDRC) to speed up GI calculation in scenes with glossy surfaces. Efficiency of SDRC is achieved by reusing cached radiance samples calculated adaptively on demand. In Contribution 2 we deal with *local principal component analysis* (LPCA) used for data compression in data-driven approaches. We developed an accelerated algorithm, *SortCluster-LPCA* (SC-LPCA), that produces exactly the same result as the original LPCA but more quickly by exploiting coherence in the compressed data-set. In Contribution 3 we presented an interactive system for cinematic relighting of animation sequences.

In future research it would be interesting to explore other possibilities how to utilize coherence for fast GI calculation proposing more efficient algorithms. In addition, we expect that data-driven approaches— fast estimation of the light transfer tensor in our interactive system used data-driven approach—will cement their key position in modern computer graphics. Powerful algorithms for processing and compression of large databases that exploit the coherence therein will be of foremost importance.



(a) Definition **(b)** Exploration **(c)** Compression **(d)** Refinement

Figure 5 – Conceptual overview of our offline algorithm. (a) We use a light transfer tensor to describe direct-to-indirect light transfer from one set of samples to another set of samples over multiple frames of an animation sequence. The solid line depicts the contributions of all gather samples at some frame to one view sample at the same frame. (b) We start by exploring structure of the light transfer. (c) Then we run a modified version of local principal component analysis (LPCA) to find linear subspaces that fit the light transfer tensor. (d) Finally we refine the structure of the light transfer tensor and approximate it in linear subspaces found in the previous step.

2. Run a modified version of the local principal component analysis (LPCA) to find linear subspaces that closely approximate light transfer vectors of the parts of the tensor explored so far.
3. Reconstruct light transfer in other unexplored parts of the light transfer tensor and approximate them in the previously computed linear subspaces.

Currently we have been developed our system for animation sequences. However, as it has not been implemented yet we do not provide any results. This is left as a subject for future work.

3 Conclusion

Realistic rendering of complex virtual scenes is demanded by number computer graphics applications. Accurate material and lighting models must be used for a faithful reproduction of a scene. This necessitates fast and accurate algorithms for realistic image synthesis. It has been shown that coherence of light transport can be exploited [DHS⁺05, MSRB07, PML⁺09] to accelerate these algorithms. This thesis describes three new algorithms for realistic image synthesis and shows how the coherence was used to make these algorithms efficient.

the tested cluster than to the nearest cluster found so far. We use our generalized triangle inequality to perform this test. If the data vector can be closer to the tested cluster we calculate its true distance to the tested cluster. Otherwise we simply skip the computationally costly distance calculation knowing that the tested cluster lies farther than the current nearest one. For more details about our algorithm see the thesis. To address the inaccuracy we propose a fast algorithm called *SortMeans++* that produce better initialization for the LPCA, i.e. the distribution of initially guessed clusters are closer to the final distribution after convergence.

2.2.2 Results

We tested our SC-LPCA for compression of radiance transfer matrices used in precomputed radiance transfer (PRT) and for compression of bi-directional texture function (BTF) image databases. Examples of scenes in which we precompute the radiance transfer matrices and used them as an input for our compression algorithm are in Figure 3. Overal performance and timings achieved by our SC-LPCA and the original LPCA algorithm are in table 1. The original LPCA spent from 3 to 6 hours to compress the PRT matrices. Our SC-LPCA require from 15 minutes to one hour, achieving speed-up of 20 for a simple scene with horse model and speed-up of 5 for a complex model of the Walt Disney Concert Hall. Concerning the data approximation accuracy, we consistently achieve a lower approximation error in our tested data sets compared to simple random initialization.

	vertices	PRT	Classification [s]			PCA	ϕ
scene	[#]	[s]	LPCA	SC-LPCA	speedup	[s]	[-]
Horse	67.6k	22.5	13 700	674	20.3	146	0.029
Dragon	57.5k	25.5	10 900	1700	6.38	155	0.174
Buddha	85.2k	31.6	16 700	3 020	5.55	170	0.316
Disney	106.3k	46.5	20 900	4 080	5.12	170	0.394

Table 1 – Summary results and timings for the example scenes. The columns list the total number of vertices in the scene, transfer matrix computation time (PRT) and the total classification time using original LPCA and our SC-LPCA algorithm. The rightmost two columns shows the time spent on the PCA approximation evaluation and the value of the objective function ϕ. Transfer matrices were computed on a Geforce GTX 580 GPU, while the Classification and PCA computation we performed on 4 CPU cores.

(a) Spot-light source (b) Spot and area-light sources

Figure 4 – Renderings of a scene with a hair ball relit using different configurations of light sources. Images were rendered by our implementation of cinematic relighting system [HPB06].

2.3 Relighting of Animation Sequences.

One of the important problems in computer cinematography is lighting design in a scene. Lighting design usually proceeds as follows: a lighting designer places light sources in the scene, sets their parameters and renders the scene; then he adjusts the parameters of the light sources and renders the scene again, . . . and so on until he obtains the desired lighting. Screenshots of a scene as illuminated by different lights is in Figure 4.

Several relighting systems for lighting design in computer cinematography have been proposed, mostly based on precomputed radiance transfer [KAMJ05, HPB06, KTHS06, LZT$^+$08]. They are restricted, however, for relighting of static scenes as observed from a static view point. Instead of relighting in static scenes we focus on relighting animation sequences with GI. Some existing works deal with relighting for articulated characters [NSK$^+$07, FPJY07] but these approaches do not scale to the requirements needed for our application domain, the cinematic lighting design: they mostly deal with simple characters and also deliver less accurate GI. On the other hand we aim at robust cinematic system for relighting in complex scenes while providing a high-quality rendering of the animation sequence. We believe that animation relighting would be extremely useful in computer cinematography. A designer will be able to design lighting in any frame of the animation sequence while having the possibility to play back the whole sequence with the updated lighting.

Technically we build on the idea of direct-to-indirect light transfer [HPB06] but instead of precomputing light transfer for one frame we precompute it for the entire animation sequence. We develop an efficient algorithm to make the calculation efficient by leveraging directional, spatial, and temporal coherence of light transport.

2.3.1 Algorithm Overview

To make our relighting system useful for lighting design in computer cinematography we must deliver high-quality rendering of the animation sequence with indirect lighting. But high-quality indirect lighting is time-consuming and cannot be rendered in real-time even on the latest graphic hardware. To achieve this goal, our relighting system is split into two parts: an off-line part for precomputing the direct-to-indirect (DTI) light transfer tensor, and a run-time part for high-quality rendering of the animation sequence with indirect lighting.

Run-time phase. The run-time part of our relighting system uses the precomputed DTI light transfer to interactively render global illumination in the predefined animation sequence.

1. Calculate direct lighting at frame t on a set of points (*gather samples*) distributed uniformly in the scene.
2. Use the precomputed light transfer tensor to transform the direct lighting on gather samples to indirect lighting at points (*view samples*) visible through camera at frame t.
3. Calculate direct lighting on the view samples and add it to indirect lighting, obtaining final rendering of the scene at frame t.
4. Shift to the next frame, i.e. $t \leftarrow t + 1$, and repeat all steps until the end of the animation sequence is reached.

Pre-computation phase. In the off-line part we pre-compute the light transfer tensor. Since the tensor is huge, containing several Tera (i.e. 10^{12}) elements, a problem arises: how to make its pre-computation feasible in terms of memory space and computation time. But as we mentioned above the light transfer tensor contains a high degree of coherence that can be exploited to make the evaluation practical. We use the following strategy to evaluate the light transfer tensor in a compressed form while keeping the memory requirements tractable. See Figure 5 for a conceptual overview of our off-line algorithm.

1. Explore the structure of the light transfer tensor; elements of the light transfer tensor in which the light transfer is likely to change rapidly are sampled more densely than other elements.