Physically Based Shading in Theory and Practice

SIGGRAPH 2020 Course

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Course Description

Physically based shading has transformed the way we approach production rendering and simplified the lives of artists in the process. By employing shading models that adhere to physical principles, one can readily create high quality, realistic materials that maintain their appearance under a variety of lighting environments. In contrast, traditional ad hoc models required extensive tweaking to achieve comparable results — due to less intuitive behavior or unnecessary complexity — and were liable to break under different illumination.

Consequently, physically based models have become widely adopted in film and game production, particularly as they are often no more difficult to implement or evaluate. That being said, physically based shading is not a solved problem, and thus the aim of this course is to share the latest theory as well as lessons from production.

Level of Difficulty: Intermediate

Intended Audience

Practitioners from the video game, CG animation, and VFX fields, as well as researchers interested in shading models.

Prerequisites

An understanding of shading models and their use in film or game production.

Course Website

All course materials can be found here.

Contact

Please address questions or comments to `pbs@selfshadow.com`.

Organizers

Stephen Hill is a Principal Rendering Engineer within Lucasfilm's Advanced Development Group, where he is engaged in physically based rendering R&D for productions such as *Carne y Arena*, and more recently *The Mandalorian*. He was previously a 3D Technical Lead at Ubisoft Montreal, where he contributed to a number of *Splinter Cell* titles as well as *Assassin's Creed Unity*.

Stephen McAuley started in video games in 2006 at Bizarre Creations before moving to Ubisoft in 2011, where he spearheaded the graphical vision on the *Far Cry* brand. In 2020, he joined Sony Santa Monica as a Lead Rendering Engineer. He focuses on physically based lighting and shading, data-driven rendering architecture and overall improvements in visual quality. He is also passionate about sharing his knowledge with the industry as a whole, running internal and external training and conferences.

Presentation Schedule

08:30–09:00	**Some Thoughts on the Fresnel Term** *(Hoffman)*
09:00–09:20	**Bringing an Accurate Fresnel to Real-Time Rendering: A Preintegrable Decomposition** *(Belcour)*
09:20–09:40	**MaterialX Physically Based Shading Nodes** *(Stone and Harrysson)*
09:40–10:00	**Putting the Pieces Together: A Physically(ish) Based Approach to Material Composition** *(Kerley)*
10:00–10:20	**Physically Based and Scalable Atmospheres in Unreal Engine** *(Hillaire)*
10:20–11:00	**Samurai Shading in *Ghost of Tsushima*** (Patry)
11:00–11:30	**Let's Get Physical: The Hairy History of Shading at MPC** *(Pieké, Skliar and Earl)*
11:30–12:00	**Q & A**

Abstracts

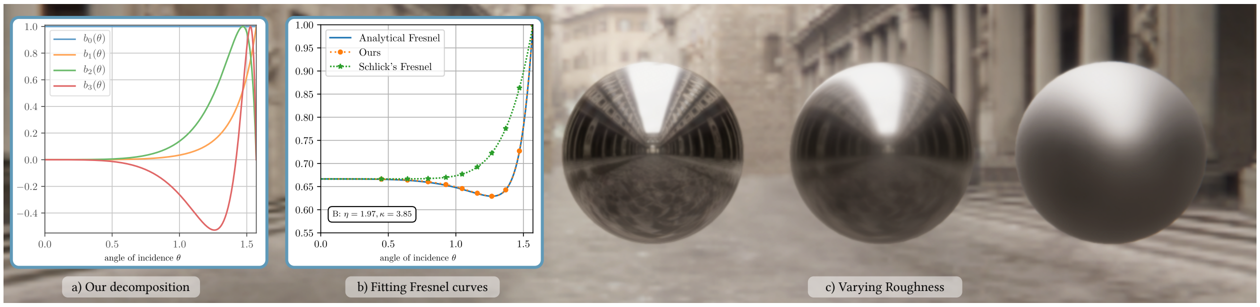
Some Thoughts on the Fresnel Term

Naty Hoffman

The Fresnel term would appear to be the best-understood part of the microfacet model — one can simply use the original equations, or an approximation (usually Schlick's) if computation cost is at a premium. However, in this talk, we will show that all is not as it seems, and that even the humble Fresnel term can hold some surprises.

This talk builds on a previous presentation at the 2019 Eurographics Workshop on Material Appearance Modeling [Hof19], extending it into a more comprehensive overview.

NATY HOFFMAN is a Principal Engineer & Architect in the Lucasfilm Advanced Development Group. Previously he was the Vice President of Technology at 2K, and before that he worked at Activision (doing graphics R&D for various titles, including the *Call of Duty* series), SCE Santa Monica Studio (coding graphics technology for *God of War III*), Naughty Dog (developing PS3 first-party libraries), Westwood Studios (leading graphics development on *Earth and Beyond*) and Intel (driving Pentium pipeline modifications and assisting the SSE/SSE2 instruction set definition).



Bringing an Accurate Fresnel to Real-Time Rendering: A Preintegrable Decomposition

Laurent Belcour, Mégane Bati and Pascal Barla

Real-time rendering engines are increasingly finding a role in visual effects productions alongside offline renderers. However, for this to work effectively, it is critical for the shading models to be consistent across renderers. Unfortunately, while real-time and offline renderers have converged to a common set of microfacet shading models, their treatment of Fresnel reflectance is different, which can lead to noticeable visual discrepancies. Offline renderers can afford to use the accurate Fresnel equations, and they commonly employ Gulbrandsen's parametrization [Gul14]. Real-time engines, on the other hand, typically use Schlick's approximate model [Sch94], both for its lower evaluation cost and because it allows for more efficient tabulation of preconvolved terms used by various shading operations. As such, Schlick's Fresnel approximation is currently the state of the art for real-time rendering.

In this talk, we will discuss a new Fresnel approximation that is tailored to real-time rendering. It is based on an empirical decomposition of the space of possible Fresnel curves and produces a close match to the ground truth. Importantly, it remains compatible with the aforementioned precomputation methodology of real-time rendering engines. In addition, we introduce an alternative parametrization to Gulbrandsen's, directly built on top of our new approximation, which provides more visually uniform variations in the *edge tint* parameter that controls grazing angle variations.

Laurent Belcour is a research scientist at Unity Technologies, focused on real-time and offline rendering. He completed his PhD on theoretical light transport at the University of Grenoble, under the supervision of Cyril Soler and Nicolas Holzschuch. Since then, his research interests have expanded to material modeling and Monte-Carlo integration.

Mégane Bati is a PhD student since Sept. 2018 at LP2N in Bordeaux (France), under the supervision of Romain Pacanowski and Pascal Barla. She is interested in material appearance modeling, and especially the inverse design of layered materials.

Pascal Barla received his PhD in 2006 on the topic of *Expressive Rendering* at INP Grenoble (France). After being recruited as a permanent researcher at Inria Bordeaux Sud Ouest in 2007, his research has expanded to the more general domain of visual appearance, with interests in both optics and perception.

MaterialX Physically Based Shading Nodes

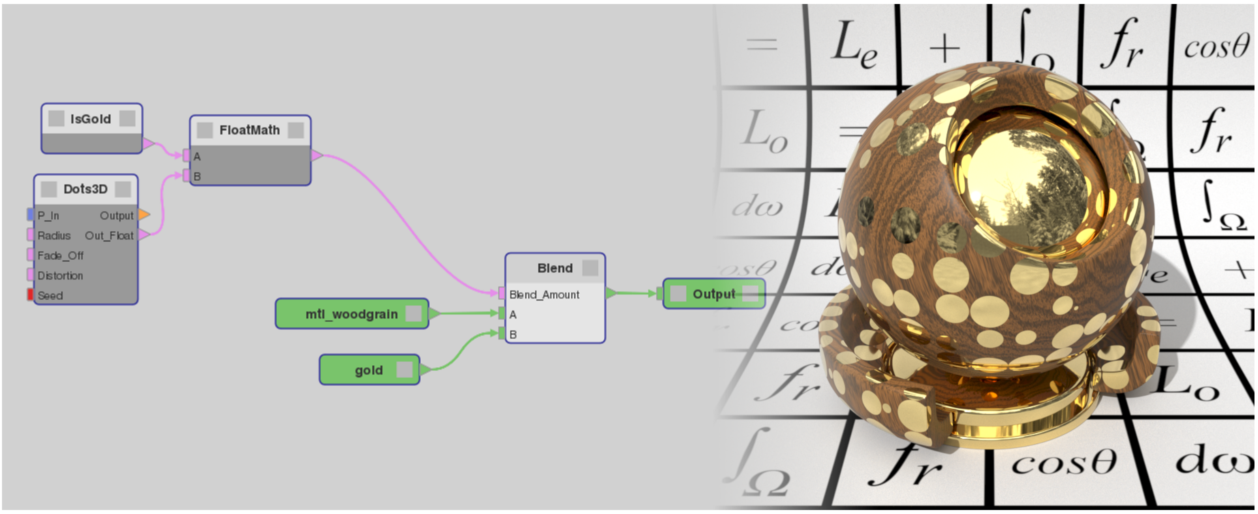
Jonathan Stone, Niklas Harrysson and Iliyan Georgiev

In 2016, Lucasfilm and Autodesk began a collaboration to develop a standard set of physically based shading nodes for MaterialX, along with a framework for converting node graphs into renderable shading code, and these features were integrated into the MaterialX project in 2019. In this talk, we will show how the MaterialX physically based shading nodes can be used to compose layered, artist-facing shading models such as Autodesk Standard Surface and UsdPreviewSurface, and will dive into technical aspects of converting physically based shading graphs into renderable shaders in languages such as OSL and GLSL. The course notes from this talk will describe in detail how to implement the various BRDFs and shader building blocks that are part of this library, both in the context of real-time rendering and offline production rendering.

Jonathan Stone is a Senior Software Engineer in the Lucasfilm Advanced Development Group and the lead developer of MaterialX. He has designed real-time rendering and look-development technology for Lucasfilm since 2010, working on productions including *The Mandalorian*, *Star Wars: The Force Awakens*, and *Pacific Rim*. Previously he led graphics development at Double Fine Productions, where he designed the rendering engines for *Brütal Legend* and *Psychonauts*.

Niklas Harrysson is a Principal Software Engineer working at Autodesk. For the past ten years, his work has been focused around rendering, shading and lighting in Autodesk's M&E products. Prior to joining Autodesk, he worked at Illuminate Labs for eight years, developing ray tracing and light simulation software. His current projects are centered around MaterialX and in particular physically based shader construction and code generation.

Iliyan Georgiev is a researcher and principal software engineer at Autodesk. He holds a PhD degree from Saarland University, Germany, for which he received the Eurographics PhD Thesis Award. His research is focused primarily on Monte Carlo methods for physically based light transport simulation. Iliyan publishes regularly at top-tier scientific journals and conferences, and his work has been incorporated into various production rendering systems.



Putting the Pieces Together: A Physically(ish) Based Approach

Lee Kerley

Real world units, physically based lights, and shading models are just part of the solution. In this talk, we will examine the tools and ideas behind how these elements are presented to the artists at Sony Pictures Imageworks, enabling them to produce physically based (and sometimes non-physically based) production imagery.

We will discuss a powerful and dynamic procedural texturing system built inside of Katana. This, together with a similarly dynamic parameter blending–based material composition system, allows for a wide range of materials to be authored and reused by a small team of artists while working in ever-shrinking production timelines. We will also touch on the potential pitfalls of such a flexible system.

Lee Kerley is the Head of Shading at Sony Pictures Imageworks, where he has worked as part of the shading team for over twelve years. He focuses on the approaches the studio takes towards look development, lighting, shading, and rendering. Most recently, he has been working on user-facing material authoring tools and dynamic material composition in a production environment. While at Imageworks, he has contributed to movies as diverse as *Spider-Man 3*, *The Amazing Spider-Man*, and *Spider-Man: Into the Spider-Verse*.

Physically Based and Scalable Atmospheres in Unreal Engine

Sébastien Hillaire

Rendering a planet's atmosphere requires the simulation of light scattering and shadowing within its constituent elements: molecules, dust and cloud participating media. Rendering all of these complex interactions — especially multiple scattering — is challenging, especially if such effects need to scale from PC to mobile with acceptable performance and quality. Furthermore, previous methods suffered from limitations, such as: restricted to views from the ground; can only represent a single atmosphere type; require computationally expensive update of lookup tables (LUTs) when atmosphere properties are changed; even visual artifacts in some cases.

We present a new physically based method that supports the rendering of views from ground to space, dynamically updated atmospheric properties, and simulation of light multiple scattering in a non-iterative fashion, all while being scalable from high-end PC to mobile hardware. We will present an evaluation of the method's accuracy as well as how it compares to ground truth path-traced results. We also cover cloud rendering in this context, together with some improvements over the state of the art.

Sébastien Hillaire is a Senior Rendering Engineer at Epic Games, focusing on the Unreal Engine renderer. He is pushing visual quality and performance in many areas, such as physically based shading, volumetric simulation and rendering, and visual effects, to name a few. Before joining Epic Games, he worked at Dynamixyz, then Criterion Games and Frostbite at Electronic Arts.

Samurai Shading in *Ghost of Tsushima*

Jasmin Patry

In this talk, we describe some of the physically based shading research performed at Sucker Punch since the release of *Infamous: First Light*. This work was used in the development of the upcoming PlayStation 4 game *Ghost of Tsushima*, an open-world action adventure set in 13th-century feudal Japan.

First, we describe our anisotropic specular material representation, inspired by *The SGGX Microflake Distribution* of Heitz et al. [Hei+15]. This allows us to encode anisotropic GGX roughness with spatially varying orientation in a single compressed texture, supporting hardware filtering and mipmapping. We also show how we use the SGGX representation to prefilter normal and anisotropic roughness maps; this allows us to preserve the appearance of anisotropic normal distributions at varying scales with no additional run-time cost.

We then present a new real-time asperity scattering model that is able to recreate the anisotropic appearance of materials such as crushed velvet. We also describe a simplified version of this BRDF (developed by Eric Wohllaib for use in our deferred renderer), suitable for representing materials such as felt and moss-covered rocks.

Next, we describe an improvement to the well-known *Pre-Integrated Skin Shading* technique by Penner and Borshukov [PB11] via the use of mesh curvature tensors, which better approximate the geometry in the direction of scattering. We also emphasize the importance of using the correct integration method when computing lookup tables for punctual lights and spherical harmonics.

Finally, in extra slides not included in the recorded talk, we present a novel approach for authoring physically based materials at low and high spatial frequencies. The approach we developed takes the idea of traditional "detail maps" and turns it on its head, allowing artists to intuitively author large-scale variation on top of physically based tileable materials, while minimizing run-time memory and shader overhead.

Jasmin Patry is a Lead Rendering Engineer at Sucker Punch Productions, where he has worked on *Infamous 2*, *Infamous Second Son*, *Infamous First Light*, and *Ghost of Tsushima*. Prior to that, he was at Radical Entertainment and contributed to their *Hulk*, *Scarface*, and *Prototype* titles. As a graduate student in the Computer Graphics Lab at the University of Waterloo, he created the popular Linux game *Tux Racer*, which was named "Best Free Software" by PC Magazine and has downloads numbering in the millions. His interests include physically based rendering, scientific computing, and performance optimization — and anything that makes games look better and run faster.

Let's Get Physical: The Hairy History of Shading at MPC

Rob Pieké, Igor Skliar and Will Earl

MPC has been pursuing increasingly physically motivated and grounded approaches to shading and rendering for the last fifteen years. This journey has involved a constant reassessment of pragmatic decision-making based on: the computational power available, the way our artists speak about and interact with shading, and advances by both academia and elsewhere in the industry.

In the early 2000s, MPC was already using image-based lighting to help our CG content integrate more naturally into the filmed content. Environment maps would be decomposed into a set of distant lights, which, when then used to light complex shots (such as the enormous battle shots in 2007's *The Chronicles of Narnia: Prince Caspian*), transformed the role of a Lighter into a data wrangler needing to manage thousands of shadow passes and maps. Bespoke surface shaders with little to no grounding in real-world physics further complicated the life of Lighters who needed to invest heavily in shot-specific look development to ensure not only that individual assets felt believable in isolation, but also in relation to neighbouring assets.

One of our first efforts to reduce this workload was to pursue materials that were energy-conserving, by introducing surface shading based on work by Ashikhmin and Shirley [AS00], complemented with "albedo pump-up" based on work by Neumann et al. [NNS99]. This was complemented by an in-house framework for importance-sampled materials (where the number of reflection/occlusion rays was driven by surface roughness, for example), first used on 2010's *Clash of the Titans*. To reduce the shading cost of indirect hits, we first baked direct illumination to point clouds and used Pixar-provided tools to calculate brick maps with indirect lighting for tracing against.

Not long after this work, Pixar released a framework for physically plausible shaders in RenderMan, and we transitioned to use it. This continued our trend to embrace ray tracing, and started a movement away from bespoke materials and towards more general-purpose ones. These trends surged around 2015 with the release of the RIS path tracing framework in RenderMan. This was the final nail in the coffin for shadow maps, point clouds and brick maps, and we now ray trace all our lighting, direct and indirect. While we initially ported our shader library to the new RIS APIs, we have since largely migrated to using Pixar-provided shaders. This has revived interesting discussions internally about artist experience, whether energy conservation is critical, and how layered materials should be represented.

In the most recent years, MPC has invested significantly in hair and fur shading, initially for *The Lion King* and *Maleficent 2*, but continuing for all the furry shows that have since followed. Inspired by the physical properties of real hair, we have stopped deriving the colour from the outer shell, but instead from volumetric scattering within the core. This has not only given us visually pleasing results such as paler desaturated tips "for free", but also allows us to leverage scientific measurements of the optical properties of different species' fur in real life.

This, of course, raises the pragmatic challenge that the majority of our artists today are not scientists, and it is not intuitive what the visual result of increasing or decreasing a parameter such as "melanin concentration" will be. Further, when the resulting appearance is derived predominantly from indirect or volumetric lighting effects, anticipating the final result is extremely difficult. To that end, we work closely with artists to understand where their language is aligned with physics (e.g., "the IOR of this material is 1.6") and where it's not (e.g., "the fur should be brown"). In the case of the latter, we still strive to be as physically driven as possible within the shading calculations, but provide a user experience that maps artistic intent into our physical parameters. For example, we may provide a texture artist with a familiar colour swatch picker (with colors based on melanin concentrations), which, in the end, bakes absorption coefficient values into a map for the shader.

Looking ahead, we continue to push for more physically accurate (or at least physically motivated) effects in our shading and rendering. We continue to have internal discussions about layered materials, weighing up pros and cons (technical, artistic, etc.) of parameter blending, adding more lobes to existing BxDFs, etc. This discussion influences other discussions about how many different BxDFs we should have (e.g., should there be bespoke materials for glass and/or cloth?). Lastly, with increased confidence in our materials, we're taking an increased interest in how we describe the lights that illuminate our world, and the cameras and sensors that consume this illumination.

Rob Pieké was a Principal Architect at MPC Film. He dabbled in computer graphics programming in BASIC on the PCjr from an early age, and was completely hooked by the visual effects industry after seeing *Jurassic Park* in the cinema. After studying Computer Engineering at the University of Waterloo, Rob led a small VFX R&D team at C.O.R.E. Digital Pictures in Toronto, before moving to London to join MPC for *The Chronicles of Narnia: Prince Caspian*. He has since developed a wide range of technologies used on Hollywood blockbusters, from the *Harry Potter* series to *Guardians of the Galaxy*, *The Jungle Book* and, most recently, *The Lion King*. With a particular skew towards rendering, Rob is always interested in the use and abuse of new technologies, and what "the next big thing" for the visual effects industry might be. He recently joined SideFX as a Senior Software Developer.

Igor Skliar is a Senior Shader Writer at MPC Film. Graduating from the School of Art (majoring in Fine Art) as well as the National Research University of Electronic Technology, he combined his interests in math, physics and fine art, seeking to create the finest materials for the CG industry. Igor has a keen interest in rendering technologies and PBR for real production, developing and supporting the evolution of shaders to be more physically plausible and energy conserving. After joining MPC, his passion in rendering made him a key shader writer for such projects as *The Lion King* (for which he introduced a new fur BxDF), *Maleficent: Mistress of Evil* (for which he extended the BxDF to work efficiently on feathers), *Blade Runner 2049*, *Ghost in the Shell*, *Passengers* and many others.

Will Earl is Head of Optimization at MPC Film, working on improving efficiencies within asset development and production rendering. He has worked for several years at MPC Film as a lighting and look-development lead, most recently on *Pokémon Detective Pikachu* and *Sonic The Hedgehog*. Prior to that, he worked at Aardman Animations as Shot Technical Director and got his start in visual effects at Weta Digital as a Modeller on *King Kong*.

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