Note 1, 2019: This talk was presented at the first Radiance workshop 2002 in Fribourg, Switzerland. It uses the term BRTF (birectional-reflection-transmission-function), the more commonly accepted term is BSDF (bidirectional-scatter-distribution-function), which I adapted later.
Note 2, 2019: The measurements presented here had been measured in 2002 with my old and first gonio-photometer at Fraunhofer ISE. My second design, the PG2 gonio-photometer, had been started outside Fraunhofer ISE in 2004.
Note 3, 2019: These pages have been converted 1:1 to PDF, original URL of this text

On material modelling in Radiance

author: Dr. Peter Apian-Bennewitz, pab-opto

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All in all, Radiance models the every-day experience with light in an efficient and field-tested way. More specific, Radiance calculates light levels by simulating light transport from light emitting surfaces while taking into account other light reflecting surfaces.
This text tries to put modelling of the surface properties in a general context and gives some examples. Physics are described loosely, while avoiding to be incorrect. Check here for a more complete discussion (currently in German).

Physics

Introduction

Electro-magnetic radiation with a wavelength between ~400nm and ~700nm stimulates receptors in the human eye and is called *light*.
Radiance works within the concept of photometry, itself a part of geometrical optics, which is embedded into more general theories (diagram 1). Therefore, it excludes some of the more complex phenomenona: diffraction (e.g. light emitting surfaces and holes cannot be arbitrarily small without diffracting effects), coherence (how holograms work), polarisation (light waves can oscillate in different ways) and non-linear optics (two photons together are more than the sum). Also material properties don’t depend on the incoming radiation energy (e.g. they don’t heat up and re-radiate).

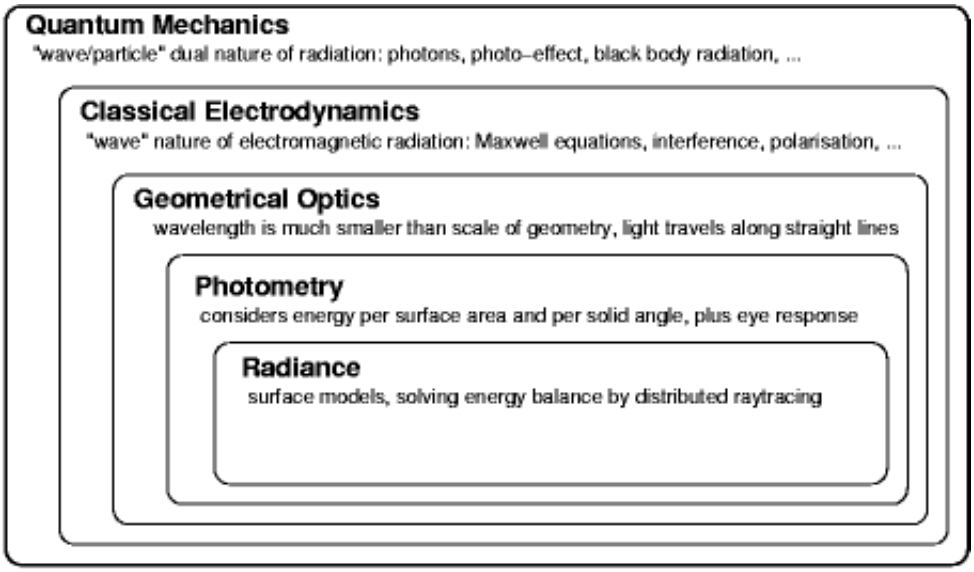

Diagram 1: Radiance within current theoretic frameworks of optics

Units

Most general, the "thing" transported between surfaces by radiation is physically termed *power*, energy per second, it's unit being *Watt*. For radiative transport, the most practical value which is used everywhere is termed *Radiance*: Power per solid angle and emitting/receiving surface area, it's unit being $Watt/sr.m^2$.
If the direction of radiation is of no concern, the sum (more precisely the integral) over all incoming (or outgoing) directions for a receiving/emitting surface element is termed *Irradiance*, $Watt/m^2$.
Wavelength dependency sneaks into the concept since the human eye is not equally sensitive to visible radiation: 1Watt of red light doesn't look as bright as 1Watt of green light. So, for practical reasons, the unit of *Lumen* was defined, as the radiated power at a given wavelength multiplied by the standard human eye response at that wavelength. 1Lumen of red light looks as bright as 1Lumen of green light to the standard human observer. Units which use Lumen are called *photometric*, whereas units using Watt are called *radiometric*. The two most useful photometric units are termed *Luminance*: $Nits=Lumen/sr.m^2$ and *Illuminance*: $Lux=Lumen/m^2$.
Standard Radiance cares for wavelength dependency by computing three channels in parallel, so every constant and input/output value is given as a triple. Typically these three channels are associated with three wavelength intervals vaguely described as *red-green-blue*. The exact wavelength intervals are up the user and have to be known to calculate the triples fed to Radiance as surface properties and for the interpretation of output triples. Internally, Radiance calculates "radiometric" and assumes specific wavelength association of the three channels only at interpretation of the results (e.g. when "falsecolor" or "ximage" are called). This text will ignore any specific wavelength dependency.

BRTF

Power is assumed to travel along straight lines between surfaces, at which the incoming energy interacts with the surface properties and leaves the surface in various directions with various power. The space between surfaces is assumed to be empty, apart from possibly modeled volume scattering, which is not considered here.
The surface properties are completely and generally described by the

Bi-Directional-Reflectance-Transmission-Function (BRTF, also termed BRTD and some other four-letter-acronyms starting with B). Its mathematically sound definition is implicit, the incoming Radiance (symbol: *L*) is folded by the BRTF to give the outgoing Radiance:

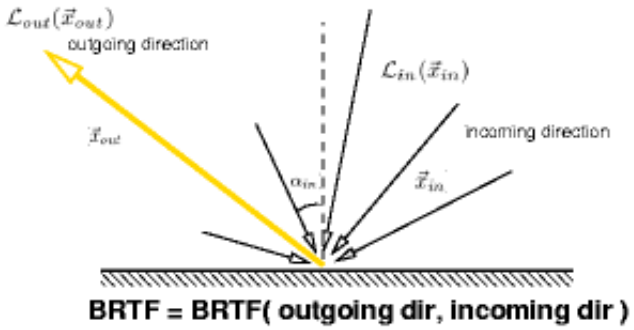

Diagram 2: BRTF parameters

$$\mathcal{L}_{out}(\vec{x}_{out}) = \int_{\vec{x}_{in}}^{\Omega_{in}=4\pi} BRTF(\vec{x}_{out}, \vec{x}_{in})\ \mathcal{L}_{in}(\vec{x}_{in})\ \cos(\alpha_{in})\ d\Omega_{in}$$

Diagram 3: BRTF definition

$L(x_{in})$ and $L(x_{out})$ are the incoming and outgoing Radiance. x_{in} and x_{out} specify the incoming/outgoing directions (given as normalized vectors or two angles). $dOmega_{in}$ is the infinitesimal solid angle for each incoming direction, and the integral extends over the incoming hemisphere (or the full sphere if the BRTF includes both transmission and reflection).
While it seem counter-intuitive at first, this notation is of fundamental usefulness to describe and understand measurements, models and limits thereof.
Note that the BRTF is not limited to [0..1]. In fact any ideal specular surface is described by a Dirac Delta-function, which is zero except for a single point, at which it is infinity.
Energy conservation implies that the integral over all incoming directions of the BRTF must be less than 1 and geometrical optics enforce $max(L_{out}) <= max(L_{in})$.
Truly, the BRTF depends on a fifth parameter, the wavelength. As announced earlier, this text concentrates on the spatial properties of the BRTF and will not explicitly write out any wavelength dependency.

Since the BRTF is not a single number, it is not very well suited to describe materials in brochures, sales documentation and labels. On the other hand, most materials used in architecture have either ideal specular BRTF (incorporating all sorts of coated glass through which the outside can be clearly seen) or a smooth BRTF (Gaussian shaped, non-specular), optionally plus a specular part.
So, for most common materials, it makes sense to boil the BRTF down to a single number per incident direction. In common use are two values: *direct-hemispherical reflection* (rho_{dh}) and *direct-hemispherical transmission* (tau_{dh}). For an incoming direction, the *direct-hemispherical transmission* is the integral of the BRTF over the outgoing hemisphere: (rho_{dh} is defined the same way)

$$\tau_{dh}(\vec{x}_{in}) := \tau(d\Omega_{in}, 2\pi) = \int_{\vec{x}_{out}}^{2\pi} BRTF(\vec{x}_{out}, \vec{x}_{in})\ \cos(\alpha_{out}) d\Omega_{out}$$

Diagram 4: tau_{dh} definition

tau_{dh} and rho_{dh} values are limited to [0..1] .
If not explicitly stated, the values are typically measured for an incident direction normal to the surface (transmission) or for $\text{alpha}_{\text{in}} = 8^{\text{o}}$ (reflection).

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Getting materials into Radiance

Most commonly, material parameters are guessed with minimal assumptions about the physical material properties. Comparing the rendered image with reality and then fine tuning the parameters iteratively works pretty well and is effective if based on experience. But only for a scene with fixed lamps and fixed observer.
To come up with a material model that behaves well for various incident and observer directions proves quite difficult without some help from physics and by using measured BRTF data.

Raw data

To model surfaces, rho_{dh} and tau_{dh} are only useful as first approximation, sine they don't specify what the angular distribution of the reflected/transmitted light is. Sadly, in most cases that's what is solely available from manufactures. Special measurement devices (e.g. pab gonio-photometer) give the full information needed, or more exact, they measure the BRTF of the surface in question averaged over the solid angles of a detector and light source at specific angles x^i_{in}, x^j_{out}.
Gonio-Photometers differ in angular resolution, solid angles of source and detector, dynamic range of the detector and whether they do relative or absolute measurements. Broadly scattering materials are easy to measure, shiny materials with very "peakish" BRTFs are trickier and need higher classes of instrument precision.
Measurements are typically done by adjusting the incident direction and taking measurements for different outgoing angles, than stepping to the next incident direction and repeating the process. Outgoing resolution can be very fine, up to 100000 directions on the hemisphere. The more "peakish" the BRTF, the finer the angular resolution needed to resolve the peaks. The incident directions depend on symmetries of the BRTF and vary typically in steps of $5\text{-}10^o$.
For one incident direction a file with measured BRTF values of the above mentioned ISE-FhG gonio-photometer looks rather trivial:

```
#using beam file: pab-aluA-st1:beam.mpc.refint 0.063626
#measurements done at Fraunhofer Institute for Solar Energy Systems, FhG-ISE
#contact tmess@ise.fhg.de for details
#...
#small beam, no-lense detector
#input aperture used: def
#detector aperture used: def
#incident angle theta [degree]:
30
#incident angle phi [degree]:
#0
#backgrounds: left side lamp on/off, right side lamp on/off, [uA]
#background2: 2.73701e-06 2.57384e-06
#theta phi beam-ref org-data minus-background/beam-ref cosine-out-corrected brtf voronoi-cell-size
95.5176 119.535 9.9e+37 5.14761e-06 -1.60952e-05 -0.000167394 -0.00263091 0.0351119
95.526 240.467 9.9e+37 1.96535e-06 -1.92775e-05 -0.000200187 -0.0031463 0.0351942
96.2589 235.494 9.9e+37 2.20671e-06 -1.90361e-05 -0.000174609 -0.0027443 0.0110056
96.2645 124.505 9.9e+37 5.79507e-06 -1.54477e-05 -0.000141569 -0.00222501 0.0110376
96.9904 230.514 9.9e+37 2.04376e-06 -1.91991e-05 -0.000157753 -0.00247938 0.0119793
97.0222 129.481 9.9e+37 0.000205099 0.000183856 0.00150389 0.0236364 0.0120372
...
```

with the outgoing direction given as theta_{out}, phi_{out} in column 1 and 2 and the absolute BRTF in column 7.

Directly using raw measured data in Radiance (e.g. as *brightdata*) is not advisable for two reasons: raw data files are large and more important, they don't provide a sound way to interpolate between directions: Interpolation for x_{out} is typically done by indexing into an array and works only for data values on a regular x_{out} grid, which is either very coarse or even larger than the original measured data. [1] Interpolation for x_{in} is even harder: The shape of the BRTF for an x_{in} given e.g. as (theta_{in}, phi_{in})=(45,0) is only the average of the BRTF measured at (40,0) and (50,0), if the BRTF is totally flat and the material is ideal diffuse. For all other materials, the BRTF shape changes, typically its maximum in x_{out} moves with x_{in}, and the interpolation would have to be done in a much smarter way. By the way, the same problem holds for all compression techniques of the BRTF in x_{out} using a non-physical motivated, general method, e.g. spherical harmonics or wavelets.

Fitting of BRTF models

The idea described in 1995 by the author is quite simple and works in two steps: First a reasonably decent model of the BRTF and its dependency on incoming and outgoing directions is fitted with a minimum of parameters to the measured BRTF in x_{out}, while x_{in} is kept constant. This works for data measured on a regular grid or on an adaptive one, and results in some (approx 2-6) parameters for each x_{in}. For consecutive x_{in}, e.g. (theta_{in},phi_{in})=(40,0),(50,0),(55,0) , these parameters should be well behaved and depend smoothly on variations in theta_{in}, phi_{in} . Interpolation between x_{in} is thereby solved. Obviously, this depends on a good choice of the "reasonably decent model" in the first place. This choice is not easily automated for new classes of materials with different BRTF types, which is the main drawback of this idea.

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[1] Radiance could, in theory, use the indexing function of *brightdata* to generate an index with a higher angular resolution in specific regions of the hemisphere, but I don't see a decent reason someone wants to take the hassle of synchronizing the mapping function and the data values in a general and automatic way, especially because the next problem is much trickier and important anyway.

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Note 1, 2011: The text was written in 2002, meanwhile (2011) a BRTF,BSDF database is available at: http://www.pab.eu/bme/
Note 2, 2019: Cosmetic overhauled in August 2019: The old server-parsed-html constructs for the data files had been phased out on my server long ago. The text uses the term BRTF (bidirectional-reflection-transmission-function), the more uniformly accepted term is BSDF (bidirectional-scatter-distribution-function), which I conformed to later.
Note 3, 2019: The measurements presented here had been measured in 2002 with my old and first gonio-photometer at Fraunhofer ISE. My second design, the PG2 gonio-photometer, had been started, outside Fraunhofer ISE, then in 2004.
Note 4, 2019: If you read this as PDF, the old data files and images are still available.

Examples

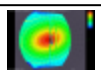
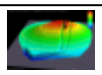
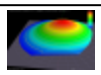
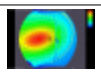
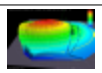
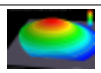
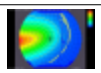
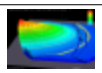
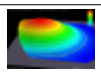
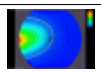
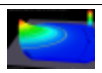
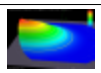
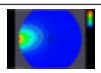
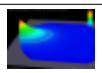
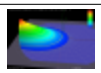
The classical *metal* model of Radiance was fitted to the BRTF data using standard Levenberg-Marqwardt fitting methods. Gray reflectance (R=G=B for the first three parameters of the model) was assumed. Light source was a XBO short arc lamp.
The incident angle theta_{in}, phi_{in} is encoded into the file name. For `pab-xenon-aluA-st1:+15+0.mpc`: $\text{theta}_{in}=15^{o}$, $\text{phi}_{in}=0^{o}$.
The following tables give the measured BRTF, their visualization, the parameters *RGB*, *specularity* and *roughness*, and the error (sum of weighted, squared difference between model and data at measured positions).
Visualizations were done using *mountain*, a custom written program for displaying BRTF measurements done by the above mentioned gonio-photometer. The BRTF of a perfectly diffuse material would show as flat surface. For high values, the measurements are done at finer angular resolution (see my Phd for a discussion on measurement technique). The small gaps in the data are due to self shadowing of the ISE-FhG gonio-photometer.

Aluminium sheet, *metal* model

photo of pab-xenon-aluA-elox1-b								
data file	**visualization**		**Radiance *metal* model**					
	orthogonal	oblique	RGB,spec,rough fit				visualization	
			R,G,B	spec.	rough.	error	model	difference
raw/pab-xenon-aluA-elox1-b:+0+0.mpc			0.891	0.657	0.13	3.6e+03		
raw/pab-xenon-aluA-elox1-b:+15+0.mpc			0.877	0.606	0.142	3.5e+02		
raw/pab-xenon-aluA-elox1-b:+30+0.mpc			0.878	0.665	0.17	1.7e+02		
raw/pab-xenon-aluA-elox1-b:+45+0.mpc			0.893	0.73	0.195	1.4e+02		
raw/pab-xenon-aluA-elox1-b:+60+0.mpc			0.878	0.853	0.192	8.9e+02		

Sand blasted aluminium sheet, *metal* model

Aluminium sheet blasted with small glass spheres. More isotropic than raw aluminium sheet, but still showing asymmetric scattering

photo of pab-xenon-aluA-st1-b								
data file	**visualization**		**Radiance *metal* model**					
	orthogonal	oblique	RGB,spec,rough fit				visualization	
			R,G,B	spec.	rough.	error	model	difference
raw/pab-xenon-aluA-st1-b:+0+0.mpc			0.624	0.706	0.437	20		
raw/pab-xenon-aluA-st1-b:+15+0.mpc			0.857	1	0.497	2.8		
raw/pab-xenon-aluA-st1-b:+30+0.mpc			0.937	0.981	0.479	6.7		
raw/pab-xenon-aluA-st1-b:+45+0.mpc			1.06	0.999	0.45	21		
raw/pab-xenon-aluA-st1-b:+60+0.mpc			1.46	1.15	0.436	2e+02		

work-in-progress. Please bear with us while the rest is under construction. Thanks

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