Tutorial Notes
EUROGRAPHICS 2007
Tutorial 6

Capturing Reflectance - From Theory to Practice

September 3, 2007

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Abstract

One important problem in photorealistic or predictive rendering nowadays is to realistically model the light interaction with objects. Measurements can capture the reflection properties of real world surface, i.e., they are one way of obtaining realistic reflection properties.

For arbitrary (non-fluorescent, non-phosphorescent) materials, the reflection properties can be described by the 8D reflectance field of the surface, also called BSSRDF. Since densely sampling an 8D function is currently not practical various acquisition methods have been proposed which reduce the number of dimensions by restricting the viewing or relighting capabilities of the captured data sets. In this tutorial we will mainly focus on three different approaches, the first allowing to reconstruct opaque surfaces from a very small set of input images, the second allows for arbitrary surfaces but under the assumption of distant light sources and the last which allows for relighting an arbitrary scene with arbitrary spatially varying light patterns.

After a short introduction explaining some fundamental concepts regarding measuring and representing reflection properties, the basics of data acquisition with photographs will be addressed. The tutorial present the set of current state-of-the art algorithms for acquiring and modeling 3D objects. The tutorial investigates the strengths and limitations of each technique and sorts them by their complexity with regard to acquisition costs. Besides describing the theoretical contributions we will furthermore point out the practical issues when acquiring reflectance fields in order to help interested users to build and implement their own acquisition setup.

Syllabus

8:30 **Introduction** (Lensch)
material properties
classification of techniques

8:45 **Acquisition Basics** (Goesele)
light sources
cameras
HDR

9:15 **Reflectance Sharing** (Goesele)
image-based BRDF measurement
spatially varying BRDFs

9:45 **BREAK**

10:00 **Reflectance Fields for Distant Lights** (Müller)
BTFs
light stage
acquisition, compression, synthesis and rendering

10:40 **Near-field Reflectance Fields** (Lensch)
relighting with 4D reflectance fields
dual photography

11:15 **Conclusion, Q/A** (all)

Resume of the Presenters

Michael Goesele is a postdoctoral research associate in the computer graphics and vision group at the University of Washington. In 1999, he joined the computer graphics group at the MPI Informatik and received his PhD from Saarland University in 2004. His research is focused on a broad range of acquisition techniques for computer graphics. Among others, he recently published two papers at ACM SIGGRAPH about the acquisition of light sources (Accurate Light Source Acquisition and Presentation) and translucent objects (DISCO – Acquisition of Translucent Objects). He has given several lectures and tutorials (e.g. at Eurographics 2002 and SIGGRAPH 2005) about the topics covered in the tutorial.

Gero Mueller currently works as a research assistant and Ph.D. student in the computer graphics group of Prof. Reinhard Klein at the University of Bonn, Germany. He received his diploma in computer science from the University of Bonn in 2002. His main research interests are realistic material representations, in particular BTFs. He has authored and co-authored several papers about this topic. At Eurographics 2004 he presented a state-of-the-art report covering the acquisition, compression, synthesis and rendering of BTFs and gave tutorials about the topic at various events (e.g. at Siggraph 2005).

Hendrik P. A. Lensch is the head of an independent research group ”General Appearance Acquisition and Computational Photography” at the MPI Informatik in Saarbrücken, Germany. The group is part of the Max Planck Center for Visual Computing and Communication. He received his diploma in computers science from the University of Erlangen in 1999 and after joining the computer graphics groupat MPI received his PhD from Saarland University in 2003. Dr. Lensch spent two years (2005-2006) as a visiting assistant professor at Stanford University, USA.His research interests include 3D appearance acquisition, image-based rendering and computational photography. For his work on reflectance measurement he received the Eurographics Young Researcher Award 2005. He was awarded an Emmy Noether Fellowship by the German Research Foundation in 2007. He has given several lectures and tutorials at various conferences including SIGGRAPH courses on realistic materials in 2002 and 2005.

Annotated Bibliography

Introduction

The goal of this annotated bibliography is to provide an overview over the most important publications in the areas covered by the course. Our goal was especially to help newcomers to the field to quickly become familiar with the main papers and serve as a starting point for further literature study. This is naturally always a subjective choice and we claim therefore by no means that the list of selected papers is complete and apologize for any important papers we missed.

General References

[1] Richard S. Hunter and Richard W. Harold. *The Measurement of Appearance*. Wiley, 2. ed., 5. print. edition, 1987.

> In this book, the various effects of reflections off surfaces are carefully described and analized. The authors provide valuable and intuitive insights on how to distinguish the appearance of two different materials. The book furthermore illustrates how the appearance of real world surfaces can be measured giving examples of techniques commonly applied in print industry. The main focus is on measuring the appearance of planar surfaces.

[2] Fred E. Nicodemus, Joseph C. Richmond, Jack J. Hsia, I. W. Ginsberg, and T. Limperis. Geometrical Considerations and Nomenclature for Reflectance. National Bureau of Standards, 1977.

> This report introduces the basic concepts of BSSRDFs, BRDFs, and related functions to describe reflectance. It also defines the nomenclature for all of them and describes their relationships such as the derivation of the BRDF from the BSSRDF.

BRDFs

[1] James F. Blinn. Models of Light Reflection for Computer Synthesized Pictures. In *SIGGRAPH '77: Proceedings of the 4th annual conference on Computer graphics and interactive techniques*, pages 192–198. ACM Press, 1977.

> This paper introduces the empirical Blinn-Phong model (based on the earlier Phong model [18]. It can model more realistic reflections using three parameters (diffuse and specular coefficient, specular exponent). The specular lobe is computed based on the halfway vector.

[2] Samuel Boivin and André Gagalowicz. Image-based rendering of diffuse, specular and glossy surfaces from a single image. In Eugene Fiume, editor, *Proceedings of SIGGRAPH 2001*, Computer Graphics Proceedings, Annual Conference Series, pages 107–116. ACM Press / ACM SIGGRAPH, August 2001. ISBN 1-58113-292-1.

> This paper tries to solve the difficult problem of measuring BRDF in indoor scenes from a single observation. The hope is that the global illumination and grouping of measurements of multiple surface points provide sufficient constraints to estimate a per-patch BRDF. At first a simple diffuse BRDF model is assumed. If the observed error is still insufficient a specular lobe is added. In case of failure, further tests involve anisotropic or mirroring BRDFs.

[3] R. Cook and K. Torrance. A reflection model for computer graphics. *ACM Transactions On Graphics*, 1(1):7–24, 1982.

> The Cook-Torrance model is a modification of earlier reflectance models. The main assumption is that the surface is composed of tiny, perfectly reflective, smooth microfacets oriented at different directions. The facets are assumed to be V-shaped and their distribution is isotropic. The model takes into account the fact that the light might be blocked by other microfacets (shadowing). Similarly, it also considers the fact that the viewer does not see some of the microfacets since they are blocked by the other microfacets (masking effect). The model takes into account an average Fresnel term (polarization is not considered) when modelling the reflectance of individual microfacets. However, it does not allow for multiple light bounces between the microfacets. The orientation of the facets is assumed to have some distribution - Cook and Torrance use the Beckman distribution function.

[4] P. Debevec, T. Hawkins, C. Tchou, H.-P. Duiker, W. Sarokin, and M. Sagar. Acquiring the Reflectance Field of a Human Face. In *Proc. SIGGRAPH*, pages 145–156, July 2000. ISBN 1-58113-208-5.

> While this paper actually introduced the concept of reflectance fields it also contains a section where a BRDF model is fit to the measured data of each texel. The spatially varying BRDF yields some compression compared to the full reflectance field data set.

[5] Paul Debevec, Chris Tchou, Andrew Gardner, Tim Hawkins, Charis Poullis, Jessi Stumpfel, Andrew Jones, Nathaniel Yun, Per Einarsson, Therese Lundgren, Marcos Fajardo, and Philippe Martinez. Estimating Surface Reflectance Properties of a Complex Scene under Captured Natural Illumination. Technical Report ICT-TR-06.2004, USC ICT, December 2004.

> This reports combines the idea of clustered BRDFs with global inverse illumination. For a number of representative spots/materials the BRDF is captured using standard image-based BRDF measurement techniques under controlled illumination conditions. In order to capture the spatially varying BRDF of a building the incident light onto ths building is captured by an environment map which serves as a illumination source in a global illumination framework. Based on the differences between the synthesized images and the captured HDR images the weight for combining the cluster BRDFs are updated for each texel individually.

[6] A. Gardner, C. Tchou, T. Hawkins, and P. Debevec. Linear light source reflectometry. *ACM Trans. Graphics.*, 22(3):749–758, 2003.

> In this paper the fully spatially varying BRDF and a transmission term is estimated for rather flat documents. The illumination is provided by a linear light source which has to be considered during the BRDF estimation. The same data is also used to scan the 3D geometry of the surface.

[7] Athinodoros S. Georghiades. Recovering 3-d shape and reflectance from a small number of photographs. In *Eurographics Symposium on Rendering: 14th Eurographics Workshop on Rendering*, pages 230–240, June 2003.

> Georghiades addresses the problem of estimating shape and reflection properties at the same time. Given a set of images of the scene illuminated by a point light source of unknown position the approach sets up an optimization problem that solves for the diffuse component of the BRDF and the actual surface normal per pixel as well as a global specular component and the light source positions in the individual images. As in other shape-from-shading approaches assuming a continuous surface introduces a regularization term that allows for solving the large optimization problem.

[8] X. He, K. Torrance, F. Sillon, and D. Greenberg. A comprehensive physical model for light reflection. *Computer Graphics*, 25(Annual Conference Series):175–186, 1991.

> This paper presents a reflectance model that accounts for the phenomena that can be explained using both geometrical optics and wave optics (diffraction, interference). The

model supports arbitrary polarization of incident light, but the simplifications for unpolarized light are also presented. In general, the reflectance is modelled as a sum of three components: specular, directional diffuse, and uniform diffuse. The specular component accounts for mirror-like reflection. It depends on the Fresnel reflectivity, roughness, and shadowing factors. The directional diffuse contribution of the reflectance function is the most complex term. It accounts for diffraction and interference effects. It depends on surface statistics (the effective roughness and the autocorrelation length). The uniform-diffuse contribution is a result of multiple microfacet reflections and subsurface reflections. It is expressed as a simple function of wavelength. The resulting isotropic reflectance model for unpolarized light is a function of four parameters. Each of the parameters has some physical meaning and (at least theoretically) can be measured separately.

[9] Eric P. F. Lafortune, Sing-Choong Foo, Kenneth E. Torrance, and Donald P. Greenberg. Non-linear Approximation of Reflectance Functions. In *SIGGRAPH '97: Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, pages 117–126. ACM Press/Addison-Wesley Publishing Co., 1997.

The Lafortune model presented in this paper is an extension of the Phong model [18] with a diffuse term and multiple lobes. Each lobe consists of a weighted dot product between viewing and lighting direction raised to some power. This empirical model can handle off-specular peaks, backscattering and anisotropy and is frequently used to model the reflection properties of real, measured materials.

[10] Hendrik P. A. Lensch, Jan Kautz, Michael Goesele, Wolfgang Heidrich, and Hans-Peter Seidel. Image-based reconstruction of spatially varying materials. In *Rendering Techniques 2001: 12th Eurographics Workshop on Rendering*, pages 103–114. Eurographics, June 2001. ISBN 3-211-83709-4.

This paper introduces the concept of capturing cluster BRDFs and expressing the spatially variation by per-texel weighted sums of cluster BRDFs. Making use if the idea of image-based BRDF measurments samples from multiple surface points are combined when determining the cluster BRDFs. This results in more reliable, that is, more plausible BRDF parameters and at the same time reduces the number of required input images. Drastically different materials distributed in the same patch can be reproduced faithfully.

[11] Hendrik P. A. Lensch, Jan Kautz, Michael Goesele, Wolfgang Heidrich, and Hans-Peter Seidel. Image-Based Reconstruction of Spatial Appearance and Geometric Detail. *ACM Transactions on Graphics*, 22(2):234–257, April 2003.

This paper extends the previous work towards estimating per-texel normals. Starting from a scanned and smoothed 3D geometry model the per-texel BRDF is estimated. In a photometric stereo approach the current estimate of the BRDF is used to update the surface normal.

[12] S. Marschner, S. Westin, E. Lafortune, and K. Torrance. Image-based measurement of the Bidirectional Reflection Distribution Function. *Applied Optics*, 39(16):2592–2600, 2000.

> Marschner et al. describe an image-based BRDF measurement system. They use a material sample with different surface normals. Each point with a different surface normal gives a different BRDF measurement. Their system uses a spherical sample of homogenous material. A fixed camera takes images of the sample under illumination from an orbiting light source. The system, although limited to only isotropic BRDF measurements, is both fast and robust. Furthermore, they extend their method to surface geometry acquired with a laser range scanner to acquire reflectance of a human face.

[13] S. Marschner, S. Westin, E. Lafortune, K. Torrance, and D. Greenberg. Image-based BRDF Measurement Including Human Skin. In *10th Eurographics Workshop on Rendering*, pages 131–144, June 1999.

> This paper applied the idea of image-based BRDF measurement to objects of arbitrary geometry. A 3D scan of the object provides the geometric information. Multiple images illuminated by a flash light are combined in order to estimate a single BRDF for the object.

[14] Wojciech Matusik, Hanspeter Pfister, Matt Brand, and Leonard McMillan. A data-driven reflectance model. *ACM Trans. Graph.*, 22(3):759–769, 2003.

> The authors built an automatic measurement setup to densely capture isotropic BRDFs using spherical material samples. They analyze the data and construct a low-dimensional data-driven BRDF model using non-linear dimensionality reduction techniques.

[15] D. McAllister, A. Lastra, and W. Heidrich. Efficient rendering of spatial bi-directional reflectance distribution functions. *Graphics Hardware 2002*, 2002.

> The authors present the first real-time rendering framework for BTFs. They used the Lafortune model to approximate the spatially varying BRDFs which leads to an extreme compact representation amendable to hardware implementation. Since the Lafortune model does not approximate meso-scale shadowing and masking effects well, it is only suitable for materials with minor depth variation (SVBRDFs).

[16] Addy Ngan, Frédo Durand, and Wojciech Matusik. Experimental analysis of brdf models. In *Proceedings of the Eurographics Symposium on Rendering*, pages 117–226. Eurographics Association, 2005.

> This paper extends the measurement setup of [14] to anisotropic BRDFs. It furthermore fits the parameters of several BRDF models to the measured materials and alayzes the fitting quality.

[17] K. Nishino, Z. Zhang, and K. Ikeuchi. ”determining reflectance parameters and illumination distribution from a sparse set of images for view-dependent image synthesis”. In *in Proc. of Eighth IEEE International Conference on Computer Vision ICCV ’01*, pages 599–606, july 2001.

Nishino et al. address the complicated problem of reconstructing BRDF and incident illumination at the same time. Specular highlights observed in the individual images are projected into a global environment map to estimate incident illumination. In the next step the BRDF is estimated. Spatial variation is restricted to the diffuse component.

[18] Bui Tuong Phong. Illumination for Computer Generated Pictures. *Commun. ACM*, 18(6):311–317, 1975.

This paper introduces the Phong model – one of the earliest empirical lighting models for computer graphics. The model consists of a diffuse term and one specular lobe. It is neither energy conserving nor reciprocal and is only well-suited to approximate plastic-like materials. Improvements and extensions of the model include [1, 9].

[19] Ravi Ramamoorthi and Pat Hanrahan. A signal-processing framework for inverse rendering. In Eugene Fiume, editor, *Proceedings of SIGGRAPH 2001*, Computer Graphics Proceedings, Annual Conference Series, pages 117–128. ACM Press / ACM SIGGRAPH, August 2001. ISBN 1-58113-292-1.

This paper as well presents a solution to the problem of estimating BRDF and illumination from the same set of images for which an iterative algorithm has been developed. The paper is mostly well-known for the use of spherical harmonics to represent environment maps as well as BRDFs. This representation allows for computing the convolution of the BRDF with the environment map by a simple dot product.

[20] Y. Sato, M. Wheeler, and K. Ikeuchi. Object Shape and Reflectance Modeling from Observation. In *Proc. SIGGRAPH*, pages 379–388, August 1997.

In this paper shape and reflectance properties are captured using the same sensor but different illumination. There is no explicit registration step necessary to match 3D geometry and 2D images. The diffuse component of the BRDF is estimated per pixel while the specular component is constant per patch.

[21] G. Ward. Measuring and modeling anisotropic reflection. *Computer Graphics*, 26(Annual Conference Series):265–273, 1992.

This paper presents one of the first methods to speed up the BRDF measurement process. Ward's measurement device (imaging gonio-reflectometer) consists of a hemispherical mirror and a CCD camera with a fisheye lens. The main advantage of his system is that the CCD camera can take multiple, simultaneous BRDF measurements. Each photosite of the imaging sensor contains a separate BRDF value. Moving the light source and material over all incident angles enables the measurement of arbitrary BRDFs. Ward also presents a BRDF model that is based on the elliptical Gaussian distribution. The model is carefully designed to be physically plausible - it supports energy conservation and reciprocity. It is also relatively simple and can be evaluated efficiently. The parameters of the model have physical meaning and theoretically can be measured independently.

[22] Y. Yu, P. Debevec, J. Malik, and T. Hawkins. Inverse Global Illumination: Recovering Reflectance Models of Real Scenes From Photographs. In *Proc. SIGGRAPH*, pages 215–224, August 1999.

> This paper considers indoor scenes. A few input images are aligned with a geometry model of the rooom and the furniture. Given the positions of the light sources, the light transport in the room can be simulated incorporating global illumination effects. The estimated BRDF minimizes the error between the measured values and a global illumination forward solution.

[23] Y. Yu and J. Malik. Recovering Photometric Properties of Architectural Scenes from Photographs. In *Proc. SIGGRAPH*, pages 207–218, July 1998.

> The BRDFs of buildings in outdoor scenes are estimated considering the incident illumination from the sun and the sky. Only the diffuse component is allowed to vary freely across the surface.

BTFs

[1] Kristin J. Dana, Bram van Ginneken, Shree K. Nayar, and Jan J. Koenderink. Reflectance and texture of real-world surfaces. In *IEEE Conference on Computer Vision and Pattern Recognition*, pages 151–157, 1997.

> This paper introduced Bidirectional Texture Functions to the computer graphics community. The authors present the CUReT reflectance and texture database which made BTF and BRDF measurements publicly available for the first time. The sampling density of the BTFs (205 images per material) was not yet sufficient for high-quality rendering.

[2] Jefferson Y. Han and Ken Perlin. Measuring bidirectional texture reflectance with a kaleidoscope. *ACM Trans. Graph.*, 22(3):741–748, 2003.

> A promising approach for capturing several BTF samples at once using a kaleidoscope is presented. A problem with the approach is that it is quite sensitive to imperfections in the mirrors and their configuration because the light is reflected several times within the kaleidoscope.

[3] Xinguo Liu, Yaohua Hu, Jingdan Zhang, Xin Tong, Baining Guo, and Heung-Yeung Shum. Synthesis and Rendering of Bidirectional Texture Functions on Arbitrary Surfaces. *IEEE Transactions on Visualization and Computer Graphics*, 10(3):278–289, 2004.

> This paper can be regarded as a follow up paper to the BTF synthesis paper of Tong et al. from Siggraph 2002. It uses SVD to compress the BTF data and shows how the BTF can be synthesized and rendered from this compressed representation while achieving a significant speed up compared to the original method. It is also shown how the BTF can be rendered with graphics hardware.

[4] D. McAllister, A. Lastra, and W. Heidrich. Efficient rendering of spatial bi-directional reflectance distribution functions. *Graphics Hardware 2002*, 2002.

> The authors present the first real-time rendering framework for BTFs. They used the Lafortune model to approximate the spatially varying BRDFs which leads to an extreme compact representation amendable to hardware implementation. Since the Lafortune model does not approximate meso-scale shadowing and masking effects well, it is only suitable for materials with minor depth variation (SVBRDFs).

[5] Jan Meseth, Gero Müller, and Reinhard Klein. Reflectance field based real-time, high-quality rendering of bidirectional texture functions. *Computers and Graphics*, 28(1):103–112, February 2004.

> This paper addresses the problem of using parametric functions for representing BTFs with significant meso-structure. They propose to fit parametric functions not to the whole per-texel apparent BRDF but to the per-view per-texel reflectance functions which use to be relatively smooth functions.

[6] G. Müller, G. H. Bendels, and R. Klein. Rapid synchronous acquisition of geometry and btf for cultural heritage artefacts. In *The 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST)*, pages 13–20. Eurographics Association, Eurographics Association, November 2005.

> Based on a camera array of 151 of-the-shelf digital cameras a method for rapidly acquiring the geometry and reflectance of objects with significant meso-scale geometry is presented. It combines image-based 3D reconstruction and BTF compression and rendering techniques.

[7] G. Müller, J. Meseth, M. Sattler, R. Sarlette, and R. Klein. Acquisition, synthesis and rendering of bidirectional texture functions. *Computer Graphics Forum*, 24(1):83–109, March 2005.

> This comprehensive overview discusses from acquisition, over synthesis to rendering of BTFs most of the topics covered in the BTF-part of this tutorial. The relevant publications in the field of BTFs up to the year 2005 are introduced.

[8] G. Müller, R. Sarlette, and R. Klein. Data-driven local coordinate systems for image-based rendering. *Computer Graphics Forum*, 25(3), September 2006.

> In this paper a data-driven technique for computing local coordinate systems from image-based reflectance measurements is presented. These coordinate systems allow to align the per-texel reflectance measurements which results in increased compression performance with negligible run-time overhead.

[9] M. Sattler, R. Sarlette, and R. Klein. Efficient and realistic visualization of cloth. *Proceedings of the Eurographics Symposium on Rendering 2003*, 2003.

> In this paper the first BTF real-time rendering framework based on statistical data analysis is presented. It describes the whole pipeline from measurement using a fully automatic setup over compression to rendering including image-based illumination and large scale shadows. It also introduces the BTF Database Bonn which still offers the most detailed publicly available BTF data.

[10] Peter-Pike Sloan, Xinguo Liu, Heung-Yeung Shum, and John Snyder. Bi-Scale Radiance Transfer. *ACM Transactions on Graphics*, 22(3):370–375, 2003.

The authors combine Precomputed Radiance Transfer with BTFs to achieve striking real-time renderings of BTF-covered objects realistically lit by environment maps. They represent the BTF by projecting the data per sampled view direction into the Spherical Harmonics basis.

[11] Frank Suykens, Karl vom Berge, Ares Lagae, and Philip Dutré. Interactive Rendering of Bidirectional Texture Functions. In *Eurographics 2003*, pages 463–472, September 2003.

This BTF compression and rendering method approximates the BTF data per texel using a sophisticated factorization scheme called Chained Matrix Factorization. The idea is to factorize the data with different parameterizations which are suitable for the different significant features of the per-texel apparent BRDFs. Thereby the data can be reliably represented with a much smaller number of factors compared to standard matrix factorization based on SVD.

[12] M. A. O. Vasilescu and Demetri Terzopoulos. Tensortextures: Multilinear image-based rendering. In *Proceedings of SIGGRAPH*, August 2004.

This work introduces tensor representations for image-based datasets. In contrast to the classic matrix representation multi-linear tensors allow a so-called strategic dimensionality reduction. This means that e.g. more components can be spent for encoding the view variation which results in perceptually more satisfying reconstructions.

[13] Hongcheng Wang, Qing Wu, Lin Shi, Yizhou Yu, and Narendra Ahuja. Out-of-core tensor approximation of multi-dimensional matrices of visual data. *ACM Trans. Graph.*, 24(3):527–535, 2005.

This paper improves the 3D tensor representation of Vasilescu et al. by arranging the data in higher-dimensional tensors (e.g. 5D). This allows to exploit the coherence along other dimensions like between the rows and columns of the measured images. The method achieves very high compression rates, generalizes to higher-dimensional datasets like time-varying BTFs and can be implemented as an out-of-core technique. The reconstruction costs are a disadvantage of the method.

Near-field Reflectance Fields

[1] Billy Chen and Hendrik P. A. Lensch. Light source interpolation for sparsely sampled reflectance fields. In Günther Greiner, Joachim Hornegger, Heinrich Niemann, and Marc Stamminger, editors, *Vision, Modeling, and Visualization 2005 (VMV'05)*, pages 461–469, Erlangen, Germany, November 2005. Aka.

> Captured reflectance fields are typically sparsely sampled in the light direction domain. In this paper, a method is presented that allows for smoothly moving light sources in near-field reflectance fields. The system treats high frequency illumination effects such as highlights and shadows separately from slowly moving effects such as the cosine fall-off and interreflections, for which linear blending is sufficient to reproduce the appearance of intermediate light source positions. Highlights and shadows are detected using intrinsic images and then moved according to the detected optical flow. The technique further exploits the properties of near-field reflectance fields to perform virtual 3D scanning.

[2] Yanyun Chen, Xin Tong, Jiaping Wang, Stephen Lin, Baining Guo, and Heung-Yeung Shum. Shell texture functions. *ACM Transactions on Graphics*, 23(3):343–353, August 2004.

> This paper presents an appearance representation approach that is particularly suited for heterogeneous translucent objects. The translucent object is divided into a homogeneous diffusely scattering core surrounded by volume of heterogeneous translucent material. The shell texture function (STF) provides an intermediate data structure representing the light transport and the mesostructure of the outer shell. For each voxel in the shell volume the irradiance due to light impinging from arbitrary directions is precomputed and stored in a 5D data structure.

[3] Frédo Durand, Nicolas Holzschuch, Cyril Soler, Eric Chan, and François X. Sillion. A frequency analysis of light transport. *ACM Transactions on Graphics*, 24(3):1115–1126, August 2005.

> This paper analyzes the different effects of occluders, reflectors, or the propagation of light in free space on the spatial and angular frequency content of the transformed light field. The authors propose a signal-processing framework and show a large set of instructive examples. They further show how the analysis of the frequency content of the light field can be used to control sampling rates or the choice of reconstruction kernels in rendering, pre-computed radiance transfer, and inverse rendering.

[4] Gaurav Garg, Eino-Ville Talvala, Marc Levoy, and Hendrik P. A. Lensch. Symmetric photography: Exploiting data-sparseness in reflectance fields. In *Rendering Techniques 2006: 17th Eurographics Workshop on Rendering*, pages 251–262, June 2006.

> Capturing dense light transport matrices so far required a sequential sensing of individual incident light rays. In this paper, two techniques are combined in order to allow for fast acquisition of arbitrarily complex reflectance fields. The first is the use of H-matrices which subdivide a matrix hierarchically until each sub-block can be represented sufficiently well using a low-rank approximation of the block. The second ingredient is an symmetric acquisition system where cameras and projectors are coupled by a beam splitter allowing for emitting light and sensing light along exactly the same rays. This turns the captured reflectance field into a symmetric tensor whose sub-blocks can be determined in parallel given that they are of low rank. The paper features one of the first full 8D reflectance fields, at a rather low resolution, though.

[5] Michael Goesele, Hendrik P. A. Lensch, Jochen Lang, Christian Fuchs, and Hans-Peter Seidel. DISCO – Acquisition of Translucent Objects. *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2004)*, 23(3), 2004.

> This is the first paper that captured the diffuse reflectance R_d of a real translucent object with inhomogeneous material properties. The object is pointwise illuminated and its impulse response function is captured with a HDR camera. A hierarchical model of transfer functions is computed from a large number of input images. Rendering can be performed in real time using an earlier approach.

[6] Akira Ishimaru. *Wave Propagation and Scattering in Random Media*. Academic Press, 1978.

> This book describes the physical principles of single and multiple scattering in various types of media and derives the mathematical formulations.

[7] Henrik Wann Jensen and Juan Buhler. A Rapid Hierarchical Rendering Technique for Translucent Materials. In *SIGGRAPH 2002*, pages 576–581, 2002.

> The authors propose a hierarchical evaluation technique to speed up the rendering of translucent objects using the dipole model [8]. This is the first of a whole series of papers proposing various rendering techniques to speed up evaluation of the dipole model – see e.g. [5] for a list of such publications.

[8] Henrik Wann Jensen, Stephen R. Marschner, Marc Levoy, and Pat Hanrahan. A Practical Model for Subsurface Light Transport. In *SIGGRAPH 2001*, pages 511–518, 2001.

> This paper introduces the dipole model as an approximation for translucent objects in computer graphics. It describes the derivation of the model, it's use for rendering, and compares the results to Monte-Carlo simulations. The authors describe also a measurement setup to determine the required parameters for real materials and provide a table of measured values. The dipole model is used in many publications including [7] as a fast method to evaluate the effects of subsurface scattering.

[9] Shree K. Nayar, Gurunandan Krishnan, Michael D. Grossberg, and Ramesh Raskar. Fast separation of direct and global components of a scene using high frequency illumination. In *SIGGRAPH '06: ACM SIGGRAPH 2006 Papers*, pages 935–944, New York, NY, USA, 2006. ACM Press.

> In this paper a very efficent method is presented for separating the direct and the global compoent of the light reflected by a scene due to illumination by a projector. The key observation is that global light transport is due to multiple scattering and therefore dampens high frequency in spatially varying illumination patterns. The technique makes use of multiple shifted high frequency patterns and provides a very simple formula to perform the separation from the minimum and maximum intensity observed for each pixel in the sequence of shifted patterns. The separation results to some extent depend on the frequency of the illumination pattern.

[10] Pieter Peers, Karl vom Berge, Wojciech Matusik, Ravi Ramamoorthi, Jason Lawrence, Szymon Rusinkiewicz, and Philip Dutré. A compact factored representation of heterogeneous subsurface scattering. *ACM Transactions on Graphics*, 25(3):746–753, July 2006.

> This paper presents a method for transferring the reflection properties of one heterogeneous translucent object onto novel geometry. In an initial acquisition the diffuse subsurface reflectance is measured on a planar slab of material by illuminating individual points. The effect of subsurface scattering is assumed to be localized having a well controlled support. In order to compress the captured reflectance function the illumination peaks are aligned to one column and a set of homogeneous BSSRDFs is determined to describe the general shape. Dividing the measured samples by the homogeneous approximation results in a representation of the heterogeneous effects which can be factored in a compact way. When transferring the reflectance function to novel geometry only the light transport in a local neighborhood is considered.

[11] Steven M. Seitz, Yasuyuki Matsushita, and Kiriakos N. Kutulakos. A theory of inverse light transport. In *ICCV '05: Proceedings of the Tenth IEEE International Conference on Computer Vision*, pages 1440–1447, Washington, DC, USA, 2005. IEEE Computer Society.

> Given a captured near-field reflectance field between a projector and a camera, this paper analyzes how the reflectance field can be inverted in order to render the scene after the first, the second, or after multiple light indirections. The results indicate that it is sometimes possible to remove multiple scattering effects from captured reflectance fields. Note that the inversion of the reflectance field is possible only for a couple of special cases.

[12] Pradeep Sen, Billy Chen, Gaurav Garg, Stephen R. Marschner, Mark Horowitz, Marc Levoy, and Hendrik P. A. Lensch. Dual photography. *ACM Transactions on Graphics*, 24(3):745–755, August 2005.

> This paper presents an acquisition system for capturing near-field reflectance fields, i.e. measuring the light transport on a ray-to-ray basis. Using an adaptive algorithm, the reflectance field between a camera and a projector is measured such that the influence of

every projector pixel to every camera pixel is determined, yielding a 4D light transport matrix. Exploiting Helmholtz reciprocity, the light transport direction can be inverted. Instead of sending out light from the projector it is turned virtually into a sensing camera capturing the scene as if illuminated by a virtual projector at the location of the original camera. The adaptive and parallel capturing scheme acceleration the acquisition time for sparse light transport matrices by three orders of magnitude.

[13] Xin Tong, Jiaping Wang, Stephen Lin, Baining Guo, and Heung-Yeung Shum. Modeling and rendering of quasi-homogeneous materials. *ACM Transactions on Graphics*, 24(3):1054–1061, August 2005.

This paper features an acquisition system and a model for capturing and rendering quasi-homogeneous materials. The model consist of a homogeneous subsurface reflectance function augmented by two functions modeling the mesostructure effects locally, i.e. independently for the incident and the exitant point of the light transport. The subsurface scattering effect is captured by sweeping a line stripe laser over the surface from various directions. In addition, a full BTF is acquired.

Presenters’ Slides

Capturing Reflectance
From Theory to Practice

Introduction

Hendrik P.A. Lensch

MPI Informatik

Material Samples

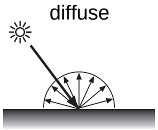
diffuse

glossy

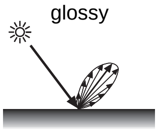
mirror

Material Samples

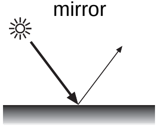
diffuse



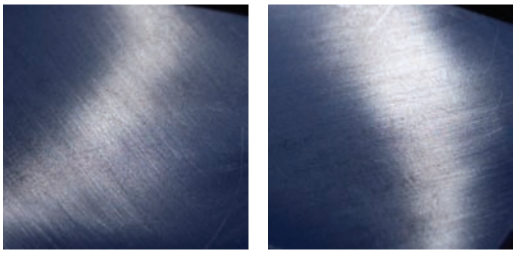
glossy



mirror



Material Samples



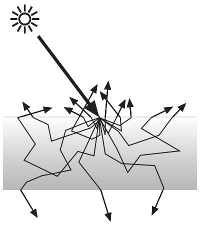
anisotropic

Material Samples

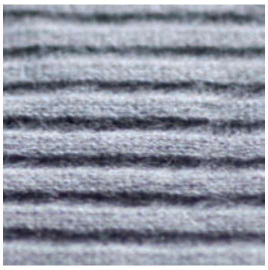
translucent

Material Samples

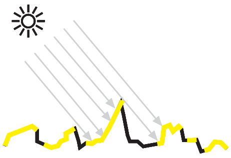
translucent



Material Samples



complex surface structure



Material Samples

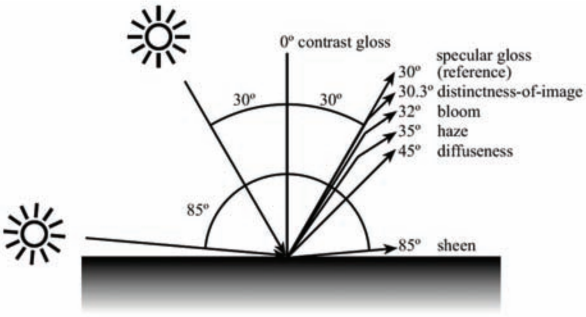
fibers

How to describe materials?

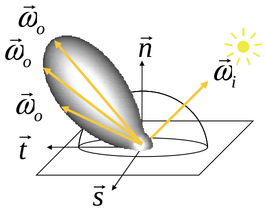
- mechanical, chemical, electrical properties
- reflection properties
- surface roughness
- geometry/meso-structure

- **relightable** representation of appearance

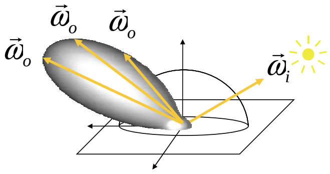
Gloss Model



Reflection of an Opaque Surface



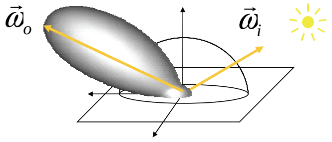
Reflection of an Opaque Surface



BRDF – 4D

(bidirectional reflectance distribution function)

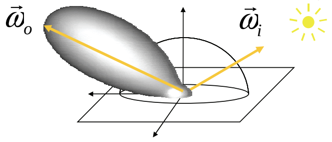
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



BRDF – 4D

(bi-directional reflectance distribution function)

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o) = \frac{dL(\vec{\omega}_o)}{dE(\vec{\omega}_i)}$$

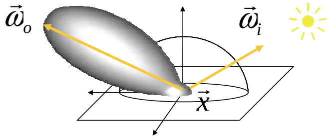


ratio of reflected radiance to incident irradiance

Spatially Varying BRDF – 6D

- heterogeneous materials

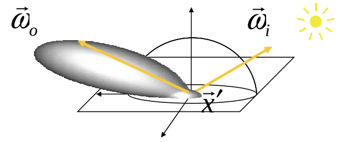
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Spatially Varying BRDF – 6D

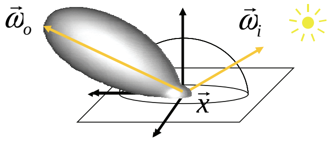
- heterogeneous materials

$$f_r(\vec{x}, \vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Isotropic BRDF – 3D

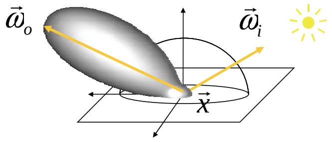
- invariant with respect to rotation about the normal

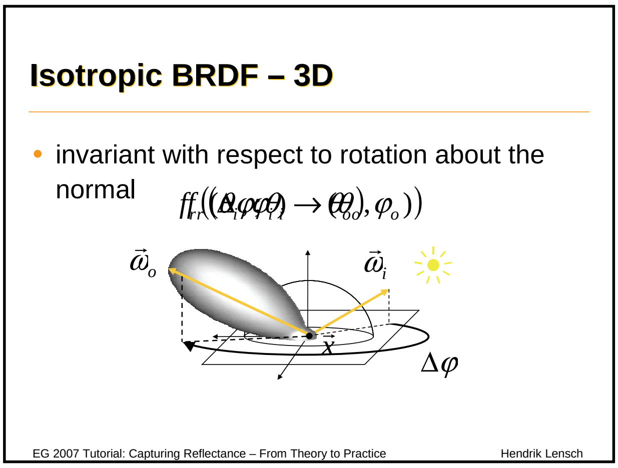


Isotropic BRDF – 3D

- invariant with respect to rotation about the normal

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$





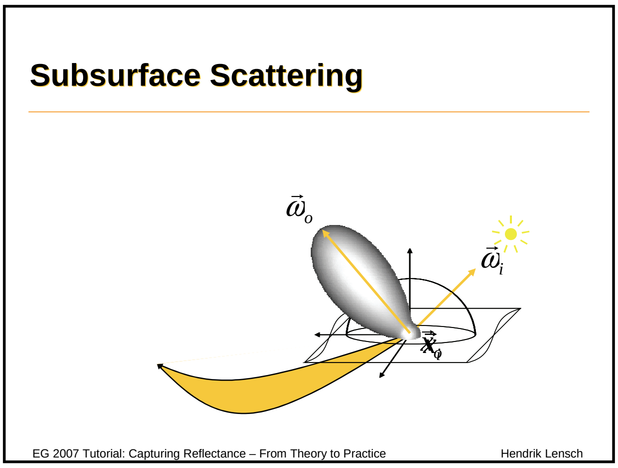
Isotropic BRDF – 3D

- invariant with respect to rotation about the normal

$$f_r((\theta_i,\varphi_i)\rightarrow(\theta_o,\varphi_o))$$

$$f_r(\Delta\varphi,\theta_i\rightarrow\theta_o)$$

EG 2007 Tutorial: Capturing Reflectance – From Theory to Practice Hendrik Lensch



Subsurface Scattering

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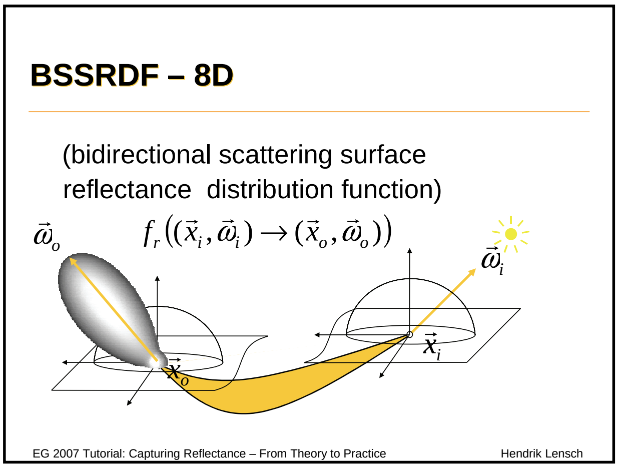

BSSRDF – 8D

(bidirectional scattering surface reflectance distribution function)

$$f_r((\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o))$$

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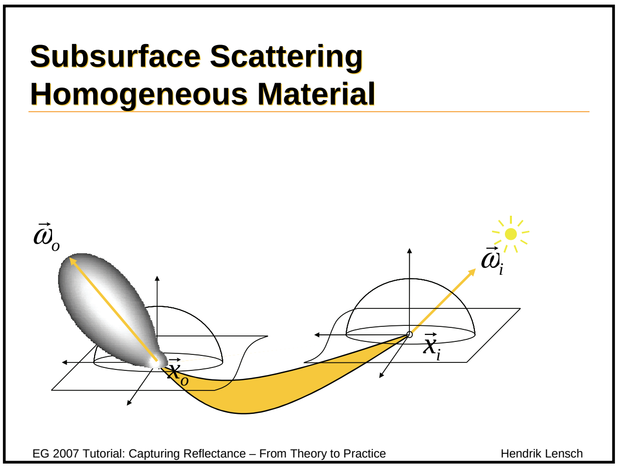

Subsurface Scattering Homogeneous Material

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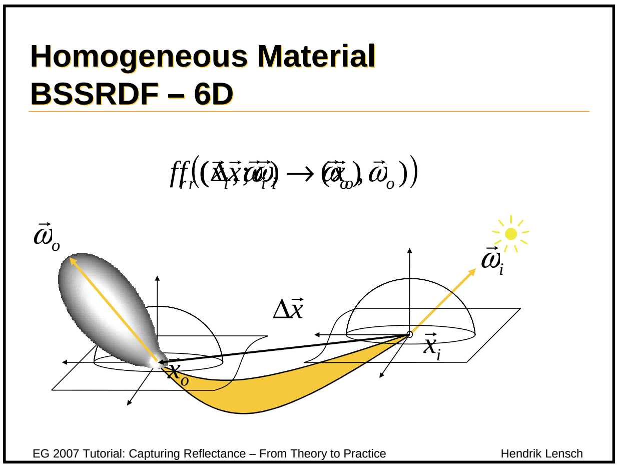

Homogeneous Material BSSRDF – 6D

$$f_r((\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o))$$

$$f_r(\Delta\vec{x},\vec{\omega}_i\rightarrow\vec{\omega}_o)$$

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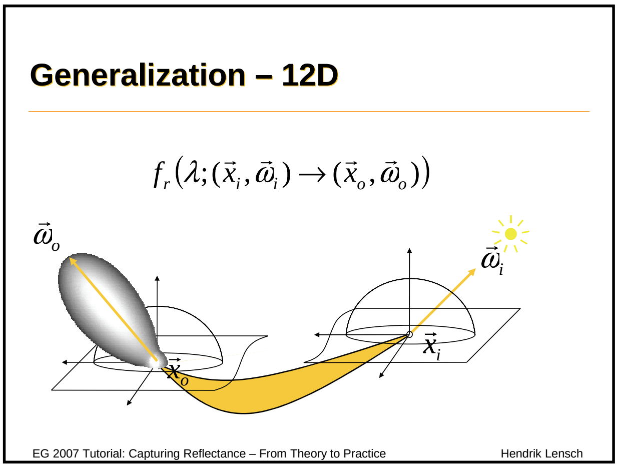

Generalization – 12D

$$f_r(\lambda;(\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o))$$

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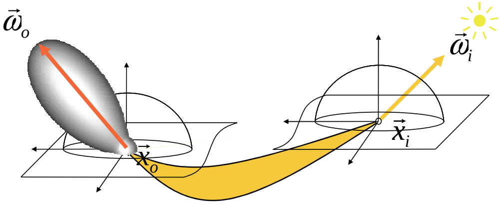
Generalization – 12D

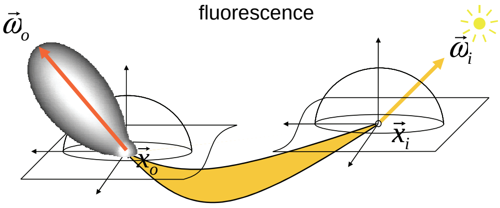
$$f_r\left(\lambda;(\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o)\right)$$



Generalization – 12D

$$f_r\left((\vec{x}_i,\vec{\omega}_i,\lambda_i)\rightarrow(\vec{x}_o,\vec{\omega}_o,\lambda_o)\right)$$

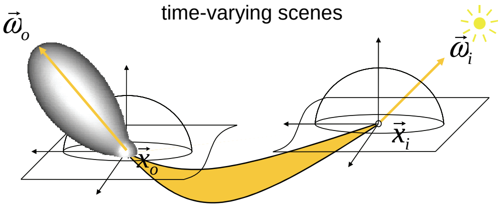
fluorescence



Generalization – 12D

$$f_r\left(t;(\vec{x}_i,\vec{\omega}_i,\lambda_i)\rightarrow(\vec{x}_o,\vec{\omega}_o,\lambda_o)\right)$$

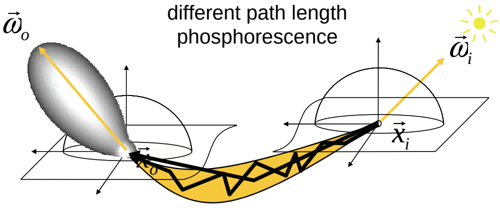
time-varying scenes



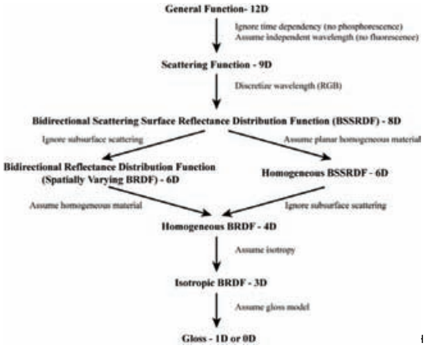
Generalization – 12D

$$f_r\left((\vec{x}_i,\vec{\omega}_i,t_i,\lambda_i)\rightarrow(\vec{x}_o,\vec{\omega}_o,t_o,\lambda_o)\right)$$

different path length
phosphorescence



Taxonomy of Appearance Representations

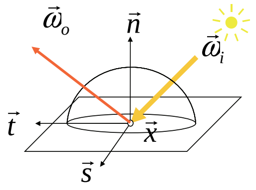


Properties of Reflectance Functions

- Helmholtz reciprocity
- energy conservation
- Fresnel effect

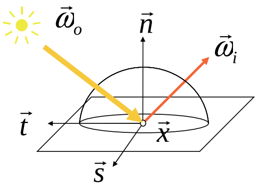
Helmholtz Reciprocity

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



Helmholtz Reciprocity

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o) = f_r(\vec{\omega}_i \leftarrow \vec{\omega}_o)$$



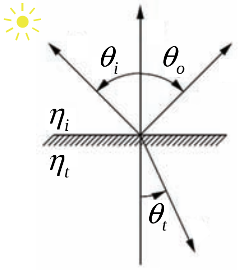
Energy Conservation

- The sum of energy reflected into all directions has to be smaller or equal than the incident energy.

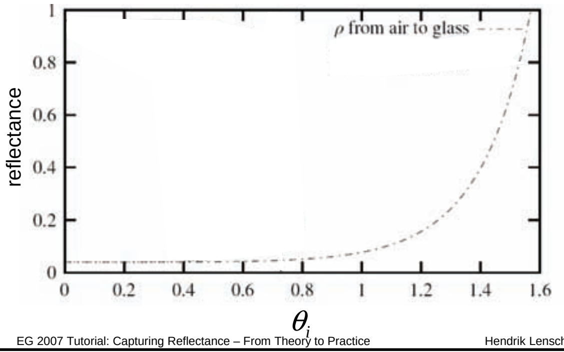
$$\int_{\Omega_o} f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)\cos(\theta_i)d\omega_o \leq 1$$

Snell's Law

$$\eta_i(\lambda)\sin\theta_i = \eta_t(\lambda)\sin\theta_t$$



Fresnel Formula



Material Acquisition

- single picture
  - no interaction

Material Acquisition

- diffuse color + geometry model
  - no relighting

Material Acquisition

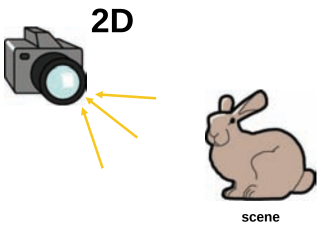
- BRDF + geometry model
  - moving highlights

Material Acquisition

- spatially-varying BRDF + geometry model
  - moving highlights

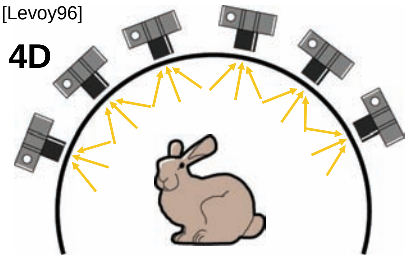
Digitizing real-world Objects

a single photograph



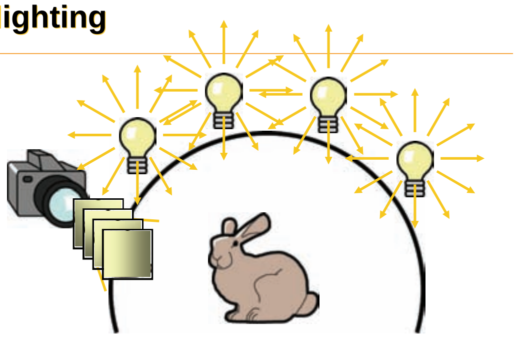
Light Fields

[Gortler96], [Levoy96]

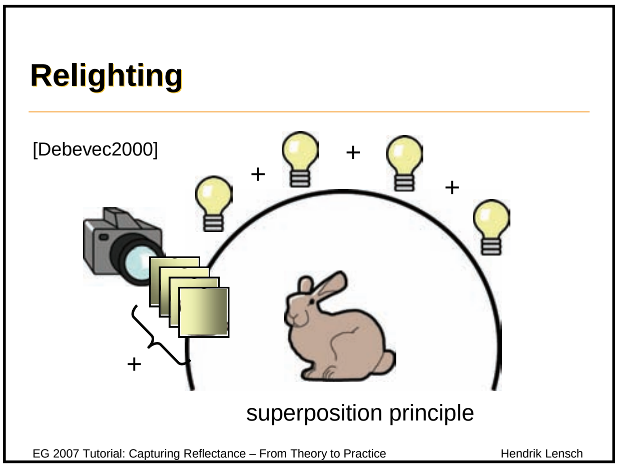


distribution of all reflected light rays

Relighting



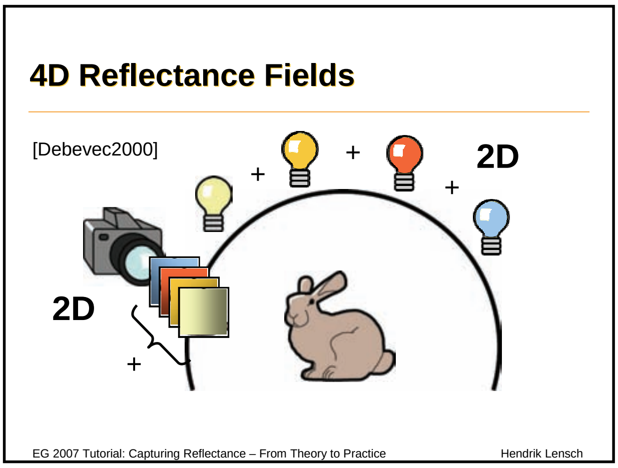
one picture for each light direction



Relighting

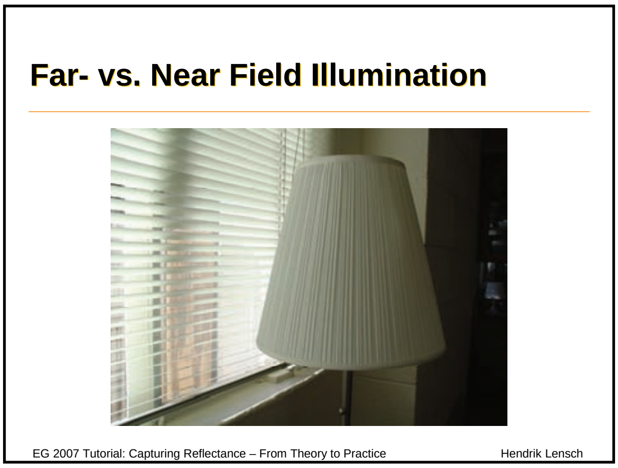
[Debevec2000]

superposition principle

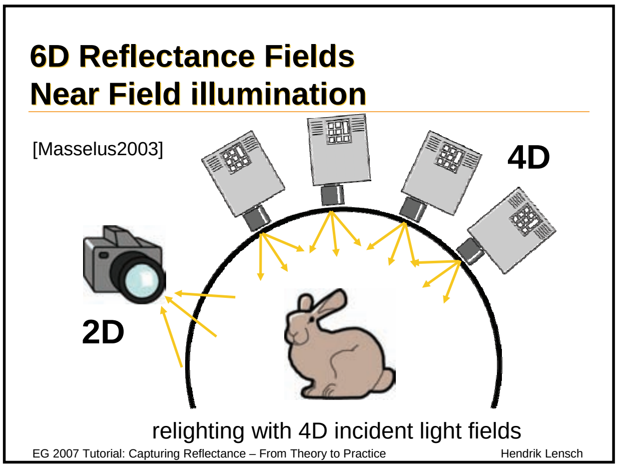


4D Reflectance Fields

[Debevec2000]



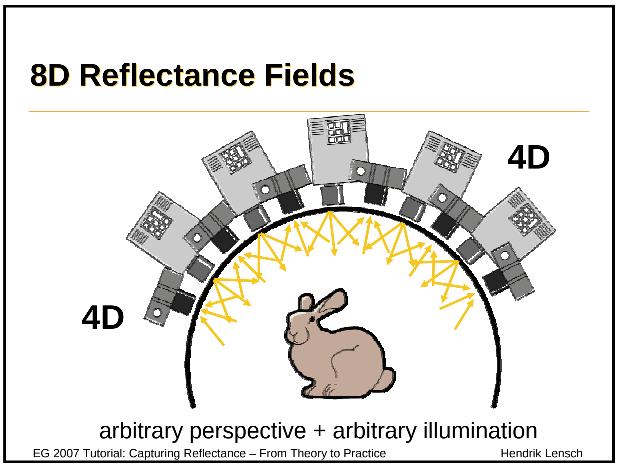
Far- vs. Near Field Illumination



6D Reflectance Fields
Near Field illumination

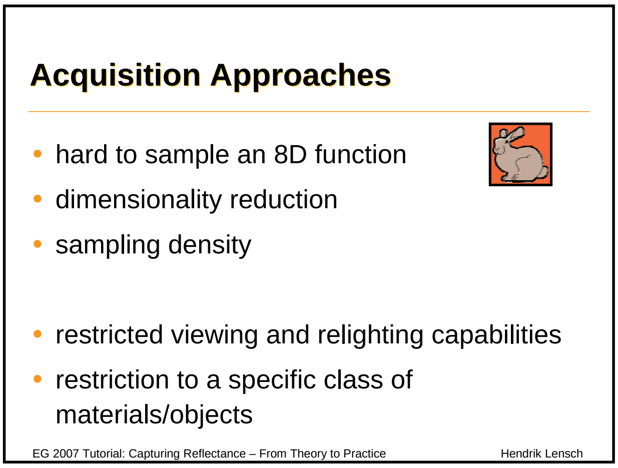
[Masselus2003]

relighting with 4D incident light fields



8D Reflectance Fields

arbitrary perspective + arbitrary illumination

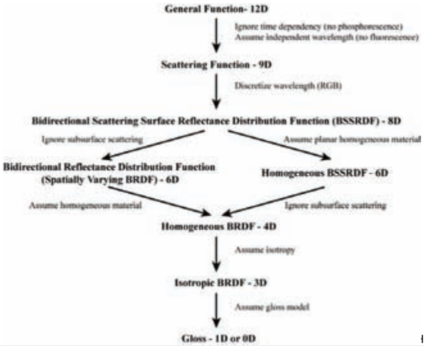


Acquisition Approaches

- hard to sample an 8D function
- dimensionality reduction
- sampling density

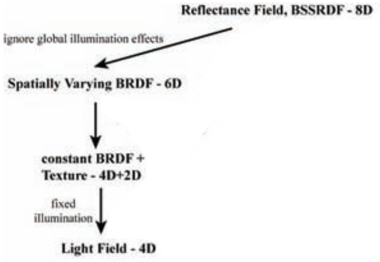
- restricted viewing and relighting capabilities
- restriction to a specific class of materials/objects

Taxonomy of Appearance Representations

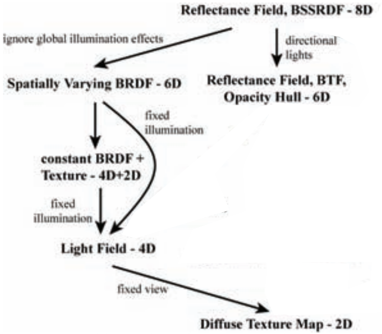


Acquisition Taxonomy

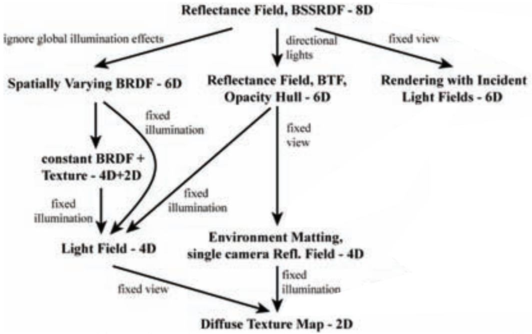
Acquisition Taxonomy



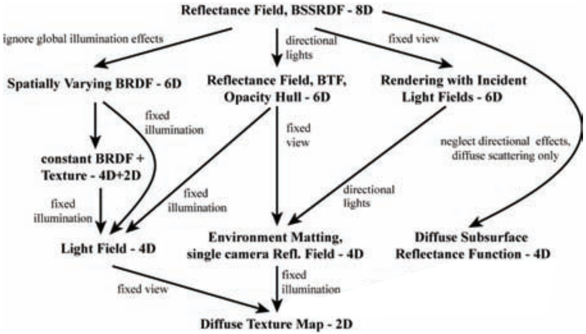
Acquisition Taxonomy



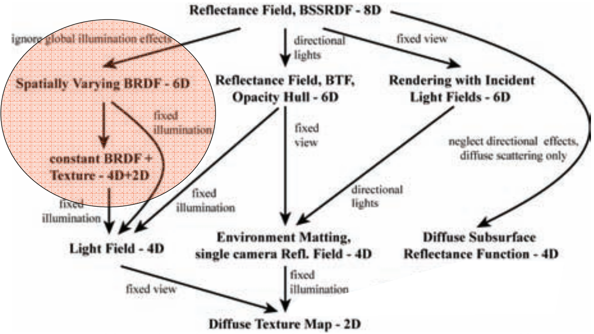
Acquisition Taxonomy



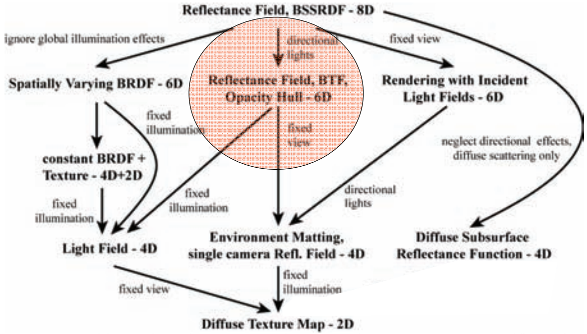
Acquisition Taxonomy



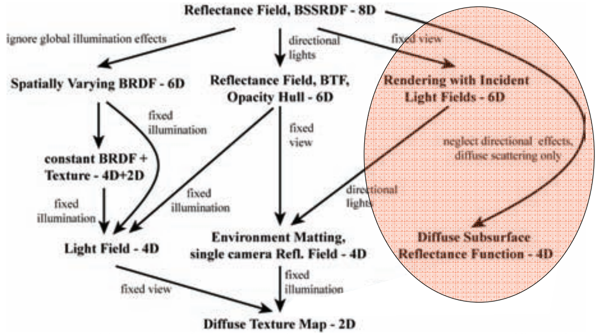
Reflectance Sharing



Reflectance Fields for Distant Lights



Near-Field Reflectance Fields



Summary

- densely sampling 8D functions almost impossible
- less dimensions might be sufficient for specific tasks / materials

Capturing Reflectance
From Theory to Practice

Acquisition Basics

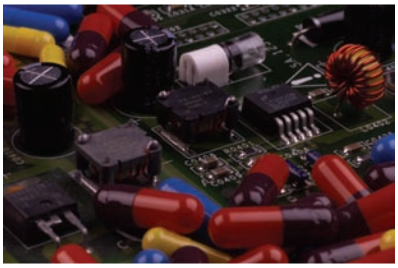
Michael Goesele
University of Washington

Goal of this Section

- practical, hands-on description of acquisition basics
- general overview, caveats, misconceptions, solutions, hints, …
- biased to the techniques used in our lab

How can we measure material properties?

- color
- texture
- reflection properties
- normals
- ...



Special Purpose Tools

- gloss meter, haze meter, …
  - various appearance characteristics
- spectrophotometer
  - spectral reflectance of a surface
- often used in industry where single parameters of one material are important

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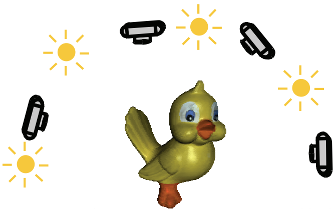
General Purpose Tools

- setup with digital camera(s), controlled lighting, …
- foundation of image-based techniques



General Purpose Tools

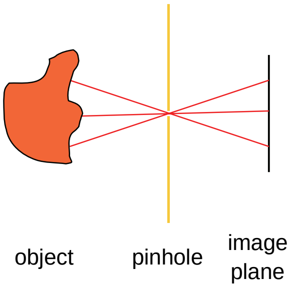
- digital camera as
  - massively parallel sensor
  - mostly tristimulus color
  - often high quality optical system
  - tuned to make good and/or correct pictures

Overview Acquisition Basics

- digital cameras
  - geometric and photometric calibration
  - high dynamic range imaging
- light sources
- lab setup

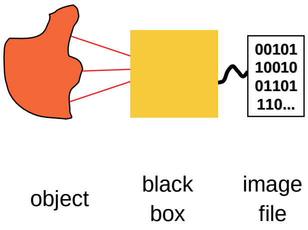
Pinhole Camera Model

- “each pixel corresponds to one ray through the pinhole onto the object”
- not valid for most digital cameras!!!

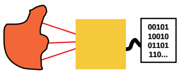


(Pessimistic) Digital Camera Model

- digital camera as a black box
- take only for granted what you measured (or what is given in the manual)



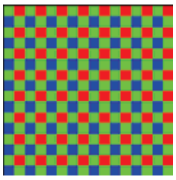
(Pessimistic) Digital Camera Model



- optical lens system instead of pinhole aperture (aberration, vignetting)
- CCD/CMOS chip and A/D conversion
- normally only one color per pixel (e.g. Bayer pattern) requires demosaicing
- camera image processing
- …

Bayer Pattern

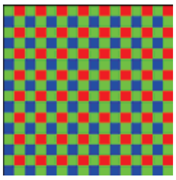
- sensor records only one color per pixel
  - higher sampling rate in green channel (luminance channel)
- remaining two color values per pixel must be reconstructed
  - artifacts possible



Bayer pattern

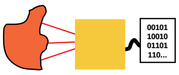
Demosaicing

- common approach
  - combining an interpolation and a pattern matching scheme
  - groups pixels into regions and makes some continuity assumption within the regions
  - “nice pictures”, but no guarantee that two of the R,G,B values per pixel are correct



Bayer pattern

(Pessimistic) Digital Camera Model



- often globally correct image
- no guarantee that each pixel contains reliable color values
- some issues can be solved using camera calibration
- careful choice of camera for measurements

Overview Acquisition Basics

- digital cameras
  - **geometric and photometric calibration**
  - **high dynamic range imaging**
- light sources
- lab setup

Geometric Camera Calibration

- get transformation between points in space and image coordinates
- intrinsic camera parameters
  - focal length, distortion coefficients, …
- extrinsic parameters
  - position, orientation

Geometric Camera Calibration

- several methods commonly used, e.g., [Tsai ’87, Heikkila ’97, Zhang ’99]
- Matlab calibration toolbox by Jean-Yves Bouguet
  - http://www.vision.caltech.edu/bouguetj/calib_doc/
  - also included in the OpenCV Open Source Computer Vision library distributed by Intel

Camera Model (simplified from Bouguet)

- point in camera reference frame is mapped to normalized pinhole coordinates

$$x_n = \begin{bmatrix} x_n(1) \\ x_n(2) \end{bmatrix} = \begin{bmatrix} X_c / Z_c \\ Y_c / Z_c \end{bmatrix}$$

Camera Model (simplified from Bouguet)

- normalized point coordinates are computed using distortion model
  - only parameterized by distance from center

$$x_d = \begin{bmatrix} x_d(1) \\ x_d(2) \end{bmatrix} = (1 + kc(1)r^2 + kc(2)r^4 + kc(3)r^6)x_n$$

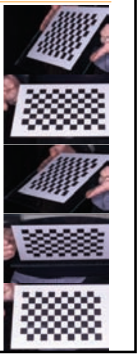
$$r^2 = x_n(1)^2 + x_n(2)^2$$

Camera Model (simplified from Bouguet)

- final pixel coordinates are computed using focal length and principal point

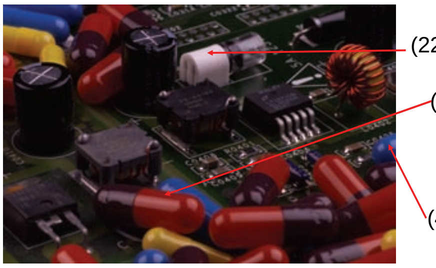
$$\begin{bmatrix} x_p(1) \\ x_p(2) \end{bmatrix} = \begin{bmatrix} fc(1)\cdot x_d(1) \\ fc(2)\cdot x_d(2) \end{bmatrix} + \begin{bmatrix} cc(1) \\ cc(2) \end{bmatrix}$$

Calibration Approach



- capture images of test target with known geometry
  - cover space and angles with planar target
- solve for intrinsic and extrinsic parameters
- quality can be checked by reprojection

Photometric Calibration



(225,203,216)

(141,25,4)

(40,70,143)

What do these RGB values (digital counts) mean?

Camera Response Curve (OECF)

- relationship between digital counts and luminance is unknown (and often non-linear)
  - gamma correction
  - image optimizations
  - ...
- can be described by response curve or OECF (Opto-Electronic Conversion Function)

Camera Response Curve (OECF)

- direct measurement via test chart
  - patches with known gray levels
  - uniform illumination
- patches arranged in a circle to suppress lens effects (e.g. vignetting)
- inversion using OECF leads to pixel values linearly related to luminance values

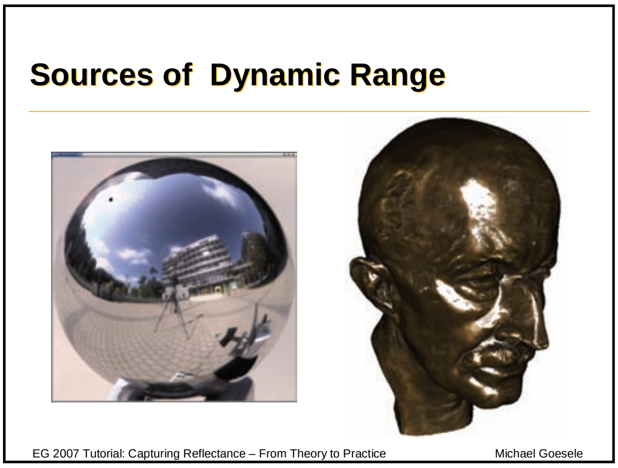
Definition of Dynamic Range

- dynamic range is the ratio of brightest to darkest (non-zero) intensity values in an image
  - assuming linear intensity
- often given as
  - ratio: 1:100.000
  - orders of magnitude: 5 orders of magnitude
  - in decibel: 100 dB

Sources of Dynamic Range

- diffuse materials reflect 0.5% – >90% of incoming light
  - specular highlights much brighter
- lit regions vs. in shadow regions
- moonless night vs. sunny day

→ high dynamic range mainly caused by illumination effects

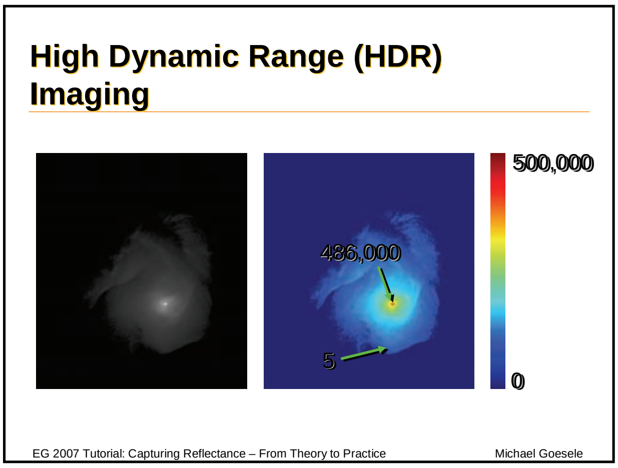


Sources of Dynamic Range

Dynamic Range of Cameras

- example: photographic camera with standard CCD sensor

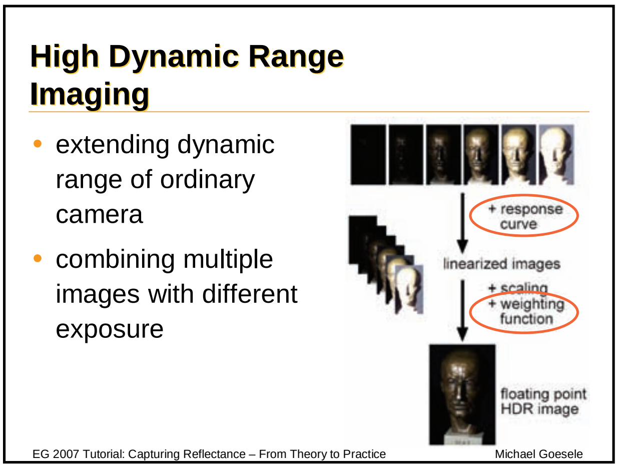
– dynamic range of sensor	1:1000
– exposure variation 1/60th s – 1/6000th s (handheld camera/non-static scene)	1:100
– varying aperture f/2.0 – f/22.0	~1:100
– exposure bias/varying "sensitivity"	1:10
– total (sequential)	1:100,000,000
– simultaneous dynamic range still only	1:1000



High Dynamic Range (HDR) Imaging

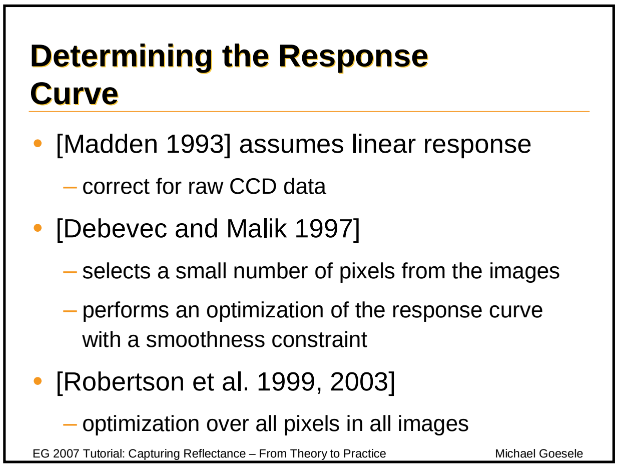
High Dynamic Range (HDR) Imaging

- analog false-color film with several emulsions of different sensitivity levels by Wyckoff in the 1960s
  - dynamic range of about 10^8
- modern CMOS sensors can achieve a dynamic range of $10^6 – 10^8$
  - logarithm in analog domain
  - multiple exposure techniques



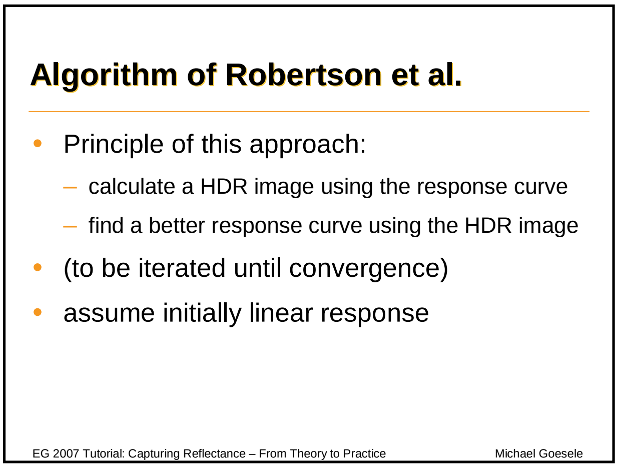
High Dynamic Range Imaging

- extending dynamic range of ordinary camera
- combining multiple images with different exposure



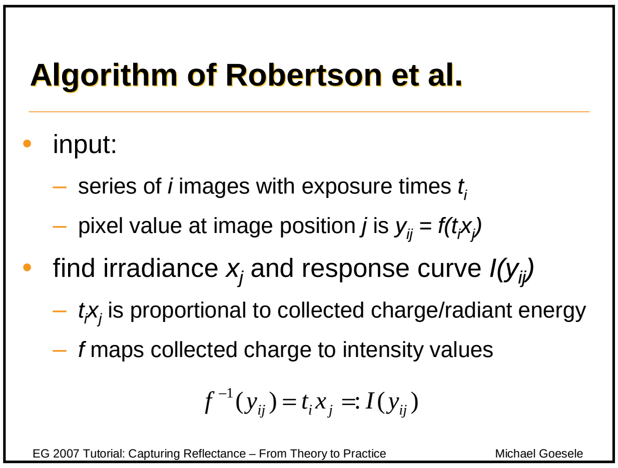
Determining the Response Curve

- [Madden 1993] assumes linear response
  - correct for raw CCD data
- [Debevec and Malik 1997]
  - selects a small number of pixels from the images
  - performs an optimization of the response curve with a smoothness constraint
- [Robertson et al. 1999, 2003]
  - optimization over all pixels in all images



Algorithm of Robertson et al.

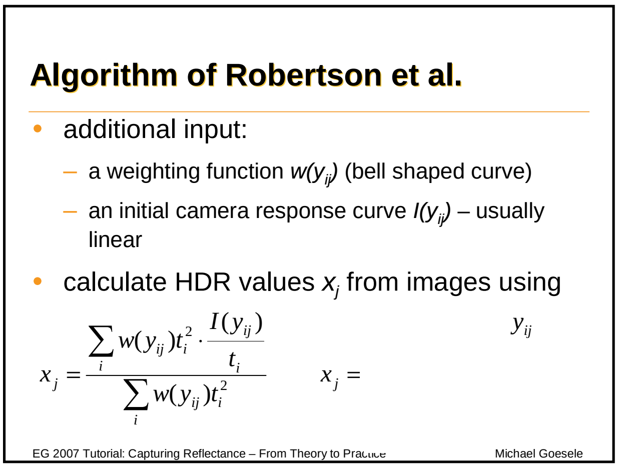
- Principle of this approach:
  - calculate a HDR image using the response curve
  - find a better response curve using the HDR image
- (to be iterated until convergence)
- assume initially linear response



Algorithm of Robertson et al.

- input:
  - series of *i* images with exposure times t_i
  - pixel value at image position *j* is $y_{ij} = f(t_i x_j)$
- find irradiance x_j and response curve $I(y_{ij})$
  - $t_i x_j$ is proportional to collected charge/radiant energy
  - *f* maps collected charge to intensity values

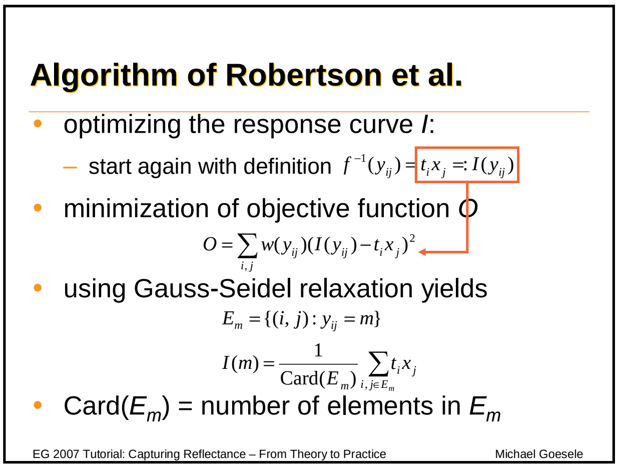
$$f^{-1}(y_{ij}) = t_i x_j =: I(y_{ij})$$



Algorithm of Robertson et al.

- additional input:
  - a weighting function $w(y_{ij})$ (bell shaped curve)
  - an initial camera response curve $I(y_{ij})$ – usually linear
- calculate HDR values x_j from images using

$$x_j = \frac{\sum_i w(y_{ij}) t_i^2 \cdot \frac{I(y_{ij})}{t_i}}{\sum_i w(y_{ij}) t_i^2} \qquad y_{ij} \qquad x_j =$$



Algorithm of Robertson et al.

- optimizing the response curve *I*:
  - start again with definition $f^{-1}(y_{ij}) = \boxed{t_i x_j =: I(y_{ij})}$
- minimization of objective function *O*

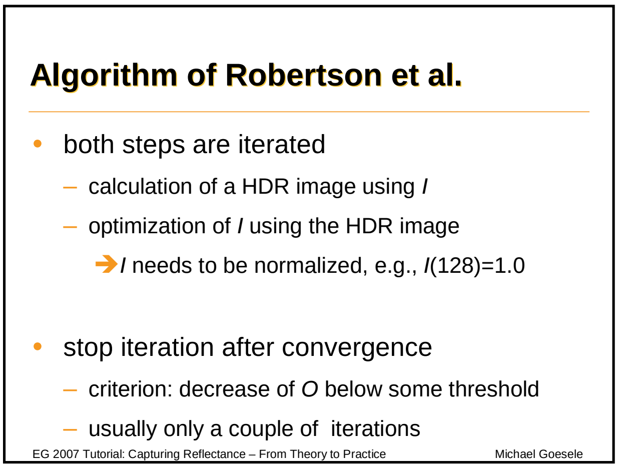
$$O = \sum_{i,j} w(y_{ij})(I(y_{ij}) - t_i x_j)^2$$

- using Gauss-Seidel relaxation yields

$$E_m = \{(i,j) : y_{ij} = m\}$$

$$I(m) = \frac{1}{\mathrm{Card}(E_m)} \sum_{i,j \in E_m} t_i x_j$$

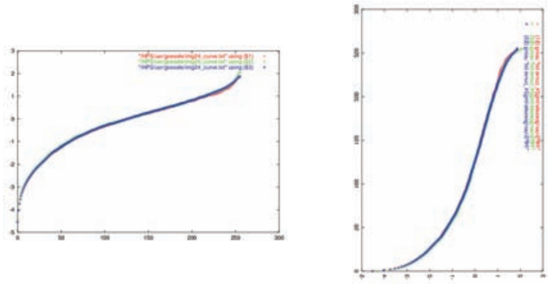
- Card(E_m) = number of elements in E_m



Algorithm of Robertson et al.

- both steps are iterated
  - calculation of a HDR image using *I*
  - optimization of *I* using the HDR image
    - ➔ *I* needs to be normalized, e.g., *I*(128)=1.0
- stop iteration after convergence
  - criterion: decrease of *O* below some threshold
  - usually only a couple of iterations

HDR Imaging: Algorithm of Robertson et al.



$\log(I(y_{ij}))$

HDR Example: Capturing Environment Maps

1/2000s **1/500s** **1/125s** **1/30s** **1/8s**

series of input images

HDR Example: Capturing Environment Maps

Algorithm of Robertson et al.

- choice of weighting function *w(y_{ij})* for response recovery

$$w_{ij} = \exp\left(-4\frac{(y_{ij}-127.5)^2}{127.5^2}\right)$$

  - for 8 bit images
  - possible correction at both ends (over/underexposure)
  - motivated by general noise model

Algorithm of Robertson et al.

- choice of weighting function *w(y_{ij})* for HDR reconstruction
  - introduce certainty function *c* as derivative of the response curve with logarithmic exposure axis
  - approximation of response function by cubic spline to compute derivative

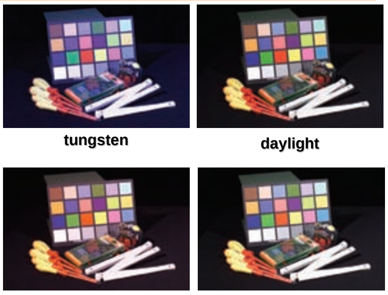
$$w_{ij} = w(y_{ij}) = c(I_{y_{ij}})$$

Input Images for Response Recovery

- my favorite:
  - grey card, out of focus, smooth illumination gradient
- advantages
  - uniform histogram of values
  - no color processing or sharpening interfering with the result

White Balance

capture the spectral characteristics of the light source to assure correct color reproduction



tungsten

daylight

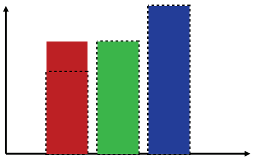
flourescent

flash

images taken with different camera settings

White Balance

- capture white surface under target illumination
- scale color channels to achieve uniform intensity values
- often built-in function

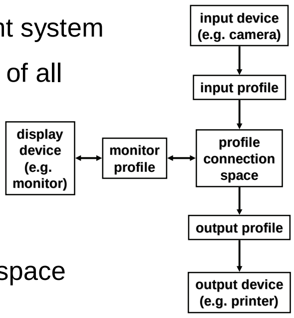


Color Calibration

- BRDF model of real object
- long processing pipeline
- which image is (more) correct?

Color Calibration

- ICC color management system
- capture the properties of all devices
  - camera and lighting
  - monitor settings
  - output properties
- common interchange space



input device (e.g. camera)

input profile

display device (e.g. monitor)

monitor profile

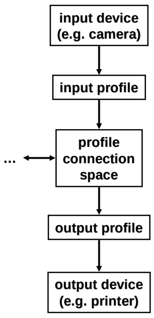
profile connection space

output profile

output device (e.g. printer)

Color Calibration

- profile connection spaces
  - CIELAB (perceptual linear)
  - linear CIEXYZ color space
- can be used to create an high dynamic range image in the profile connection space
- allows for a color calibrated workflow



input device (e.g. camera)

input profile

...

profile connection space

output profile

output device (e.g. printer)

Color Calibration

[Goesele et al. 2004]

Limits of White Balance and Color Calibration

- fluorescence effects
  - signal colors
  - optical brighteners
  - test targets
- color calibration impossible
- cannot be solved using white balance


daylight (HMI)

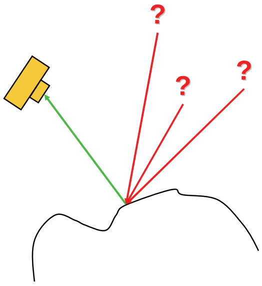

green LED

Overview Acquisition Basics

- digital cameras
  - geometric and photometric calibration
  - high dynamic range imaging
- **light sources**
- lab setup
- geometry acquisition

General Measurement Approach

- find relation between incoming and outgoing light at a surface point
- derive information from this data
- knowledge and control over light sources needed



Lighting Requirements

- photometric properties
  - uniform spatial distribution
  - color constant over time
  - even spectral distribution
  - very bright and efficient

Lighting Requirements

- emission pattern
- requirements depend on application, e.g.,
  - well defined light source
  - incident angle as small as possible
    - ➔ *parallel light source (e.g. laser beam)*
    - ➔ *point light source*
  - lens or reflector based systems are not ideal

Point Light Source Example

- 800 W HMI light source
- very efficient (equals 2500 W tungsten light)
- (almost) daylight spectrum
- constant colors
- point light source

Point Light Source Example

- more information about lighting in the individual sections of the course …

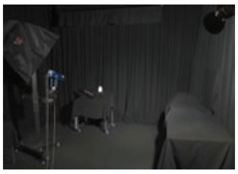
Overview Acquisition Basics

- digital cameras
  - geometric and photometric calibration
  - high dynamic range imaging
- light sources
- **lab setup**

Lab Setup

- part of the lighting considerations
- often low and diffuse reflection required to minimize the influence of the environment
- MPI photo studio
  - walls and ceiling covered with black felt
  - black needle fleece carpet

Lab Setup



Lab Setup

- tuned for efficiency and flexibility
  - enough space
  - enough stands, supporting materials, …
- have some lighting available in dark areas
  - e.g., radio controlled light switch
- safety concerns

Capturing Reflectance
From Theory to Practice

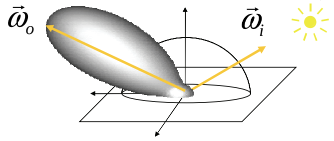
Reflectance Sharing

Michael Goesele
University of Washington

BRDF

(bi-directional reflectance distribution function)

$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o) = \frac{dL(\vec{\omega}_o)}{dE(\vec{\omega}_i)}$$



ratio of reflected radiance to incident irradiance

BRDF Measurement

- Gonioreflectometer

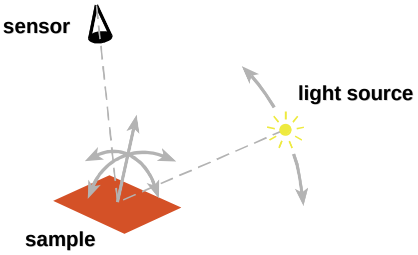


Image-Based BRDF Measurement

- [Marschner 1999, Lu & Koenderink 1998, …]
- capture lots of BRDF samples at one shot by a sensor array / camera

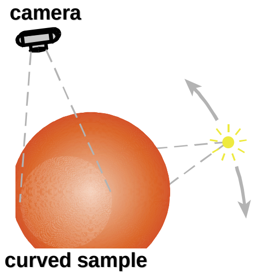


Image-Based BRDF Measurement

- [Marschner 1999, Lu et al. 1998, …]
  - capture lots of BRDF samples at one shot by a sensor array / camera
  - homogeneous, isotropic materials only

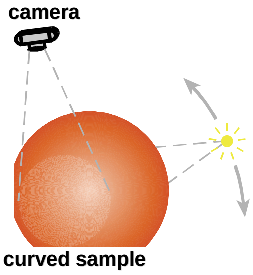


Image-Based BRDF Measurement

- [Matusik et al. 2003, Ngan et al. 2005]
  - systematic capture effort for large number of materials
  - includes anisotropic materials
  - BRDF database available online
  - analysis of captured data using dimensionality reduction techniques

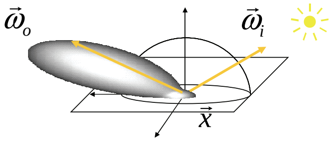
Homogeneous BRDF

Spatially Varying BRDF

Spatially Varying BRDF

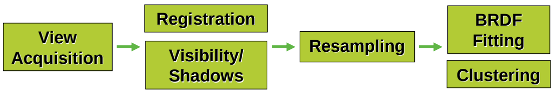
- heterogeneous materials

$$f_r(\vec{x};\vec{\omega}_i \to \vec{\omega}_o)$$



Spatially Varying BRDF

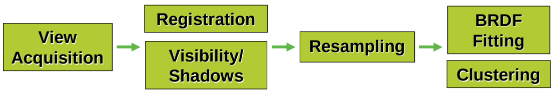
- measurement approach by [Lensch et al. 2003]

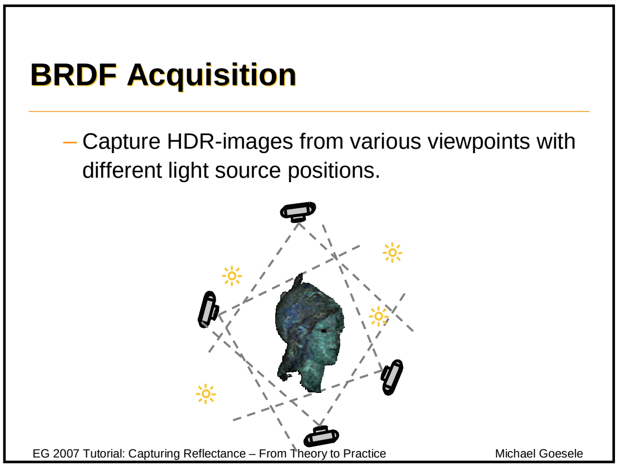


Acquisition Setup

- Camera and light source are moved manually around the object.
- Positions are calibrated with respect to the object.
- The dark room reduces reflections from the environment.

BRDF Fitting and Clustering

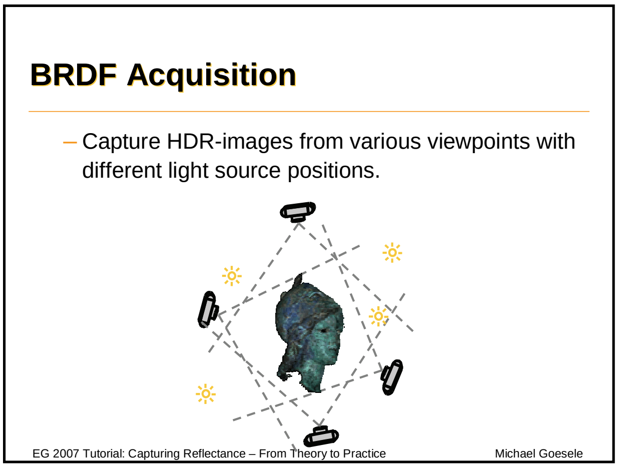




BRDF Acquisition

- Capture HDR-images from various viewpoints with different light source positions.

EG 2007 Tutorial: Capturing Reflectance – From Theory to Practice Michael Goesele



BRDF Acquisition

- Capture HDR-images from various viewpoints with different light source positions.

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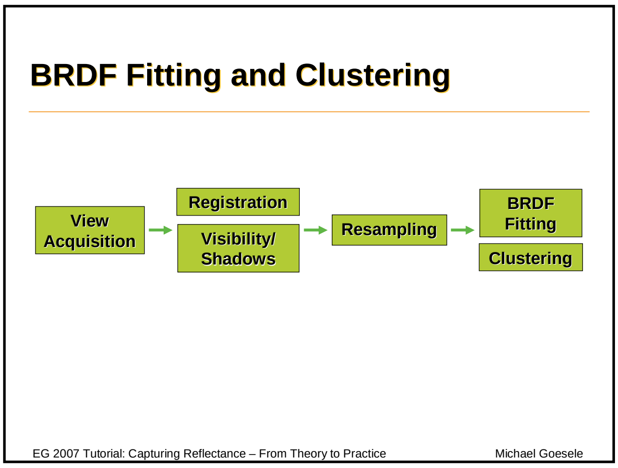

BRDF Fitting and Clustering

View Acquisition → **Registration** / **Visibility/ Shadows** → **Resampling** → **BRDF Fitting** / **Clustering**

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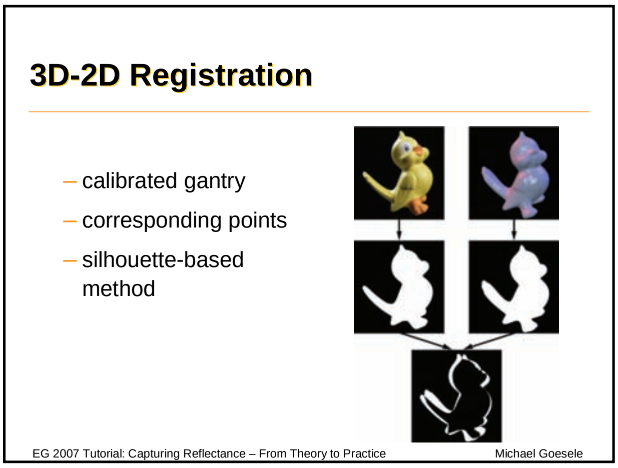

3D-2D Registration

- calibrated gantry
- corresponding points
- silhouette-based method

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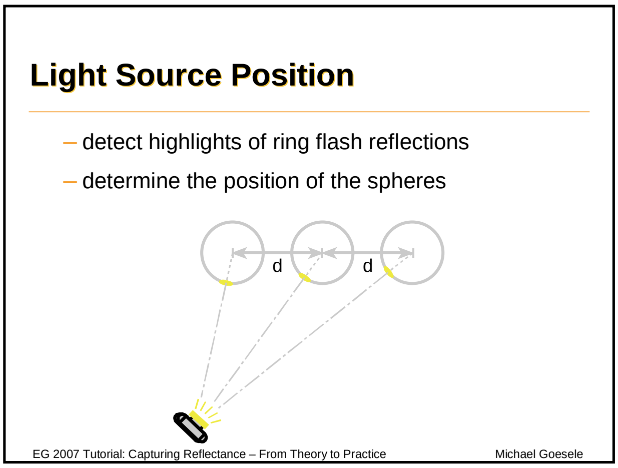

Light Source Position

- detect highlights of ring flash reflections
- determine the position of the spheres

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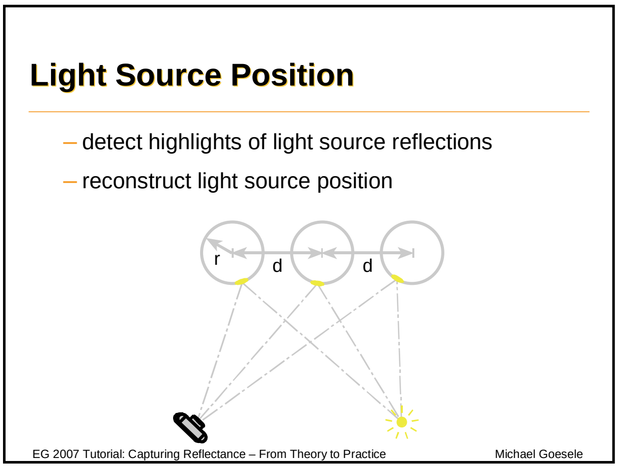

Light Source Position

- detect highlights of light source reflections
- reconstruct light source position

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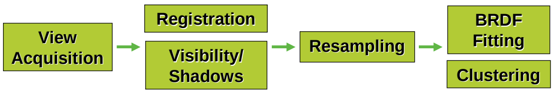
Light Source Position

BRDF Fitting and Clustering



View Acquisition → Registration / Visibility/ Shadows → Resampling → BRDF Fitting / Clustering

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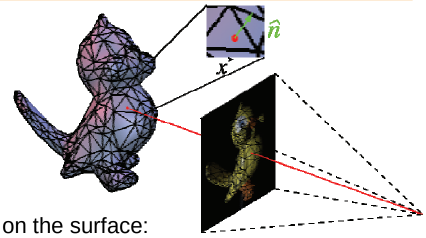
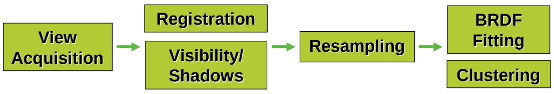
Resampling



- for each point on the surface:
  find all images where the point is visible and lit
  take sample at corresponding pixel position

$$(r, \vec{x}, \vec{\omega}_i, \vec{\omega}_o)$$

BRDF Fitting and Clustering



View Acquisition → Registration / Visibility/ Shadows → Resampling → BRDF Fitting / Clustering

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Key Idea

- Very few radiance samples per texel
  - ⇒ no dense sampling of the BRDF
- Most real-world objects consist of a small set of distinct materials.
  - ⇒ fit a BRDF model for each basis material
  - ⇒ start with the avg. BRDF of the entire surface

The Lafortune Model

$$f_r(\hat{\omega}_i, \hat{\omega}_o) = \rho_d + \sum_j \left(C_{x,j} (\omega_{ix}\omega_{ox} + \omega_{iy}\omega_{oy}) + C_{z,j} \omega_{iz}\omega_{oz} \right)^{N_j}$$

- physically plausible
- diffuse component plus a number of lobes
- 3*(1+ i*3) parameters (12 for a single lobe model)
- fit parameters to samples using Levenberg-Marquardt

Fitting BRDFs to Lumitexels

- define error measure between a BRDF and a lumitexel:

$$E_{f_r}(L) = \frac{1}{|L|}\sum_{R_j \in L}\left(f_r(\vec{\omega}_{i_j},\vec{\omega}_{o_j})\vec{\omega}_{i_j z} - r_j\right)^2$$

= average error over all radiance samples

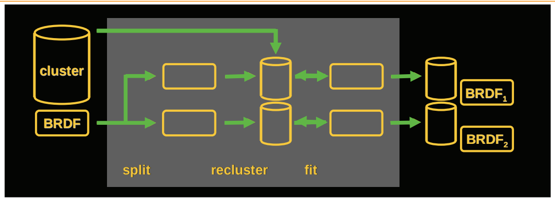
- perform non-linear least square optimization for a ***set*** of lumitexels using Levenberg-Marquardt
- yields a single BRDF (i.e. its parameters) per ***set*** of lumitexels

Fitting Result

Clustering

- Goal: separate the different materials
  - similar to Lloyd iteration
  - start with a single cluster containing all lumitexels
  - split cluster along direction of largest variance
  - stop after *n* clusters have been constructed

Split-Recluster-Fit Cycle



- split into two BRDFs along direction of largest variance of parameters (covariance matrix)
- distribute initial lumitexels forming two new clusters
- refit new BRDFs
- repeat reclustering and fitting until clusters are stable

Clustering Results

Spatially Varying Materials

Projection

- Goal: assign a separate BRDF to each lumitexel
  - too few radiance samples for a reliable fit
  - represent the BRDF f_π of every lumitexel by a linear combination of already determined BRDFs of the clusters $f_1, f_2, \ldots, f_m$

$$f_\pi = t_1 f_1 + t_2 f_2 + \ldots + t_m f_m$$

  - determine linear weights $t_1, t_2, \ldots, t_m$

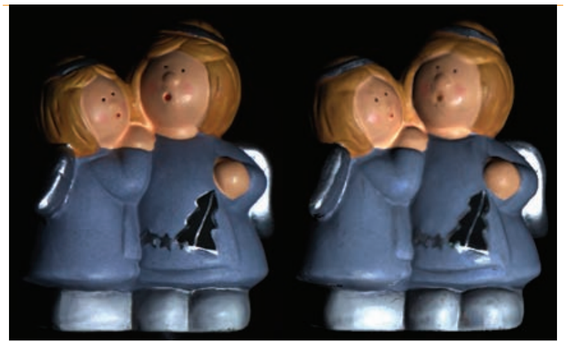
Projection

- compute the pseudo-inverse using non-negative SVD to get a least squares solution for

$$\begin{pmatrix} r_1 \\ r_2 \\ \vdots \\ r_{|L|} \end{pmatrix} = \begin{pmatrix} f_1(\hat{\omega}_{i1}, \hat{\omega}_{o1})\hat{\omega}_{i1,z} & f_2(\hat{\omega}_{i1}, \hat{\omega}_{o1})\hat{\omega}_{i1,z} & \cdots & f_m(\hat{\omega}_{i1}, \hat{\omega}_{o1})\hat{\omega}_{i1,z} \\ f_1(\hat{\omega}_{i2}, \hat{\omega}_{o2})\hat{\omega}_{i2,z} & f_2(\hat{\omega}_{i2}, \hat{\omega}_{o2})\hat{\omega}_{i2,z} & \cdots & f_m(\hat{\omega}_{i2}, \hat{\omega}_{o2})\hat{\omega}_{i2,z} \\ \vdots & \vdots & \ddots & \vdots \\ f_1(\hat{\omega}_{i|L|}, \hat{\omega}_{o|L|})\hat{\omega}_{i|L|,z} & f_2(\hat{\omega}_{i|L|}, \hat{\omega}_{o|L|})\hat{\omega}_{i|L|,z} & \cdots & f_m(\hat{\omega}_{i|L|}, \hat{\omega}_{o|L|})\hat{\omega}_{i|L|,z} \end{pmatrix} \cdot \begin{pmatrix} t_1 \\ t_2 \\ \vdots \\ t_m \end{pmatrix}$$

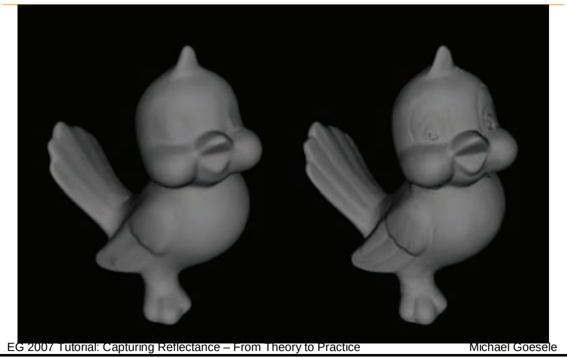
- it is a linear problem!

Results

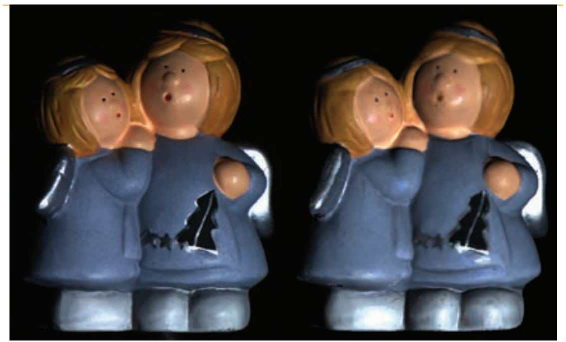


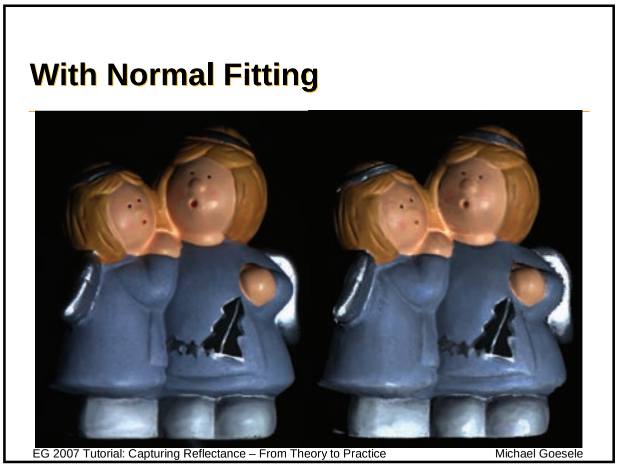
Why to do the complicated clustering?

Normal Fitting



Without Normal Fitting





With Normal Fitting

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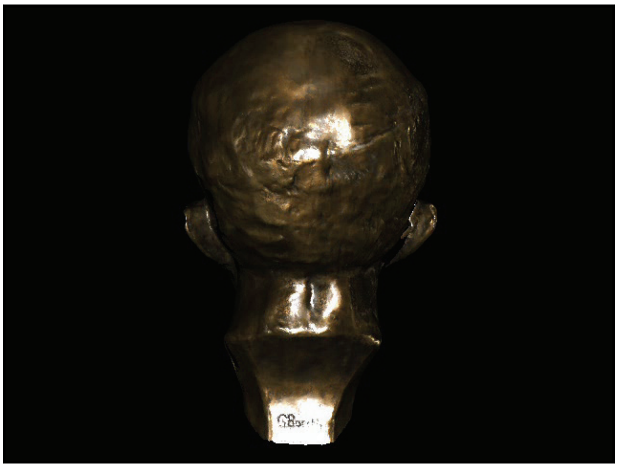

Conclusion

- determine BRDF of a few basis materials
- spatial variation as a blend of basis BRDFs
- highly efficient acquisition

- model based
- requires geometry model

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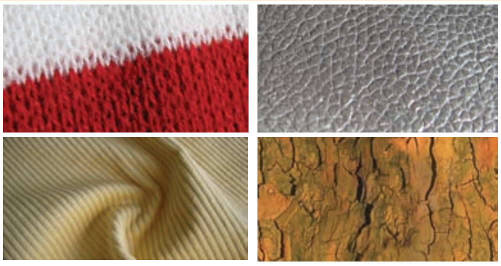
Capturing Reflectance
From Theory to Practice

Bidirectional Texture Functions

Gero Müller

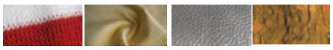
University of Bonn

Introduction



- Opaque materials with complex mesogeometry (rough textures)

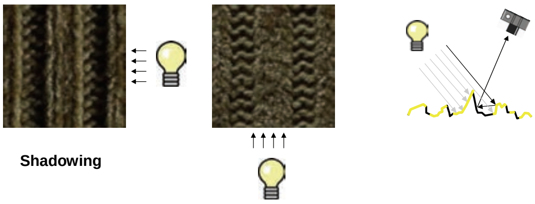
Introduction



- Goal
  - Capture „look-and-feel“ of those materials independent of a specific physical object
- Capture appearance from material samples
- Standard: single RGB-image
  - Appearance captured only for one view and one lighting situation
  - Valid only for flat and diffuse materials (paper, cardboard,...)

Introduction

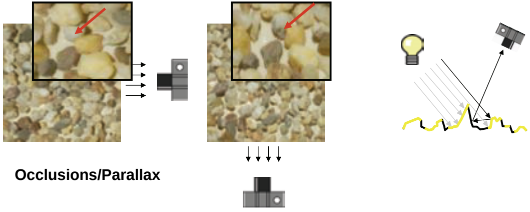
- Images of rough textures with meso-structure contain view- and light dependent shadows, occlusions and local/global illumination effects



Shadowing

Introduction

- Images of rough textures with meso-structure contain view- and light dependent shadows, occlusions and local/global illumination effects



Occlusions/Parallax

Introduction

- Lighting distance large compared to extent of material sample
- Materials are applied to opaque physical objects (furniture, walls, car interior, cloth, ...)

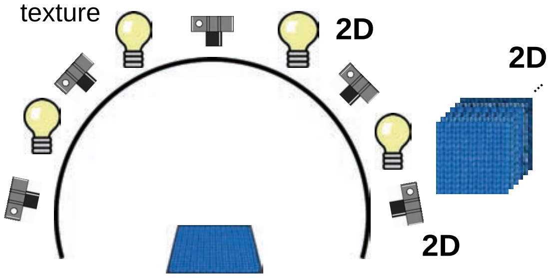
➔Neglect near-field illumination and explicit light-transport between surface points

➔Measure only far-field reflectance field of sample

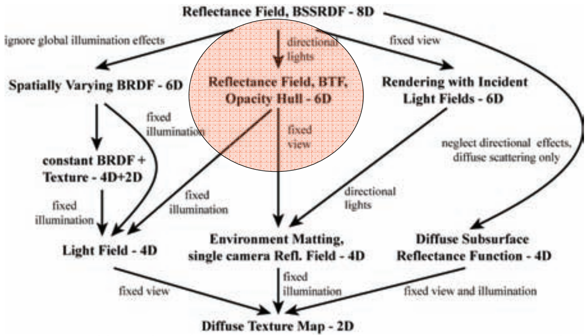
➔**B**idirectional **T**exture **F**unction [Dana et al. 1997]

Introduction

- BTF ⇔ 6D far-field reflectance field of texture



Taxonomy



Overview

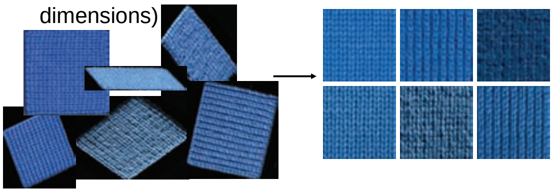
- Acquisition
- Compression
- Rendering
- Non-planar objects

- Synthesis not part of this talk

Acquisition

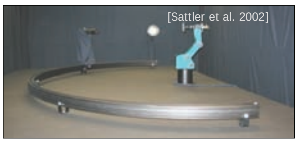
BTF Acquisition

- Sampling a 6D-function $BTF_{rgb}(\mathbf{x}, \mathbf{v}, \mathbf{l})$
  - Take pictures… (spatial dimension)
  - ...under various view and light directions (angular dimensions)



Measurement setups

- Gonioreflectometer-like
  - Advantages
    - fully automatic
    - flexible sampling rate
  - Problems
    - measurement time: ~14h (81x81=6561 images)
    - moving parts:
      camera, light, sample carrier


[Sattler et al. 2002]

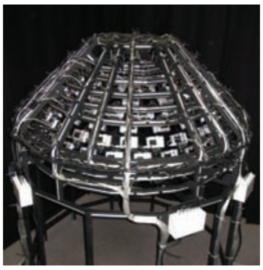

[McAllister 2002]

Measurement setups

- Using Mirrors [Han et al. 2003]
  - Advantages
    - parallel
    - fast
    - no moving parts
  - Problems
    - small resolution
    - non-perfect mirrors

Measurement setups

- Using a camera array [Uni Bonn 2005]
  - Advantages
    - fast, parallel ~1 hour (151x151=22501 images)
    - no moving parts
    - high resolution
  - Problems
    - fixed angular sampling
    - complex control apparatus



BTF Camera Array

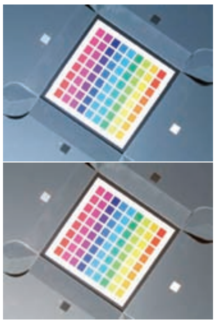
- Custom built hemi-spherical aluminium gantry (80 cm radius) mounted on aluminium base rack
- 151 Canon Powershot A75 digicams (3.2 mpixel)
  - cheapest consumer camera with powerful SDK
  - built-in light source
    (supports different intensities)
- USB-controllable 160-port relay box for on/off toggling
- Custom built power supply

Tasks

- Synchronized control
  - One camera flashes while all cameras take picture
  - High dynamic range
    - 4 passes with different flash intensities and exposures
  - 8 PCs (~19 cameras/PC)
  - 1 Master PC for synchronization

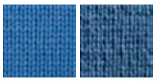
Tasks

- Calibration
  - Response curve
  - Color calibration
  - Varying flash intensity
  - Camera mapping
    - Lens distortion
    - Intrinsic + extrinsic camera parameters



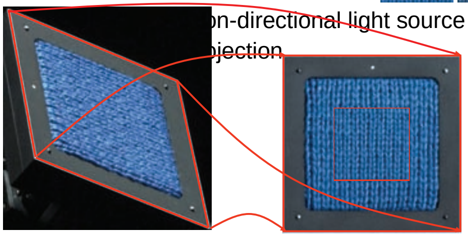
Post-processing

- Extraction of consistent ROI
  - Backprojection onto planar base geometry

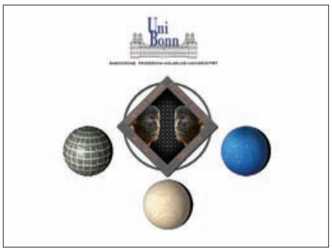


…

- on-directional light source and
  jection
-

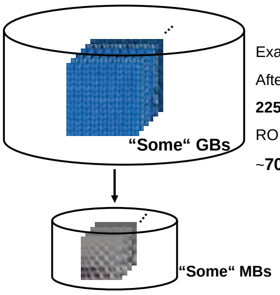


BTF Database Bonn



www.cg.cs.uni-bonn.de/btf

Compression

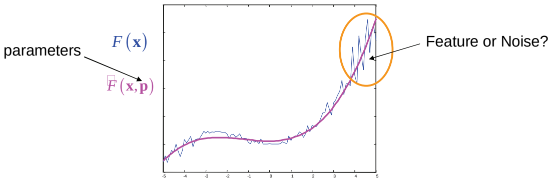


Example (Camera array):
After postprocessing:
22501 hdr-images (OpenEXR)
ROI-size **1024x1024**
~**70-90 GB**

Compression

- Preferable properties:
  - fast (real-time), random access decompression
  - preservation of visual important features
  - maximum of a few MBs
- Two main approaches
  - Fitting analytical functions
  - Statistical data analysis

Fitting Analytical Functions



- $|\mathbf{p}|$ small, evaluation of $\tilde{F}(\mathbf{x},\mathbf{p})$ cheap

➔Good compression and fast evaluation

Fitting Analytical Functions

- Spatial variation (texture domain) too complex

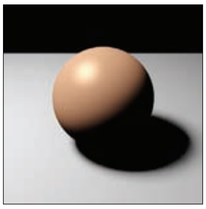
➔Fixing spatial position

$$B_{\mathbf{x}}(\mathbf{v},\mathbf{l}) := BTF(\mathbf{x},\mathbf{v},\mathbf{l})$$

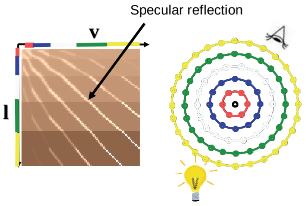
Apply techniques from BRDF modeling

Fitting Analytical Functions

- How do these functions look like?
- How do typical BRDFs look like?

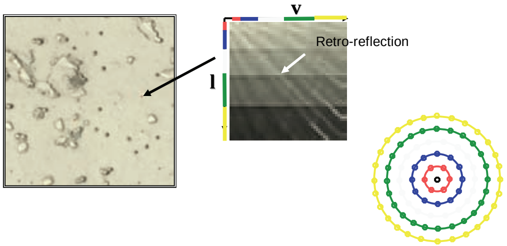


shiny plastic



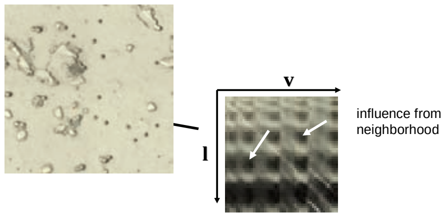
Fitting Analytical Functions

- How do these functions look like?



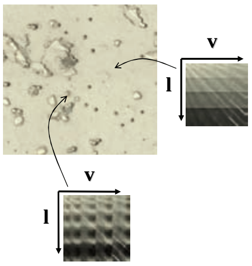
Fitting Analytical Functions

- Are these functions typical BRDFs?



Fitting Analytical Functions

- ABRDF = Apparent BRDF [Wong et al. 97]
  - Contains also influence from neighborhood:
    - Self-Shadowing
    - Self-Occlusion
    - Sub-Surface Scattering
    - Resampling artefacts
    - ...



Fitting BRDF-Models

- Generalized Cosine-Lobe Model [Lafortune et al. 97] :

$$\Rightarrow BTF(\mathbf{x},\mathbf{v},\mathbf{l}) \approx f_{\mathbf{x}}(\mathbf{v},\mathbf{l},\mathbf{p}) = \underset{\nwarrow\ \text{diffuse color}}{\rho_{d,\mathbf{x}}} + \sum_{i=1}^{k} \underset{\uparrow\ \text{specular color}}{\rho_{s,\mathbf{x}}} \cdot \underbrace{\left(\mathbf{v}^T \mathbf{D}_{\mathbf{x},i} \mathbf{l}\right)^{n_{\mathbf{x},i}}}_{\text{specular lobe}}$$

- Non-linear least-squares fitting (Levenberg-Marquardt)
- typically around 2 lobes
- Improvement [Daubert et al. 2001]:
  view-dependent scale factor per texel to account for shadowing effects

---

Fitting BRDF-Models

- Advantages
  - High compression
  - Efficient evaluation
- Problems
  - loss of depth impression
  - Non-linear fitting
    - expensive
    - results depend on initialization

McAllister 2002

Fitting (Hemi-) Spherical Functions

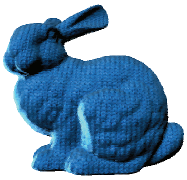
- Approximate hemispherical slices (fixing e.g. view direction) of per-texel ABRDF separately and blend

$$\Rightarrow BTF(\mathbf{x},\mathbf{v},\mathbf{l}) \approx \sum_{v \in N(\mathbf{v})} \underset{\nwarrow\ \text{Interpolation weights}}{w_{\mathbf{v},v}} \underset{\swarrow\ \text{Hemispherical Function (2D)}}{HSF_{\mathbf{x},v}}(\mathbf{l})$$

- [Meseth et al. 2004] used polynomials and cosine lobes
  [Sloan et al. 2003] used spherical harmonics
  (consider also [Masselus et al. EGSR04])

Summary: Fitting Hemispherical Functions

- Advantages
  - Better preservation of ABRDF features
- Problems
  - Chosen approximation for HSF may introduce artifacts
  - Memory consuming (Apply clustering $\Rightarrow$ quantization artifacts)
  - More expensive evaluation (view-interpolation required)



Meseth et al. 2004

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Statistical Data Analysis

- Motivation
  - Assuming general basis functions (polynomials, lobes, etc…) suboptimal for a given measured BTF-dataset
- Idea
  - Find customized basis functions adapted for the actual data set
  - Exploit the inherent redundancy more effectively

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Statistical Data Analysis

- Linear approaches
  - Full BTF-matrix factorization [Koudelka et al. 2003] [Liu et al. 2004]
  - Per-texel ABRDF factorization [Suykens et al. 2003]
  - Per-view factorization [Sattler et al. 2003]
  - Per-cluster factorization [Mueller et al. 2003]
- Tensor approaches
  - TensorTextures [Vasilescu et al. 2004]
  - Out-of-Core Tensor Approximation [Wang et al. 2005]

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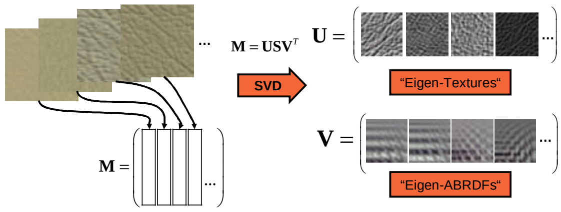
Full BTF-Factorization

- Stack images as column vectors into large matrix



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Full BTF-Factorization

- Write the BTF as sum of products of two functions

$$\Rightarrow BTF(\mathbf{x},\mathbf{v},\mathbf{l}) = \sum_j^N \sigma_j \cdot t_j(\mathbf{x}) b_j(\mathbf{v},\mathbf{l}) \approx \sum_j^c \sigma_j \cdot t_j(\mathbf{x}) b_j(\mathbf{v},\mathbf{l})$$

"Eigen-Textures" "Eigen-ABRDFs"

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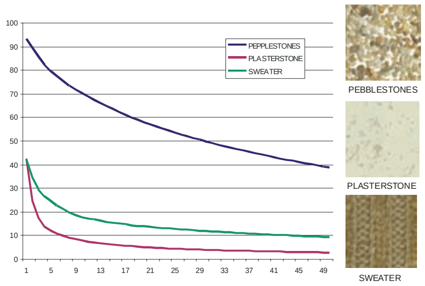
Full BTF-Factorization

- Number of terms

RMS-Error

$$\varepsilon = \sqrt{\sum_{i=c+1}^{N} \sigma_i^2}$$



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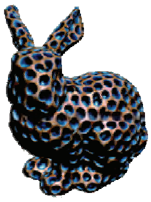
Full BTF-Factorization

- Advantages
  - simple and straight-forward
- Problems
  - complex materials require many terms
  - ➔not suitable for real-time reconstruction



Liu et al. TVCG2004

Per-Texel ABRDF Factorization

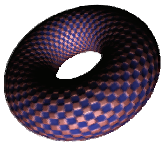
- Chained-Matrix Factorization [Suykens et al. 2003]
  - Generalization of common BRDF-Factorization techniques [Kautz&McCool 1999],[McCool et al. 2001]
  - Idea:
    - Apply chain of factorizations (SVD) to reparameterized data
    - Each parameterization accounts for certain ABRDF-features

$$BTF(\mathbf{x},\mathbf{v},\mathbf{l}) \approx \prod_{j}^{d} \sum_{k}^{c_j} P_{\mathbf{x},j,k}\left(\pi_{j,1}(\mathbf{v},\mathbf{l})\right) \cdot Q_{\mathbf{x},j,k}\left(\pi_{j,2}(\mathbf{v},\mathbf{l})\right)$$

Different parameterizations for each factor j

Per-Texel ABRDF Factorization

- Advantanges
  - Suitable for real-time rendering: Combination of few factors on GPU
- Problems
  - Resampling artifacts
  - Memory consumption (authors propose clustering of factors ⇒ quantization artifacts)



Suykens et al. 2003

Per-View Factorization

- Apply SVD to BTF-slices with fixed view direction (Spatially varying Hemispherical Functions)
- Idea
  - Increase quality of low-term factored approximations by factorizing fixed subsets of the data

$$\Rightarrow BTF(\mathbf{x},\mathbf{v},\mathbf{l}) \approx \sum_{v \in N(\mathbf{v})} w_v \sum_{j}^{c} r_{v,j}(\mathbf{l})\, t_{v,j}(\mathbf{x})$$

"Eigen-Hemispherical-Functions"

"Eigen-Textures" (per view)

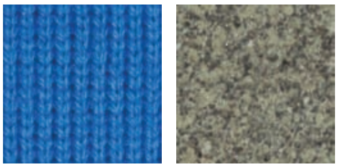
Per-View Factorization

- Advantages
  - Low-term factorization enables high-quality interactive rendering on graphics hardware
- Problems
  - Memory consumption
  - Coherence between different views not exploited

Sattler et al. 2003

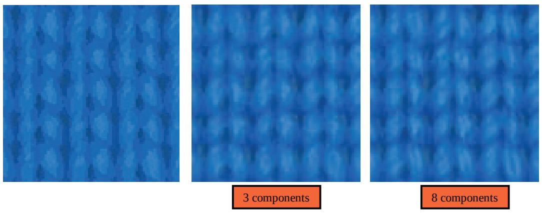
Statistical Data Analysis

- Per-texel or per-view factorization factorize fixed subsets of the BTF data
- Use clustering across spatial dimension to find better subsets



Statistical Data Analysis

- Clustering alone leads to quantization artifacts



- Solution: linear approximation of data in each cluster (Local-PCA)

Per-Cluster Factorization

- Clustering BTF-texels (ABRDFs) leads to

$$\Rightarrow BTF(\mathbf{x},\mathbf{v},\mathbf{l}) \approx \sum_{j}^{c} t_j(\mathbf{x}) b_{k(\mathbf{x}),j}(\mathbf{v},\mathbf{l})$$

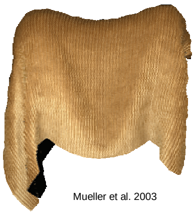
"Eigen-Textures" (segmented)

"Eigen-BRDFs" (per cluster)

- Clustering with generalized Lloyd-algorithm and re-construction error as distance metric

Per-Cluster Factorization

- Advantages
  - Low-term factored representation suitable for GPU implementation
  - Good compression
  - Reconstruction per cluster reduces quantization artifacts
- Problems
  - Expensive fitting



Mueller et al. 2003

Storage Requirements

Model	Storage (|L|,|V|,|T|)	|V|=|L|=81, |T|=256² 8-Bit per channel
Raw BTF	|L|*|V|*|T|	1.2 GB
Analytical BRDF-Model	*f*(k)*|T|	(k=2) 2.4 MB
Hemispherical Function	*f*(k)*|V|*|T|	(k=2) 95 MB
BTF Factorization	c*(|V|*|L| + |T|)	(c=40) 8.6 MB
ABRDF Factorization	d*(|V|+|L|)*|T|	(d=2) 63 MB
Per-View Factorization	|V|*c*(|L|+|T|)	(c=4) 64 MB
Per-Cluster Factorization	c*(k*(|V|*|L|) + |T|)	(k=32, c=8) 6.6 MB

Practical Issues

- Factorization approaches require computing SVD of large matrices (up to several GBs)
- Use incremental/online SVD methods
  - Arnoldi iteration
  - EM-PCA [Roweis 1998]
  - Online SVD [Brand 2003]
  - ...

Using geometry information

- Fitting local coordinate systems
  - In-between image- and geometry-based BTF representation
- Can be done efficiently using FFT over the group of rotations SO(3) [Müller et al. EG2006]

2 SVD components, 200 KB — aligned, 2 SVD components, 200 KB — uncompressed 900 MB

Rendering

Rendering

- Determine color / visible radiance for every point

„Exitant Radiance = Emitted Rad. + Reflected Rad.“

$$L_r(\mathbf{x},\mathbf{v}) = L_e(\mathbf{x},\mathbf{v}) + L_{ref}(\mathbf{x},\mathbf{v})$$

„Reflected Rad. = Incoming Rad. combined with reflection properties“

$$L_{ref}(\mathbf{x},\mathbf{v}) = \int_{\Omega_i} \rho^*_{\mathbf{x}}(\mathbf{v},\mathbf{l}) \cdot L_i(\mathbf{x},\mathbf{l})\, d\mathbf{l}$$

spatially varying reflectance includes foreshortening term

Point- and Directional Light Sources

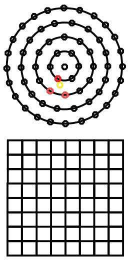
- Finite number of light directions

$$L_{ref}(\mathbf{x},\mathbf{v}) = \int_{\Omega_i} \rho^*_{\mathbf{x}}(\mathbf{v},\mathbf{l}) \cdot L_i(\mathbf{x},\mathbf{l})\, d\mathbf{l}$$

$$\Downarrow$$

$$L_{ref}(\mathbf{x},\mathbf{v}) = \sum_{i=1}^{n} \rho^*_{\mathbf{x}}(\mathbf{v},\mathbf{l}_i) \cdot \hat{L}_i(\mathbf{x},\mathbf{l}_i)$$

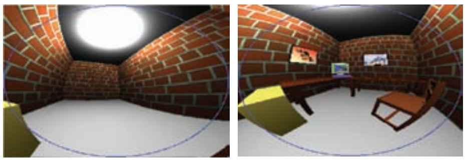
Rendering with GPUs



- Measured BTFs
  - Evaluation for directions not in the measured set
    - Interpolation in angular domain
  - Interpolation rather expensive
    - ➔graphics hardware
    - ➔Interpolation from regular samples

Hardware Supported Angular Interpolation

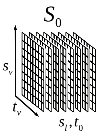
- Reparameterization
  - Approximately uniform sampling of hemisphere
  - Suitable for hardware filtering
  - ➔Parabolic Maps



Heidrich + Seidel 1998

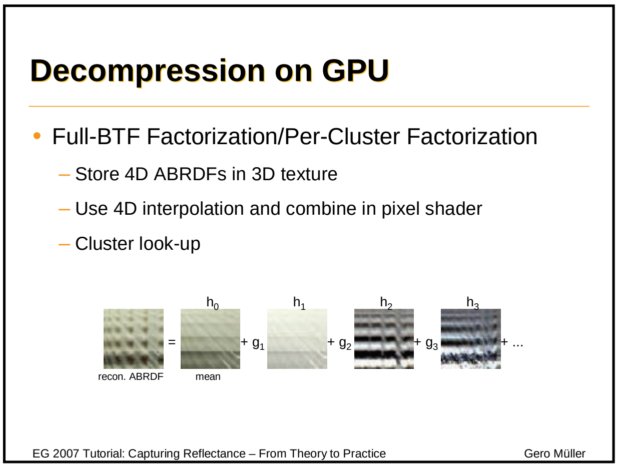
Hardware Supported Angular Interpolation

- 2D Data
  - Bilinear filtering on graphics hardware
- 4D Eigen-ABRDFs
  - Quadrilinear filtering
  - Hardware: trilinear filtering
  - ➔Trilinear filtering of s_v, t_v, s_l
    - ➔3D textures S_i for fixed t_l
  - ➔Interpolate t_l in fragment shader



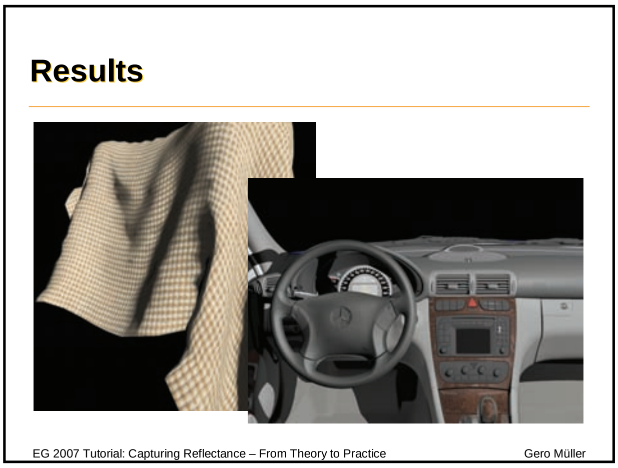
Anti-Aliasing

- Mip-Mapping compressed BTFs
  - No problem for Eigen-Texture based compression (full-matrix factorization, per-view factorization)
  - Other techniques depend non-linear on compression parameters
  - GPU supported Mip-Mapping not possible
  - ➔ Standard Mip-Mapping on uncompressed data
  - ➔ Compression of each individual Mip-Map level



Decompression on GPU

- Full-BTF Factorization/Per-Cluster Factorization
  - Store 4D ABRDFs in 3D texture
  - Use 4D interpolation and combine in pixel shader
  - Cluster look-up



Results

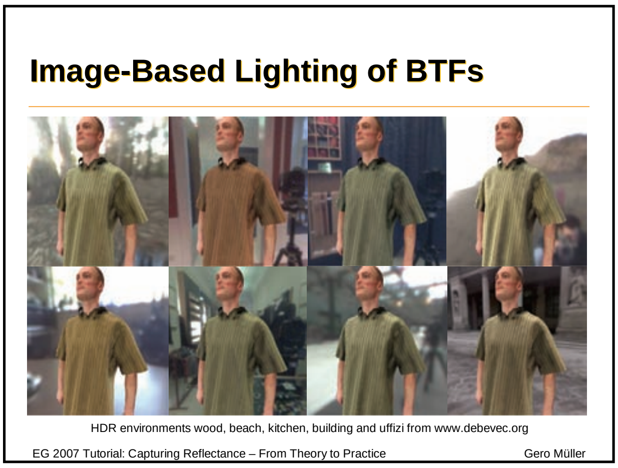
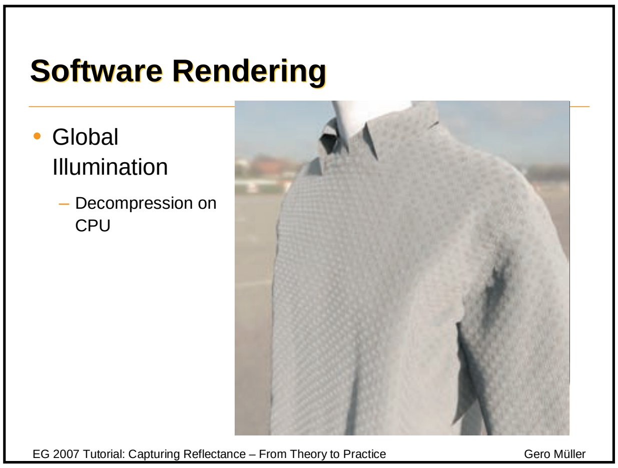


Image-Based Lighting of BTFs

HDR environments wood, beach, kitchen, building and uffizi from www.debevec.org



Software Rendering

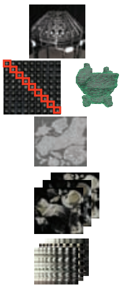
- Global Illumination
  - Decompression on CPU

Non-Planar Objects

- BTF techniques can be applied to non-planar objects
  - [Furukawa et al. EGRW 2002]
  - [Matusik et al. SIG 2002]
  - [Mueller et al. VAST 2005]
- Use 3D reconstructed base-geometry instead of planar base geometry

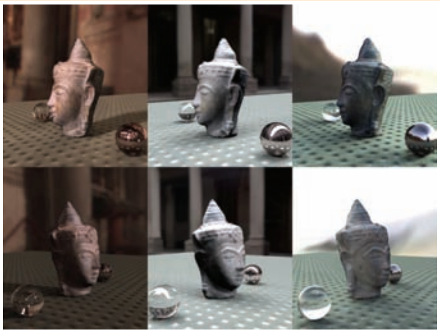
Non-Planar Objects

- Processing steps



  - Image acquisition
  - Image-based 3D-reconstruction
  - Mesh parameterization
  - BTF generation
  - BTF compression

Non-Planar Objects



Conclusions

- BTFs capture 6D-slice of the reflectance field of a complex material
- Represents the “look-and feel” of a material
- Several high-quality acquisition setups
- Effective and appearance preserving compression algorithms available
- Real-time rendering possible with point light sources and image-based lighting

---

Challenges

- Editing and modeling
  - [Kautz et al. SIG 2007]
  - [Müller et al. EGSR 2007]
- Material Perception
- Time variation (recent work only SVBRDFs)
- Spectral measurements
- Highly reflective materials

Acknowledgements

- Reinhard Klein, Ralf Sarlette, Dirk Koch, Jan Meseth, Mirko Sattler
- EPOCH NoE
- RealReflect
- University of Bonn

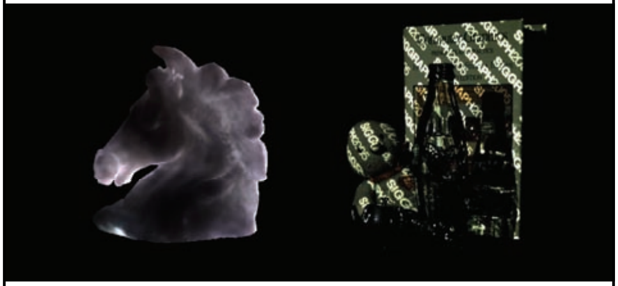
Capturing Reflectance
From Theory to Practice

Near-field Reflectance Fields

Hendrik P.A. Lensch

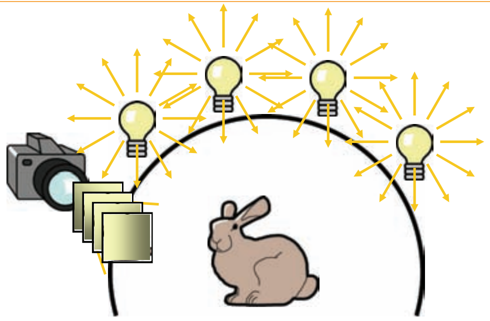
MPI Informatik

Digitizing Real World Objects



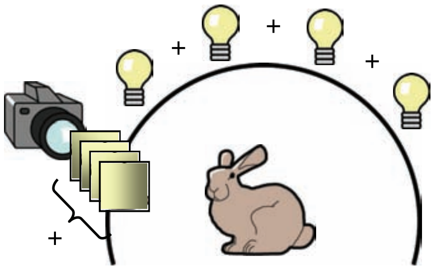
relighting with arbitrary illumination patterns

Relighting



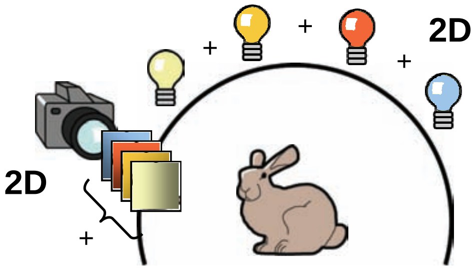
Relighting

[Debevec2000]

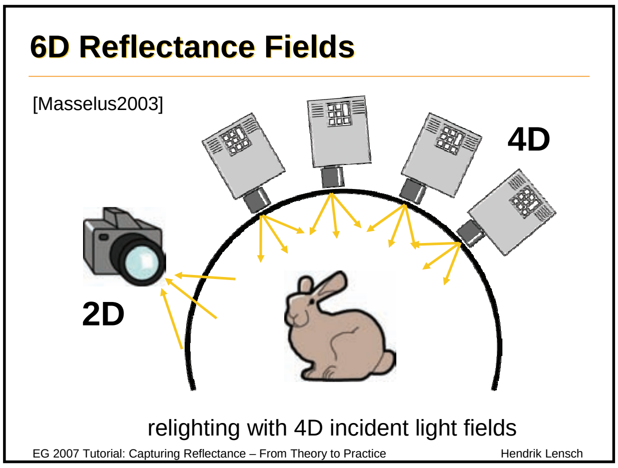


Far-Field Reflectance Fields

[Debevec2000]



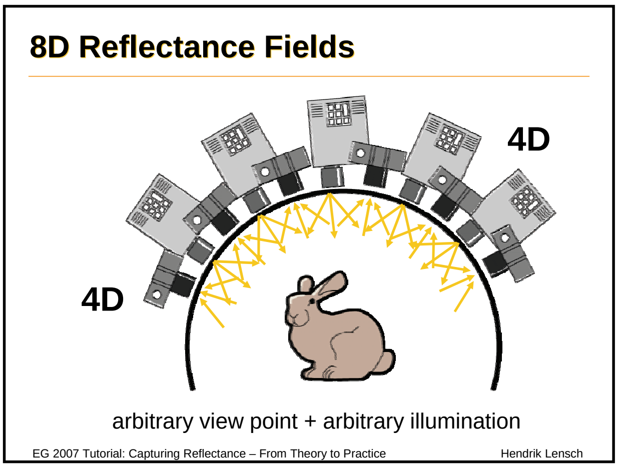
Far and Near Field Illumination



6D Reflectance Fields

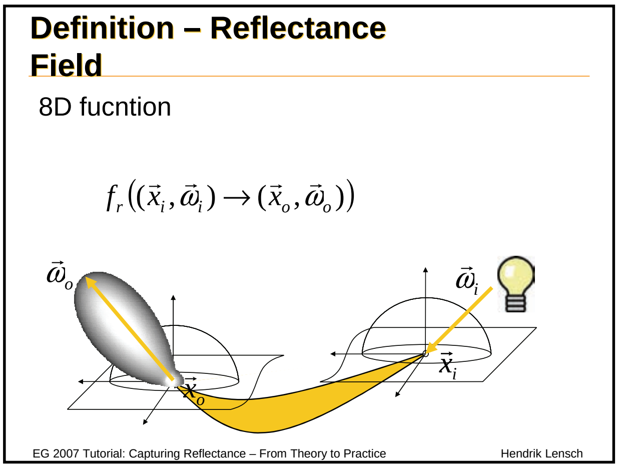
[Masselus2003]

relighting with 4D incident light fields



8D Reflectance Fields

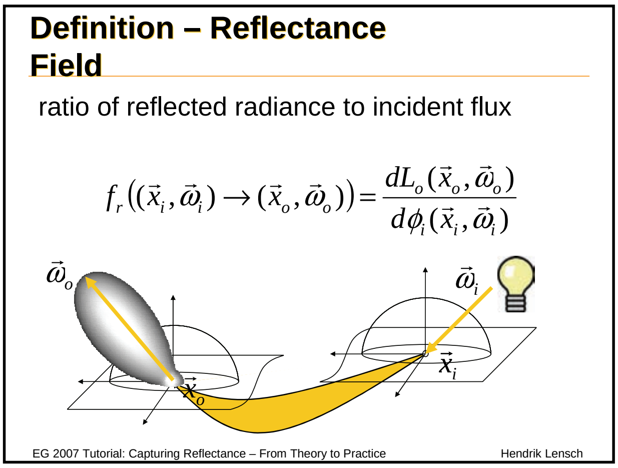
arbitrary view point + arbitrary illumination



Definition – Reflectance Field

8D fucntion

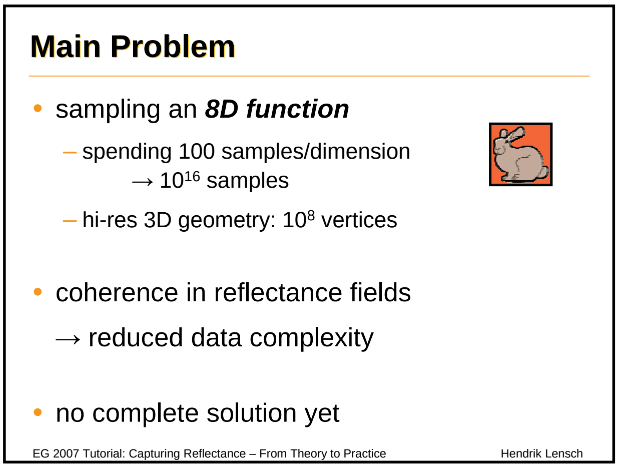
$$f_r\left((\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o)\right)$$



Definition – Reflectance Field

ratio of reflected radiance to incident flux

$$f_r\left((\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o)\right)=\frac{dL_o(\vec{x}_o,\vec{\omega}_o)}{d\phi_i(\vec{x}_i,\vec{\omega}_i)}$$



Main Problem

- sampling an ***8D function***
  - spending 100 samples/dimension → 10^{16} samples
  - hi-res 3D geometry: 10^8 vertices
- coherence in reflectance fields
  → reduced data complexity
- no complete solution yet

Approaches

- limited reflectance model
- limited reproduction
  - viewer position
  - incident illuminaton
- adaptive parallel acquisition
- advanced interpolation

Relighting with 4D Incident Light Fields

- goal: relighting with spatially varying illumination, e.g. spot lights

[Masselus2003]

Acquisition with Large Blocks

- fixed camera perspective
- rotating illumination

Relighting Results

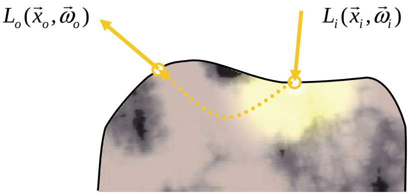
Translucent Objects

- light transport through the object
- scattering dampens high frequencies

BSSRDF – 8D

bidirectional scattering-surface reflectance distribution function [Nicodemus77]

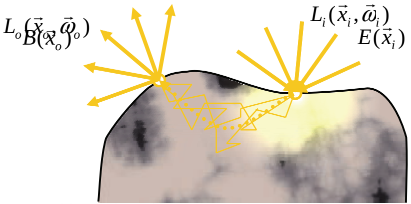
$$f_r\left((\vec{x}_i,\vec{\omega}_i)\rightarrow(\vec{x}_o,\vec{\omega}_o)\right)$$



Diffuse Approximation

neglect directional dependency [Jensen 2001]

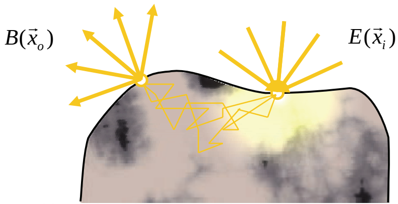
- multiple scattering leads to diffuse light transport



4D - Diffuse Approximation

⇒ diffuse reflectance function $R_d(\vec{x}_i, \vec{x}_0)$

  - four dimensions only
  - dense sampling is possible



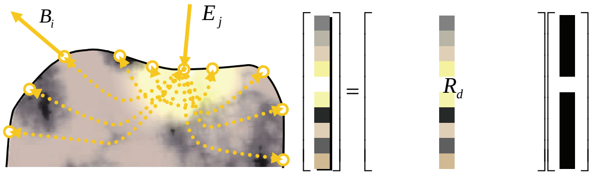
Diffuse Reflectance Fucntion R_d

- discretize the surface
  - enumerate all surface points
  - vectors for irradiance E and radiosity B
- matrix R_d
  - linear point-to-point transport

$$\begin{bmatrix} B_i \end{bmatrix} = \begin{bmatrix} \quad R_d \quad \end{bmatrix} \begin{bmatrix} E_j \end{bmatrix}$$

Basic Idea

- direct measurement of R_d
  - illuminate individual surface points
  - capture impulse response function



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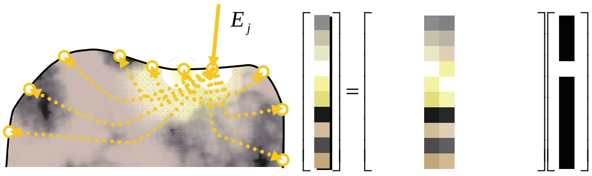

Basic Idea

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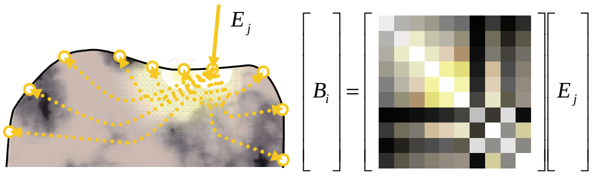
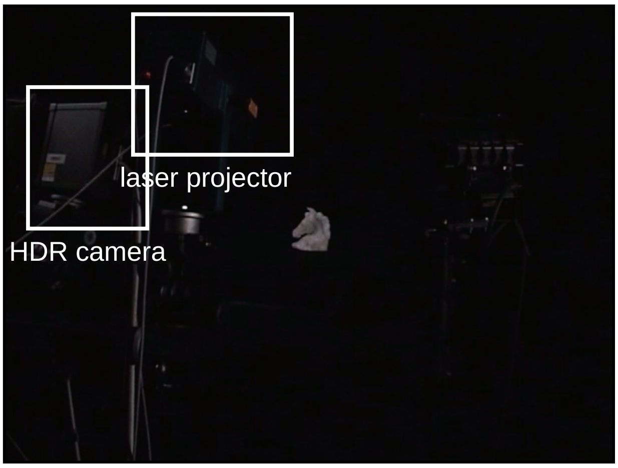




Matrix Representation

- 500.000 – 1.000.000 input images

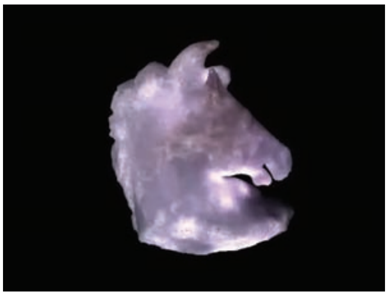
  ⇒ ~100.000^2 entries

- fill up holes (inpainting)
- hierarchical representation
- hardware assisted rendering
  - analysis
  - real-time rendering

[Lensch, Goesele, Bekaert, Magnor, Lang, Seidel – PG2003]

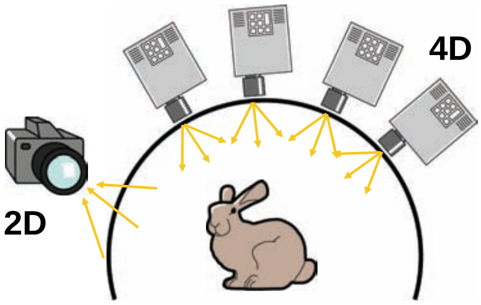
Video

1.000.000 images, 22 hours → model - 800MB

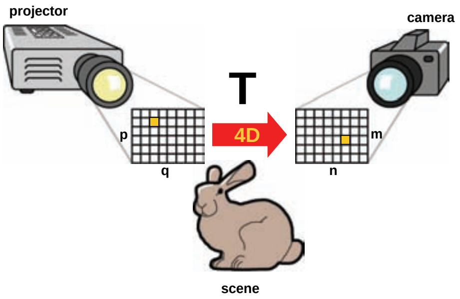


[Goesele, Lensch, Lang, Fuchs, Seidel - SIGGRAPH 2004]

Fixed Perspective + Arbitrary Illumination

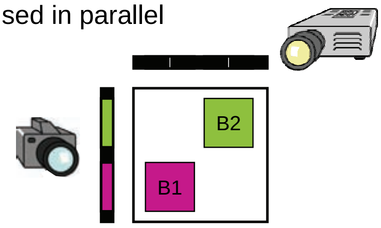


Pixel-to-Pixel Transport



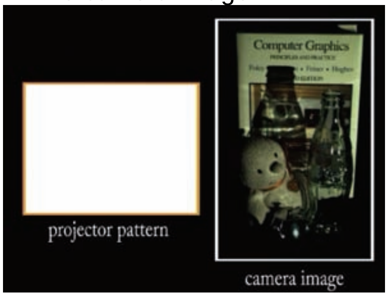
Adaptive Parallel Acquisition

- assumption: sparse matrix
- radiometrically independent blocks can be sensed in parallel



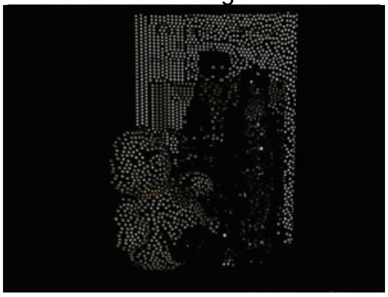
Adaptive Parallel Acquisition

parallelized acquisition of regions which do not overlap in the camera image



Adaptive Parallel Acquisition

parallelized acquisition of regions which do not overlap in the camera image



Relighting with Arbitrary Patterns

1.200 images, 2 hours → model - 220MB

Captured Global Light Transport

Helmholtz Reziprocity

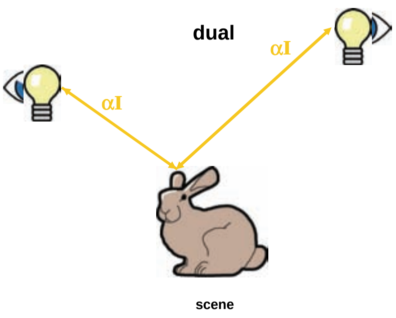


Image Acquisition without a Camera

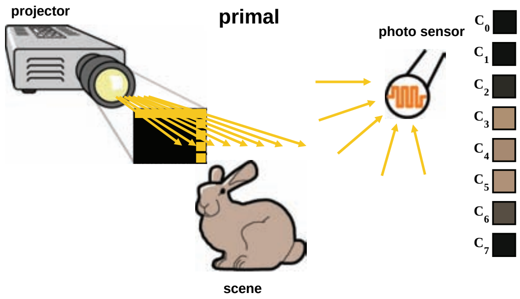
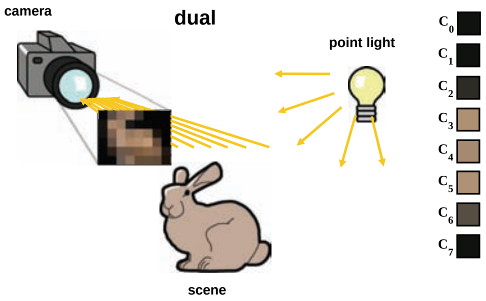


Image Acquisition without a Camera



Dual Photography


photograph from camera

dual image from projector

[Sen, Chen, Garg, Marschner, Horowitz, Levoy, Lensch - SIGGRAPH 2005]

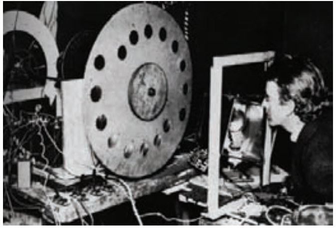
Examples

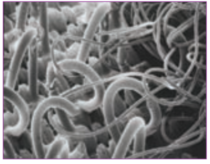

primal

dual

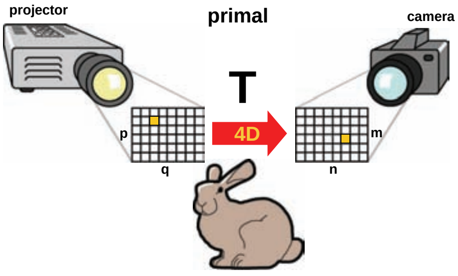
Related Techniques

- “Flying-spot” TV camera [Baird 1926]
- scanning electron microscope


[Baird 1926]

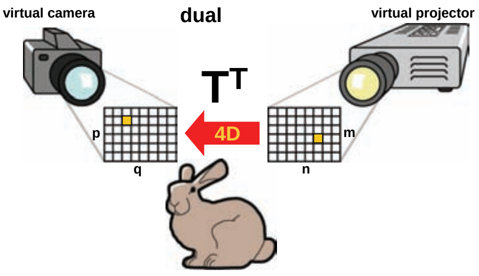

35x magnification
[museum of Science, Boston]

Relighting with Dual Photography



scene

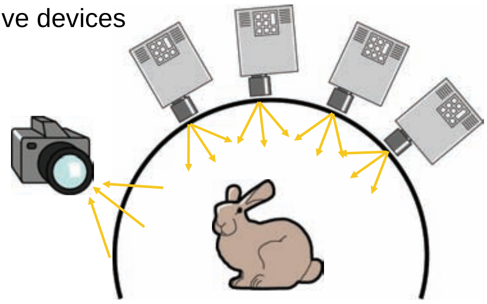
Relighting with Dual Photography



scene

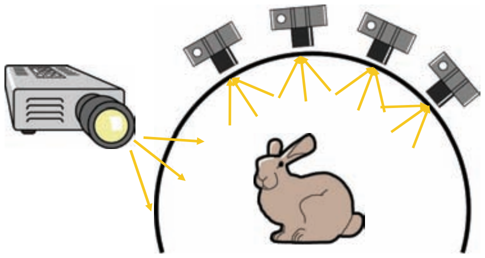
Acquisition of 6D Reflectance Fields

active devices



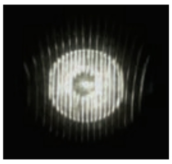
Dual Acquisition Process

parallel acquisition by passive devices



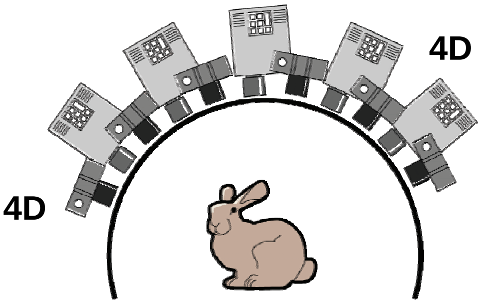
Smooth Interpolation

100.000 images, 26 hours → model - 4.5GB



[Chen, Lensch - VMV2005]

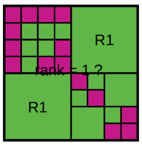
8D Reflectance Fields



arbitrary view point + arbitrary illumination

ℋ-Matrices

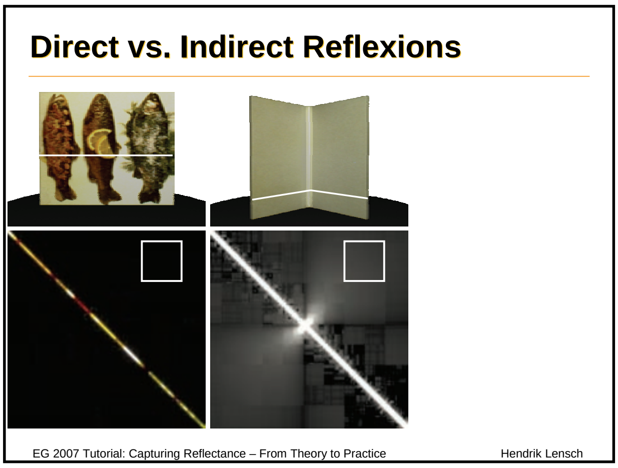
[Hackbusch2000]



efficient representation of dense but ***data-sparse*** matrices

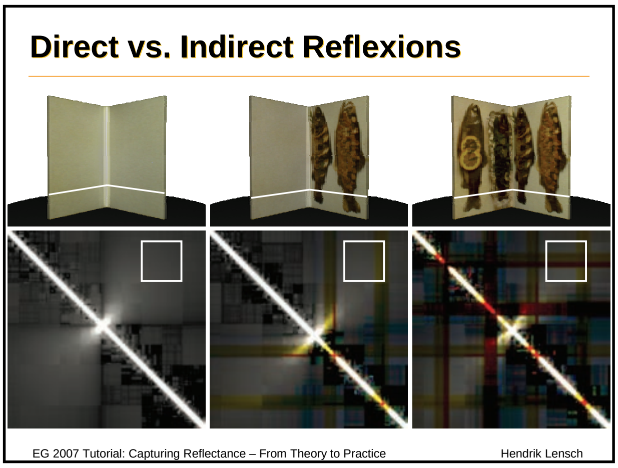
- subdivision hierarchy
- local low-rank approximation
- efficient evaluation

Direct vs. Indirect Reflexions



Direct vs. Indirect Reflexions

EG 2007 Tutorial: Capturing Reflectance – From Theory to Practice Hendrik Lensch

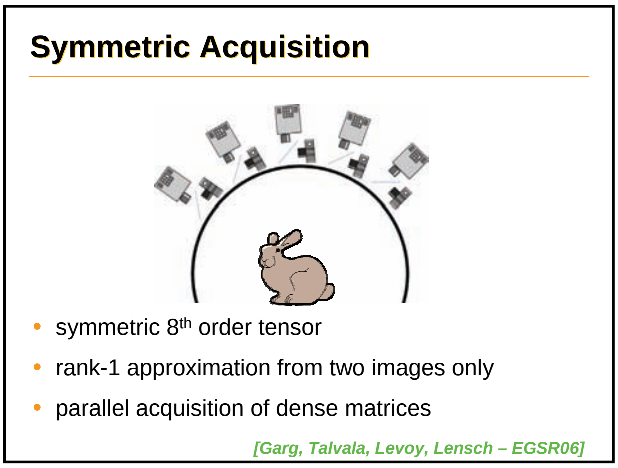


Direct vs. Indirect Reflexions

EG 2007 Tutorial: Capturing Reflectance – From Theory to Practice Hendrik Lensch

2D Slices through a Reflectance Field

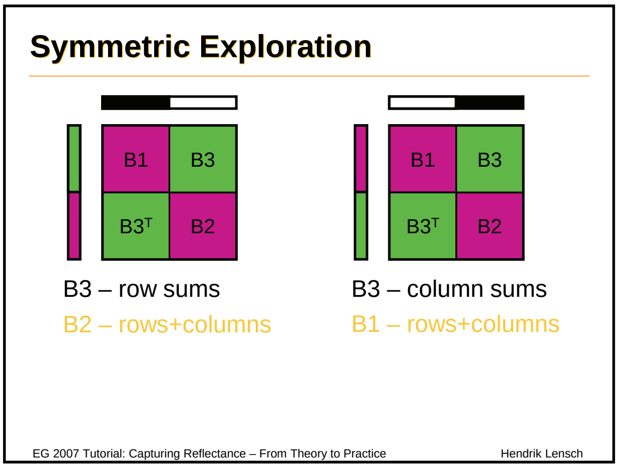
EG 2007 Tutorial: Capturing Reflectance – From Theory to Practice Hendrik Lensch



Symmetric Acquisition

- symmetric 8th order tensor
- rank-1 approximation from two images only
- parallel acquisition of dense matrices

[Garg, Talvala, Levoy, Lensch – EGSR06]



Symmetric Exploration

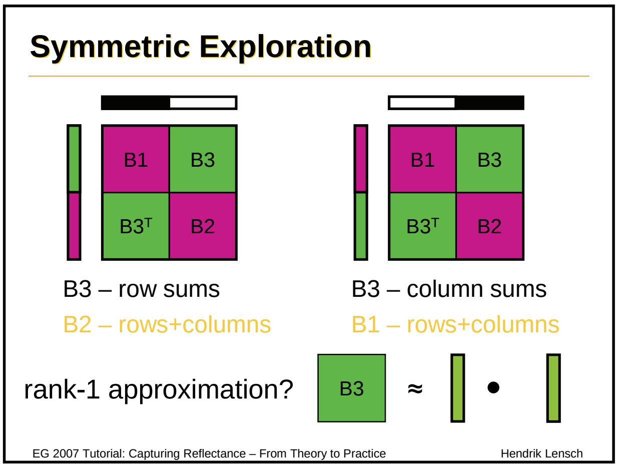
B3 – row sums

B2 – rows+columns

B3 – column sums

B1 – rows+columns

EG 2007 Tutorial: Capturing Reflectance – From Theory to Practice Hendrik Lensch



Symmetric Exploration

B3 – row sums

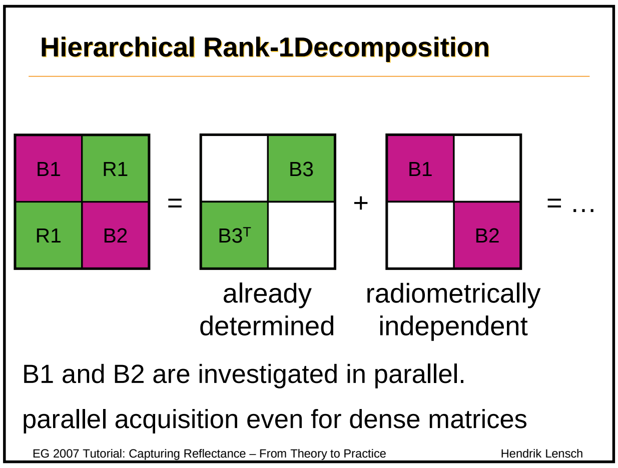
B2 – rows+columns

B3 – column sums

B1 – rows+columns

rank-1 approximation? B3 ≈ ▯ • ▯

EG 2007 Tutorial: Capturing Reflectance – From Theory to Practice Hendrik Lensch



Hierarchical Rank-1Decomposition

B1	R1
R1	B2

=

	B3
$B3^T$	

already determined

\+

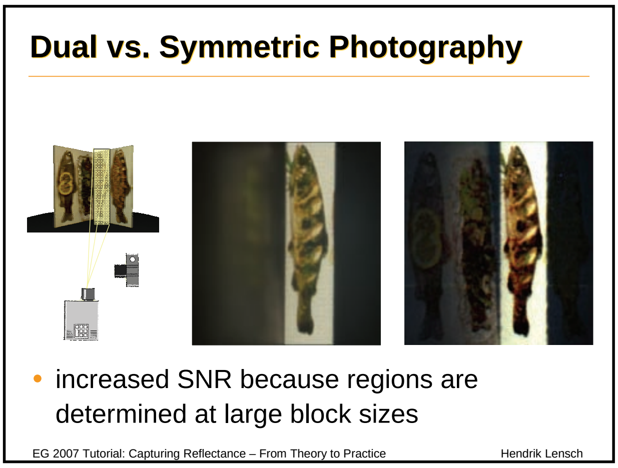
B1	
	B2

radiometrically independent

= …

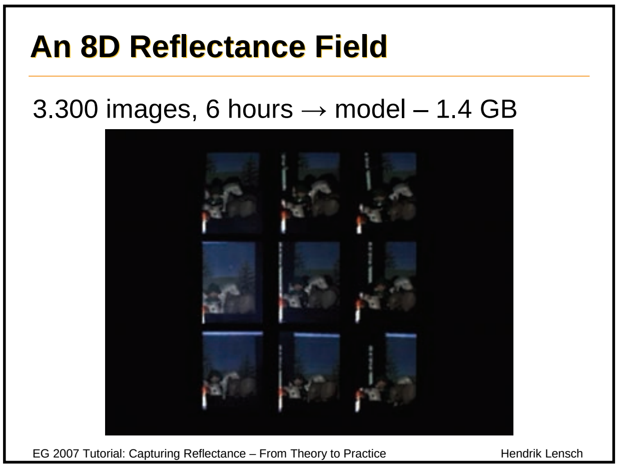
B1 and B2 are investigated in parallel.

parallel acquisition even for dense matrices



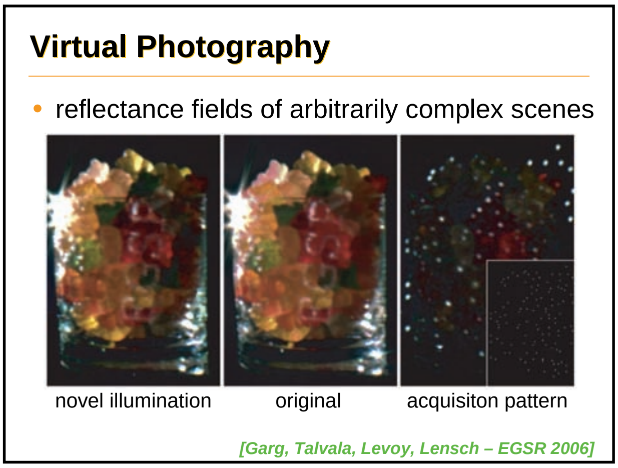
Dual vs. Symmetric Photography

- increased SNR because regions are determined at large block sizes



An 8D Reflectance Field

3.300 images, 6 hours → model – 1.4 GB

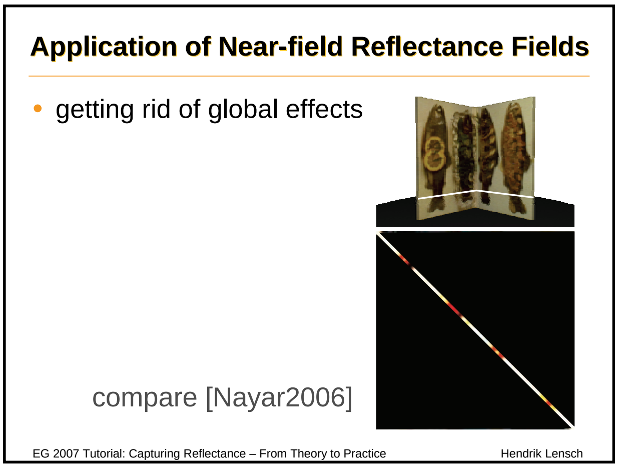


Virtual Photography

- reflectance fields of arbitrarily complex scenes

novel illumination original acquisiton pattern

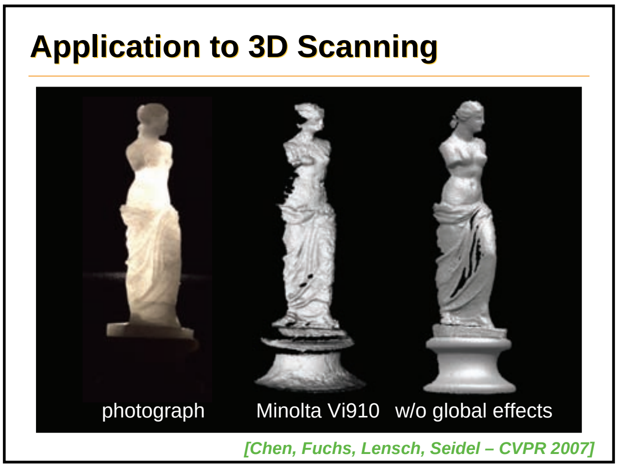
[Garg, Talvala, Levoy, Lensch – EGSR 2006]



Application of Near-field Reflectance Fields

- getting rid of global effects

compare [Nayar2006]

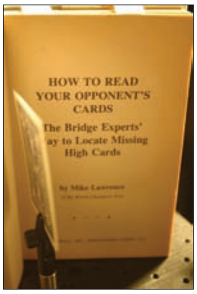


Application to 3D Scanning

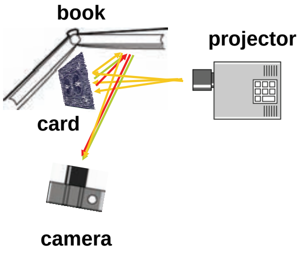
photograph Minolta Vi910 w/o global effects

[Chen, Fuchs, Lensch, Seidel – CVPR 2007]

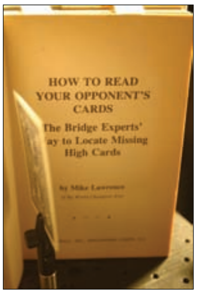
Card Experiment



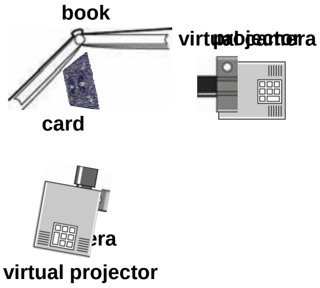
primal



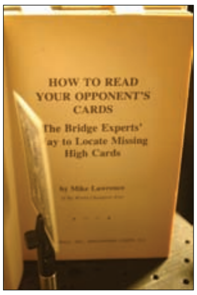
Card Experiment



primal



Card Experiment



primal

dual

Near-Field Reflectance Fields

- Sequential Sampling
- Dual Photography
- Symmetric Photography based on $\mathscr{H}$–matrices
- first methods for acquiring the global light transport in arbitrary scenes

Challenges

- densely sampled 8D reflectance fields
- upsampling / interpolation
- dynamic near-field reflectance fields
- interactive relighting
- global illumination with reflectance fields
- theory on the complexity of reflectance fields

Thanks

- BMBF (FKC01IMC01)
- DFG – Emmy Noether Program

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