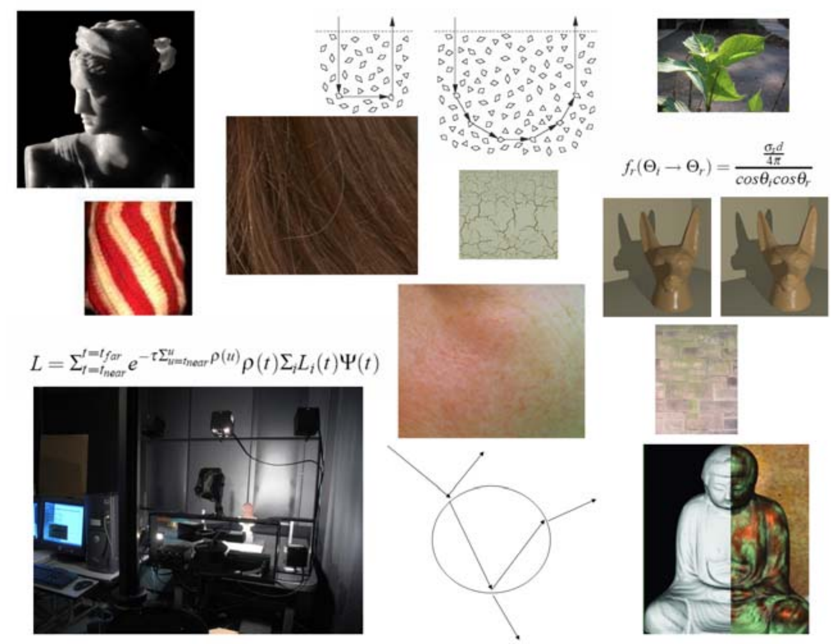
SIGGRAPH 2009 Course

Advanced Material Appearance Modeling



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Course Description

For many years appearance models in computer graphics focused on general models for reflectance functions coupled with texture maps. Recently it has been recognized that even very common materials such as hair, skin, fabric, and rusting metal require more sophisticated models to appear realistic. We will begin by briefly reviewing basic reflectance models and the use of texture maps. We then describe common themes in advanced material models that include combining the effects of layers, groups of particles and/or fibers. We will survey the detailed models necessary needed to model materials such as skin (including pigmentation, pores, subsurface scattering), plants (including internal structure) and automotive paints (including color flop and sparkle). We will then treat the modeling of complex appearance due to aging and weathering processes. A general taxonomy of effects will be presented, as well as methods to simulate and to capture these effects. We close with a summary of current trends in material appearance research and a discussion of existing and needed resources.

Prerequisites

Knowledge of basic rendering and reflectance functions.

Syllabus/Approximate Schedule

Introduction: 15 min.
Background: 50 min.
Specialized Material Models:
- Common Themes: 20 min
- Natural Materials: 30 min.
- Manufactured/Processed Materials: 25 min.

Aging and Weathering Processes:
- Taxonomy: 10 min.
- Simulation: 20 min.
- Capture Approaches: 15 min.

Current Trends and Needs 40 min.

Speakers

Julie Dorsey is a Professor of Computer Science at Yale University, where she teaches computer graphics. She came to Yale in 2002 from MIT, where she held tenured appointments in both the Department of Electrical Engineering and Computer Science (EECS) and the School of Architecture. She received undergraduate degrees in Architecture and graduate degrees in Computer Science from Cornell University.

With architecture as a driving application, she has studied a wide range of problems in computer graphics, including sketch-based interfaces for early conceptual design, acceleration methods for real-time rendering, and the creation of detailed photorealistic renderings. Her contributions also include algorithms for lighting and acoustical design and visualization. She is particularly well known for her research in modeling the appearance of materials -- for example, she pioneered techniques to model the visual richness of irregular metal patinas and eroded stone. Her current research interests include photorealistic image synthesis, material and texture models, illustration techniques, and interactive visualization of complex scenes, with an application to urban environments.

In addition to serving on numerous conference program committees, she has served as an associate editor for *IEEE Transactions on Visualization and Computer Graphics* and The *Visual Computer*, and was Papers Chair for ACM SIGGRAPH 2006. She has received several professional awards, including MIT's Edgerton Faculty Achievement Award, a National Science Foundation CAREER Award, and an Alfred P. Sloan Foundation Research Fellowship.

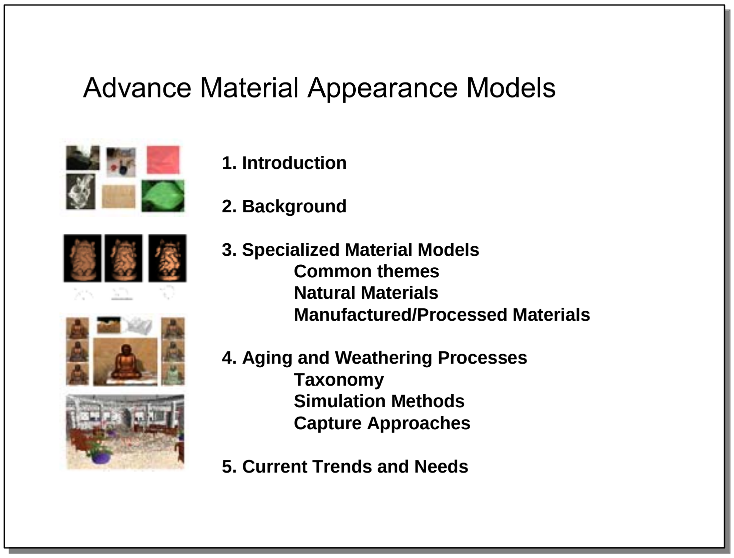
Holly Rushmeier received the BS, MS and PhD degrees in Mechanical Engineering from Cornell University in 1977, 1986 and 1988 respectively. Between receiving the BS and returning to graduate school in 1983 she worked as an engineer at the Boeing Commercial Airplane Company and at Washington Natural Gas Company (now a part of Puget Sound Energy). In 1988 she joined the Mechanical Engineering faculty at Georgia Tech. While there she conducted sponsored research in the area of computer graphics image synthesis and taught classes heat transfer and numerical methods at both the undergraduate and graduate levels. At the end of 1991 Dr. Rushmeier joined the computing and mathematics staff of the National

Institute of Standards and Technology, focusing on scientific data visualization.

From 1996 to early 2004 Dr. Rushmeier was a research staff member at the IBM T.J. Watson Research Center. At IBM she worked on a variety of data visualization problems in applications ranging from engineering to finance. She also worked in the area of acquisition of data required for generating realistic computer graphics models, including a project to create a digital model of Michelangelo's Florence Pieta, and the development of a scanning system to capture shape and appearance data for presenting Egyptian cultural artifacts on the World Wide Web.

Dr. Rushmeier was Editor-in-Chief of *ACM Transactions on Graphics* from 1996-99. She has also served on the editorial board of *IEEE Transactions on Visualization and Computer Graphics*. She is currently on the editorial boards of *Computer Graphics Forum*, *IEEE Computer Graphics and Applications, ACM Journal of Computing and Cultural Heritage* and *ACM Transactions on Applied Perception*. In 1996 she served as the papers chair for the ACM SIGGRAPH conference, in 1998, 2004 and 2005 as the papers co-chair for the IEEE Visualization conference and in 2000 as the papers co-chair for the Eurographics Rendering Workshop. She has also served in numerous program committees including multiple years on the committees for SIGGRAPH, IEEE Visualization, Eurographics, Eurographics Rendering Workshop, and Graphics Interface.

Additional information The speakers are (along with François Sillion) the authors of *Digital Modeling of Material Appearance* published by Morgan Kaufmann/Elsevier. Further information about the speakers can be found at http://graphics.cs.yale.edu/

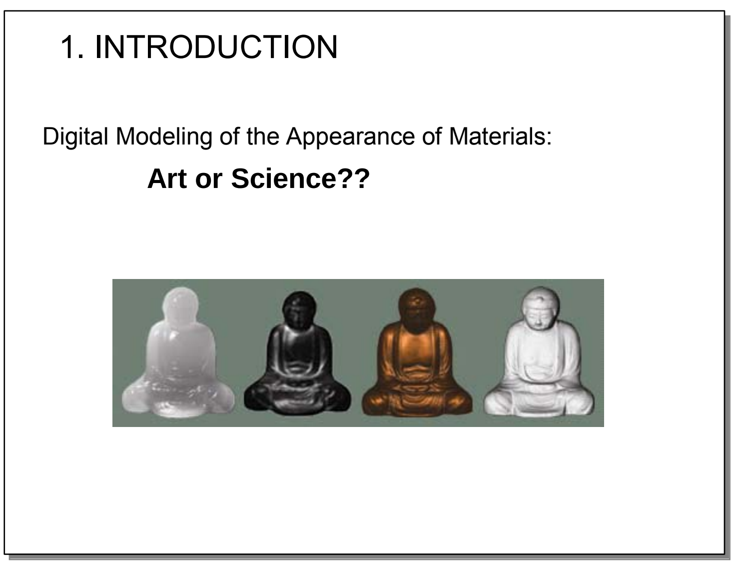


In these course notes we present principles of defining numerical models to be used in rendering realistic imagery of physical materials. Additional information can be found at http://graphics.cs.yale.edu/. The in person presentation of this course varies from these notes in the interest of timeliness, and considering the fact that "fair use" materials can not be posted for distribution to non-course attendees.

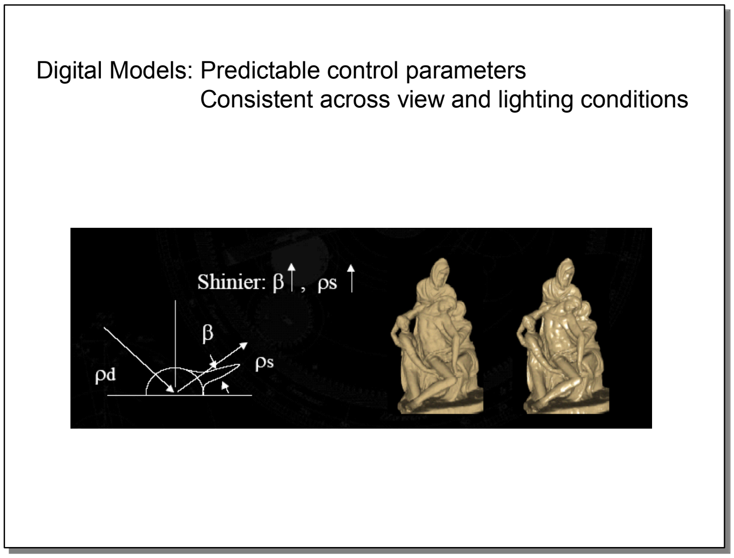
These notes are a revised version of the notes for the SIGGRAPH 2008 class on Advanced Material Appearance Models.

These notes also draw on the text:

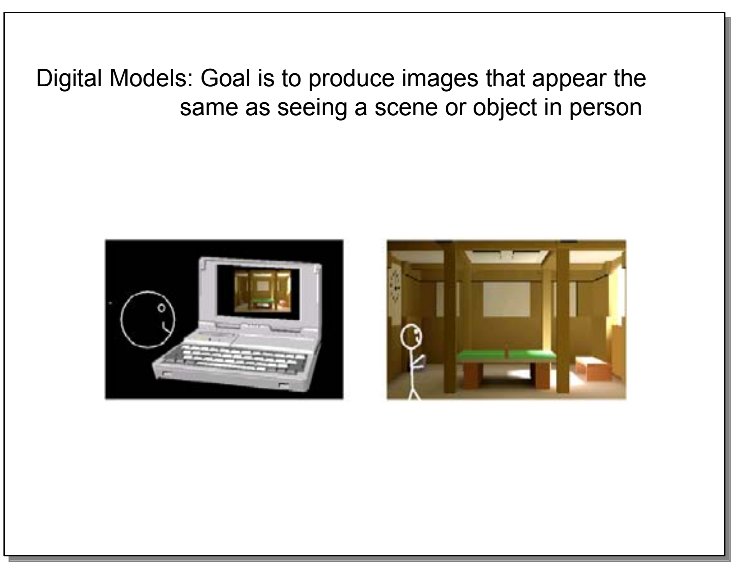
"Digital Modeling of Material Appearance" (Morgan-Kaufmann/Elsevier.)



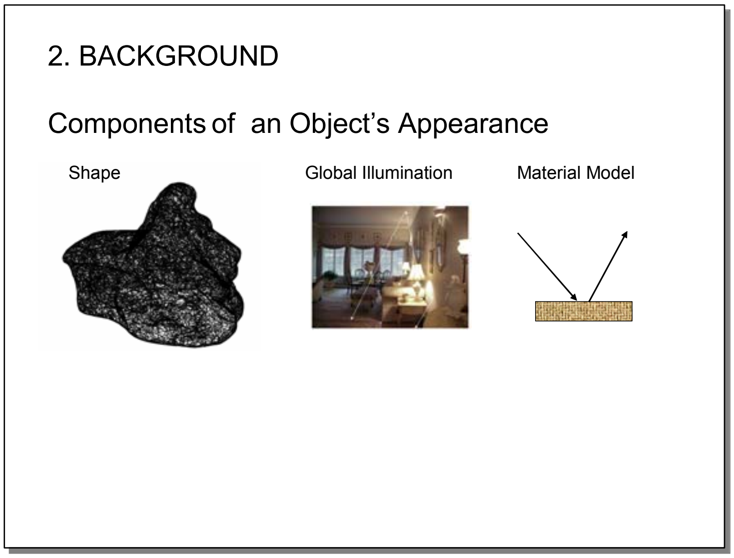
The materials here are rendered with models. An artist conceived the shape. A purely artistic approach could be used to digitally paint the shades of light and dark on the digital shapes to give the illusion of translucent stone or copper metal. However, to generate these images material models are expressed numerically and rendered using lighting simulations. That is their appearance – the colors, shades of light and dark, were computed, rather than being digitally painted on the model.



We define a model as taking a physically measurable input and producing a predictive output that can be verified by physical measurement. A model of a material makes possible the reliable rendering of the appearance of that material in any geometric and lighting conditions. An artistic technique as takes an input which is not necessarily measurable, and produces an output that may or may not reproduce the appearance of an object under arbitrary circumstances. Human judgment is required to use an artistic technique, and to evaluate its success.

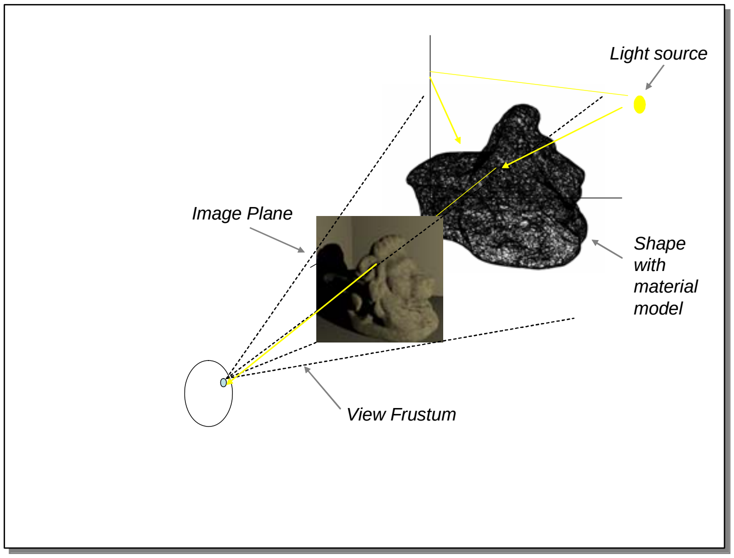


Our goal is to make predictive images that give a view of a scene or object that is the same as if the person were viewing it directly. Material modeling is one aspect of this. We need to consider the object's shape, and the light incident on it.

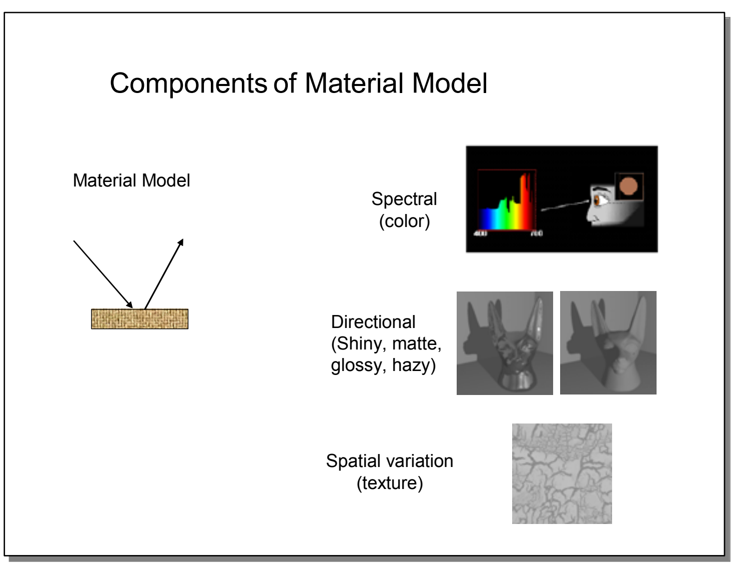


Shape is the large scale form or geometry of the object. The shape is needed to place the image of the object correctly with respect to other objects in the scene, to determine which other objects are occluded by the object, and what areas are cast into shadow by the object. Fine scale geometric variations in the object we define as part of the object's material from the point of view of creating digital models in computer graphics. For a close view of a tree branch, a leaf is defined by a flat shape, with the number of lobes or points depending on the type of tree. In an aerial photograph, a leaf is a small facet in a tree canopy material that covers the terrain. Many methods can be used to represent shape. The area of computer-aided geometry is devoted to the study of shape representation, and extensive descriptions of representations such as NURBs (non-uniformrational B-splines), triangle meshes, subdivision surfaces and implicit surface are documented at length in references such as **Farin *Curves and Surfaces for Computer-Aided Geometric Design: A Practical Code*. Academic Press, Inc., 1996.**

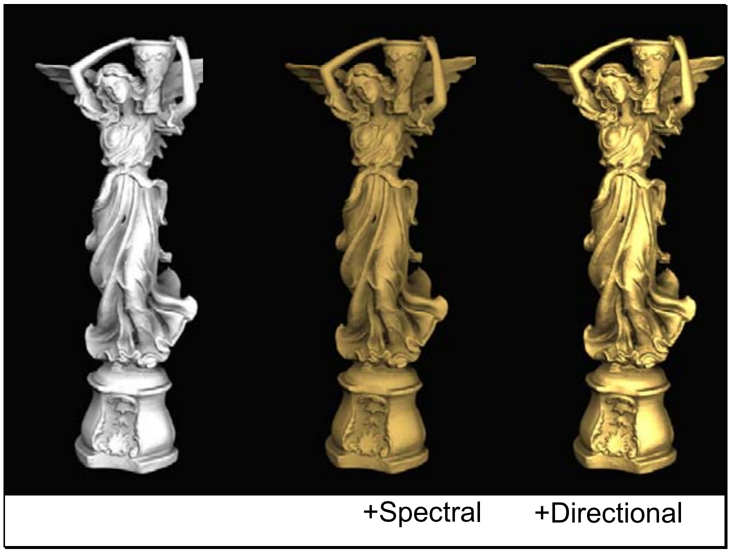
Many methods can be used to compute the interreflections of light between objects in an environment. These methods, referred to as "global illumination" methods, include ray tracing, radiosity, photon mapping and hybrids of these various approaches. Thorough discussions of these methods can be found in **Dutre, Bekaert and Bala, *Advanced Global Illumination*. AK Peters Limited, Wellesley, MA, 2003.** For rendering appearance, the essential feature of a global illumination method is that for a given ray direction the quantity of light from that direction at a particular point can be efficiently computed.



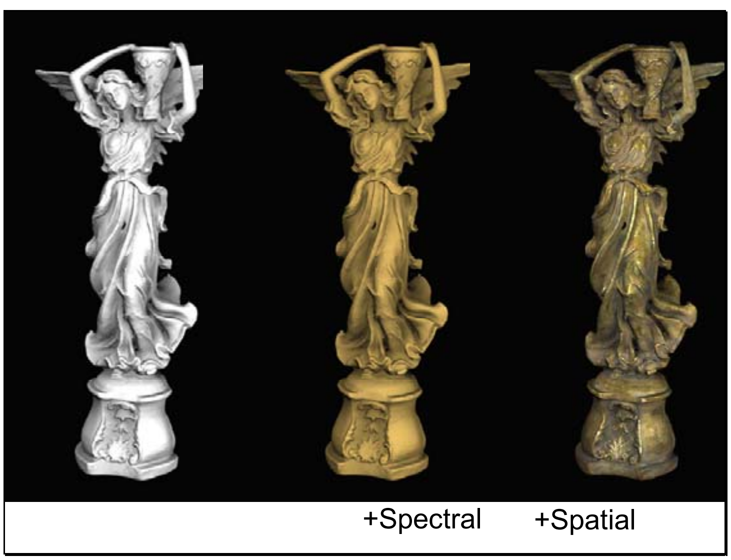
An environment consists of a set of objects, each defined by a shape and material description, and at least one light source. An infinite number of images could be created of such an environment, and to specify a particular image a viewpoint, view direction and view frustum (i.e. field of view) need to be specified. The image is formed by projecting the objects in the environment seen through the frustum onto an image plane that spans the field of view and is perpendicular to the view direction. In a digital image, the image is discretized into pixels, and the display values for that pixel are set by determining the light that would arrive at the viewer from the object visible through that pixel.



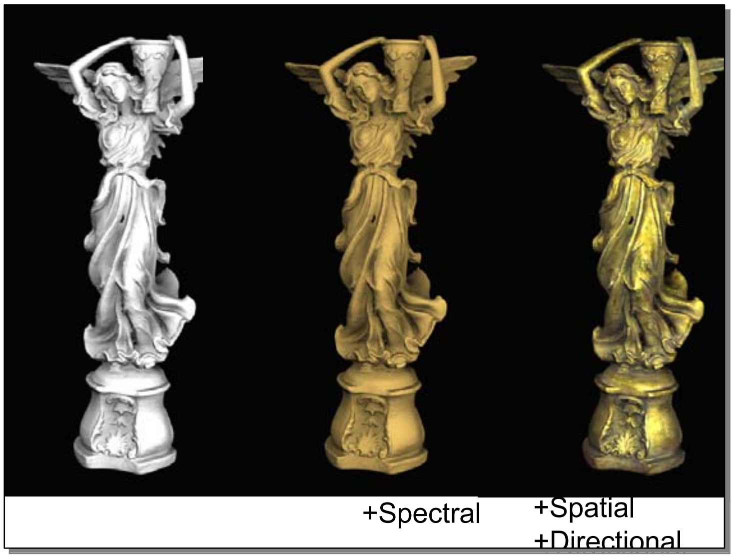
There are three important components of a material model that allow us to recognize a material – spectral, directional and spatial. We notice the color of an object (resulting from the spectral composition of light), its directionality (hazy, glossy, shiny,) and small spatial variations (textures formed by light and dark, or little bumps.)



Example of introducing spectral and directional variations

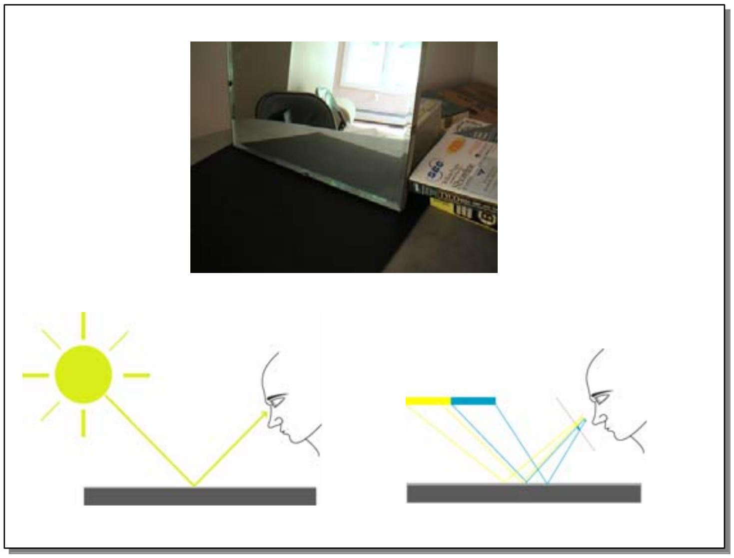


Introducing spatial variations

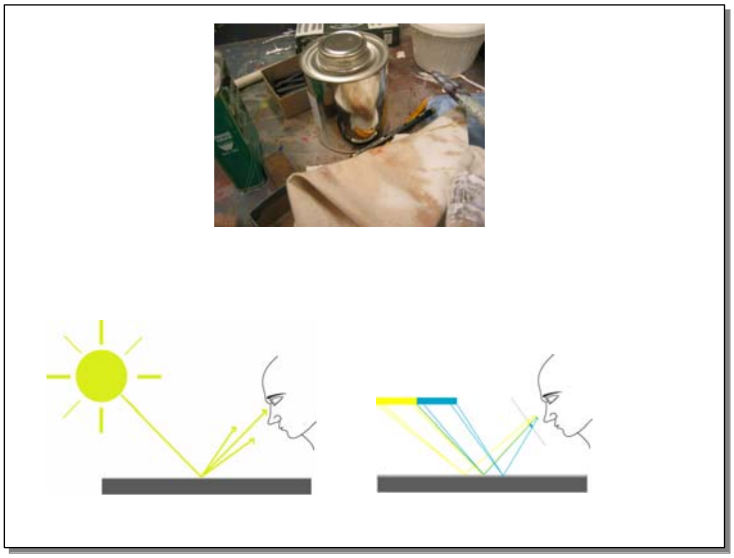


Spatially varying spectral and directional variations to make this look like a worn,dirty metallic object.

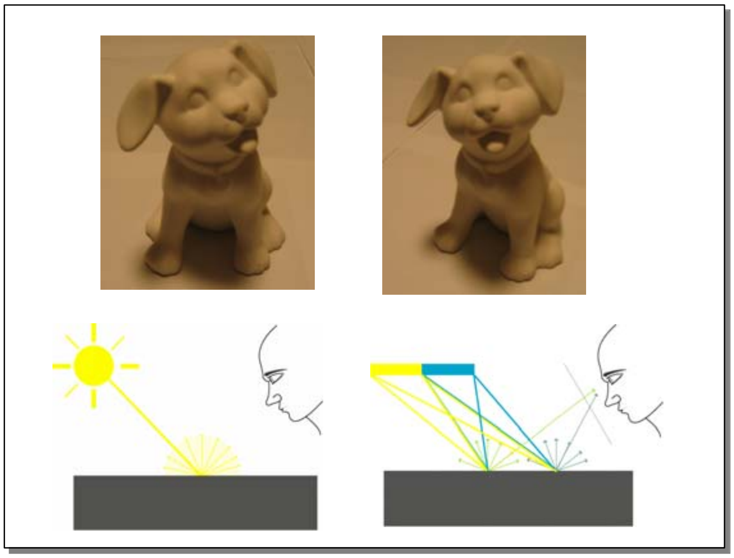
Examples of directionality beyond directional reflectance



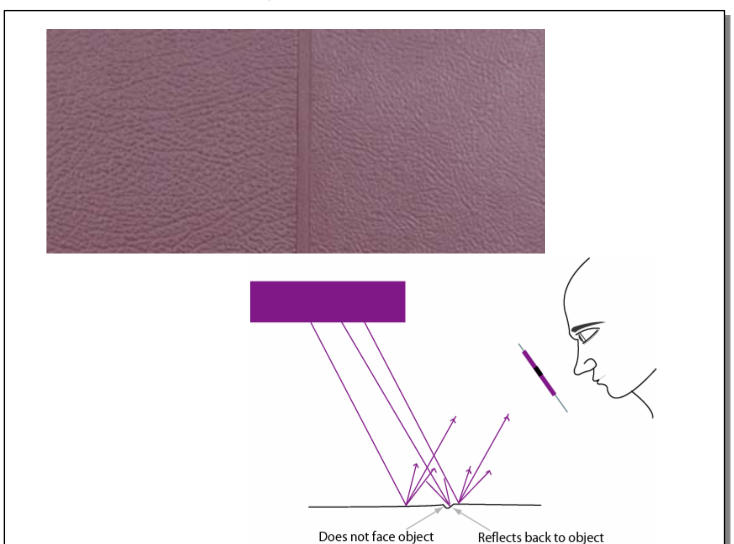
The most familiar and basic light scattering is regular or "mirror-like" reflection, as shown in the photo at the top. Light rays reflect into one single direction, and that direction forms the same angle to the surface normal as the incident direction, as shown on the lower left. Because the reflected rays stay organized as they were when they left the previous objects, a sharp image is formed just as though you were looking directly at the objects. This regular, or mirror-like reflection is referred to as pure or ideal specular reflection.



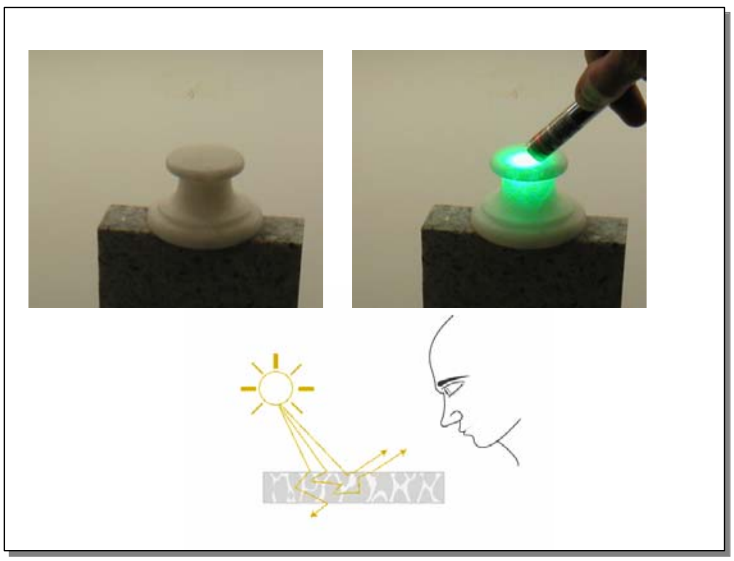
Many materials are shiny or glossy, but not purely specular. In these materials, incident beams of light are distributed into a cone or lobe of directions centered around the specular, or mirror direction. The result of this is when you are looking at such materials the light reflected from each point of the surface includes light from an a range of surfaces in the environment, instead of just reflecting one point. Instead of seeing sharp edges reflected, everything looks blurred. By observing the reflections in the paint can in the image, you can see that how blurred things look depends on how close the objects being reflected are to the glossy surface. If they are relatively close, the cross section of the cone from which a point is reflecting light is relatively small, and lines like that between the yellow and blue surfaces above are only blurred a bit. As the objects get further away, the cross section of the cone becomes large, and can include entire objects which then do not appear with any detail when reflected in the glossy surface.



Objects that appear to have the same pattern of light and dark regardless of how you view them (as long as you don't block a significant source of light from the environment as you move to another view) are diffuse. An ideal diffuse (also referred to as Lambertian) object reflects an incident beam of light as light rays of much lower magnitude in all directions. The light coming from any point on the object in any direction is a product of light coming from many different sources in the environment. The contribution of each source in the environment varies very slowly from point to point on the object, so the amount of light varies slowly from point to point, and there no clear images of the environment can be seen in the object.



In addition to the reflectance that depends on material microstructure and chemical composition, the appearance depends on small scale geometric structure. Just as some materials are characterized primarily by the spatial variations in reflectance, other materials are characterized primarily by their small scale geometric structure. “Small” is defined as orders of magnitude smaller than the overall object. The image above shows a piece of plastic with a pattern pressed into it that changes the surface from smooth to bumpy. The small scale geometric structure shown here is characteristic of leather material, and this fact is used in the production of physical materials to make a plastic look like leather. The variation of light and dark in the image of the plastic is not due to spatial changes in reflectance, but to the change of surface orientation caused by the small scale geometry. Even small indentations can cause large changes in the surface normal. The surface normal, rather than the absolute surface position, determines in which direction incident light will be reflected.



Some materials don’t just reflect light from the surface, or just transmit the light. In some cases light penetrates the material and scatters in the interior. This is referred to as subsurface scattering, and can occur in dielectrics, not metals. Under normal room illumination, surfaces which allow subsurface scattering often do not look dramatically different from completely opaque surfaces. The image on the right though shows an extreme example of illumination. A green laser is directed at the top of a small piece of stone. Besides being reflected from the top, the light is scattered in the material and is visible emerging from the sides of the stone.

Terminology and Mathematical Descriptions

Key quantities:

Radiance *L*

Bidirectional Reflectance Distribution Function (BRDF) f_r :

An explanation of the mathematics of light transport isn't possible in a brief lecture. However, a couple of key points are:

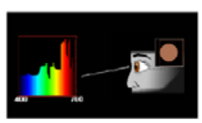
-- a lot of the notation in light transport is just denoting that quantities vary with color (spectral dependance λ), direction (given by angles θ and ϕ) and position (x,y)

-- there are two quantities that are key, but which take some getting used to . One is the quantity of light we want to compute, the radiance L. The other is the function telling how a surface scatters light, the BRDF fr.

Components of Material Model

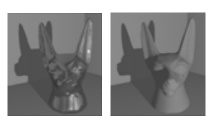
λ: wavelength dependence

Spectral (color)



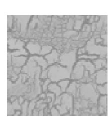
θ,ϕ : direction

Directional (Shiny, matte, glossy, hazy)



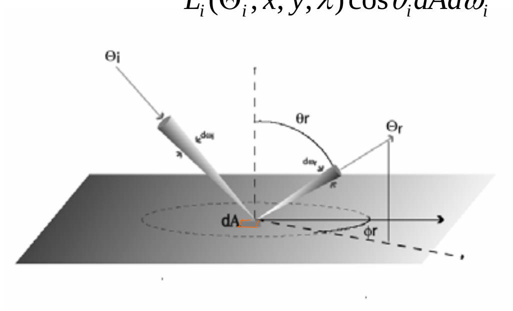
x,y: position

Spatial variation (texture)



Bidirectional reflectance distribution function, BRDF

$$f_r(\Theta_i, \Theta_r, x, y, \lambda) = \frac{d^2 L_r(\Theta_r, x, y, \lambda)}{L_i(\Theta_i, x, y, \lambda)\cos\theta_i dA d\omega_i}$$

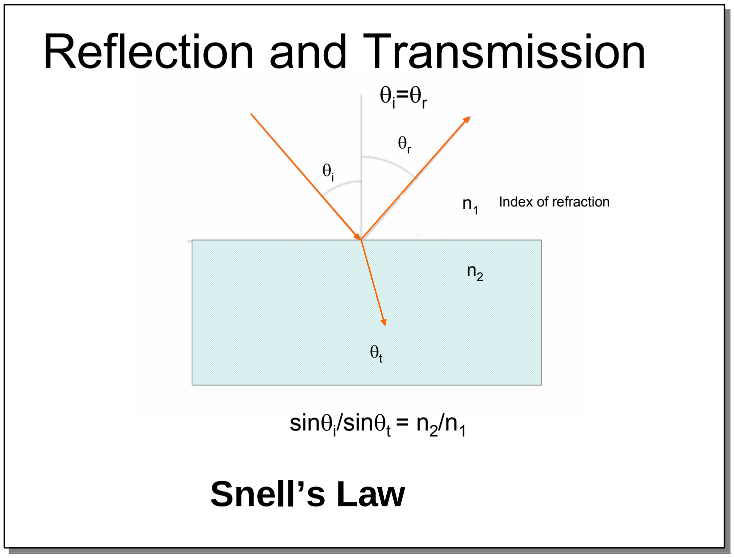


The key quantity we use to define how a surface redirects light is the BRDF, which relates incident and reflected radiance for two given directions. The BRDF is a distribution function, not a fraction from zero to one. It can take on values from zero to infinity. To conserve energy, the integral of the BRDF over all reflected directions must be less then or equal to one.

Reflectance Models

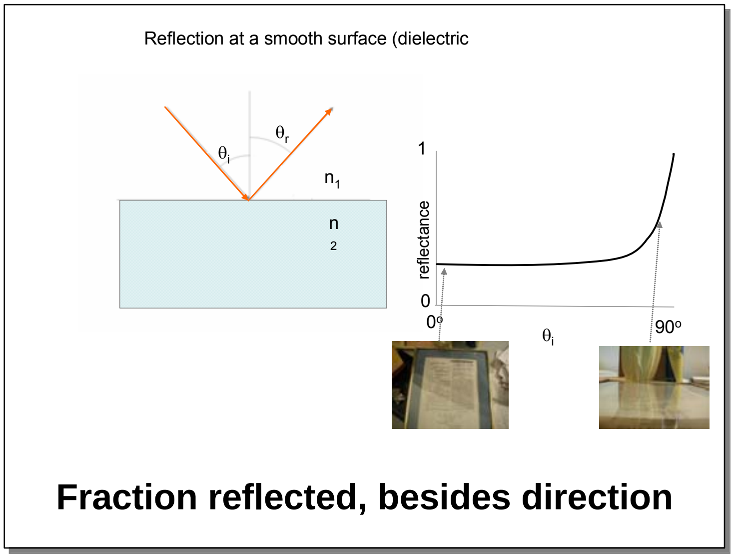
- Smooth Surfaces
  - Fresnel Equations
- Empirical
  - Lambertian, Phong, Ward, Lafortune, Ashikhmin-Shirley
- First Principles
  - Blinn, Cook-Torrance, Oren-Nayar
- Wave Optics
  - He-Torrance

Many common reflectance models are named, generally after the people who developed the models. NOTE: There are no compliance standards for claiming that a “named” model is being used, so you can’t be absolutely sure that giving the same parameters to a particular model in one software package will produce the same results in another package.

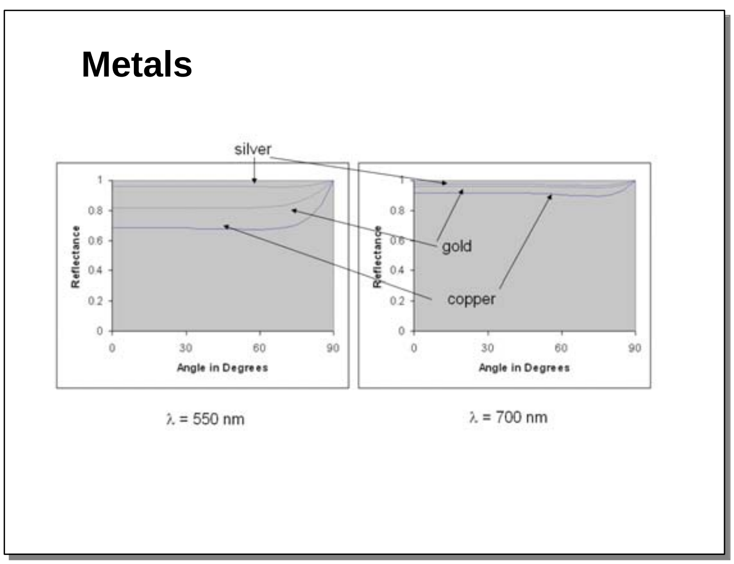


The directionality of transmission from a smooth surface is a bit more complicated that reflection. First, most metals have a high tendency to absorb electromagnetic energy, so transmission of visible light is not observed. For dielectrics, the change in the speed of light in the material causes a change in the direction. This change in direction is called refraction, and is expressed by Snell's Law as shown above. Unlike the direction of reflection, the direction of refraction depends on the properties of the materials.

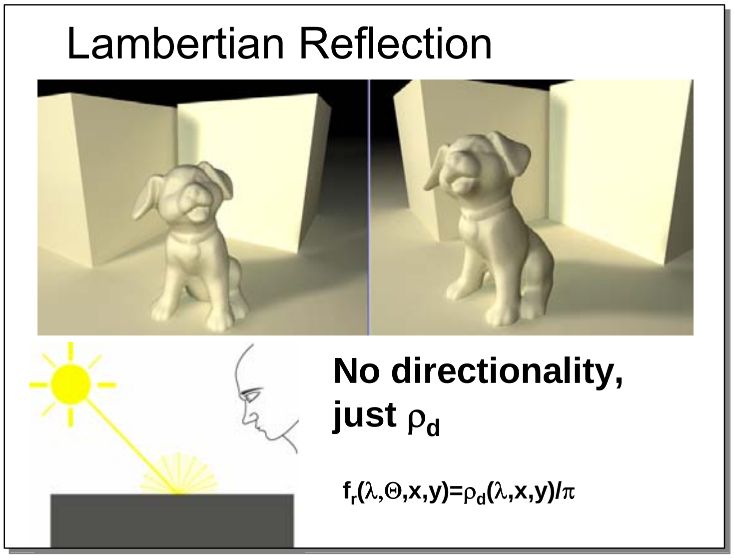
Since light is electromagnetic energy, its interaction is governed by the properties that quantify the material's interaction with electric and magnetic fields. In the solution to Maxwell's equations these properties are expressed as the index of refraction *n* and a coefficient that captures the tendency to absorb electomagnetic waves k . The value of *n* is the ratio of the speed of light in a vacuum to the speed of light in the material. The value of k is zero for dielectrics, which do not conduct electricity, and greater than zero for metals, which do. Values of k and *n* are found by measurement and can be looked up in handbooks or online resources. Generally understanding and applying the results of the smooth surface solution requires only knowing some rough estimates of typical values of these constants for common materials.



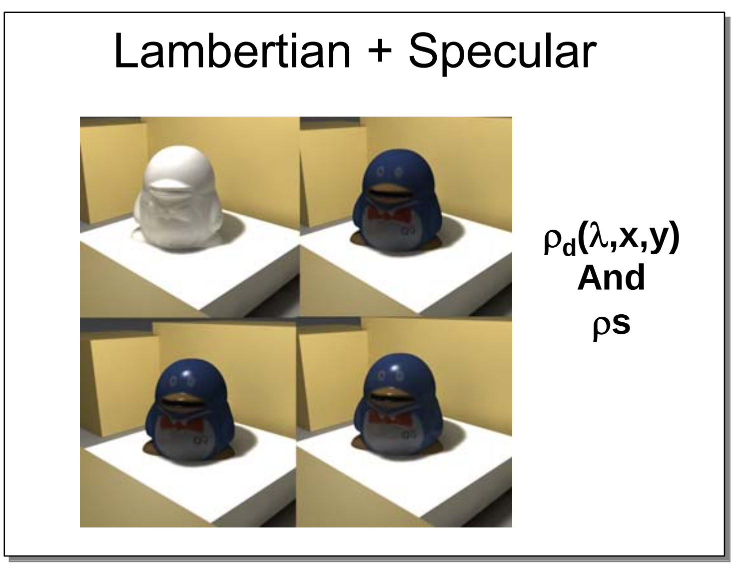
In addition to giving directionality, the fraction of light reflected can also be calculated from the solution of Maxwell's equations, and the results are referred to as the Fresnel equations. For a dielectric, the light that is not reflected from the surface is transmitted. For a metal, the light that is not reflected is absorbed. The Fresnel equations give complicated algebraic expressions for reflectance, but only straightforward number crunching is needed to evaluate given values of θ , *n* and k .



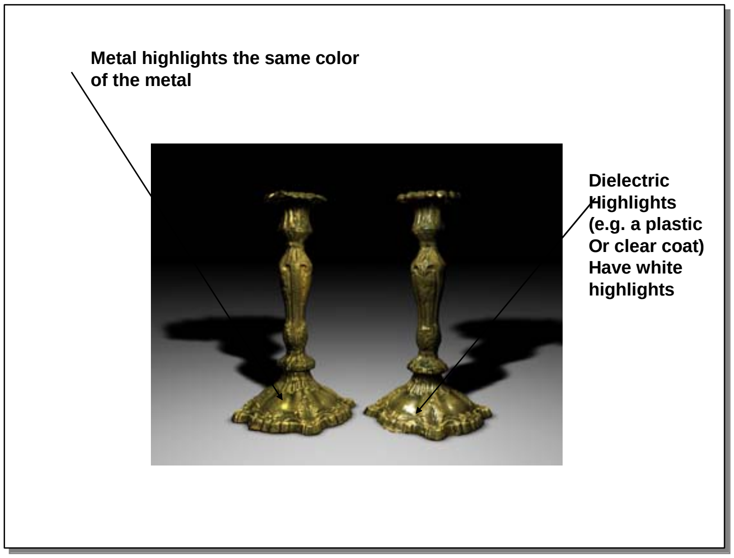
Since metals have a high reflectance for all angles, the Fresnel effect is less pronounced. Although it is rarely included in visual simulations, metals all tend to look white or gray at grazing angles.



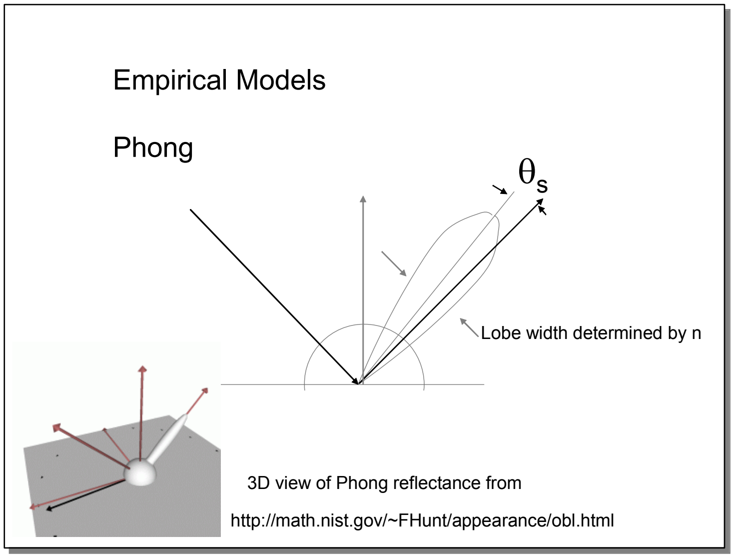
Lambertian, or "ideal diffuse" reflectance is in a sense the opposite of specular reflection. Instead of all light being reflected in a single direction, it is reflected in all directions with the same radiance. Unlike specular reflection, this is not the result of solving Maxwell's equations for some particular surface configuration. It is an approximation of the observed behavior of many materials. While real materials usually deviate from Lambertian for angles of view or incidence greater than 60 degrees, the Lambertian model is used for its computational simplicity. For measurement purposes, some materials have been designed that are very close to being to Lambertian, such as Spectralon® from Labsphere Inc.



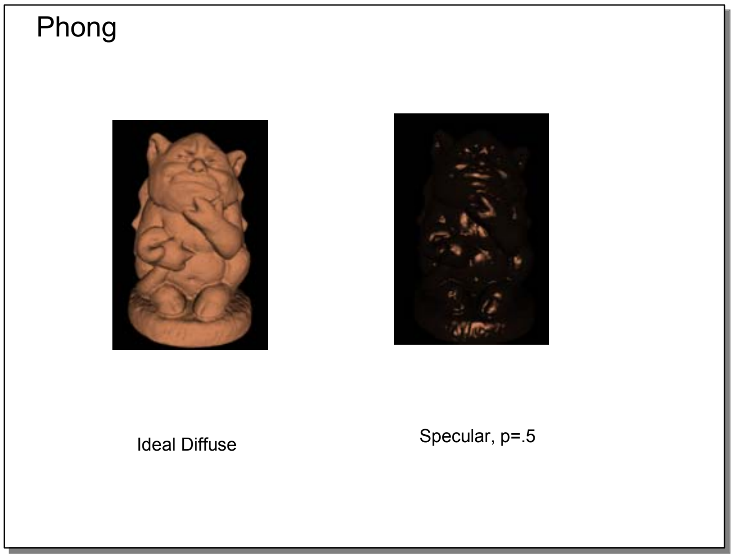
Materials can be modeled as a combination of Lambertian and mirror-like reflectance. The material can also have spectral values that vary with position. Here a scanned object is shown as white Lambertian (upper left), spectrally varying with position (upper right), with mirror-like reflection of the light source (lower left), and with mirror-like reflection of the entire environment.



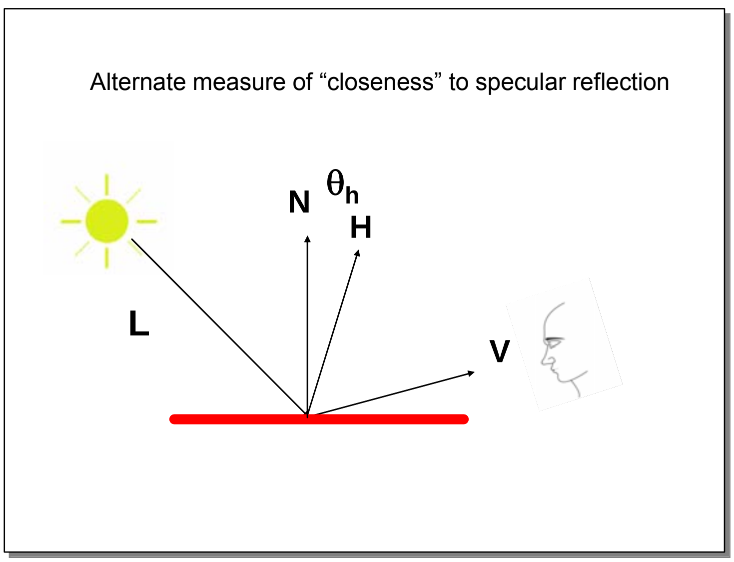
As noted in
R. L. Cook and K. E. Torrance. A reflectance model for computer graphics. *ACM Transactions on Graphics*, 1(1):7–24, January 1982.
The color of specularly reflected light is white for dielectics, and the color of the material for metals. The color is predicted using the Fresnel equation for a smooth surface.



The original Phong reflectance model is described in the classic paper: **Bui Tuong Phong "Illumination for computer generated pictures"** ***Communications of the ACM*****, v.18 n.6, p.311-317, June 1975 .** It was expressed as reflectance function for light intensity, rather than as a BRDF for computing radiance. However, it was inspired by physical observation. The effect of the model in rendering a sphere is compared to a photograph of a real sphere in the paper. The fuzziness of the specular reflection is computed as a function of the angle a between the reflected direction and the mirror reflection angle: reflectance = $\rho d (\cos \theta\iota) + \rho s (\cos \theta s)^n$

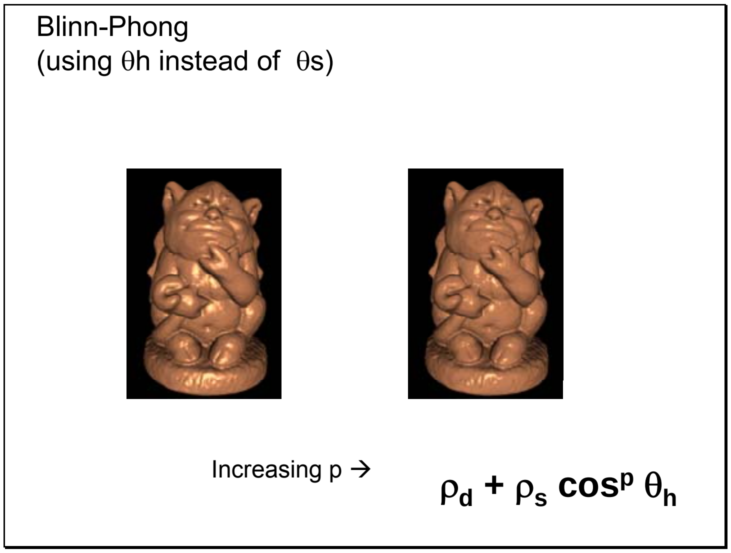


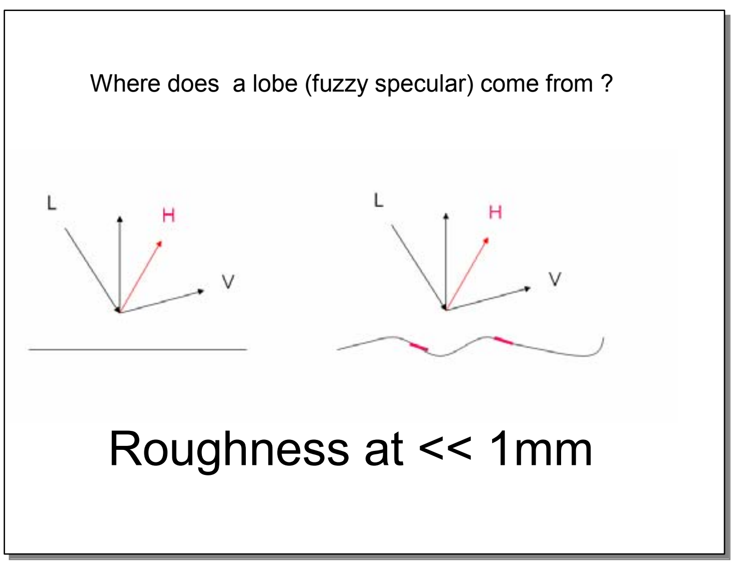
In contrast to diffuse reflection, the specular component concentrates the reflected light. The larger the value of n, the smaller the specular highlights formed by the reflection of the light source.



The specular lobe in the Phong model is taking into account roughness at a very small scale. At a small scale parts of a surface are oriented to reflect into directions that aren’t the mirror direction for the flat surface.

H is the “half way” vector, the direction a surface normal would need to be pointing for a mirror reflection to be visible for a given pair of light L and view V directions. Many reflectance models are computed in terms of this half way vector.





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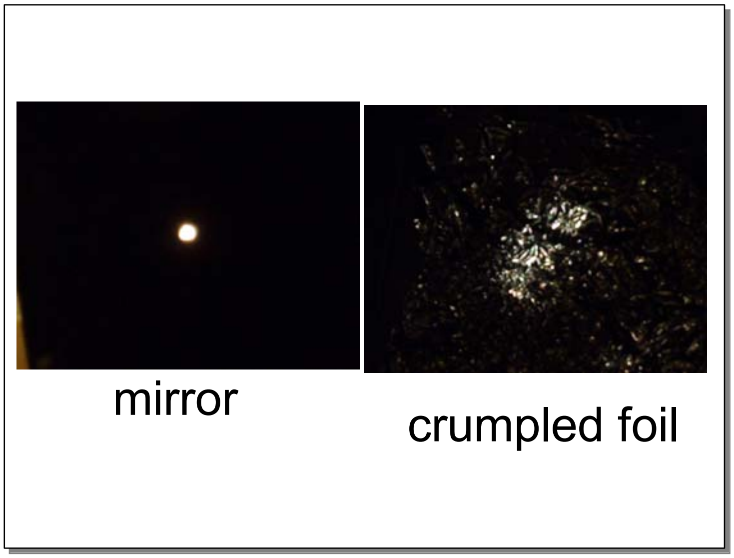
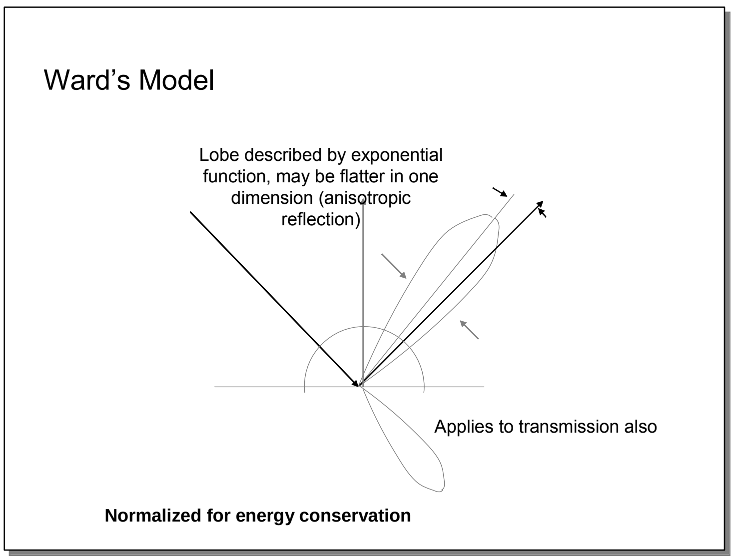
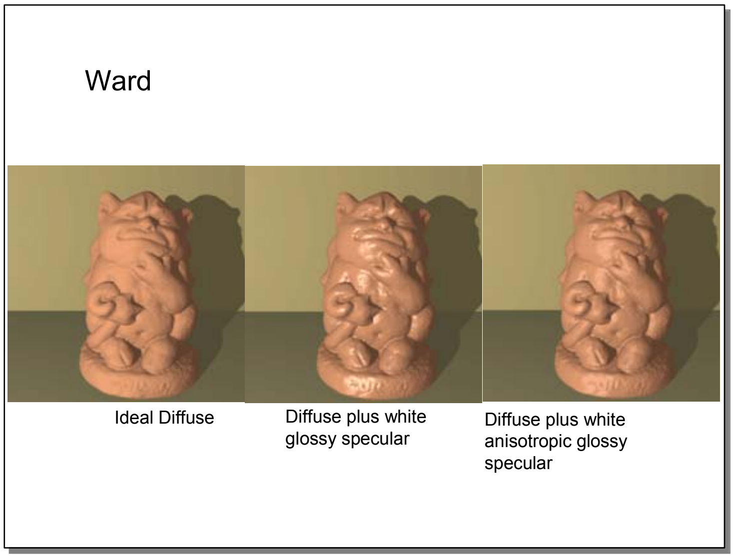


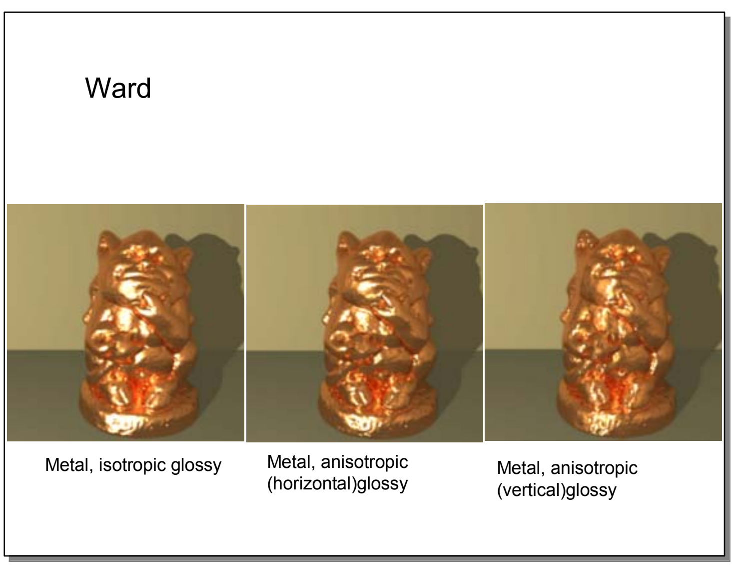
These image show a macroscopic example of the spreading effect of a rough surface. For a surface that is somewhat rough at a microscopic level, some portions of the surface are oriented in the direction of the halfway vector even when the halfway vector isn't the same as the main surface normal.



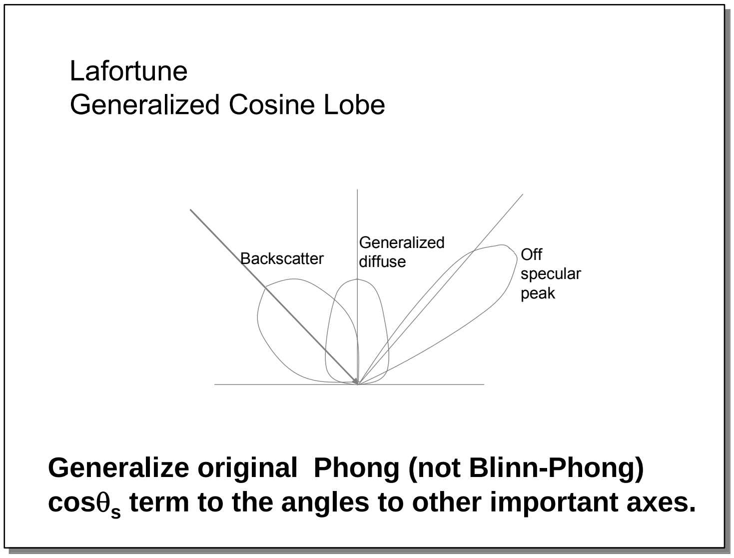
The Ward reflectance model is similar to the Phong model except it is expressed in physical terms – it expresses the relationship between incident and reflectance radiance and conserves energy. Rather than using the cosine to a power, it uses an exponential function, parameterized by an average slope, to express the shape of the specular lobe. Furthermore, the lobe can be anisotropic – by expressing different slopes for different directions on a surface (e.g. for a set of grooves the slope is zero along the grooves, and potentially steep perpendicular to the grooves).The model can be applied to regular and diffuse transmission through a thin surface. The model is fully described in as described in **Ward Larson and Shakespeare, *Rendering with radiance: the art and science of lighting visualization* (Morgan Kaufmann, 1998)**



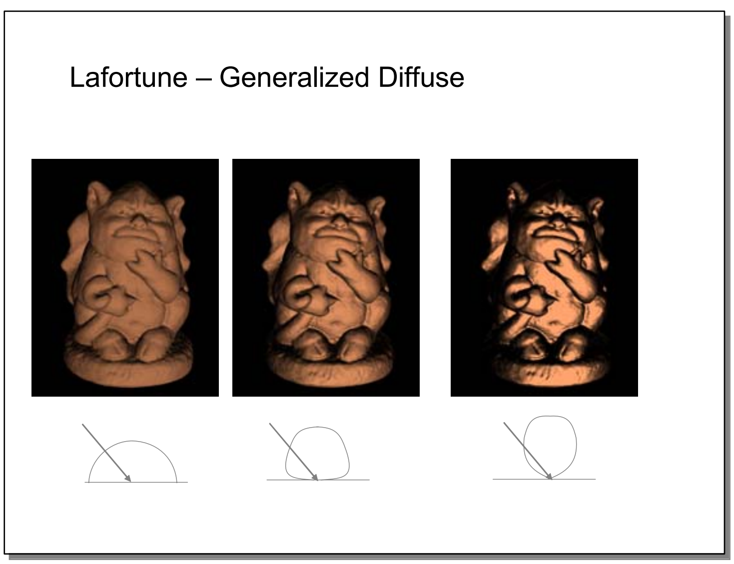
Since the Ward model is developed in physical terms of incident and reflected radiance, it works (by design) in a system that simulates physically accurate global illumination. These variations were rendered using the Radiance software system, http://radsite.lbl.gov/ A point to remember is that physically accurate material models only create realistic appearance when used in the context of a physically accurate global illumination system. Another detail to note is that a small correction to the original model is available in Arne Duer. An Improved Normalization For The Ward Reflectance Model. *JOURNAL OF GRAPHICS TOOLS*, 11(1):51, 2006.



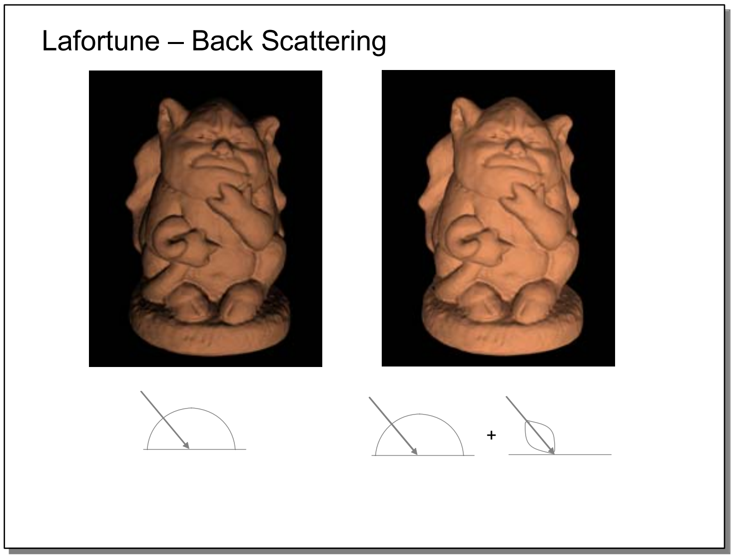
Anisotropic reflection has a significant impact on appearance, but for a complicated object its effect is only clear when the effect of isotropic, or anisotropic reflection with a different orientation is displayed.



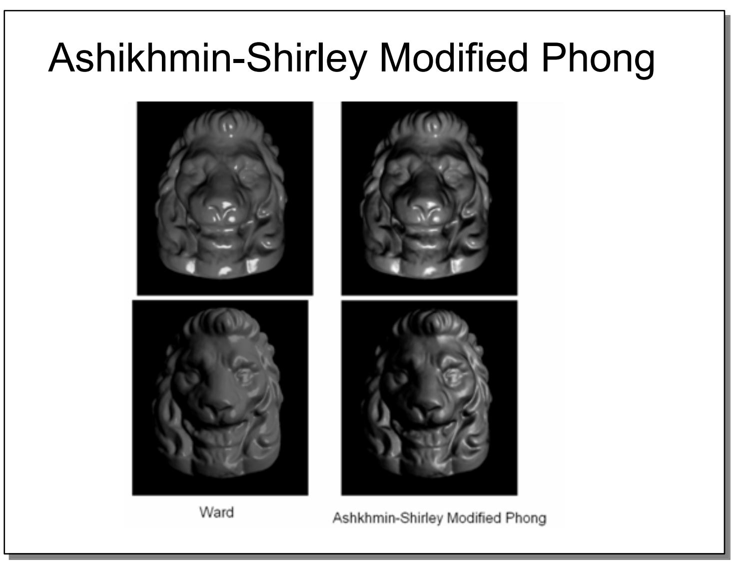
The generalized cosine lobe model described in Lafortune, Foo,Torrance, and Greenberg “Non-linear approximation of reflectance functions” In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques* (1997pp. 117– 126.) Gives a different generalization of the Phong model. Like the Ward model, it is formulated in physical terms. It conserves energy. Instead of just describing peaks of reflection around the specular direction, it allows the definition of lobes (possibly anisotropic) around any axis defined with respect to the surface. Important other axes are just off the specular direction, the normal direction and the direction of the source (for backscatter). The general form of the reflectance is fr = C(u) (Cxuxvx+Cyuyvy+Czuzvz)n where u and v are vectors in the incident and reflected directions, Cx,Cy are coefficients determining the direction and shape of the lobe, n defines how narrow it is, and C(u) is a normalizing function to insure the function conserves energy. Sets of functions of this form can be summed to form the BRDF for a single material.



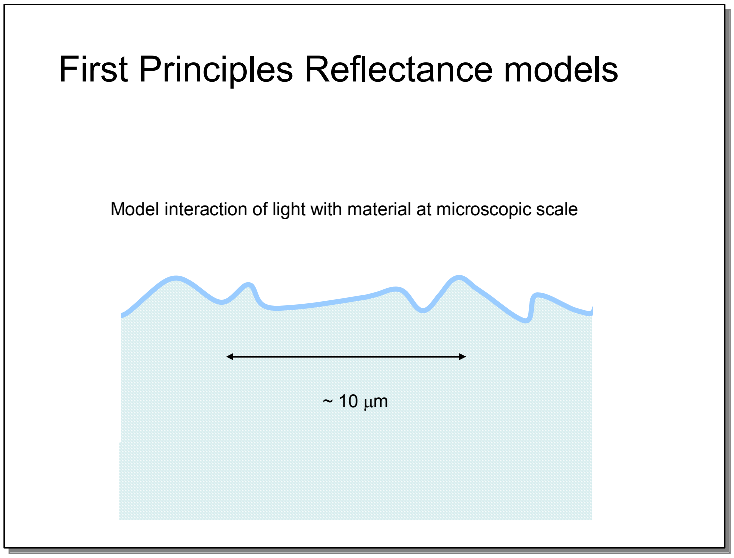
An example of a BRDF that the Lafortune model can represent that previous models could not is generalized diffuse reflectance. In general, even surfaces that appear matte or diffuse don’t reflect radiance evenly in all directions – the reflection may peak in the direction of the surface normal and fall off at near grazing viewing angles. The effects shown here are found using Cx=Cy=0, Cz=1, n equal to zero, 0.5 and 2 respectively.



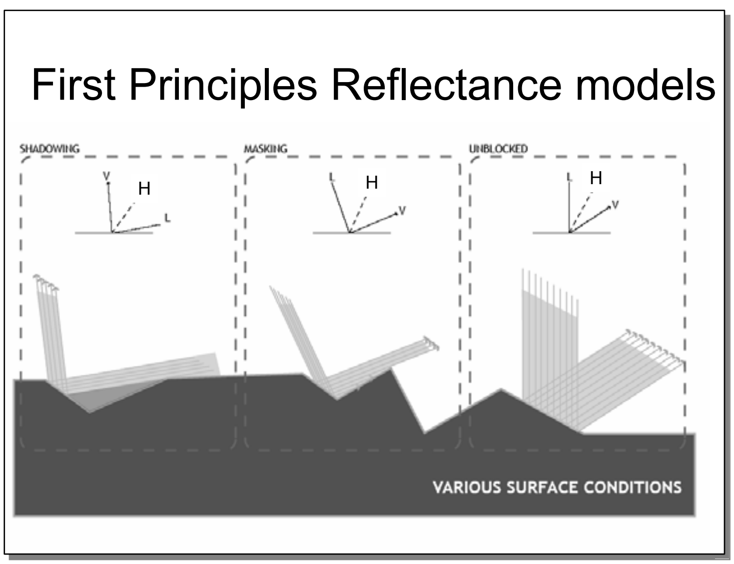
The Lafortune model, unlike Phong or Ward, also provides a mechanism for defining back scatter. In this case a sum of two Lafortune lobes is used. With summing functions, there become a large number of parameters Cx,Cy,Cz and n to be defined for specifying reflectance. This makes the model inconvenient for user interfaces. The Lafortune model is useful though for fitting masses of measured BRDF data into a compact representation.



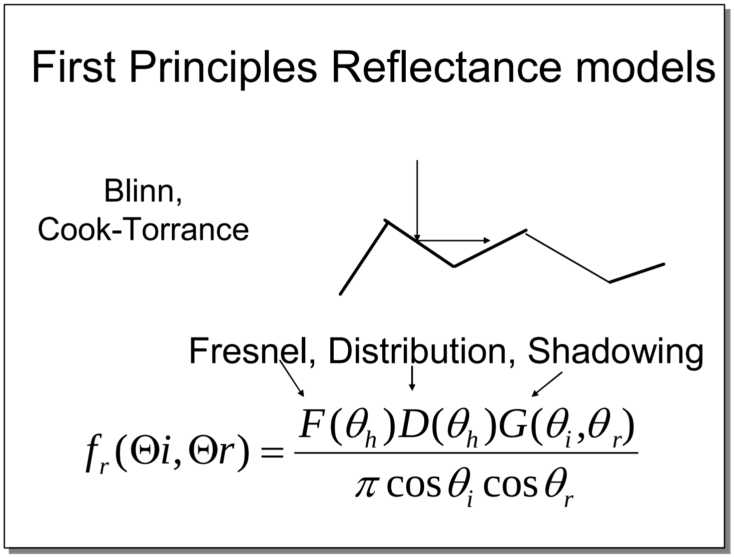
The Ashikhmin-Shirley modification of Phong reflectance *(Ashikhmin and Shirley, An Anisotropic Phong BRDF Model" Journal of Graphic Tools, 5,2, (2000), pp.25-32)* has the feature that it includes an explicit term for the Fresnel reflectance. The specular reflectance increases as the angle of incidence increases. The diffuse component is appropriately reduced at these angles to maintain energy conservation. The formulation also maintains reciprocity, and allows for anisotropy. The Fresnel component is computed with Schlick's approximation (see Christophe Schlick. A customizable reflectance model for everyday rendering. *Rendering Techniques '93*, pages 73–84.) In the examples shown, the decrease of the diffuse component with view angle relative to the ideal diffuse component used in the Ward model can be observed.



In contrast to empirical methods that look for convenient functional forms, first principles methods model the interaction with light with a mathematical model of material defined at a microscopic scale. The most frequently used first principles models use as a mathematical model a statistical distribution of surface facets to describe the details of the boundary between a material and air. The most popular methods model this interaction with geometric optics, which requires that the surface being modeled be "large" with respect to the wavelength of light (which is 0.4 to 0.7 microns) Some more complex models use wave optics to capture of the effects of diffraction at the surface.

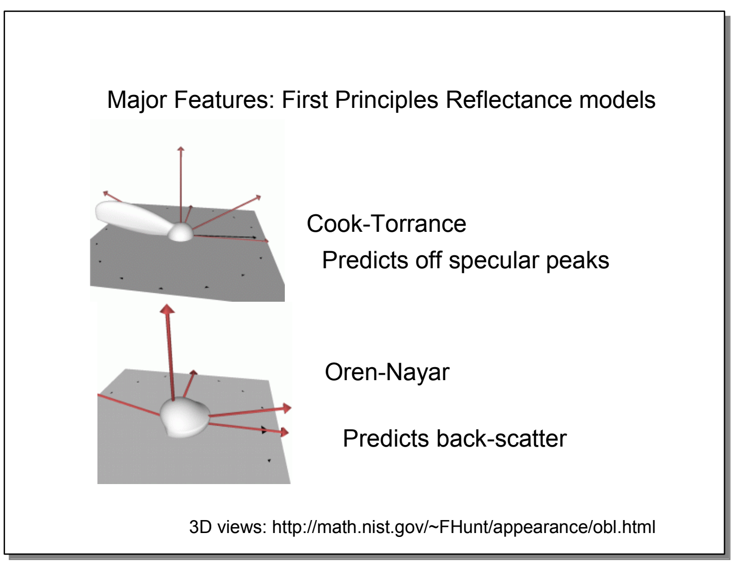


First principles models account for the effects that facets can have on one another – they may block light incident on another facet, making it appear darker, or they may block light leaving the facet before it reaches a viewer, again resulting in a darker appearance. Even unblocked, the orientation of the facets results in light being scattered in a much different directional pattern than from a smooth surface.

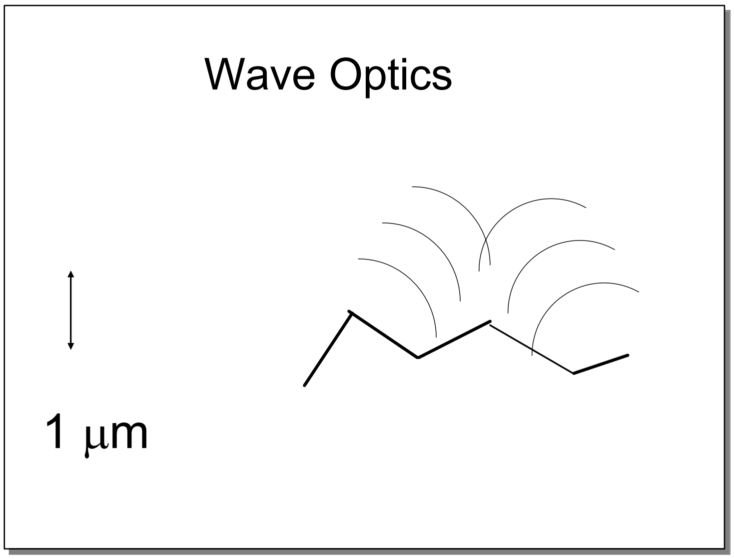


Two popular first principles models are Blinn, *"Models of light reflection for computer synthesized pictures," SIGGRAPH 1977, pp. 192-198.* and Cook-Torrance, *Cook and Torrance "A reflectance model for computer graphics". ACM Transactionson Graphics 1, 1 (Jan. 1982), 7–24*

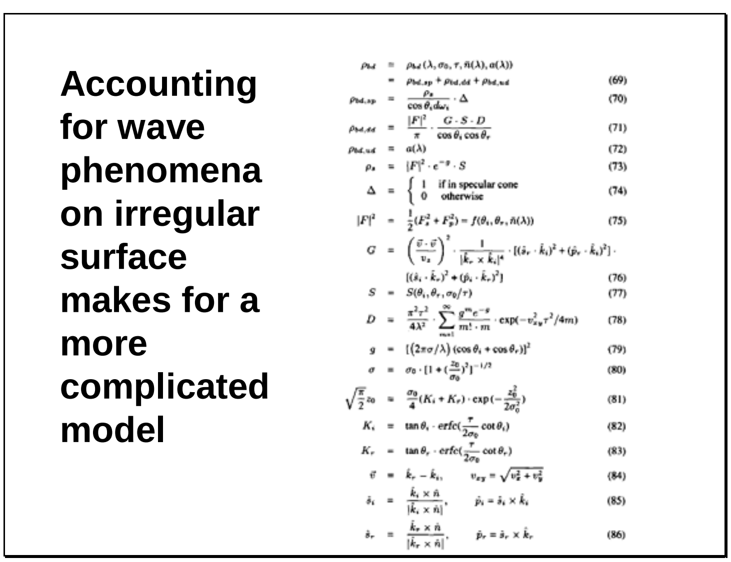
They are both based on specular reflections of distributions of facets. The difference between them is the distribution of the facets assumed.



The principle feature of the Cook-Torrance model is the prediction of off specular peaks, that are the consequences of shadowing and masking causing asymmetries. The principle feature of the Oren-Nayar model is the prediction of back scattering, that is a consequence of facets oriented towards the light source diffusely reflect some light back to the source. The result in each case are BRDF functions with lobes in the specular and backscatter directions that have more complicated structure than those used in the empirical models. The BRDF for these models is specified by giving parameters for the microscopic surface geometry. However, since the microstructure is rarely known, the facet distribution parameters are normally treated as parameters similar to n in the Phong and Lafortune models for controlling the shape of these complicated distributions.



For nearly smooth surfaces specular and/or diffuse reflectance can not be assumed at each facet. The effects of electromagnetic waves interfering with each other need to be accounted for. Methods by *Kajiya Anisotropic Reflectance Models, SIGGRAPH 1985, pp15-21* and *He et al. A Comprehensive Physical Model for Light Reflections, SIGGRAPH 91, pp175-186* account for these effects that are important for nearly smooth surfaces.



Stephen H. Westin & Hongsong Li & Kenneth E. Torrance / A Comparison of Four BRDF Models 7

Simple Mirror He-Torrance Model

Important for nearly smooth surfaces – See

http://www.graphics.cornell.edu/pubs/2004/WLT04a.pdf

These images showing the dramatic effect the He-Torrance model can have on near smooth surfaces were produced at and are copyrighted by Westin, Li and Torrance, and appear in the technical report cited .

Recent work in optics and computer vision have re-examined some assumptions made in many graphics first principles models, in particular the form of the shadowing term and the effect of interreflections in rough surfaces. For further reading consult:

J.J. Koenderink, A.J. Van Doorn, K.J. Dana, and S. Nayar. Bidirectional Reflection Distribution Function of Thoroughly Pitted Surfaces. *International Journal of Computer Vision*, 31(2):129–144, 1999.

H. Ragheb and E.R. Hancock. Testing new variants of the Beckmann–Kirchhoff model against radiance data. *Computer Vision and Image Understanding*, 102(2):145–168, 2006.

Y. Sun. Self shadowing and local illumination of randomly rough surfaces. *Computer Vision and Pattern Recognition, 2004. CVPR 2004. Proceedings of the 2004 IEEE Computer Society Conference on*, 1.

Y. Sun. Statistical ray method for deriving reflection models of rough surfaces. *Journal of the Optical Society of America A*, 24(3):724–744, 2007.

Effects that Require Keeping Track of more than just Radiance

- Polarization

Need to track state of polarization

There are some optical effects that are important for small classes of materials. One is polarization. General references for this include: David C. Tannenbaum, Peter Tannenbaum, and Michael J. Wozny. Polarization and birefringency considerations in rendering. In *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*, pages 221–222. ACM Press, 1994; Alexander Wilkie, Robert F. Tobler, and Werner Purgathofer. Combined rendering of polarization and fluorescence effects. In *Proceedings of the 12th Eurographics Workshop on Rendering*, pages 197–204, 2001; Lawrence B. Wolff and David J. Kurlander. Ray tracing with polarization parameters. *IEEE Comput. Graph. Appl.*, 10(6):44–55, 1990.

Other Effects

- Polarization

  scalar values for radiance and BRDF replaced by matrices

Wolff and Kurlander IEEE CGA 1990

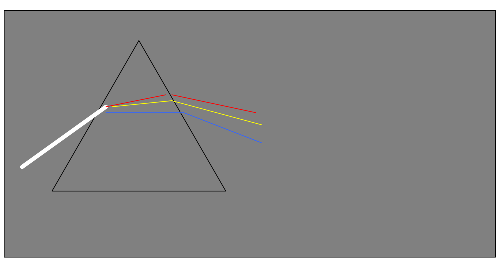
  (complete Cook-Torrance model)

Tannenbaum SIGGRAPH 1994: birefringent materials

- Code available: SCATMECH

  http://physics.nist.gov/Divisions/Div844/facilities/scatmech/html/

Spectral Effects: Dispersion



Spectral dependance of index of refraction

The index of refraction is a function of wavelength, so different wavelengths get refracted differently, causing the separation of colors we see.

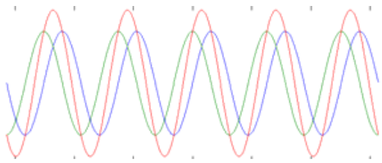
Effects that Require Keeping Track of more than just Radiance

- Diffraction and Interference

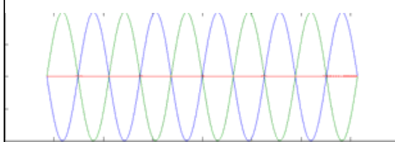
Need phase of light waves

Another classes of effects is interference and diffraction. General references for these phenomena that require modeling the wave nature of light include: Brian E. Smits and Gary W. Meyer. Newton's color: Simulating interference phenomena in realistic image synthesis. In Kadi Bouatouch and Christian Bouville, editors, *Rendering Techniques '90*, Eurographics, pages 185–194. Imprimerie de l'universit´e de Rennes, 1990. Proc. 1st Eurographics Rendering Workshop, Rennes, France, June 11–13, 1990; Yinlong Sun, F. David Fracchia, ThomasW. Calvert, and Mark S. Drew. Deriving spectrum from colors and rendering light interference. *IEEE Comput. Graph. Appl.*, 19(4):61–67, 1999.; Jos Stam. Diffraction shaders. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pages 101–110. ACM Press/Addison-Wesley Publishing Co., 1999; Yinlong Sun, F. David Fracchia, Mark S. Drew, and Thomas W. Calvert. Rendering iridescent colors of optical disks. In *Proceedings of the Eurographics Workshop on Rendering Techniques 2000*, pages 341–352, London, UK, 2000. Springer-Verlag.

Spectral Effects: Thin Film Interference (Wave effect)



In phase, reinforcement

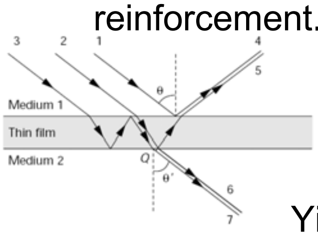


Out of phase, cancellation

A different cause of vibrant color is when light reflects and transmits through very thin films. When a layer of transmitting material has a thickness on the order of the wavelength of light, wave phenomena have to be accounted for. In particular, light waves can reiniforce one another or cancel each other out.

Spectral Effects: Thin Film Interference

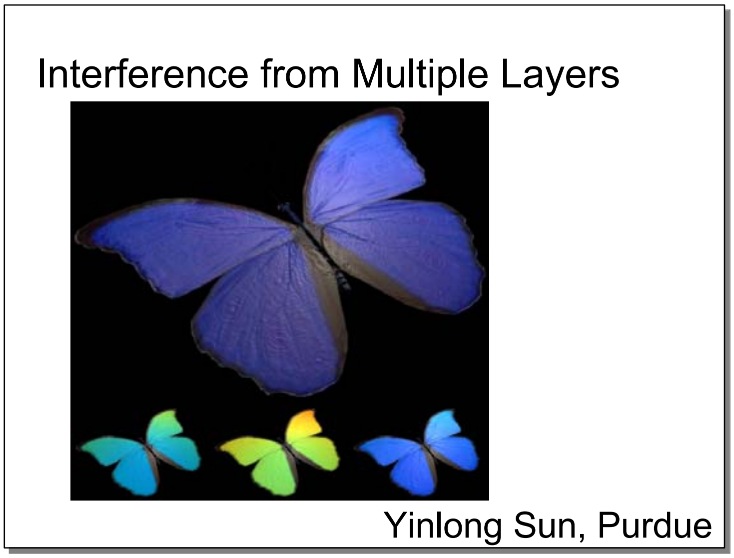
If the distance traveled in thin film is a wavelength or fraction of a wavelength get cancellation or reinforcement.



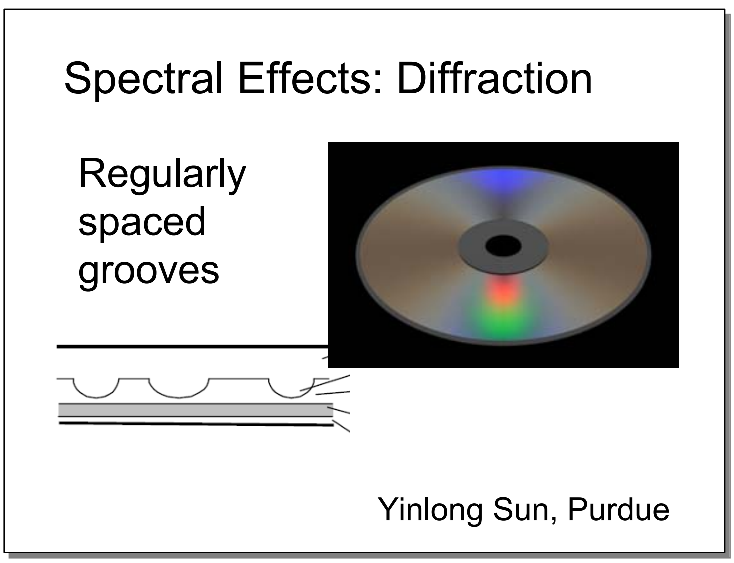
Yinlong Sun, Purdue

Whether light waves will cancel or reinforce after traveling some distance through a thin film depends on the wavelength. For a given path through the film, some wavelengths will be reinforced and some cancelled, resulting in intense colors appearing.

Yinlong Sun, F. David Fracchia, Thomas W. Calvert, and Mark S. Drew, "Deriving Spectra from Colors and Rendering Light Interference," *IEEE Computer Graphics and Application*, Vol. 19, No. 4, Jul. 1999, pp. 61-67.



This image is from : Sun, Y. 2006. Rendering biological iridescences with RGB-based renderers. *ACM Trans. Graph.* 25, 1 (Jan. 2006), 100-129. In this article a simplified model for accurating predicting these reflected colors is presented.



As mentioned earlier, when roughness is very small, wavelike phenomena need to be accounted for in computing reflectance. When there is regular spacing in the small features, there can also be the interference effect similar to the thin film effect. The simulated CD image shown here is from:

Yinlong Sun, F. David Fracchia, Mark S. Drew, and Thomas W. Calvert, "Rendering Iridescent Colors of Optical Disks," *the 11th EUROGRAPHICS Workshop on Rendering* (EGRW), Brno, Czech Republic, June 2000, pp. 341-352

Other Effects

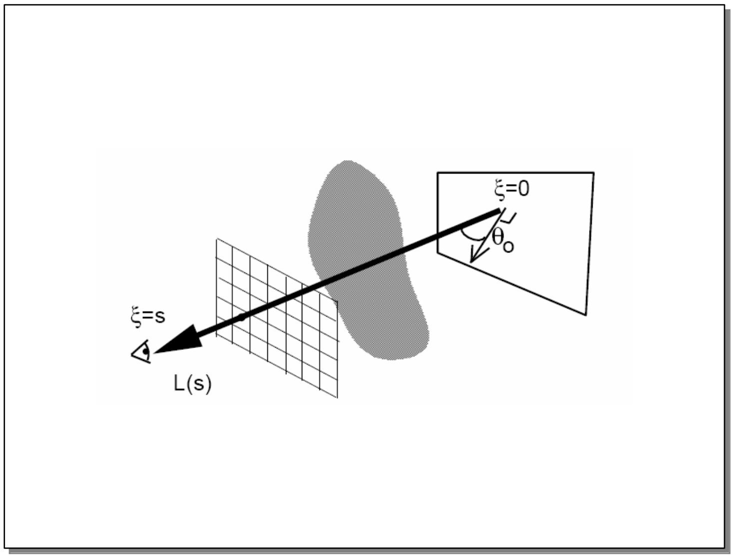
- Phosphorescence: time delay between incident and emitted light
- Fluorescence: wavelength reflected different from wavelength incident

Glassner, EGRW 94
Wilkie et al., EGRW 01

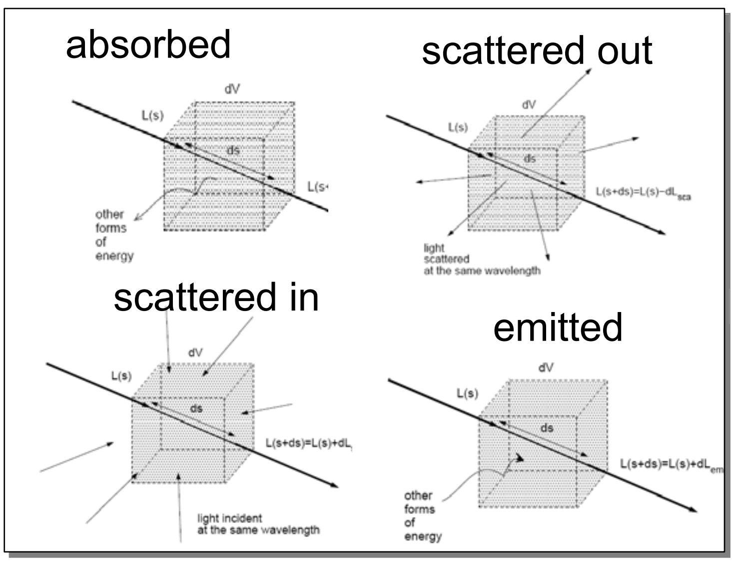
Andrew Glassner. A model of phosphorescence and fluorescence. In *5th Eurographics Rendering Workshop*, pages 57–68, 1994.; Alexander Wilkie, Robert F. Tobler, and Werner Purgathofer. Combined rendering of polarization and fluorescence effects. In *Proceedings of the 12th Eurographics Workshop on Rendering*, pages 197–204, 2001.

Scattering Absorbing Volumes

The difference in these images is the volumetric properties of the atmosphere. On the right particles that absorb and scatter light obscure anything in the distance.



For volumes the effect of material along a path needs to be considered, rather than a reflectance that encodes what happens when a ray hits a particular point on a surface.



As a ray travels through a volume, the amount of light may decrease by absorption or by light being scattered out of the ray path. The amount of light may increase by light being scattered into the path, or by light being emitted by the volume (e.g. as in a flame.)

Parameters for volumes:

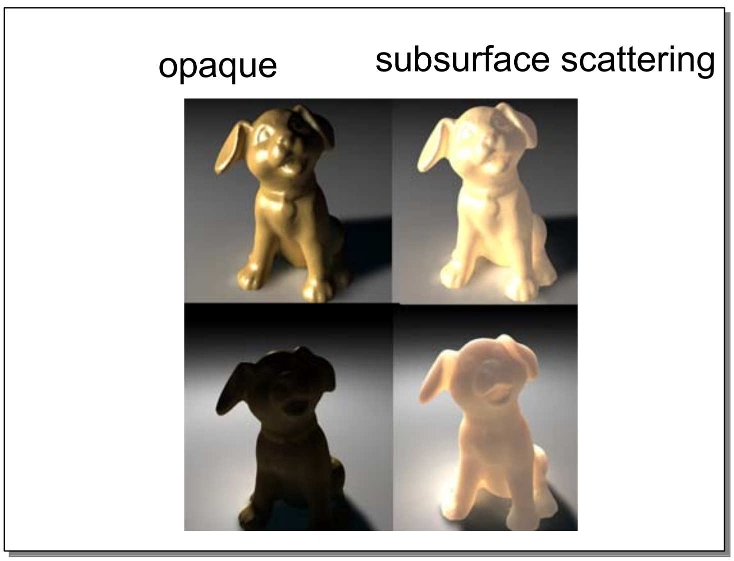
$$\sigma_a = \frac{fraction\_absorbed}{length}$$

$$\sigma_s = \frac{fraction\_scattered}{length}$$

$$P(\theta) = scattering\_phase\_function$$

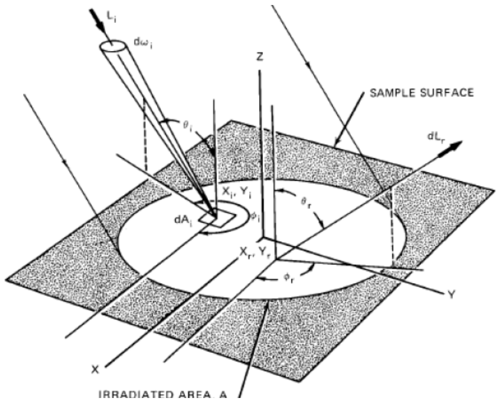
angle from original direction of travel where light is scattered

For more detail on input data for participating media, see the SIGGRAPH 95 course notes "Input for Participating Media" , that are appended at the end of this tutorial. Also see the recent paper: D. Gutierrez, F. Seron, O. Anson, A. Muñoz. Visualizing underwater ocean optics. Computer Graphics Forum (Eurographics 2008), Vol. 27(2), pp. 547-556.



Volume effects are also visible in materials where the particles are tightly packed into a solid. The result is "subsurface scattering". The only difference between the images on the left and right is the addition of subsurface scattering on the right. The top images are lit from the front, the bottom images from the back.In solids the scattering can essentially be considered isotropic in all cases.

NBS Monograph 160 (1977)



Subsurface scattering is characterized by the BSSDF that accounts for light entering a material and emerging at a different angle and noticeably different distance from where it entered.

This was original defined in **F. E. Nicodemus, J. C. Richmond, J. J. Hsia, I. W. Ginsberg, and T. Limperis, "*Geometrical considerations and nomenclature for reflectance*," NBS Monograph 160 (National Bureau of Standards, Washington, D.C., 1977).**

For densely packed solids, model as diffusion process and use dipole approximation.

$$L_o(\mathbf{x} \to \Theta) = \frac{F_t(\mathbf{x},\theta)}{F_{dr}(\mathbf{x})} M_o(\mathbf{x})/\pi$$

$$M_o(\mathbf{x}) = F_{dt}(\mathbf{x})\{C_1 \frac{e - \sigma_{tr} d_r}{d_r^2} + C_2 \frac{e - \sigma_{tr} d_v}{d_v^2}\} E_i A_i / 4\pi$$

where

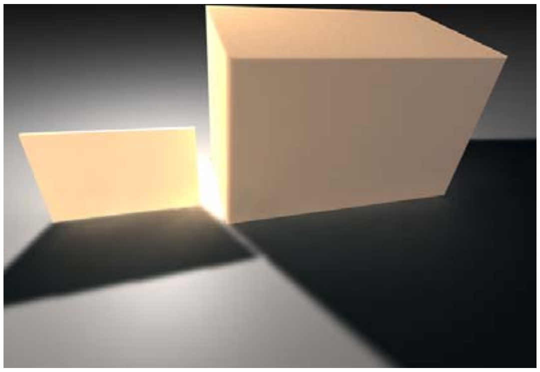
$$C_1 = z_r(\sigma_t r + \frac{1}{d_r}),\ C_2 = z_v(\sigma_t r + \frac{1}{d_v})$$

$$\sigma_t r = \sqrt{3\sigma_a \sigma_t'},\ \sigma_t' = \sigma_a + (1-g)\sigma_s$$

$$d_r = \sqrt{r^2 + z_r^2},\ d_v = \sqrt{r^2 + z_v^2},\ r = \|\mathbf{x} - \mathbf{x_i}\|,\ z_r = l_u,\ z_v = l_u(1 + 4/3A),\ l_u = \frac{1}{\sigma_t'}$$

$$A = \frac{1 + F_{dr}}{1 - F_{dr}},\ F_{dr} = \frac{-1.44}{\eta^2} + \frac{.71}{\eta} + .668 + .0636\eta,\ \eta = \frac{n_2}{n_1}$$

Jensen, H. W., Marschner, S. R., Levoy, M., and Hanrahan, P.. A practical model for subsurface light transport. SIGGRAPH '01..

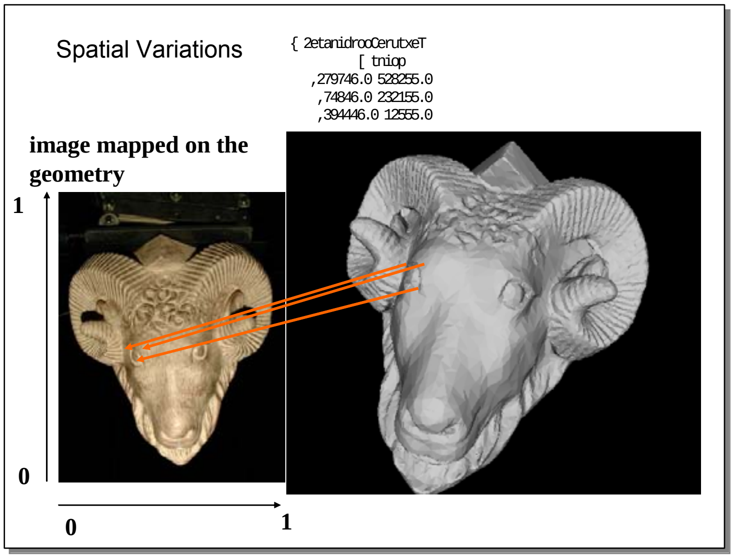


The same subsurface scattering parameters will result in different appearance depending on the thickness of the material.

For the same density of material, the ratio of scattering to absorption in the material gives a different appearance. The lighting in these three images is the same.

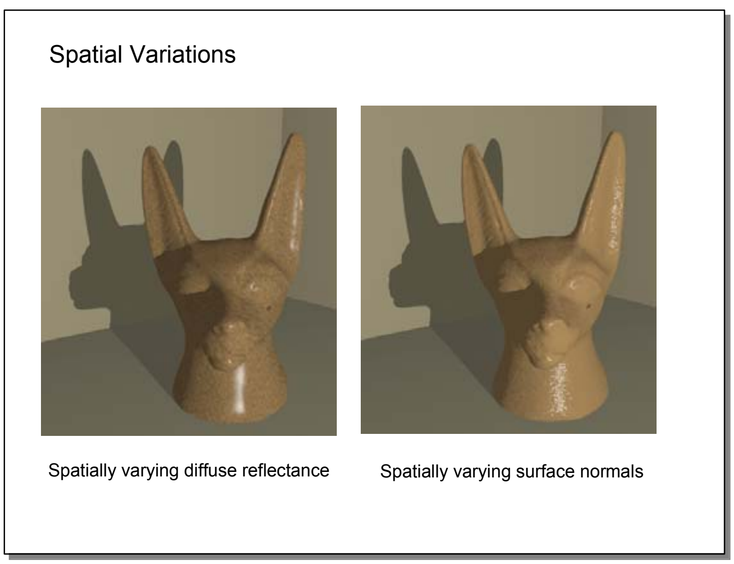
Reference for computing subsurface scattering:

Jensen, H. W., Marschner, S. R., Levoy, M., and Hanrahan, P. 2001. A practical model for subsurface light transport. In *Proceedings of the 28th Annual Conference on Computer Graphics and interactive Techniques* SIGGRAPH '01. ACM Press, New York, NY, 511-518. There have been **many** papers that build on this technique to enable rendering of subsurface scattering in real time.

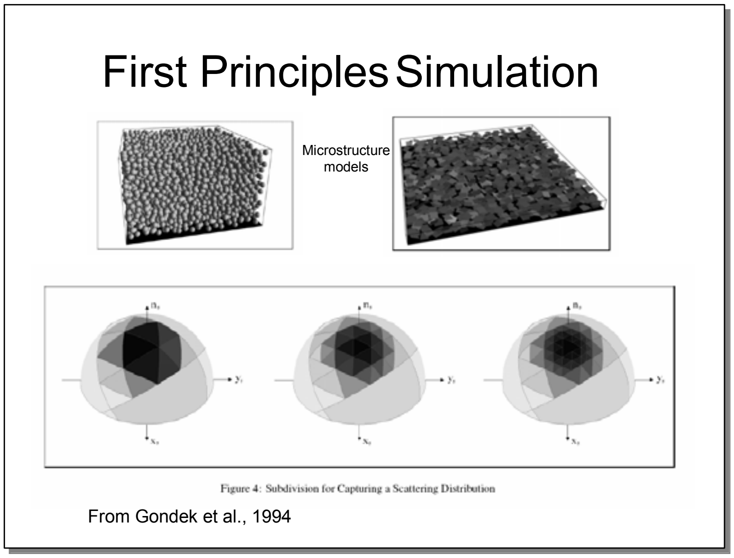


A basic mechanism for representing spatial variations that characterize a material is to use images mapped to the surface. Each pixel in the map may store simply a diffuse color, or a BRDF, a normal, a displacement, or a BTF (a virtual BRDF that includes the effect of small scale geometry). The mapping is done by storing coordinate of a location in an image with each vertex used to define a geometric model.

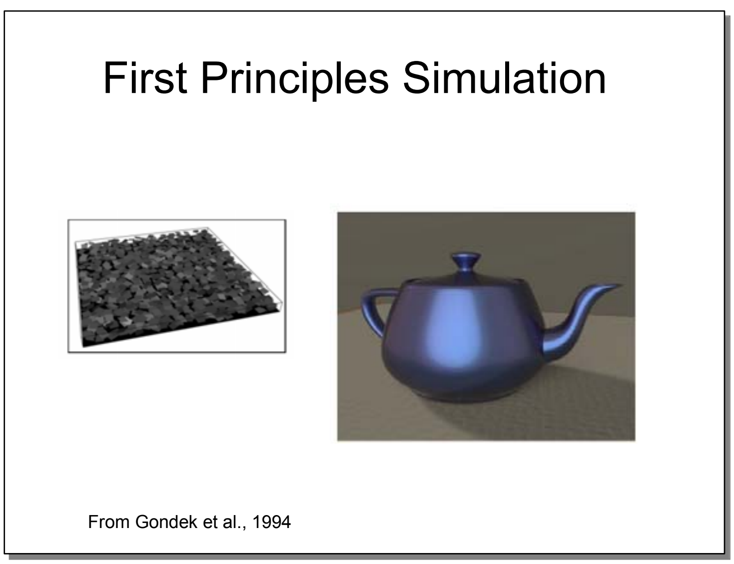
Mapping to a geometry requires that the geometry be parameterized (i.e. a two dimensional coordinate system must be defined on the surface), a topic which is studied extensively in computer aided geometric design. Parameterization is one of the topics considered in the course in SIGGRAPH 2005 **14. Discrete Differential Geometry:** Grinspun Desbrun, Schröder (in ACM Digital Library)



These two renderings were made with *Radiance* with procedural textures rather than image maps to define spatial variations on the surface (**e.g. see D. Ebert, Ed. *Texturing and Modeling: A Procedural Approach, Third Edition*. Morgan Kaufmann, San Francisco, CA, 2002**.) The same spatial frequency has different visual impact depending on whether the fraction of light is modulated, or the direction of the surface normals.



An alternative to analytic models of reflectance, is to create the small scale microstructure, and simulate its scattering effects by shooting rays at it and saving the results in a data structure designed specifically for BRDF. Two examples of this are: **Gondek, Meyer, and Newman," Wavelength dependent reflectance functions"** ***In Proceedings of the 21st annual conference on Computer graphics and interactive techniques*** **(1994), ACM Press, pp. 213–220.**
And **Westin, Arvo and Torrance, "Predicting reflectance functions from complex Surfaces"** ***In Proceedings of the 19th annual conference on Computer graphics and interactive techniques*** **(1992), ACM Press, pp. 255–264.**



An advantage of simulation is that it can be used to explore the effects of subsurface structure, and effects of interference in thin surface layers. Gondek et al used a simulation of thin titanium dioxide mica flakes to simulate an irridescent paint such as those used on automobiles.

3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

Customized Geometric Structures:

-- Fibers

-- Facets for Sparkles

Layers:

-- Structured for "depth"

-- Subsurface scattering

Measured/Captured Data

Just a reflectance model combined with a spatially varying texture isn't adequate to model all materials. In cases where this approach is adequate, it can be difficult to find the right parameters to use. A wide range of models have been developed for specialized materials. Some common themes in these models that have evolved are developing small scale geometric models, defining layers of materials and using measured or captured data.

3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

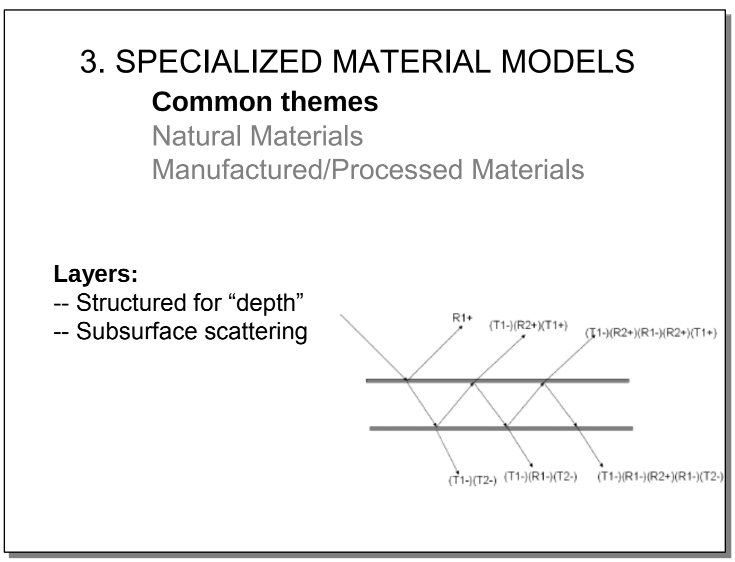
Customized Geometric Structures

-- Fibers

-- Facets for Sparkles

Many materials are composed of bundles of long thin fibers. The appearance of the bulk material is modeled by first account for reflection and transmission from individual strands. Hair, textiles and finished wood are all examples of materials modeled based on the light interactions of individual fibers.

Either naturally or by design many materials have the appearance of “sparkles” – small flecks of material that have a high specular reflectance. A challenge is to model where the sparkles appear in a way that is consistent frame to frame in animated sequences. Materials in which sparkles appear include automotive paint, man-made carpet fibers and snow.



Many materials have sense of depth because they are composed of multiple layers of material that transmit and reflect light. This effect occurs in materials as diverse as paints and the human eye.

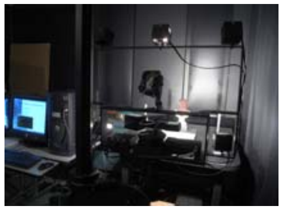
3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

Captured Data



With inexpensive digital cameras now widely available, many material models are built around data that can readily acquired. See SIGGRAPH 2009 Courses:

Acquisition of Optically Complex Objects and Phenomena

Tuesday, 4 August | 8:30 AM - 10:15 AM | Auditorium A and

Build Your Own 3D Scanner: 3D Photography for Beginners

Wednesday, 5 August | 8:30 AM - 12:15 PM | Room 260-262

3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

People/Animals

- Hair and Fur
- Skin
- Eyes
- Birda and other Non-mammals

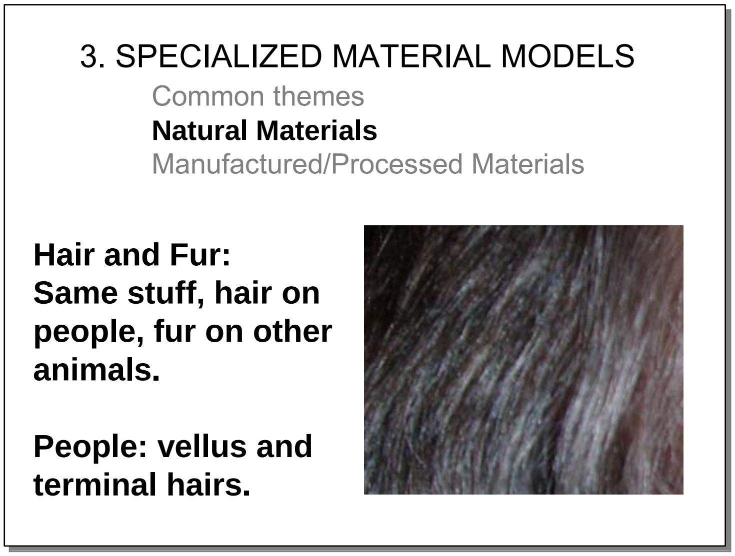
Plants

- Leaves
- Wood

Porous and Wet

Rocks

We review specialized models that have been developed by organizing them into natural and manufactured materials.



An individual hair consists of a core medulla, the cortex and exterior cuticle. The cuticle consists of lapped cells on the outside of the hair.

Coloration: granules of the melanin pigment, either eumelanins or pheomelanins . Hair with no pigment granules appears white.

There are two different types of hair – vellus hairs and terminal hairs. Terminal hairs are those typically found on the scalp. Vellus hairs are unpigmented narrow (4 micron diameter), short (1mm) hairs that grow nearly all over the body.

Some stats:

Scalp hairs on humans are 50 micron to 90 micron diameter, may be circular or ellipsoidal, with curlier hair more ellipsoidal in cross section.

Beard and moustache (rather than scalp) hair may have triangular cross section.

Eyelashes, are 20 to 120 micron in diameter.

A person has about 175 to 300 terminal hairs per *cm*2, for a total of on the order of 100,000 hairs on the typical human scalp.   Foxes and rabbits: average diameter 20 to 30 micron, and approximately 4000 hairs per *cm*2 Goats and badgers :average diameter 70 to 80 micron and approximately 100 to 200 hairs per *cm*2).

General References on types of hair and fur:

James Robertson. *Forensic Examination of Human Hair*. CRC Press, 1999.

A. A. Blazej, J. Galatik, Z. Galatik, Z. Krul, and M. Mladek. *Atlas of Microscopic Structures of Fur Skins 1*. Elsevier, New York, 1989.

Database of fur: http://www.furskin.cz/

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

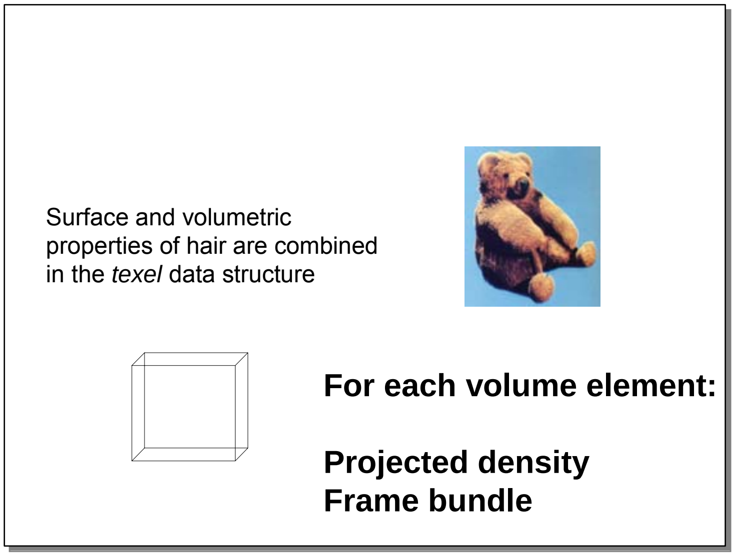
Where the common themes come in:

Terminal Hair: Fibers

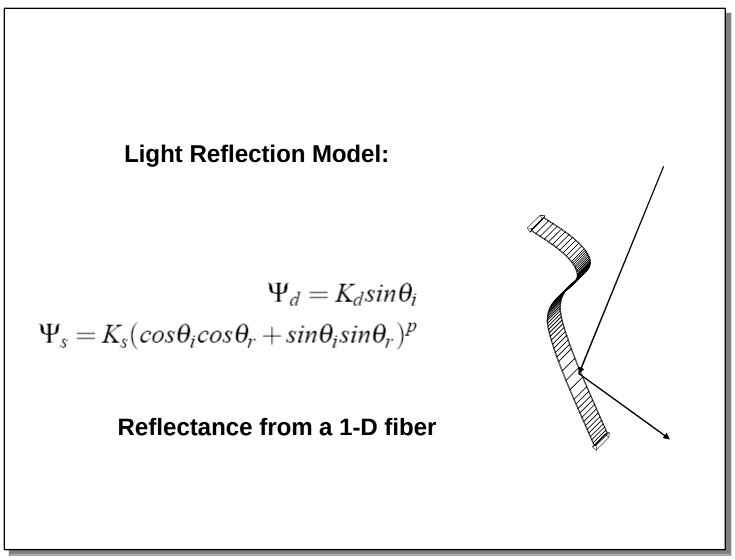
Vellus Hair: Layer

Figure from J. T. Kajiya and T. L. Kay, SIGGRAPH 1989.

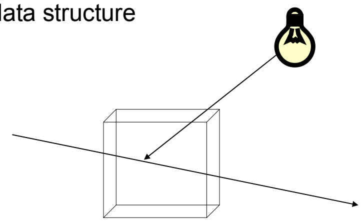
A volumetric approach for rendering fur was presented in: J. T. Kajiya and T. L. Kay. Rendering fur with three dimensional textures. In *Proceedings of the 16th annual conference on Computer graphics and interactive techniques*, pages 271–280. ACM Press, 1989. This is different from pure volume rendering because the structure of individual strands must still be visible.



The projected density accounts for the number and size of hairs, the frame bundle accounts for their orientation.

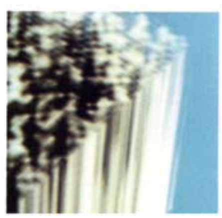


Surface and volumetric properties of hair are combined in the *texel* data structure



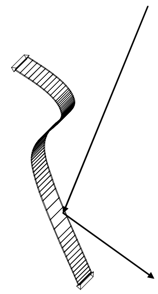
$$L = \Sigma_{t=t_{near}}^{t=t_{far}} e^{-\tau \Sigma_{u=t_{near}}^{u} \rho(u)} \rho(t) \Sigma_i L_i(t) \Psi(t)$$

Light from a volume of fibers



Example views from the original Kajiya and Kay paper.

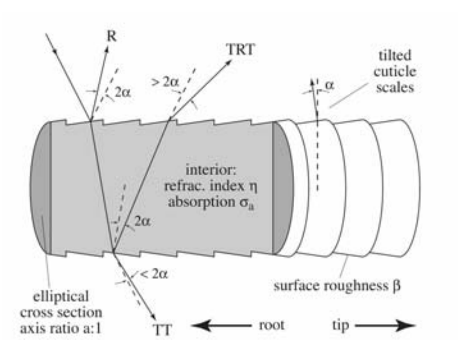
Current processing power allows modeling of individual strands.



$$attenuation = e^{-\rho(-h_o cos\theta_i)+\sqrt{1-h_o^2(1-cos^2\theta_i)}}$$

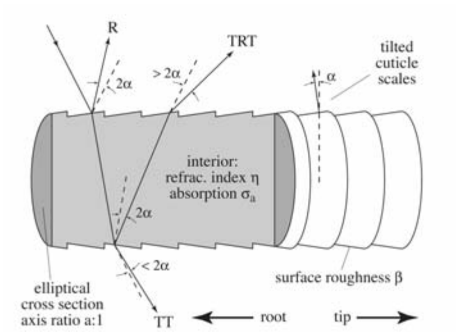
An example of modeling with strands (rather than texels): Aslan in Narnia
Brad Hiebert, Jubin Dave, Tae-Yong Kim, Ivan Neulander, Hans Rijpkema, and Will Telford. The chronicles of Narnia: the lion, the crowds and rhythm and hues. In *SIGGRAPH ’06: ACMSIGGRAPH 2006 Courses*, page 1, New York, NY, USA, 2006. ACM Press.

Figure from Marschner et al., SIGGRAPH 2003



More detailed geometry

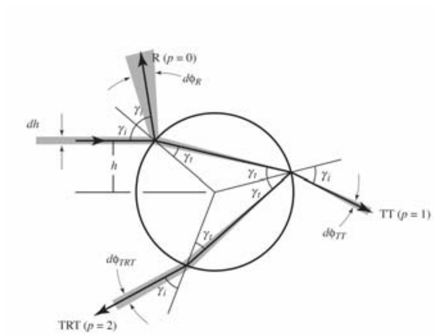
A more detailed reflectance mode for individual strands was presented in
Stephen R. Marschner , Henrik Wann Jensen , Mike Cammarano , Steve Worley , Pat Hanrahan, Light scattering from human hair fibers, ACM Transactions on Graphics (TOG), v.22 n.3, July 2003



Results in directionality of reflectance from the strand

Hair growth results in oriented scales on the hair. The orientation of the scales relative to the centerline of the hair changes the reflectance distribution relative to what would be expected from a smooth cylinder.

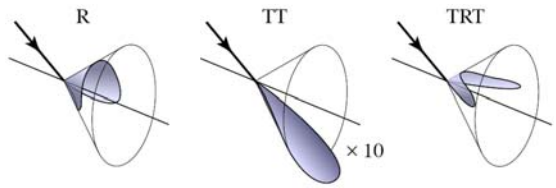
Figure from Marschner et al., SIGGRAPH 2003



More than one way to exit -> more than one highlight

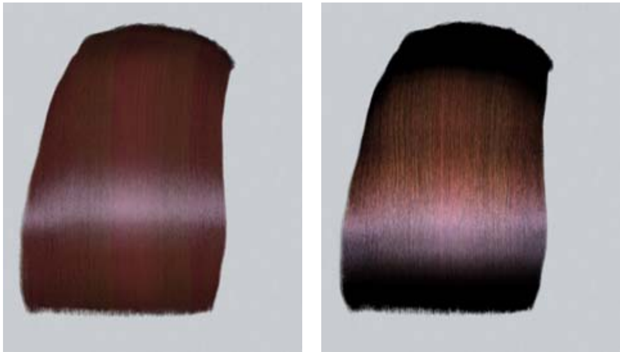
Note multiple paths like thin layers

Figure from Marschner et al., SIGGRAPH 2003



The different possible paths through the strand result in different reflectance lobes.

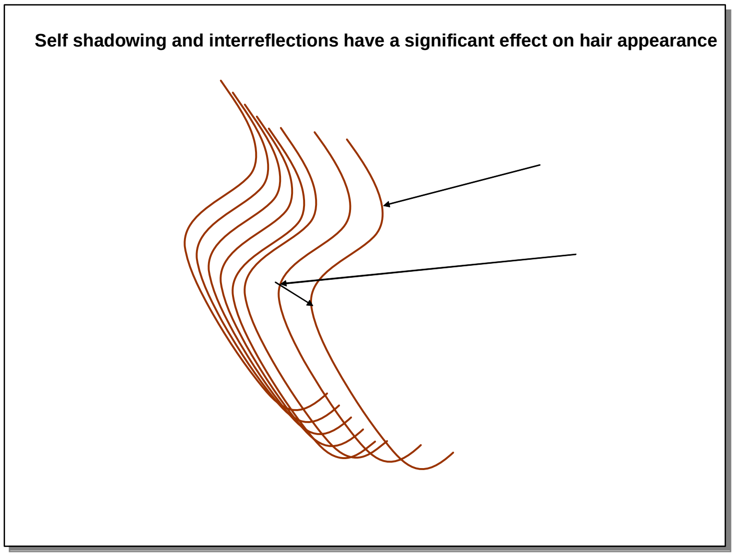
Figure from Marschner et al., SIGGRAPH 2003



Original Kajiya-Kay

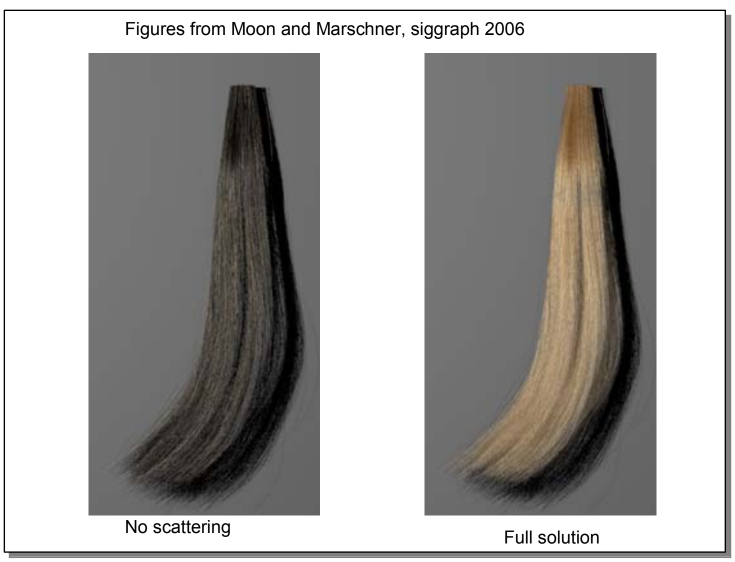
Marschner et al.

A comparison shows that the more detailed model predicts effects like secondary highlights



Effects of shadows and interreflections are studied in” Jonathan T. Moon and Stephen R. Marschner. Simulating multiple scattering in hair using a photon mapping approach. In *SIGGRAPH ’06: ACM SIGGRAPH 2006 Papers*, pages 1067–1074, New York, NY, USA, 2006. ACM Press. And

Tom Lokovic and Eric Veach. Deep shadow maps. In *SIGGRAPH ’00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 385–392, New York, NY, USA, 2000. ACM Press/Addison-Wesley Publishing Co.



Multiple scattering is particularly critical for blond hair.

3. SPECIALIZED MATERIAL MODELS

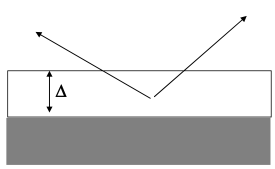
Common themes
Natural Materials
Manufactured/Processed Materials

Vellus Hairs

Machine Vision and Applications (2003)
14: 260–268
The secret of velvety skin
Jan Koenderink, Sylvia Pont

The scattering from short vellus hairs on the rest of the body is similar to the scattering of fuzz on a peach. A simple function for simulating this effect, which softens the look of a surface is described in J. Koenderink and S. Pont. The secret of velvety skin. *Machine Vision andApplications*, 14(4):260–268, 2003.

Machine Vision and Applications (2003)
14: 260–268
The secret of velvety skin
Jan Koenderink, Sylvia Pont



Asperity scattering:
Thin layer (Δ small) of thin (few particles per unit volume) participating medium formed by tiny hairs or dust.

The fuzz on a peach is another example of asperity scattering. Rather than seeing individual small fibers, we see the effect of the hazy layer, and white edges on the silhouette of the peach when it is backlit.

$$f_r(\Theta_i \rightarrow \Theta_r) = \frac{\frac{\sigma_s d}{4\pi}}{cos\theta_i cos\theta_r}$$

Asperity scattering can be modeled with a simple expression, with limits on the values of the angles so that the function doesn't go to infinity.

Human skin:

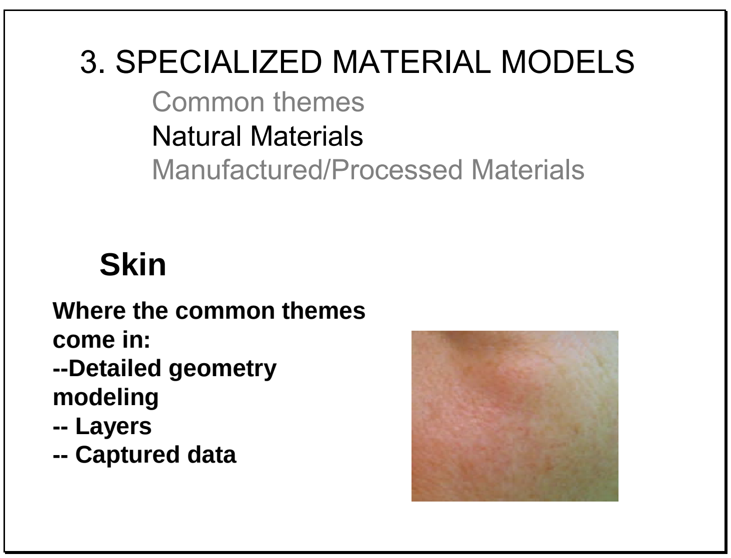
-- varies in thickness varying from 0.1 to more than 0.5 cm.

-- has three layers :

The **epidermis** is the thin outside layer, that includes the exterior layer of “dead cells” (the stratum cornuem). The **dermis** is thicker, and includes the vessels that carry blood. The **hypodermis** connects the skin to the rest of the body.

A general reference:

Kenneth A. Walters. *Dermatological and Transdermal Formulations*. Marcel Dekker Incorporated, 2002.



Skin – Model Components

-- subsurface scattering model
-- surface reflectance model (such as Cook-Torrance)
-- a model of small scale spatial variations in the spectral reflectance
--- geometry variations of the skin surface.

The need to account for subsurface scattering in skin models was first noted in:
Pat Hanrahan and Wolfgang Krueger. Reflection from layered surfaces due to subsurface scattering. In *Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, pages 165–174. ACM Press, 1993.

And more recent methods have estimated a subsurface scattering model from measurements:
Tim Weyrich, Wojciech Matusik, Hanspeter Pfister, Bernd Bickel, Craig Donner, Chien Tu, Janet McAndless, Jinho Lee, Addy Ngan, HenrikWann Jensen, andMarkus Gross. Analysis of human faces using a measurement-based skin reflectance model. In *SIGGRAPH '06: ACM SIGGRAPH 2006 Papers*, pages 1013–1024, New York, NY, USA, 2006. ACM Press.

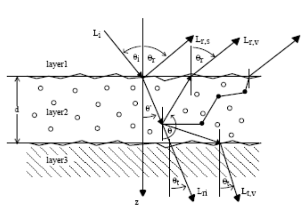
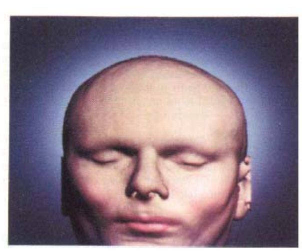


Figure 1: The geometry of scattering from a layered surface



Figures from Hanrahan and Krueger, SIGGRAPH 1993.

Diagram of scattering in subsurface layers and resulting rendering, from scattering.

Skin – Model Components

-- subsurface scattering model
-- **surface reflectance model (such as Cook-Torrance)**
-- a model of small scale spatial variations in the spectral reflectance
--- geometry variations of the skin surface.

Surface reflectance models have been fit to captured data including fitting the Lafortune model used in:
Stephen R. Marschner, Brian K. Guenter, and Sashi Raghupathy. Modeling and rendering for realistic facial animation. In *Proceedings of the Eurographics Workshop on Rendering Techniques 2000*, pages 231–242, London, UK, 2000. Springer-Verlag.
And Cook-Torrance model used in:
Athinodoros S. Georghiades. Recovering 3-d shape and reflectance from a small number of photographs. In *EGRW '03: Proceedings of the 14th Eurographics workshop on Rendering*, pages 230–240, Aire-la-Ville, Switzerland, Switzerland, 2003. Eurographics Association.

Domes:
Measure skin BRDF and facial shape simultaneously

"Recovering 3-D Shape and Reflectance From a Small Number of Photographs," Eurographics Symposium on Rendering, June 2003, pp. 230-240, 315.

Skin – Model Components

-- subsurface scattering model
-- surface reflectance model
(such as Cook-Torrance)
-- **a model of small scale spatial variations in the spectral reflectance**
--- geometry variations of the skin surface.

Spatial coloring variations are due to freckles and age spots, and temporary effects such as blushing.

A full first principles model of skin including prediction of color due to detailed composition including blood flow is the BioSpec Model:

A. Krishnaswamy and G.V.G. Baranoski. A Biophysically-Based Spectral Model of Light Interaction with Human Skin. *Computer Graphics Forum*, 23(3):331–340, 2004.

Krishnaswamy,A.; Baranoski,G.V.G.

A Biophysically-Based Spectral Model of Light Interaction with Human Skin

Computer Graphics Forum, Volume 23, Number 3, 2004, pp. 331-340.

(Proceedings of EUROGRAPHICS 2004, Grenoble, France.)

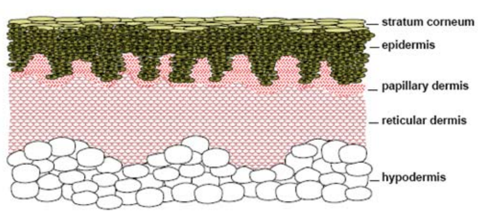


Figure 1: *Schematic cross-section of human skin tissues and the subcutaneous fat tissue (hypodermis).*

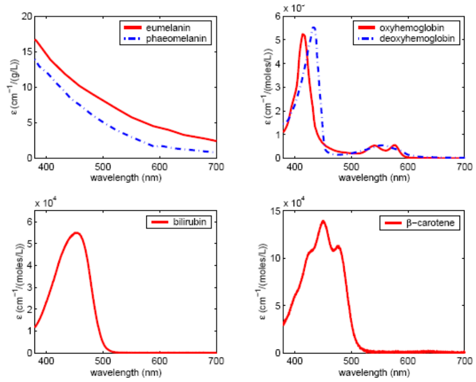


Figure 2: *Spectral extinction coefficient curves for the natural pigments present in skin tissues. Courtesy of S. Prahl and the Oregon Medical Laser Center (OMLC).*

Plots from Krishnaswamy and Baranoski, 2004 for the spectral data for various skin model components.

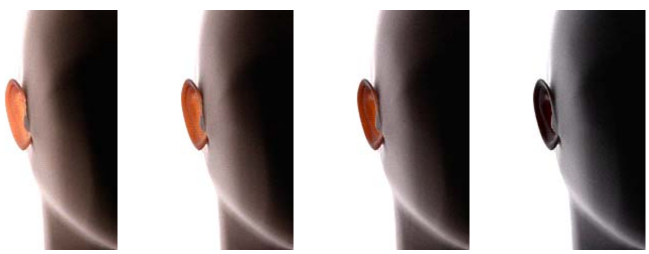


Figure 10: *Images generated using the BioSpec model to show variations in the translucency of skin tissues associated with different levels of melanin pigmentation. From left to right:* $\vartheta_m = 1.9\%$, $\vartheta_m = 5.2\%$ $\vartheta_m = 12\%$ *and* $\vartheta_m = 42\%$.

Images from Krishnaswam and Baranoski, 2004

Skin – Model Components

-- subsurface scattering model
-- surface reflectance model (such as Cook-Torrance)
-- a model of small scale spatial variations in the spectral reflectance
--- geometry variations of the skin surface.

Details of pores from molding compound used on skin: Stephen R. Marschner, Brian K. Guenter, and Sashi Raghupathy. Modeling and rendering for realistic facial animation. In *Proceedings of the Eurographics Workshop on Rendering Techniques 2000*, pages 231–242, London, UK, 2000. Springer-Verlag.

Generic wrinkle patterns are modeled in:

L. Boissieux, G. Kiss, N. Magnenat-Thalmann, and P. Kalra. Simulation of skinaging and wrinkles with cosmetics insight. *Computer Animation and Simulation 2000*, pages 15–27, 2000.

Applying wrinkles from scanned data:

lovinskiy et al., 2006] Aleksey Golovinskiy, Wojciech Matusik, Hanspeter Pfister, Szymon Rusinkiewicz, and Thomas Funkhouser. A statistical model for synthesis of detailed facial geometry. In SIGGRAPH ’06: ACM SIGGRAPH 2006 Papers, pages 1025–1034, New York, NY, USA, 2006. ACM Press.

Fig. from Haro et al., Renderin Workshop 2001

Fig. 1. Silicone mold of skin (about the size of a nickel)

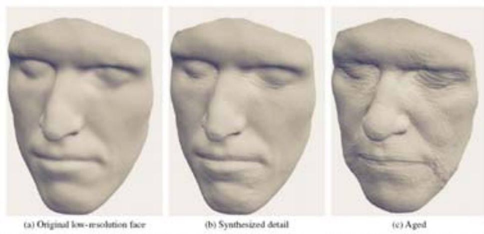
Using a molding compound to capture skin geometry

Real-time, Photo-realistic, Physically Based Rendering of

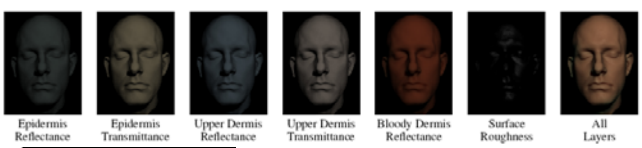
Fine Scale Human Skin Structure

A. Haro, B. Guenter, and I. Essa, Proceedings 12th Eurographics Workshop on Rendering, London, England, June 2001

Golovinskiy, A., Matusik, W., Pfister, H., Rusinkiewicz, S., and Funkhouser, T. 2006. A statistical model for synthesis of detailed facial geometry. SIGGRAPH '06. ACM, New York, NY, 1025-1034.



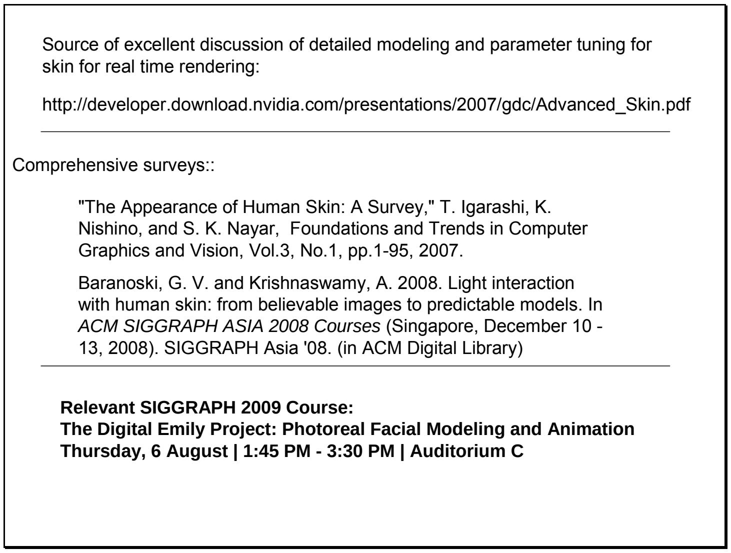
Extract detail data from scans in a form that can be reapplied.

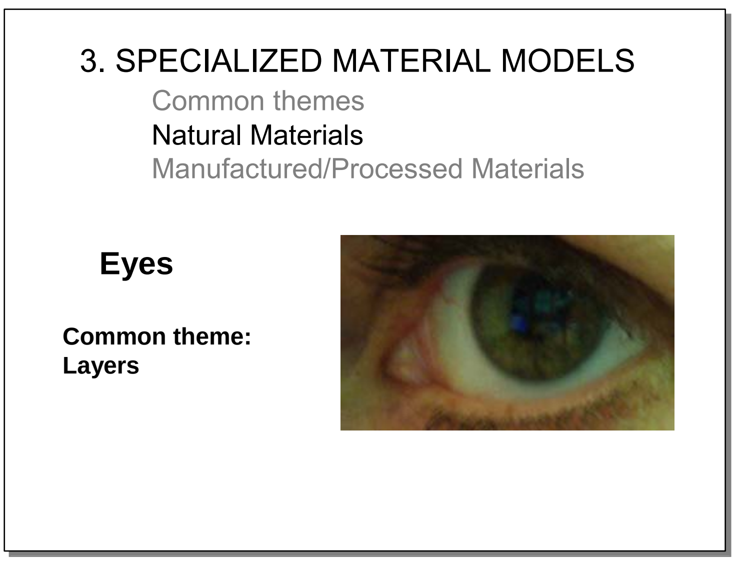


Using multiple dipoles
In thin layers:

Light Diffusion in Multi-Layered Translucent Materials
Craig Donner Henrik Wann Jensen
Proceedings of ACM SIGGRAPH 2005,

An example of combining multiple layers to form a model for skin.





Eyes have a complex appearance due to a complex layered structure. An approximation of this structure based on the manufacture of artificial eyes is given by: Aaron Lefohn, Brian Budge, Peter Shirley, Richard Caruso, and Erik Reinhard. An ocularist's approach to human iris synthesis. *IEEE Comput Graphics Appl*, 23(6):70–75, November/ December 2003.

A detailed biological model is described in:
Michael W.Y. Lam and Gladimir V.G. Baranoski. A predictive light transport model for the human iris. *Computer Graphics Forum*, 25(3):359–368, 2006.

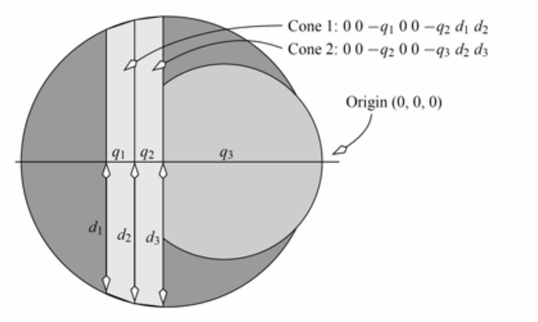


Figure from: Aaron Lefohn, Brian Budge, Peter Shirley, Richard Caruso, and Erik Reinhard. An ocularist's approach to human iris synthesis. *IEEE Comput Graphics Appl*, 23(6):70–75, November/ December 2003.

Simple geometric model of eye.

Textures for various layers that would be combined in artificial eye that together give eyes depth.

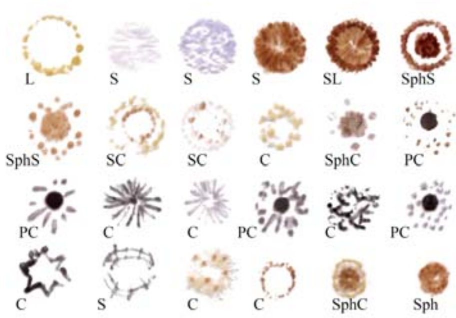


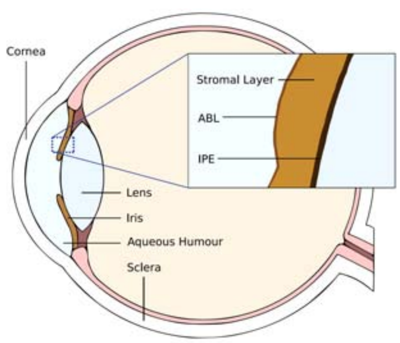
Figure from: Aaron Lefohn, Brian Budge, Peter Shirley, Richard Caruso, and Erik Reinhard. An ocularist's approach to human iris synthesis. *IEEE Comput Graphics Appl*, 23(6):70–75, November/ December 2003.

Figure from Aaron Lefohn, Brian Budge, Peter Shirley, Richard Caruso, and Erik Reinhard. An ocularist's approach to human iris synthesis. *IEEE Comput Graphics Appl*, 23(6):70–75, November/ December 2003.

Figure from: Lam,M.W.Y.; Baranoski,G.V.G.

A Predictive Light Transport Model for the Human Iris

Computer Graphics Forum, Volume 25, Number 3, 2006, pp. 359-368.



Lam and Baranoski present a biologically detailed model of the eye.

Figure from: Lam,M.W.Y.; Baranoski,G.V.G. **, 2006**

The biologically accurate model can predict eye appearance.

3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

Birds and other Non-Mammals

Common themes

--Detailed geometry modeling

Detailed geometry is important in the appearance of all animals. The details of feathers need to be modeled to render birds.A feather has a main shaft, or rachis. At the bottom of the shaft, the calamus, there is nothing attached. The vanes of the feather are formed by barbs that are attached to the rachis. Barbs are interlocked with one another by small barbules that branch off them. The vanes may be fuzzy, or plumulaceous, such as the lower section shown here or stiff, or pennaceous, as in the upper section.

3. SPECIALIZED MATERIAL MODELS

Birds

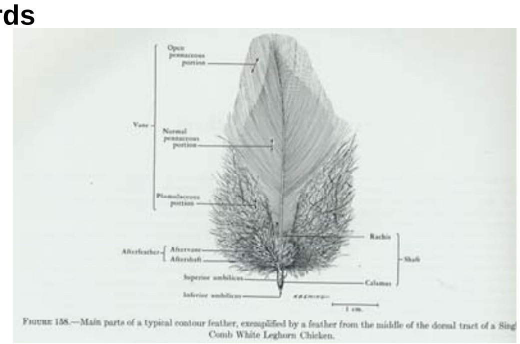


Image courtesy of Richard Prum, Yale.

A variety of methods have been proposed in graphics to model this structure:

Wen-Kai Dai, Zen-Chung Shih, and Ruei-Chuan Chang. Synthesizing feather textures in galliformes. *Computer Graphics Forum*, 14(3):407–420, August 1995.

Yanyun Chen, Yingqing Xu, Baining Guo, and Heung-Yeung Shum. Modeling and rendering of realistic feathers. In Proceedings of the 29th annual conference on Computer graphics and interactive techniques, pages 630–636.

L. Streit and W. Heidrich. A biologically-parameterized feather model. *Computer Graphics Forum*, 21(3):565–565, 2002.

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3. SPECIALIZED MATERIAL MODELS

Birds

Structural Color:

Applicable to feathers:
Yinlong Sun. Rendering biological iridescences with rgb-based renderers. *ACMTrans. Graph.*, 25(1):100–129, 2006.

Other parts of birds:
R.O. Prum and R. Torres. Structural colouration of avian skin convergent evolution of coherently scattering dermal collagen arrays. *Journal of Experimental Biology*, 206(14):2409– 2429, 2003.

3. SPECIALIZED MATERIAL MODELS

Other Non-Mammals

Simple Voronoi texture generated in Cinema4D

For other animals, most methods attempt to mimic patterns of color and small scale geometry. In particular cellular textures based on: Steven Worley. A cellular texture basis function. In *SIGGRAPH '96: Proceedings of the* 23rd annual conference on Computer graphics and interactive techniques, pages 291–294,

A method of generating of anisotropic cellular textures with examples on reptiles:
Itoh, Kazunori Miyata, and Kenji Shimada. Generating organic textures with controlled anisotropy and directionality. *IEEE Comput. Graph. Appl.*, 23(3):38–45, 2003.

3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

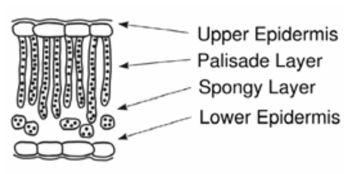
Manufactured/Processed Materials

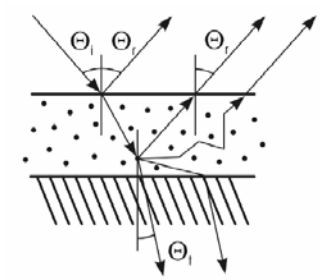
Plants

Common themes:
--Layers
---Captured Data
-- Detailed geometry

Physically detailed models of leaves are given in:
G. V. G. Baranoski and J. G. Rokne. An algorithmic reflectance and transmittance model for plant tissue. *Computer Graphics Forum*, 16(3):141–150, August 1997. ISSN 1067-7055.
Gladimir V. G. Baranoski and Jon G. Rokne. Efficiently simulating scattering of light by leaves. *The Visual Computer*, 17(8):491–505, 2001.
Lifeng Wang, Wenle Wang, Julie Dorsey, Xu Yang, Baining Guo, and Heung-Yeung Shum. Real-time rendering of plant leaves. In *SIGGRAPH '05: ACM SIGGRAPH 2005 Papers*, pages 712–719, New York, NY, USA, 2005. ACM Press.

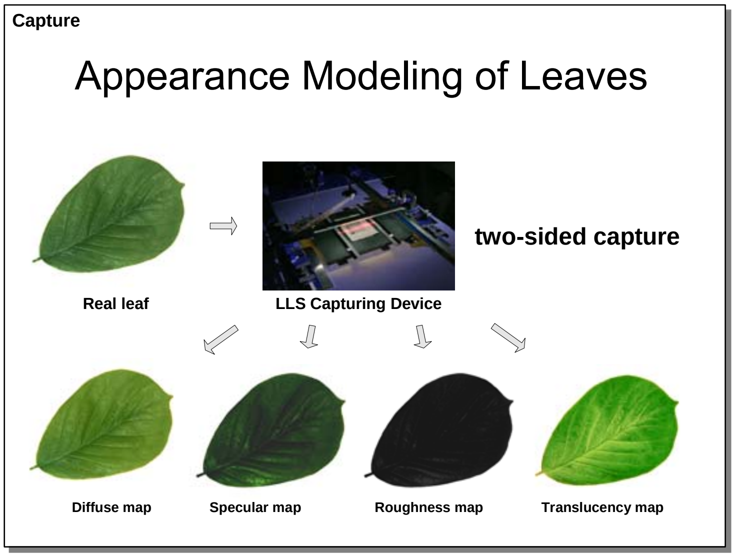
Layers:





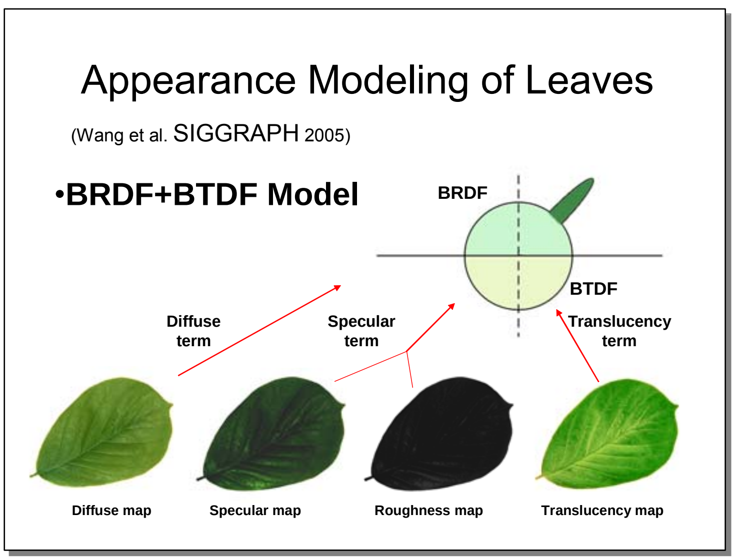
Figures from : Physically detailed models of leaves are given in:
G. V. G. Baranoski and J. G. Rokne. An algorithmic reflectance and transmittance model for plant tissue. *Computer Graphics Forum*, 16(3):141–150, August 1997. ISSN 1067-7055.

The detailed layers of plant tissue can be modeled as thin layers of scattering participating media



The spatial variation of reflectance and transmittance can be measured.

Lifeng Wang, Wenle Wang, Julie Dorsey, Xu Yang, Baining Guo, and Heung-YeungShum. Real-time rendering of plant leaves. In *SIGGRAPH '05: ACM SIGGRAPH 2005 Papers*, pages 712–719, New York, NY, USA, 2005. ACM Press.



The observations can be encoded in terms of models for reflectance and transmittance.

Sample output from appearance modeling

Detailed geomety

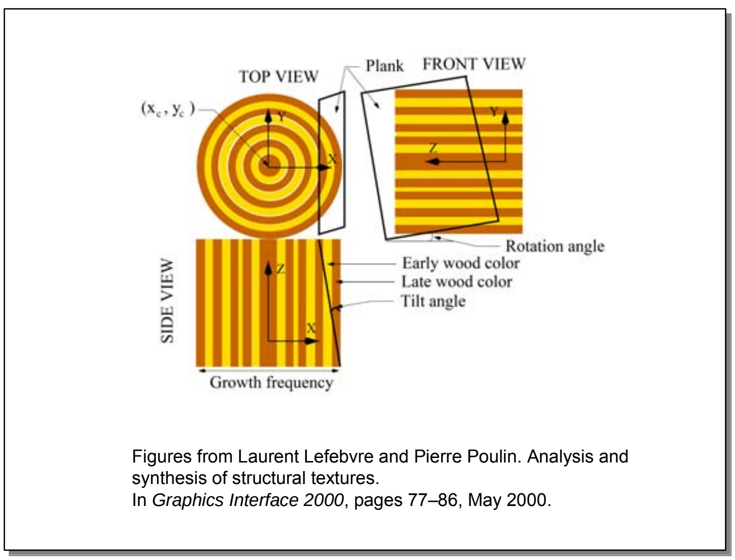
real

synthesized

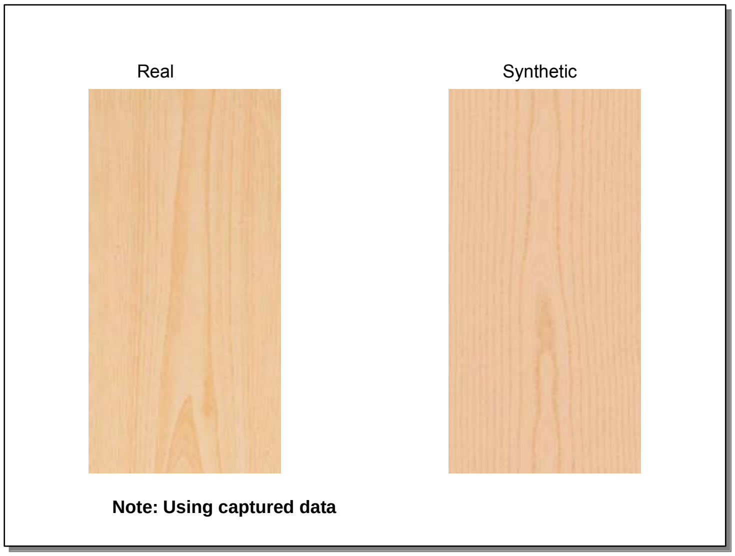
Figure from : Fuhrer, M., Jensen, H. W., and Prusinkiewicz, P. 2006. Modeling hairy plants. Graph. Models 68, 4 (Jul. 2006), 333-342.

Another feature of plants is that they may be covered by systems of small hairs. Fuhrer et al. present a method for placing and rendering such hairs.

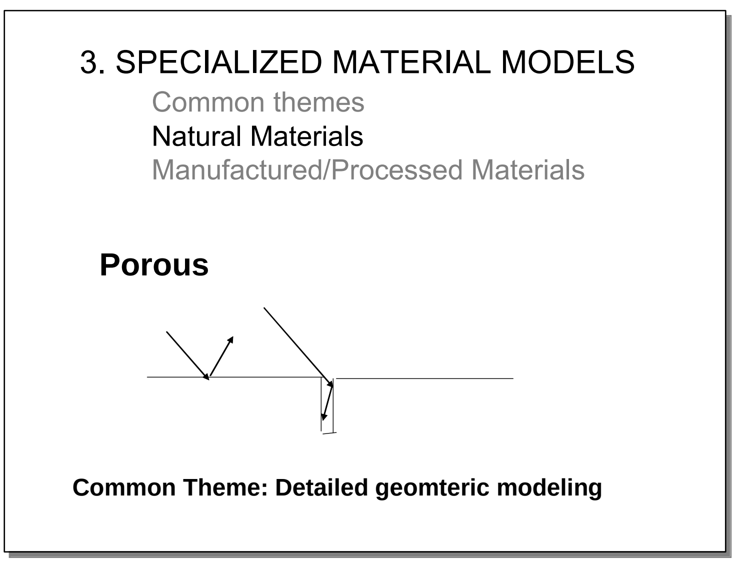
While it is a single material, wood can have a wide variety of appearance, as noted in these photographs of natural and finished wood.



Lefebre and Poulin presented a general procedural model for fitting the structure of color variation in wood.

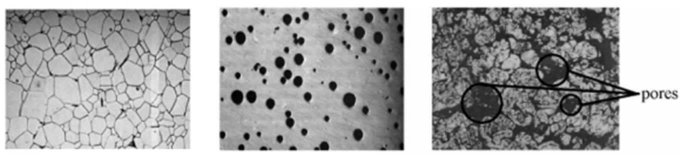


Results from Lefebvre and Poulin's work, synthesizing a new piece of wood using parameters estimated for the model from a real piece of wood.



Light incident on porous materials undergoes interreflections within pores causing darkening:S.Merillou, J.-M. Dischler, and D. Ghazanfarpour. A BRDF postprocess to integrate porosity on rendered surface. *IEEE Transactions on Visualization and Computer Graphics*, 6(4):306–318, October 2000.

Figures from A BRDF Postprocess to Integrate Porosity on Rendered Surfaces
IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER GRAPHICS, VOL. 6, NO. 4, OCTOBER-DECEMBER 2000
Stephane Merillou, Jean-Michel Dischler, Member, IEEE, and Djamchid Ghazanfarpour



ig. 3. Structural differences between porous and nonporous surfaces (microscope pictures of real materials).

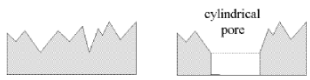


Fig. 4. (a) is the usual analytic BRDF microgeometry, (b) is the new microgeometry, showing an inserted cylindrical pore.

Pores may not be visible, but can be seen in a microscopic view

$$f_{r,poro} = k_{s,poro}.F_s + k_{d,poro}.F_d.$$

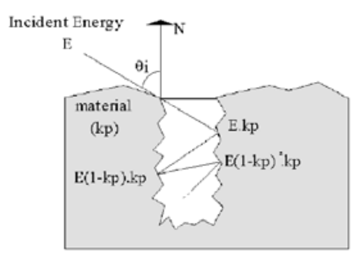
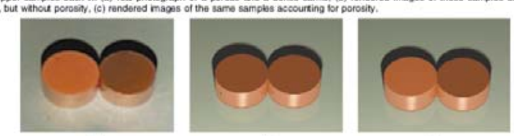


Fig. 5. Geometry of the bounce number and total loss simulation/ calculation. (The amount of energy lost on each bounce is represented.)

This figure from Merillou et al. shows the multiple reflections/absorptions that result in darkening.

(a) (b) (c)

Fig. 13. copper samples back-lit: (a) real photograph of a porous and a dense samle, (b) rendered images of these samples using measured roughness, but without porosity, (c) rendered images of the same samples accounting for porosity.



(a) (b) (c)

Fig. 14. Copper samples front-lit: (a) real photograph of a porouse and a dense sample, (b) rendered images of these samples using measured roughness, but without porosity, (c) rendered images of the same samples accounting for porosity.

From Merillou et al., comparisons to physical images.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Wet materials

Common Theme:layers
captured data

Rendering of Wet Materials
Henrik Wann Jensen Justin Legakis Julie Dorsey
Eurographics Workshop on Rendering
1999

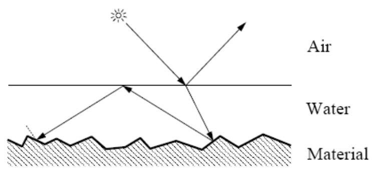


Fig. 1. A layer of water above the surface reflects less light due to the internal reflection at the water-air interface.

A top smooth layer results in specular reflection, the index of refraction of water results in total internal reflection, and so more absorption and material darkening.

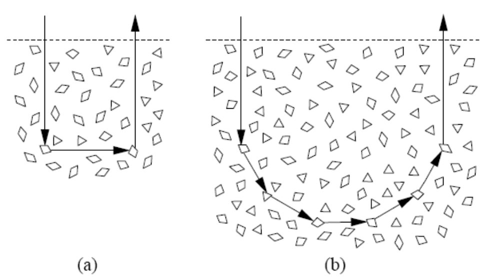


Fig. 2. After many scattering events, the shortest path a photon can take to leave the surface (a) with 90 degree average scattering angle and (b) with 30 degree average scattering angle. (Redrawn from [2].)

More scattering within the material causes more saturated color.

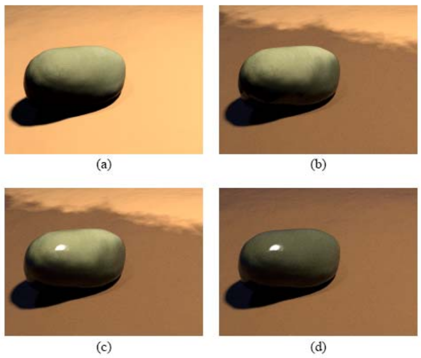


Fig. 6. Rock on sandy beach with different wetness functions. (a) dry, (b) mixed wet and dry, (c) water covering the rock and (d) completely wet.

$$f(cos\theta, g_1, g_2, w) = w\frac{1-g_1^2}{(1-2g_1\cos\theta-g_1^2)^{1.5}}+(1-w)\frac{1-g_2^2}{(1-2g_2\cos\theta+g_2^2)^{1.5}}$$

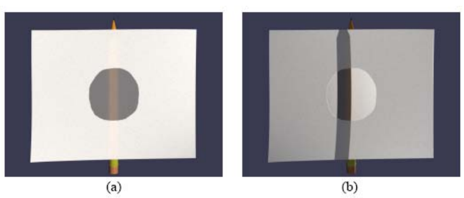
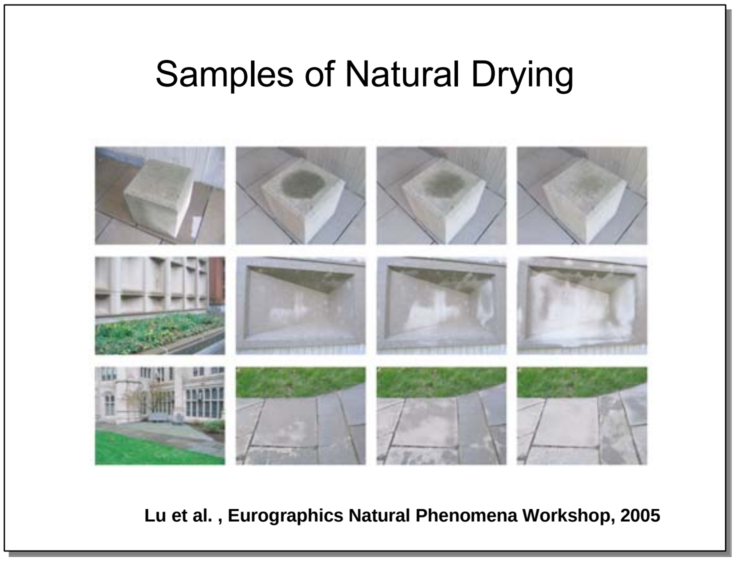


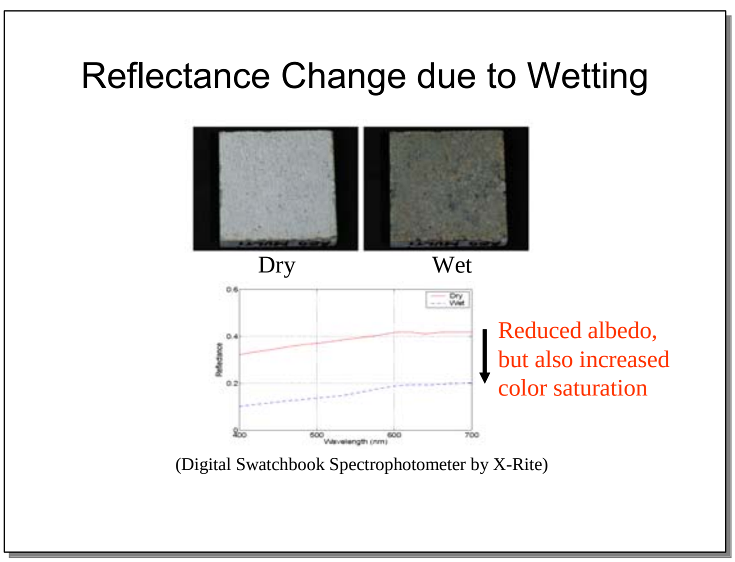
Fig. 5. Wet Paper: (a) light source in front of the paper, (b) light source behind the paper.

The wet spot is created by modulating the phase function from the dry value $g_1 = 0.05$, $g_2 = -0.05$ and $w = 0.2$ to the wet value $g_1 = 0.8$, $g_2 = -0.1$ and $w = 0.1$. This change makes the forward scattering much stronger, and this is the reason for the different appearance of the wet spot.

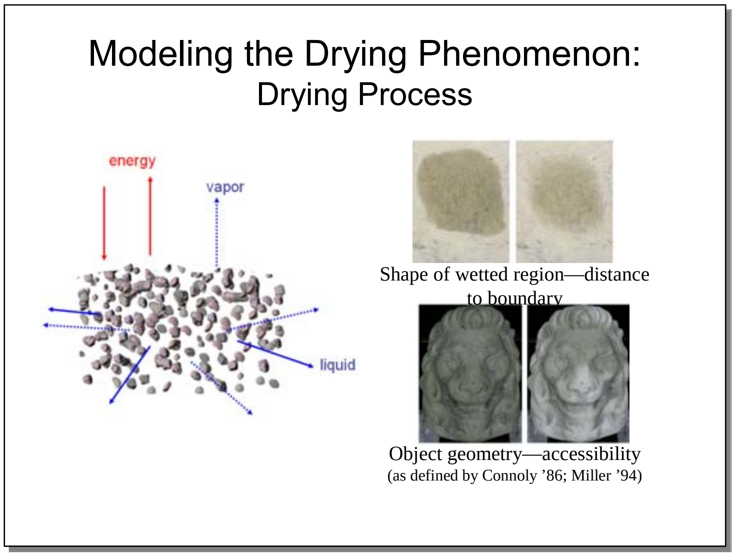
Forward scattering and index of refraction of water result in coherent transmission through a thin material.



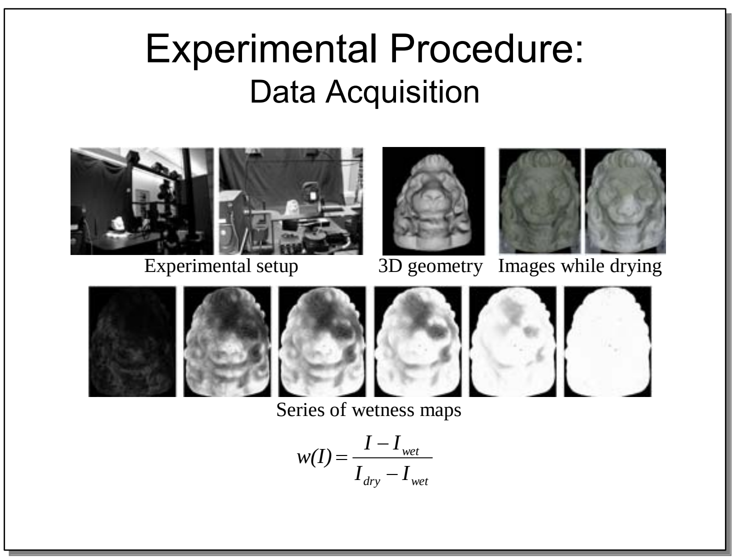
Observations of geometric variation of wet materials.



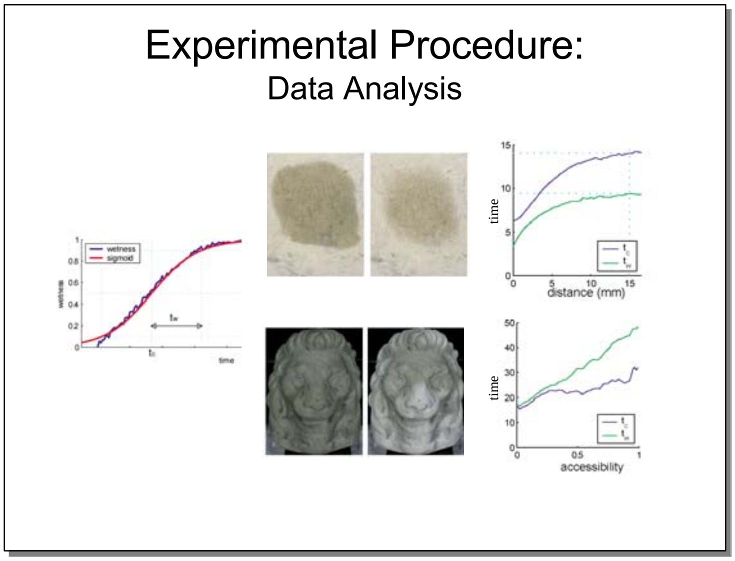
Increased saturation of material captured with digital photography.



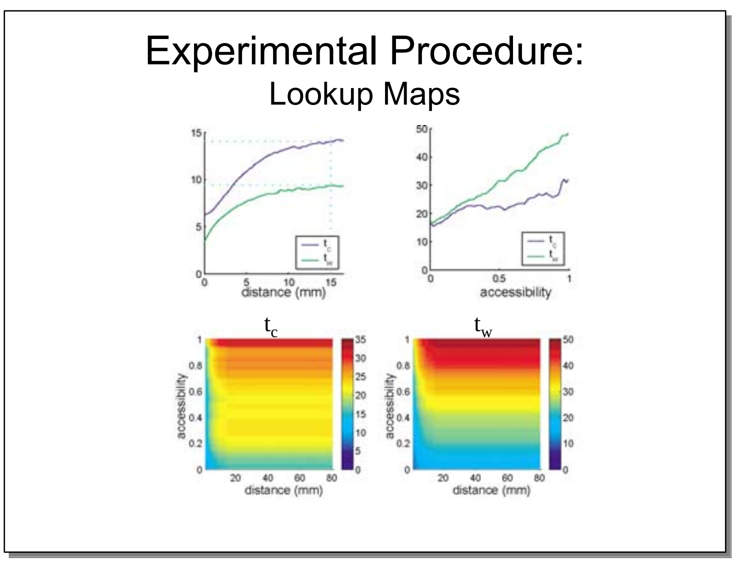
Evaporation and flow in the material contribute to drying. This means ambient occlusion (for evaporation) and distance to edge (flow in material) are significant parameters for estimating the drying pattern.



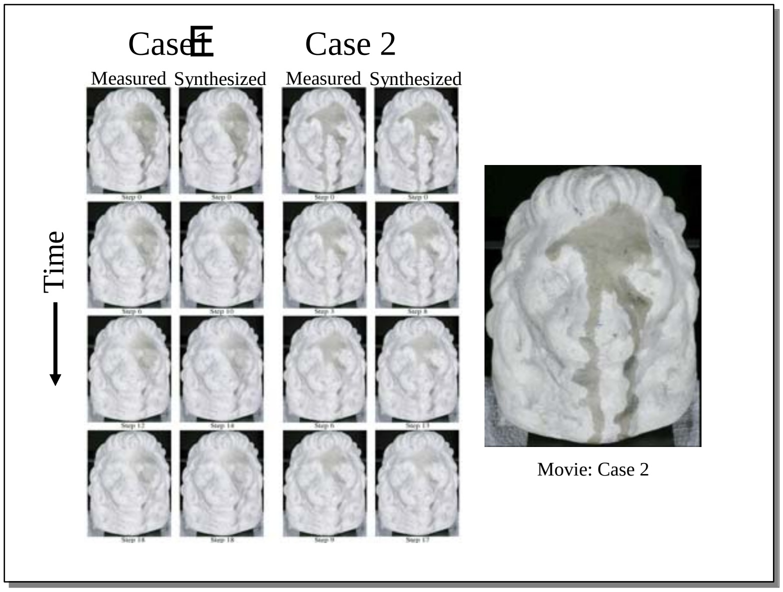
A “wetness” map is estimated for an object photographed at different times as it dries.



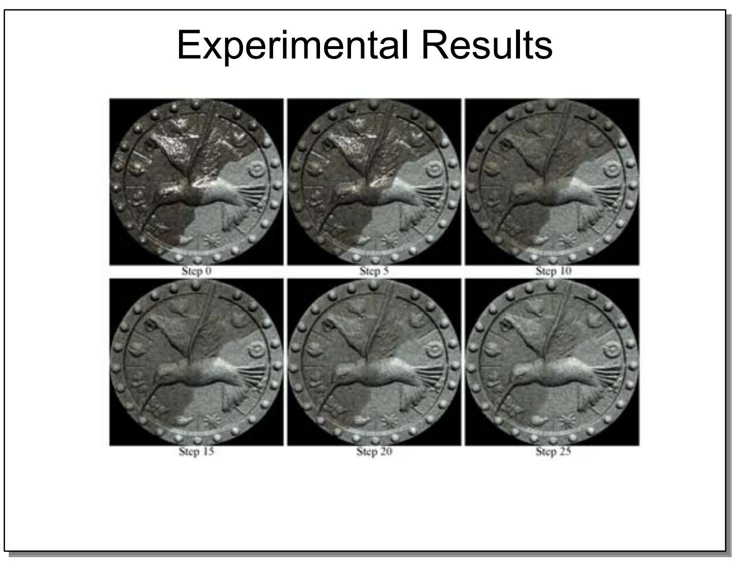
Functions can be fit to the drying time as a function of distance to edge and the ambient occlusion (or the accessibility)



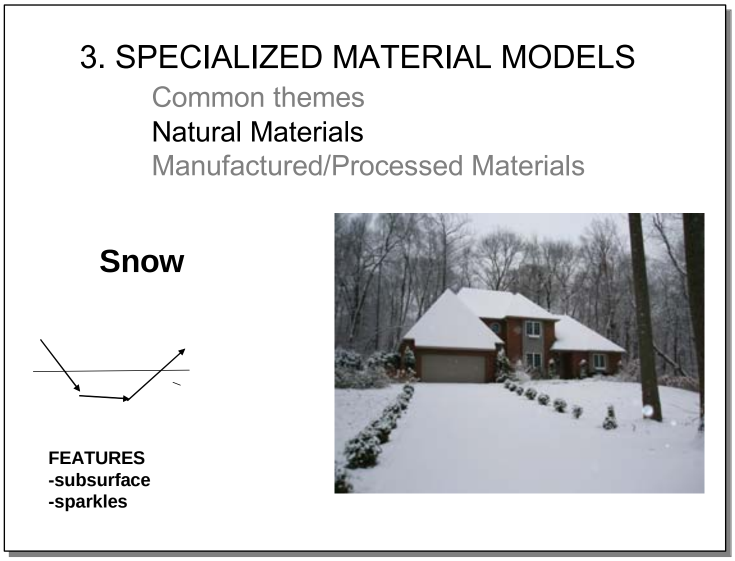
The parameters for these functions are stored as look up maps.



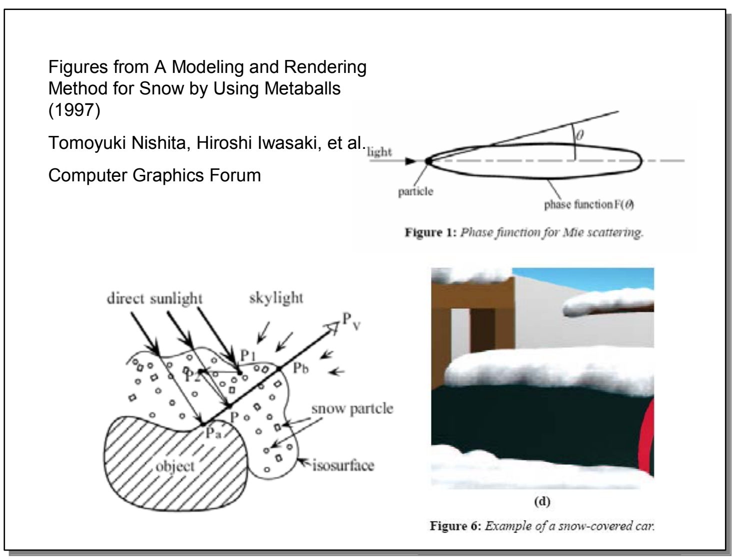
Examples of using the model compared to ground truth.



Applying the model to a synthetic example.



Important features in realistic snow are subsurface scattering within snow, and the sparkles caused by mirror reflections from individual crystals. T. Nishita, H. Iwasaki, Y. Dobashi, and E. Nakamae. A modeling and rendering method for snow by using metaballs. *Computer Graphics Forum*, 16(3):357–364, August 1997.



Nishita et al. presented a model of snow as a participating medium with embedded particles for “sparkle”

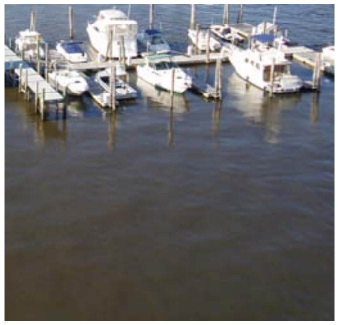
3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

Water



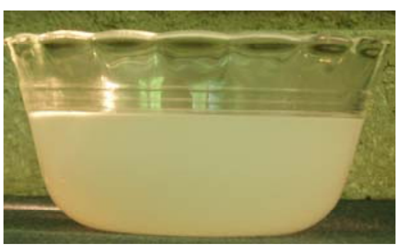
Natural waters are colored by scattering from suspended particles

We often see particles or other material suspended in water -- especially in natural settings such as ponds, rivers, lakes and oceans. These effects are discussed in more depth in the SIGGRAPH 09 course: Scattering, Thursday, 6 August | 1:45 PM - 5:30 PM | Room 265-266

Approaches:

First Principles Modeling of Scattering

Measurement of Scattering Properties



Dilute milk—
Fat globules in suspension

A detailed description of unique underwater scattering effects, including fluorescence and Raman scattering is given in:
D. Gutierrez, F. Seron, O. Anson, and A. Munoz, *Visualizing underwater ocean optics*, Computer Graphics Forum (EUROGRAPHICS 2008), 27, pp. 547--556.

Measurement of suspended particles is described in:
Srinivasa G. Narasimhan , Mohit Gupta , Craig Donner , Ravi Ramamoorthi , Shree K. Nayar , Henrik Wann Jensen, Acquiring scattering properties of participating media by dilution, ACM Transactions on Graphics (TOG), v.25 n.3, July 2006

3. SPECIALIZED MATERIAL MODELS

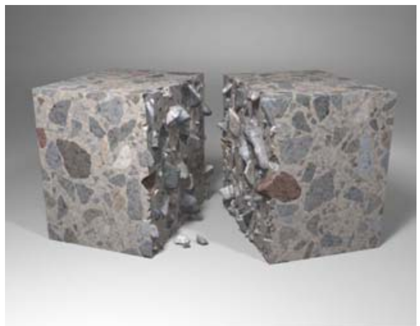
Common themes

Natural Materials

Manufactured/Processed Materials

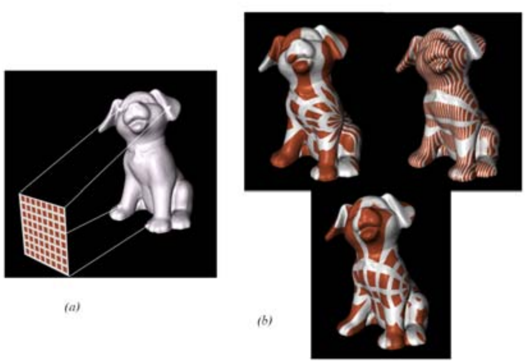
Rocks

Common
Detailed geometry
Captured datga

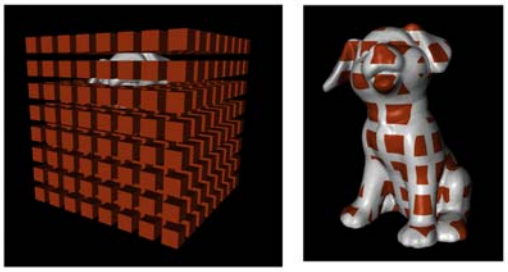


Modelling rocks requires modeling macroscopic 3D structure.

Stones, Rocks are Volumetric Materials



2D textures are inconvenient for modeling truly 3D materials such as rock/stone.



(a) (b)

Solid textures allow the separate modeling of material geometry and object geometry.

Volume 26 (2007), number 1 pp. 66–79
COMPUTER GRAPHICS *forum*
Modeling and Rendering of Heterogeneous Granular Materials: Granite Application
Romain Souli´e, St´ephane M´erillou, Olivier Romain, Terraz Djamchid and Romain Ghazanfarpour

Modeling process of heterogeneous granular materials using 3DVorono¨ diagrams to obtain a full representation of their structure.

Rendering process based on photon mapping to simulate subsurface scattering inside these materials, presented in

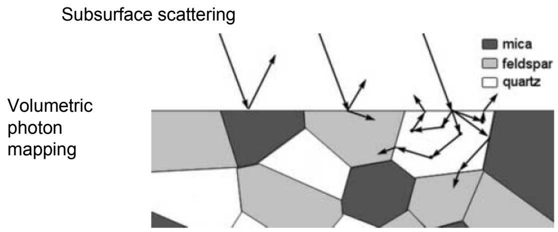


Figure 8: *Light propagation in the granitic materials.*

Material	Scattering Coefficient	Absorption Coefficient
Mica	3.15	0.0021
Quartz	2.19	0.0034
Feldspar	2.52	0.0041

Figure 9: *Materials coefficients used in rendering process.*

Figures from Soulie et al. modeling granite: the geometry is modelled using a 3D Voronoi diagram, and subsurface scattering is modeled for the individual granite components of mica, feldspar and quarts.

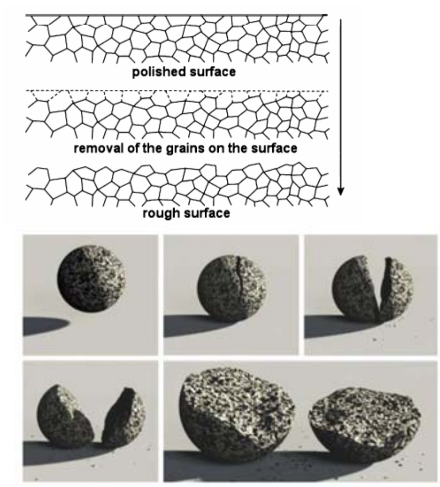
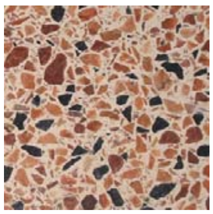


Figure from Soulie et al., modeling the material 3D structure allows modeling of geometry that is consistent with the material.

Using 2D for 3D causes multiple kinds of problems, particularly for structures



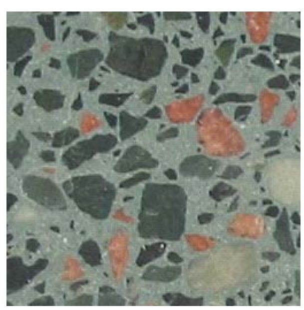
Input

Heeger & Bergen, ’95

Texture synthesis such as Heeger and Bergen’s spectral analysis fail for materials made of discrete particles embedded in a matrix.

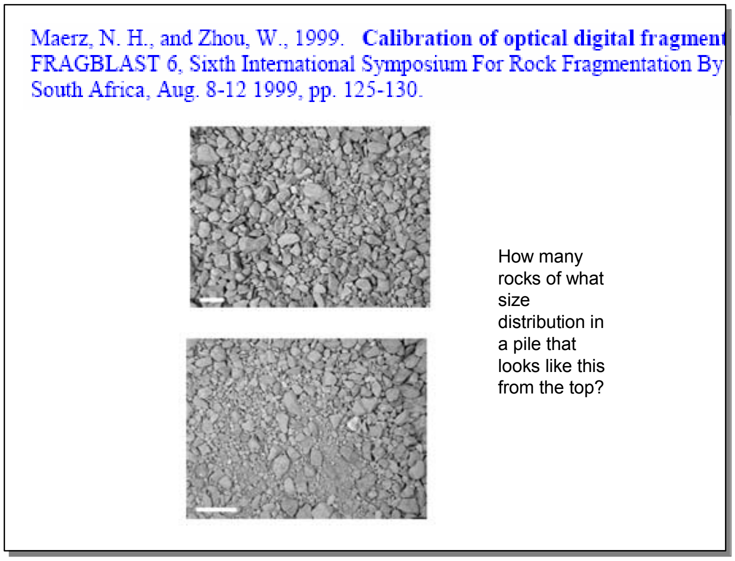
Problem Decomposition…

- Color
- Particle shape
- Particle distribution
- Residual noise

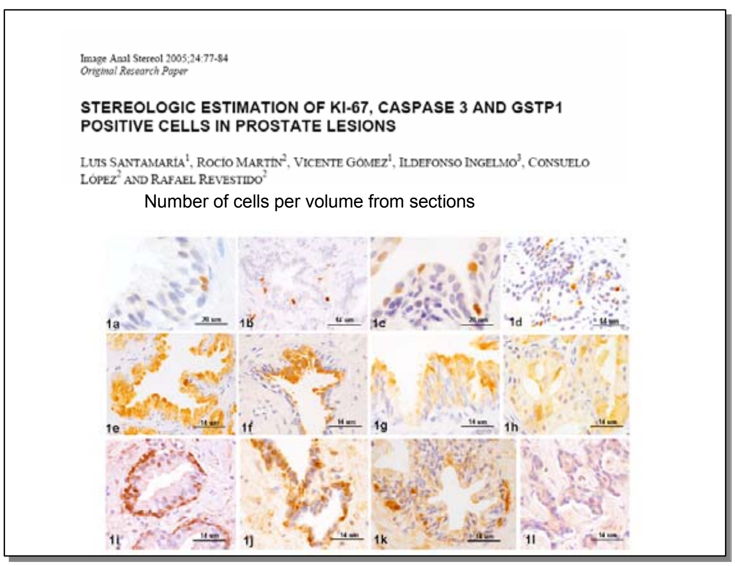


Stereological Techniques for Solid Textures

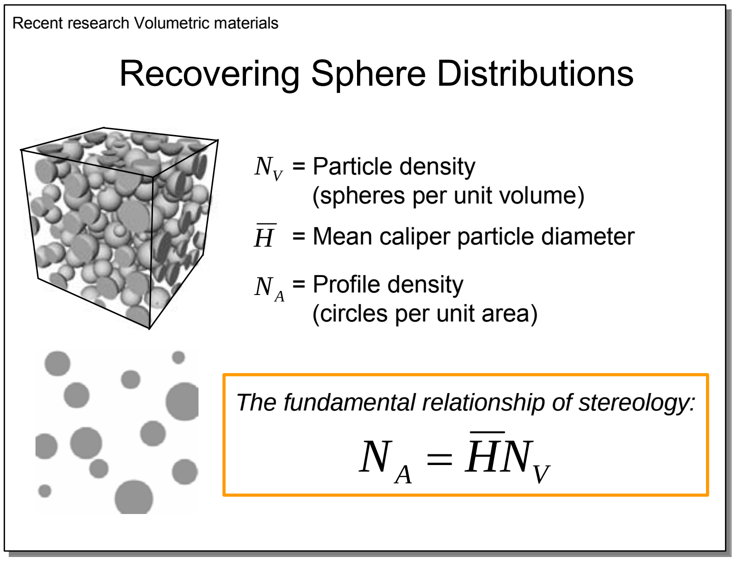
Jagnow, Dorsey, Rushmeier,SIGGRAPH 2004



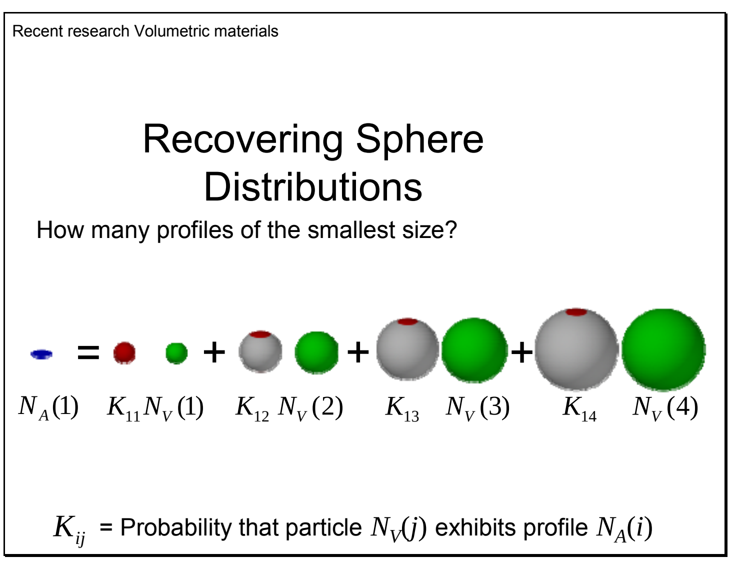
Stereology is used in the construction industry to estimate rock distributions.



Stereology is also used in biology to estimate 3D distributions fom 2D slices

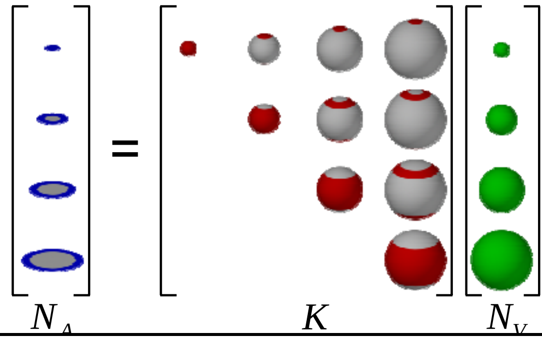


The distribution of 2D diameters in a slice is related to , but not the same as the 3D distribution.



Recovering Sphere Distributions

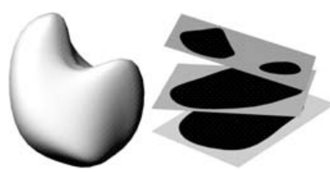
Putting it all together…

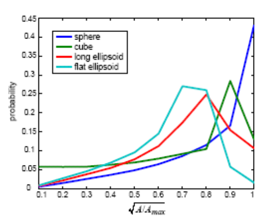


Recent research Volumetric materials

Particle Statistics

Look at thousands of random slices to obtain K and $\bar{H}$





Example probabilities of $\sqrt{A/A_{\max}}$ for simple particle types

For particles that aren't spheres, the relation between 2D and 3D needs to be calculated

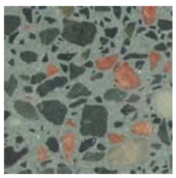
Recent research Volumetric materials

Other Particle Types

We cannot classify arbitrary particles by d/d_{max}

Instead, we choose to use $\sqrt{A/A_{\max}}$

Algorithm inputs:



+

Approach: Collect statistics for 2D profiles *and* 3D particle

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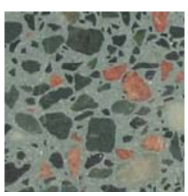
Profile Statistics

Segment input image to obtain profile densities N_A.



Bin profiles according to their area, $\sqrt{A/A_{\max}}$

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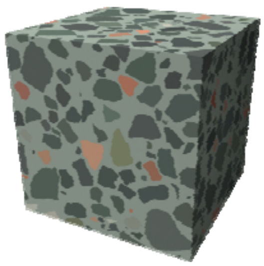
Recovering Particle Distributions

Just like before, $N_A = \overline{H} K N_V$

Solving for the particle densities, $N_V = \frac{1}{H} K^{-1} N_A$



Use N_V to populate a synthetic volume.

Color using mean particle colors from the input image

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Recovering Noise

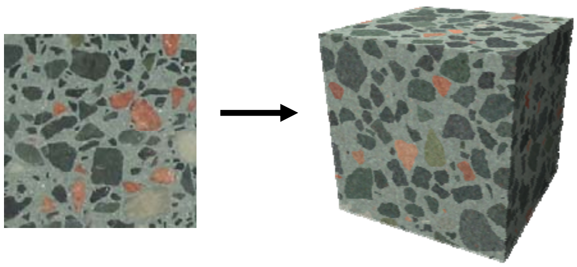
How can we replicate the noisy appearance of the input?

The noise residual is less structured and responds well to Heeger & Bergen's method

Some noise is needed, or results look too "pristine"

Recent research Volumetric materials

Putting it all together



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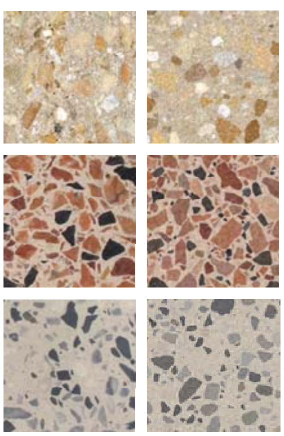
Results



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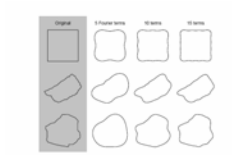
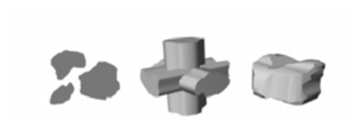
But how do you get the particle shapes?
How good do they have to be?

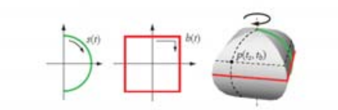
spherical harmonics



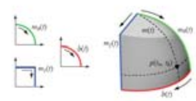
CSG



generalized cylinder



morphed generalized cylinder



Jagnow et al., ACM Transactions on Applied Perception, 2008

There is no single way to estimate particle shape from a single slice.

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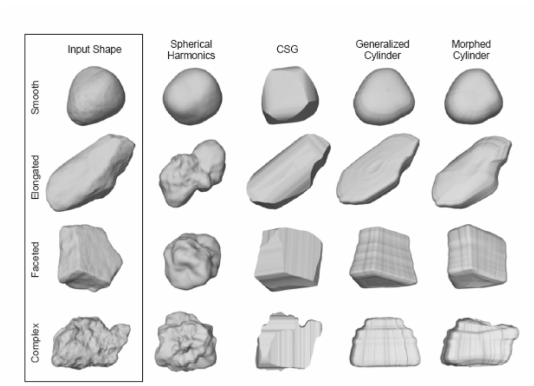

Which is better? Are results really different when viewing 2D sections?

A psychophysical test is needed to find which estimation technique is best.

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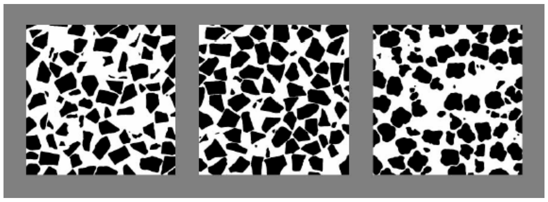
Applied Perception: Do Psychophysical Experiment

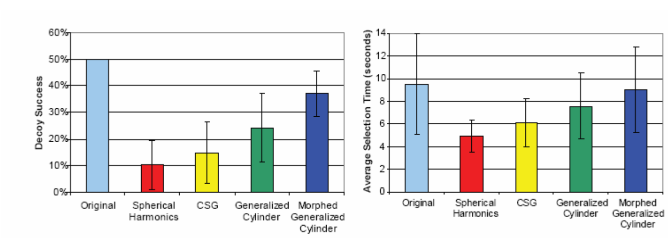


Which is the slice through the same material shown in the center?

An example of one screen view from the psychophysical test.

Recent research Volumetric materials

Results for all particle types combined



Success (50% max)   Timing

16 subjects, 80 tests; 5 method (including nul), 4 particle types

Results of test across different particle shapes.

Related issues:

General 3D Texture Synthesis

Perception of Materials

This study of touches on two areas synthesizing 3D materials and perceptual experiments .

Subsequent work on 3D texture synthesis can be found in:

Solid texture synthesis from 2d exemplars, Kopf, J. and Fu, C. and Cohen-Or, D. and Deussen, O. and Lischinski, D. and Wong, T., ACM transactions on graphics 26(3), 2007.

and

Lazy Solid Texture Synthesis, Dong, Y. and Lefebvre, S. and Tong, X. and Drettakis, G., Computer Graphics Forum, 27(4), pp. 1165—1174, 2008.

Studies on the perception of materials:

Ganesh Ramanarayanan , James Ferwerda , Bruce Walter Kavita Bala, Visual equivalence: towards a new standard for image fidelity, ACM Transactions on Graphics (TOG), v.26 n.3, July 2007

Peter Vangorp , Jurgen Laurijssen , Philip Dutré, The influence of shape on the perception of material reflectance, ACM Transactions on Graphics (TOG), v.26 n.3, July 2007

Ganesh Ramanarayanan , Kavita Bala , James A. Ferwerda, Perception of complex aggregates, ACM Transactions on Graphics (TOG), v.27 n.3, August 2008

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Finished Wood
Textiles

Fibers
Threads
Knitted
Woven

Automotive Paint
Artistic Paint
Gems

3. SPECIALIZED MATERIAL MODELS

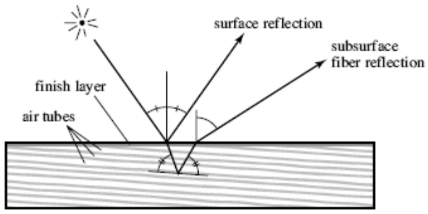
Common themes
Natural Materials
Manufactured/Processed Materials

Finished Wood

Common themes:
Detailed geometry
Layers
Capatured data

Finished wood can have a lustrous appearance that results from the internal orientation of the wood fibers, combined with the reflection and transmission from the smoothed finished top surface. Marschner et al. modeled this reflectance as a Gaussian function g that depends on parameters Psi that depend on the orientation of the wood fibers and the surface normal.

Stephen R. Marschner, Stephen H. Westin, Adam Arbree, and Jonathan T. Moon. Measuring and modeling the appearance of finished wood. *ACM Trans. Graph.*, 24(3):727–734, 2005.



Unfinished wood: top surface rough, diffuse reflectance dominates

Finished wood: top surface smooth, subsurface fiber reflectance noticeable

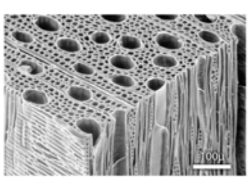
Figure from Marschner et al 2005, similar to wet surfaces, smooth surface from finish layer produces specular refection.

Measuring and Modeling the Appearance of Finished Wood

Stephen R. Marschner, Stephen H. Westin, Adam Arbree, and Jonathan T. Moon

SIGGRAPH 2005

Scattering from fibers in wood



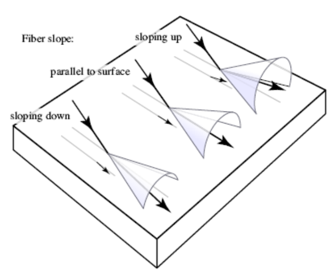


Figure 1: The basic shape of the *subsurface* reflection from fibers inclined downward, parallel to the surface, and inclined upward. Models for anisotropic *surface* reflection produce results similar to the center drawing.

Similar to hair analysis, orientation of wood fibers influences orientation of reflection.

Specular — Through finish — Fiber reflectance

$$f_r(\mathbf{v}_i,\mathbf{v}_r) = f_s(\mathbf{v}_i,\mathbf{v}_r) + T_i T_r(\rho_d + f_f(\mathbf{u},\mathbf{v}_i,\mathbf{v}_r))$$

Fiber reflectance, modeled as Gaussian

$$f_f(\mathbf{u},\mathbf{v}_i,\mathbf{v}_r) = k_f \frac{g(\beta,\psi_h)}{\cos^2(\psi_d/2)}$$

where

$$\psi_i = \sin^{-1}(s(\mathbf{v}_i)\cdot\mathbf{u}) \qquad \psi_d = \psi_r - \psi_i$$

$$\psi_r = \sin^{-1}(s(\mathbf{v}_r)\cdot\mathbf{u}) \qquad \psi_h = \psi_r + \psi_i$$

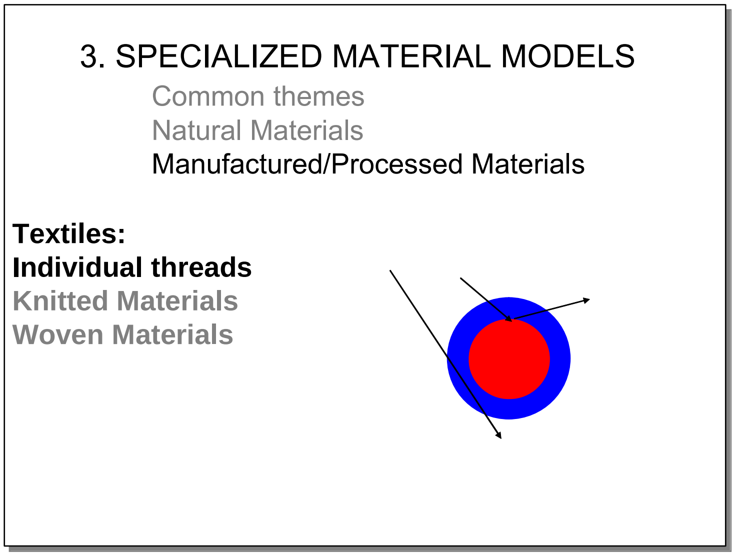
From Marschner et al.2005, full model for finished wood.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Textiles:
Individual threads
Knitted Materials
Woven Materials

Common theme:
Detailed geometry



The structure of individual threads may be designed to give particular optical effects, such as looking a different color from different view angles.

B. Rubin, H. Kobsa, and S. M. Shearer. Prediction and verification of an iridescent synthetic fiber. *Appl. Opt.*, 36:6388–6392, 1997.

3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

Textiles:

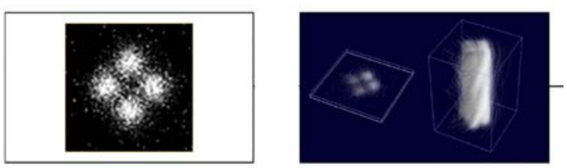
Individual threads

Knitted Materials

Woven Materials

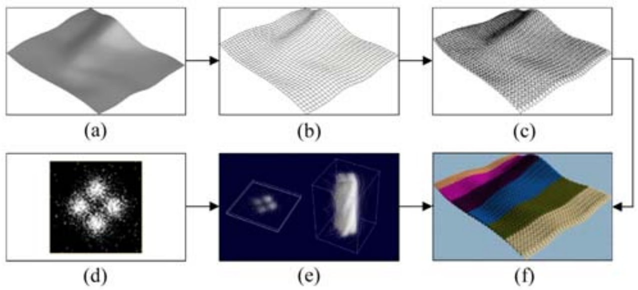
Specialized volumetric structures have been proposed to model the fuzzy nature of knitwear: Eduard Groeller, Rene T. Rau, and Wolfgang Strasser. Modeling and visualization of knitwear. *IEEE Transactions on Visualization and Computer Graphics*, 1(4):302–310, 1995.

Yarn is loose, fluffy grouping of fibers:



Ying-Qing Xu, Yanyun Chen, Stephen Lin, Hua Zhong, Enhua Wu, Baining Guo, and Heung-Yeung Shum. Photorealistic rendering of knitwear using the lumislice. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques*, pages 391–398. ACM Press, 2001.

Xu et al. model yarn as volume of fibers formed by twisting a scatter diagram in 2D along a 3D axis.



(the Lumislice)

From Xu et al. 2001, a full knitted fabric is formed from the volumetric model applied along a pattern of knitted stiches.

3. SPECIALIZED MATERIAL MODELS

Common themes

Natural Materials

Manufactured/Processed Materials

Textiles:

Individual threads

Knitted Materials

Woven Materials

The reflectance of individual threads, effect of light going through threads and weaving patterns need to be accounted for in realistically rendering woven materials Neeharika Adabala, Guangzheng Fei, and Nadia Magnenat-Thalmann. Visualization of woven cloth. *Proceedings of the 14th Eurographics workshop on Rendering*, Leuven, Belgium, 2003. pages 178–185.

Neeharika Adabala, Guangzheng Fei, and Nadia Magnenat-Thalmann. Visualization
of woven cloth. *Proceedings of the 14th Eurographics workshop on Rendering*, Leuven, Belgium, 2003. pages 178–

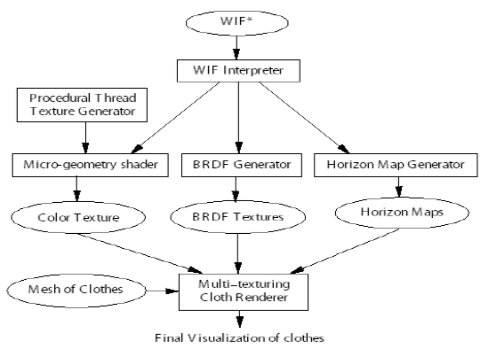


Figure from Adabla et al. showing complete process for modeling woven cloth.

Neeharika Adabala, Guangzheng Fei, and Nadia Magnenat-Thalmann. Visualization
of woven cloth. *Proceedings of the 14th Eurographics workshop on Rendering*, Leuven, Belgium, 2003. pages 178–185.

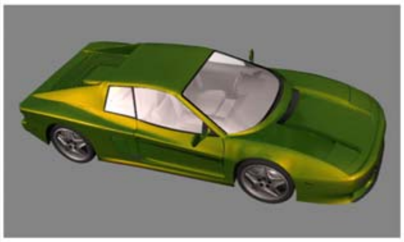
Figure showing side by side images of photographs of real cloth and the simulations performed by Adabala et al.

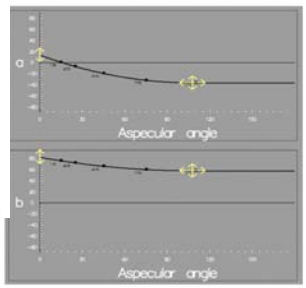
Slide 14

A first principles model for automotive paint, including the "depth" effect given by multiple layers and sparkles caused by reflections off small particles is given in: Sergey Ershov, Konstantin Kolchin, and Karol Myszkowski. Rendering pearlescent appearance based on paint-composition modelling. *Computer Graphics Forum*, 20(3), 2001. Sergey Ershov, Roman Durikovic, Konstantin Kolchin, and Karol Myszkowski. Reverse engineering approach to appearance-based design of metallic and pearlescent paints. *Vis. Comput.*, 20(8-9):586–600, 2004.
Roman Durikovic and William L. Martens. Simulation of sparkling and depth effect in paints. In *SCCG '03: Proceedings of the 19th spring conference on Computer graphics*, pages 193–198, New York, NY, USA, 2003. ACM Press

The change of color with angle for metallic car paints is modeled in a system for automotive finish design in:
Gary Meyer, Clement Shimizu, Alan Eggly, David Fischer, Jim King, and Allan Rodriguez.Computer aided design of automotive finishes. In *Proceedings of 10th Congress of the International Colour Association*, pages 685–688, 2005.

Gary Meyer, Clement Shimizu, Alan Eggly, David Fischer, Jim King, and Allan Rodriguez.
Computer aided design of automotive finishes. In *Proceedings of 10th Congress of the International Colour Association*, pages 685–688, 2005.





An interface for designing the change in paint color with view.

Johannes G¨unther, Tongbo Chen, Michael Goesele, Ingo Wald, and Hans-Peter Seidel.
Efficient acquisition and realistic rendering of car paint. In G¨unther Greiner, Joachim Hornegger, Heinrich Niemann, and Marc Stamminger, editors, *Proceedings of 10th International Fall Workshop - Vision, Modeling, and Visualization (VMV) 2005*, pages 487–494.

Using captured data to fit a multilobed Cook Torrance Model

Figure from Guenther et all using a paint model based on data capture.

Sergey Ershov, Konstantin Kolchin, and Karol Myszkowski. Rendering pearlescent appearance based on paint-composition modelling. *Computer Graphics Forum*, 20(3), 2001. ISSN 1067-7055.

Detailed geometric information within layers

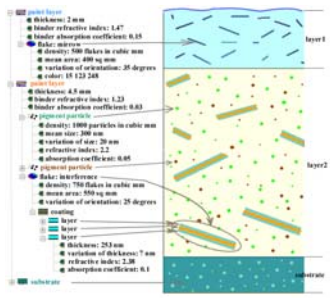
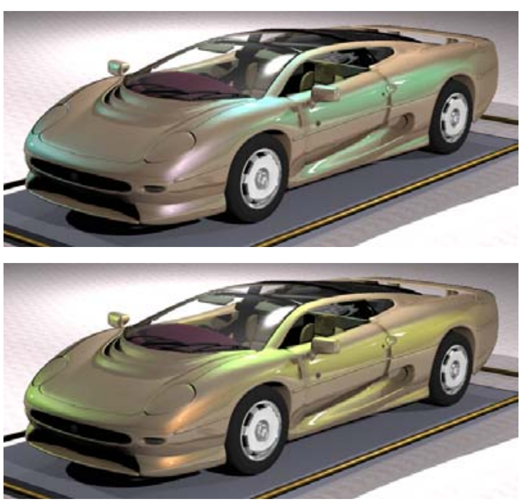


Figure from Ershov showing the detailed paint structure used in a first principles model.



Figures from Ershov et al. 2001 showing results

Artistic paints, particularly water colors, are modeled as particulates carried by a fluid modeled with either a shallow fluid model:

Cassidy J. Curtis, Sean E. Anderson, Joshua E. Seims, KurtW. Fleischer, and David H. Salesin. Computer-generated watercolor. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, pages 421–430. ACM Press/Addison-Wesley Publishing Co., 1997.

Or a Lattice-Boltzmann model:

Nelson S.-H. Chu and Chiew-Lan Tai. Moxi: real-time ink dispersion in absorbent paper. *ACM Trans. Graph.*, 24(3):504–511, 2005.

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

Artistic Paints

3. SPECIALIZED MATERIAL MODELS

Common themes
Natural Materials
Manufactured/Processed Materials

GEMS

Some geometric detailed modeling,
Make use of advanced optics effects

Yinlong Sun: Dispersion Rendering

Rendering by Yinlong Sun showing colors in a diamond produced by accounting for dispersion.

Rendering gems with aterism or chatoyancy

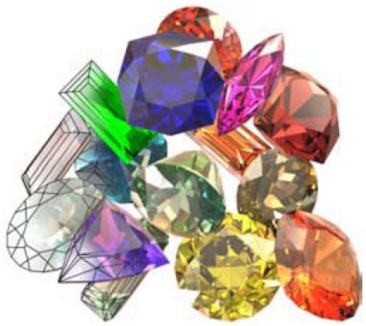
Shigeki Yokoi, Kosuke Kurashige and Jun-ichiro Toriwaki

The Visual Computer, Volume 2, Number 5 / September, 1986

Bright patterns in gems like "cat's eyes" and sapphires

These are caused by ellipsoidal inclusions of material in the gem, and are accounted for using a volume rendering method.

Guy, S. and Soler, C. 2004. Graphics gems revisited: fast and physically-based rendering of gemstones. *ACM Trans. Graph.* 23, 3 (Aug. 2004), 231-238.



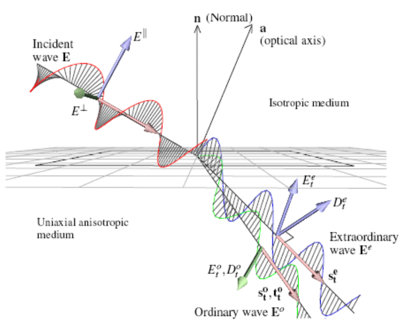


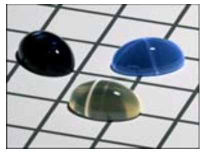
Figure 1: Formation of an ordinary and extraordinary ray when an incident light ray encounters an anisotropic medium.

Different polarizations, different directions, different amounts absorbed by the material

Figure from from Guy and Soler. For many types of gems polarization effects must be taken into account.

Pseudochromatic Color of Crystals

- Dispersion
- Asterism and Chatoyance
- Aventurescence
- Opalescence
- Labradorescence.



Chatoyance modeled and rendered by Weidlich

Recently Andrea Weidlich has done a comprehensive study of the structural colors in gems and precious stones, that encompasses the phenomena just noted, as well as others. A detailed analysis is avialable in her dissertation:

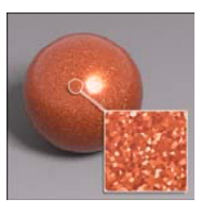
“Pseudochromatic Colourisation of Crystals in Predictive Image Synthesis”, TU Wien, 2009.

http://www.cg.tuwien.ac.at/research/publications/2009/weidlich-2009-thesis/

Pseudochromatic Color of Crystals

- Aventurescence

Aventurescence: glittering crystalline metallic inclusions



Modeled and rendered by Weidlich

WEIDLICH, A. and WILKIE, A. 2008: Modeling Aventurescent Gems with Procedural Textures. In: Proceedings of the Spring Conference on Computer Graphics (SCCG), pp. 1–8. ACM

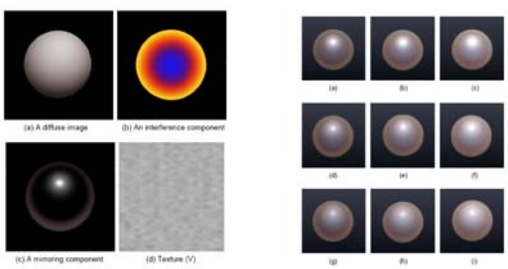
Pseudochromatic Color of Crystals

- Opalescence – diffraction phenomena
- Labradorescence – interference from multiple pairs of thin layers

See "Pseudochromatic Colourisation of Crystals in Predictive Image Synthesis", TU Wien, 2009 for multiple images of each effect, both photographed and simulated.

Andrea Weidlich, Alexander Wilkie
Rendering the Effect of Labradorescenc
In Proceedings of Graphics Interface 2009,
May 2009.

IEEE TR.
VISUALI.
GRAPHI
DECEME
Modeling
for a Pea
Noriko N.
Yoshitsu
Teruo Us



Pearls are produced organically, unlike the other gems discussed. These figures are from Nagata et al. 1997, showing the results of modeling pearls using different layers to model diffuse reflectance, interference effects, specular reflection, and spatial variations.

4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

The area of aging and weathering processes is critical in modeling natural variations in materials. Many very detailed models have been developed. A general view of the area is given by organizing the detailed models into three general categories.

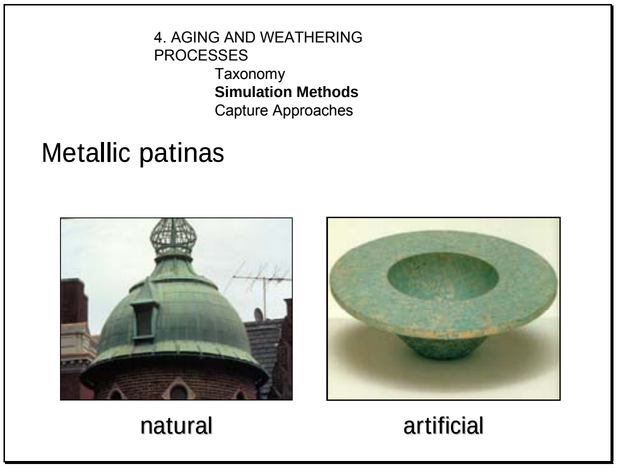
Taxonomy

Chemical Reactions

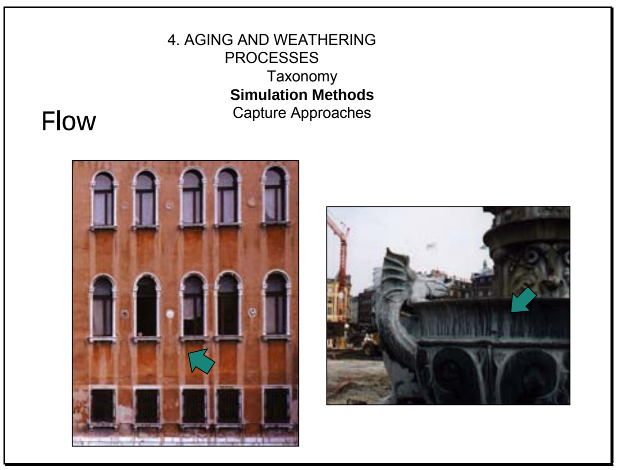
Mechanical Processes

Biological Growth

- Chemical Reactions like rusting or patination
- Mechanical Processes like paint crackling and peeling
- Biological Growth like algae, moss or mold growing



Metals often develop a characteristic patina over time. The patination process, which develops in a series of thin surface layers, is due to the chemical alteration of a surface and results in changes in color. Patination may be the result of deliberately applied craft processes or natural corrosion.



The flow of water is one of the most pervasive and important natural forces involved in the weathering of materials — producing a distinctive set of patterns of washes and stains. These photographs show the weathering of various buildings. Water may wash dirt from some areas and clean them; in other areas dirt and other materials are deposited, creating stains. The result is a visually rich set of patterns that are difficult to model with most texturing techniques.

4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Rust

Stephane Merillou, Jean-Michel Dischler, and Djamchid Ghazanfarpour. Corrosion: Simulating and rendering. In *GI 2001*, pages 167–174, June 2001.

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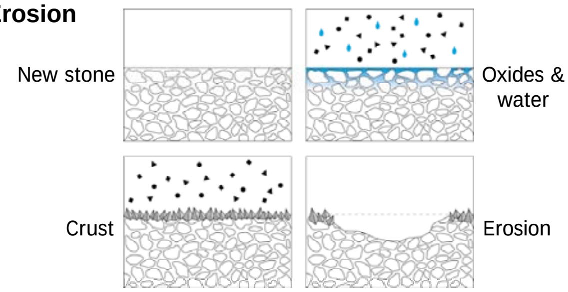
4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Erosion



Julie Dorsey, Alan Edelman, Henrik Wann Jensen, Justin Legakis, and Hans Kohling Pedersen. Modeling and rendering of weathered stone. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pages 225–234. ACM Press/Addison-Wesley Publishing
Co., 1999.

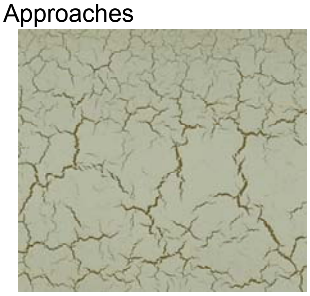
4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Cracking



Koichi Hirota, Yasuyuki Tanoue, and Toyohisa Kaneko. Generation of crack patterns with a physical model. *The Visual Computer*, 14(3):126 – 137, 1998.

Koichi Hirota, Yasuyuki Tanoue, and Toyohisa Kaneko. Simulation of three-dimensional cracks. *The Visual Computer*, 16(7):371 – 378, 2000.

4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Peeling

S. Gobron and N. Chiba. Simulation of peeling using 3d-surface cellular automata. In 9th Pacific Graphics Conference on Computer Graphics and Applications, pages 338–347, Tokyo Japan, Oct 2001. IEEE.

Eric Paquette, Pierre Poulin, and George Drettakis. The simulation of paint cracking and peeling. In *Graphics Interface 2002*, pages 59–68, May 2002.

4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Scratching

S. Merillou, J.M. Dischler, and D. Ghazanfarpour. Surface scratches: measuring, modeling and rendering. *The Visual Computer*, 17(1):30 – 45, 2001.

C. Bosch, X. Pueyo, S. M´erillou, and D. Ghazanfarpour. A physically-based model for rendering realistic scratches. *Computer Graphics Forum*, 23(3):361–370, 2004.

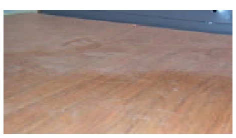
4. AGING AND WEATHERING PROCESSES
Taxonomy
Simulation Methods
Capture Approaches

Denting and Impacts

George Drettakis Eric Paquette, Pierre Poulin. Surface aging by impacts. In *Graphics Interface 2001*, pages 175–182, June 2001.

4. AGING AND WEATHERING PROCESSES
Taxonomy
Simulation Methods
Capture Approaches

Dust Accumulation



Siu-Chi Hsu and Tien-Tsin Wong. Simulating dust accumulation. *IEEE Comput Graphics Appl*, 15(1):18–22, January 1995.

4. AGING AND WEATHERING PROCESSES
Taxonomy
Simulation Methods
Capture Approaches

Lichen Growth

Brett Desbenoit, Eric Galin, and Samir Akkouche. Simulating and modeling lichen growth. *Computer Graphics Forum*, 23(3):341–350, 2004.

paper	effect	parameters†	time	data size	validation
[Dorsey and Hanrahan, 1996]	patina	accessibility, surface inclination & orientation	n/a	n/a	rendering only
[Chang and Shih, 2000]	patina	accessibility, gravity, curvatures, moisture in soil	n/a	n/a	rendering only
[Merillou *et al.*, 2001b]	rust & patina	"imperfection factor," layer protection, object collision, aeration	n/a	n/a	prediction of rate and spread of corrosion
[Chang and Shih, 2003]	rust	curvatures, accessibility, orientation, current, salts	n/a	n/a	rendering only
[Dorsey *et al.*, 1999]	erosion, efflorescence, discoloration	mineral concentration & solubility, decay index, exposure map, max. saturation, permeability, water pressure & density, fluid velocity, porosity, stone density, viscosity	24 hr. 3 hr.	2.2M tri. 1.3M tri.	rendering only
[Lu *et al.*, 2005]	drying	accessibility, distance to wet/dry boundary	n/a	n/a	ground-truth comparison
[Hirota *et al.*, 1998]	cracks	spring constant, mean and var of max strain, surface layer depth & contraction ratio, material density, time scale	24 hr.	20480 tri.	rendering only
[Hirota *et al.*, 2000]	3D cracks		8 hr. 20 hr.	1000 cu. 540 cu.	density of cracks; speed of formation
[Gobron and Chiba, 2001b]	cracks	resistance, stress	3 hr.	2017 tri.	rendering only
[Gobron and Chiba, 2001a]	peeling	n/a	11 min.	1.8M cells	rendering only
[Aoki *et al.*, 2002]	cracks	cell size, spring constant & max strain; moisture content & diffusion constant	8 hr. 1 hr.	8000 cu. 700 cu.	temporal development of cracks
[Paquette *et al.*, 2002]	crack & peeling	tensile stress, break strength, crack strength, deformation; elastic relaxation distance, shearing stress, adhesion strength; crack width, adhesion width	78 min. 23 min. 6 min.	400k poly. 150k poly. 130k poly.	visual quality
[Merillou *et al.*, 2001a]	scratch	surface type	n/a	n/a	scratch appearance
[Bosch *et al.*, 2004]	scratch	material hardness; tool shape, orientation, force	n/a	500 scratches	scratch appearance
[Eric Paquette, 2001]	impacts	tool shape, hit path	2 hr. ‡	n/a	impact size and density
[chi Hsu and tsin Wong, 1995]	dust	surface slope, stickiness, exposure; dust source	n/a	n/a	rendering only
[Dorsey *et al.*, 1996]	flow	material roughness, rate & capacity of absorption; deposits adhesion rate, solubility rate; water particle mass, position, velocity, soluble materials; rain, sunlight	3 hr.	450 poly.	rendering only
[Desbenoit *et al.*, 2004]	lichen	accessibility, light and moisture (from simulation)	n/a	n/a	rendering only
[Wong *et al.*, 1997]	general	sources; surface exposure, accessibility, curvature	n/a	n/a	rendering only

Summary table from

Jianye Lu, Athinodoros S. Georghiades, Andreas Glaser, Hongzhi Wu, Li-YiWei, Baining Guo, Julie Dorsey, and Holly Rushmeier. Context-aware textures. *ACM Trans. Graph.*, 26(1):3, 2007.

Another recent survey is

A survey of aging and weathering phenomena in computer graphic, S Merillou and D. Ghazanfarpour, C*omputers & Graphics* 32 (2) pp 159—174, 2008.

A general simulation method for many effects:

Y. Chen, L. Xia, T.T. Wong, X. Tong, H. Bao and B. Guo et al., Visual simulation of weathering by gamma-ton tracing, ACM Transactions on Graphics 24 (3) (2005), pp. 1127–1133.

4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

Capture in Context

-- appearance
--- agent causing change
-- geometry

Observing and Transferring Material Histories

- First-principles simulations are time-consuming or impossible
- New approach:
  - *Capture* time variations from real shapes, *transfer* them to generate synthetic objects

  - Shapes can be rendered at different times in their histories

While simulating aging effects produces good results, first-principles simulations are time consuming or, in some cases, impossible because the underlying physics and chemistry are not completely understood.

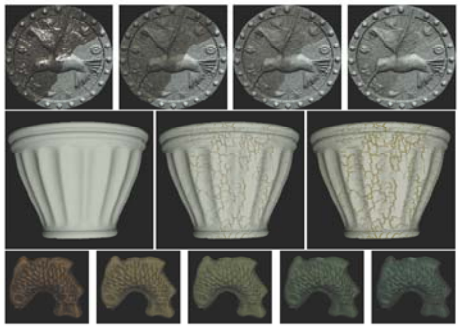
Rather than simulating aging effects, time variations from real shapes can be captured. This example shows effects captured from a copper bowl. We applied an artificial patination treatment to the bowl over a two week period and captured the shape and texture variations a frequent time intervals.

Transferred/Synthesized Effects

Drying

Crackling

Patination



Jianye Lu, Athinodoros S. Georghiades, Andreas Glaser, Hongzhi Wu, Li-YiWei, Baining Guo, Julie Dorsey, and Holly Rushmeier. Context-aware textures. *ACM Trans. Graph.*, 26(1):3, 2007.

4. AGING AND WEATHERING PROCESSES

Taxonomy
Simulation Methods
Capture Approaches

Time Varying

Additional efforts have capture time series of BRDF data

Additional time varying capture:

Jinwei Gu, Chien-I Tu, Ravi Ramamoorthi, Peter Belhumeur, Wojciech Matusik, and Shree Nayar. Time-varying surface appearance: acquisition, modeling and rendering. *ACM Trans. Graph.*, 25(3):762–771, 2006.

Sun, B.; Kalyan Sunkavalli; Ravi Ramamoorthi; Belhumeur, P.N.; Nayar, S.K., "Time-Varying BRDFs," *Visualization and Computer Graphics, IEEE Transactions on* , vol.13, no.3, pp.595-609, May-June 2007

4. AGING AND WEATHERING PROCESSES

Taxonomy

Simulation Methods

Capture Approaches

From Single Example

In some cases weathering effects can be captured by taking data from a single image of a material that has been marked with “fully aged” and “fully new” regions.

Jiaping Wang, Xin Tong, Stephen Lin, Minghao Pan, Chao Wang, Hujun Bao, Baining Guo, and Heung-Yeung Shum. Appearance manifolds for modeling time-variant appearance of materials. *ACM Trans. Graph.*, 25(3):754–761, 2006.

Su Xue, Jiaping Wang, Xin Tong, Qionghai Dai, Baining Guo Image-based Material Weathering. *Computer Graphics Forum* 27(2):617-626, 2008.

5. CURRENT TRENDS AND NEEDS

TRENDS
- Design of Physical Materials
- Editable Captured Data
- Simulated Microstructure Aging
- Inverse Aging
- Shape and Appearance

NEEDS
- INTERFACES
- DATA!!!

The trends discussed here are really mini (micro?) trends – some instances of new work that may grow into sub areas of material appearance research. The "needs" in materials continue to be large unsolved problems – interfaces for the convenient specification of materials, and data for the full range of materials we see everyday.

Design of Physical Materials

Paints

Milled Facets

Digital modeling of material appearance isn't just for image generation. Computer simulation can be used to formulate paints and to design surface microstructure to attain desired effects.

Paint design:
Ershov, S., Ďurikovič, R., Kolchin, K., and Myszkowski, K. 2004. Reverse engineering approach to appearance-based design of metallic and pearlescent paints. *Vis. Comput.* 20, 8-9 (Nov. 2004), 586-600.

Gary Meyer "Computer Graphic Tools for Automotive Paint Engineering" in Book Title - Service Life Prediction of Polymeric Materials, pp 273-282, 2009.

Milled Facets:
Tim Weyrich ,Pieter Peers, Wojciech Matusik and Szymon Rusinkiewicz ," Fabricating Microgeometry for Custom Surface Reflectance" SIGGRAPH 2009 (ACM TOG).

Editable captured data

SVBRDF's (Spatially Varying BRDF)

Subsurface scattering (BSSRDF)

Captured data is of limited usefulness if a user can not edit it to suit a new purpose:

Lawrence, J., Ben-Artzi, A., DeCoro, C., Matusik, W., Pfister, H., Ramamoorthi, R., and Rusinkiewicz, S. 2006. Inverse shade trees for non-parametric material representation and editing. *ACM Trans. Graph.* 25, 3 (Jul. 2006),

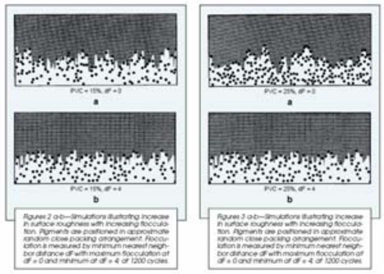
Ying Song, Xin Tong, Fabio Pellacini, Pieter Peers, SubEdit: A Representation for Editing Measured Heterogeneous Subsurface Scattering SIGGRAPH 2009, (ACM TOG)

Microstructure aging

Surface structure

Binder aging

From Hunt et al. 1998



The availability of high end computing using clusters of machines coupled with progress in understanding surface microstructure makes first principles simulation of coatings and their change with time feasible for appearance applications. Surface structure changes and binders weaken. Surface color changes as binders yellow with exposure to sunlight.

Hunt, F.Y., Galler M.A., and Martin J.W., "Microstructure of Weathered Paint and Its Relation to Gloss Loss: Computer Simulation and Modelling," J. COAT. TECHNOL., *70*, No. 880, 45 (1998).

Jenny Faucheu, Kurt A. Wood, Li-Piin Sung, Jonathan W. Martin, Relating gloss loss to topographical features of a PVDF coating, Journal of Coatings Technology and Research 3(1) pages 29- 39, 2006.

Inverse aging

If we can simulate material aging, can we "de-age" models of existing objects?

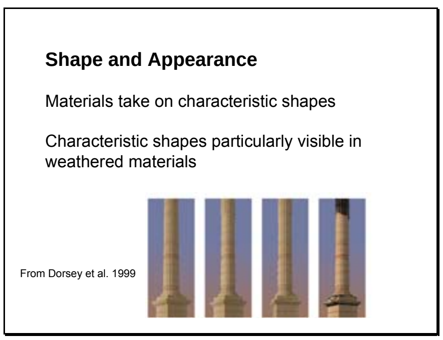
Within images

Virtual painting restoration

De-aging or cleaning objects in an image is demonstrated in:
Su Xue, Jiaping Wang, Xin Tong, Qionghai Dai, Baining Gu, Image-based Material Weathering Computer Graphics Forum (27) 2, 617-626, 2008.

Using a combination of spectral imaging and pigment mapping, RIT researchers have successfully "rejuvenated" paintings such as van Gogh's Starry night
Y. Zhao, Image Segmentation and Pigment Mapping of Cultural

Heritage Based on Spectral Imaging, Ph.D. Dssertation, R.I.T., Rochester, NY, 2008. http://www.art-si.org/PDFs/Processing/Zhao-PhD2008.pdf



As noted by Adelson, materials take on particular shapes, that is, we don't expect to see cream with sharp facets, or fluffy metals. E. Adelson, "On seeing stuff: The perception of materials by humans and machines," *Proceedings of the SPIE* **4299**, pp. 1--12, 2001.
The relationship between shape and material is particularly apparent in aged materials. Papers that deal with shape change during aging processes include:
Beardal M, Farley M, Ouderkirk D, Smith J, Rheimschussel C, Jones M, et al. Goblins by spheroidal weathering. In: Eurographics workshop on natural phenomena, 2007.
Wojtan C., Carlson M., MuchaP. J., Turk G.: Animating corrosion and erosion. In: Eurographics workshop on natural phenomena, 2007.

5. CURRENT TRENDS AND NEEDS

TRENDS
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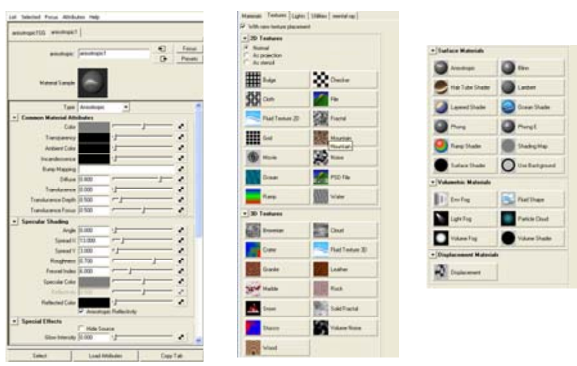
NEEDS
- INTERFACES
- DATA!!!



Most interfaces in use in modeling packages still require user to understand details of computer graphics representations, rather than allowing natural specification of material appearance.

DATA

Isolated databases exist in a variety of formats:

- Rutgers Skin database,
- Columbia Databases: BTF ,Time Varying materials
- Bonn BTF
- Matusik BRDF
- CornellMeasurements
- NIST/NEFDS
- Lightworks
- Yale “Context Aware Textures”

Can we build a materials search engine?

Yale “Context Aware Textures” database, http://graphics.cs.yale.edu/CAT
• Rutgers Skin database, http : //www.caip.rutgers.edu/rutgerstexture/
• Columbia Databases: BTF http : //www1.cs.columbia.edu/CAVE/projects/btf/, Time Varying materials: http : //www1.cs.columbia.edu/CAVE//databases/staf/staf.php
• Bonn BTF data base http : //btf.cs.uni − bonn.de/
• Matusik BRDF: http : //www.merl.com/brdf/
• CornellMeasurements http : //www.graphics.cornell.edu/online/measurements/reflectance/
• NIST/NEFDS http : //math.nist.gov/ FHunt/appearance/nefds.html
• Lightworksmaterials for a variety of building supplymanufacturers http : //www.lightworks−user.com/ (proprietary)
Currently available data is in many diverse formats

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Advanced Material Appearance Models

- General
  - BRDF's, BSSRDF's, and Textures
    [Phong, 1975],[Ward, 1992],[Lafortune *et al.*, 1997],[Ashikhmin and Shirley, 2000],[Blinn, 1977],[Cook and Torrance, 1982], [Oren and Nayar, 1994], [Jensen *et al.*, 2001]
- Specialized Material Models
  - Natural Materials – Organic
    * skin: wrinkles and pores, pigmentation, subsurface scattering, surface oils [Walters, 2002], [Marschner *et al.*, 2000],[Hanrahan and Krueger, 1993] [Stam, 2001] [Krishnaswamy and Baranoski, 2004], [Debevec *et al.*, 2000], [Georghiades, 2003] [Fuchs *et al.*, 2005] [Weyrich *et al.*, 2006] [Boissieux *et al.*, 2000], [Koenderink and Pont, 2003]
    * hair and fur: scattering from individual strands, interreflections, self-shadowing, [Robertson, 1999], [Blazej *et al.*, 1989],[Kajiya and Kay, 1989],[Hiebert *et al.*, 2006], [Marschner *et al.*, 2003],[Zinke and Weber, 2007],[Lokovic and Veach, 2000], [Moon and Marschner, 2006]
    * eyes: pigmentation, creating sense of depth, [Lefohn *et al.*, 2003],[Lam and Baranoski, 2006]
    * plants: internal structure, pigments, hairy features, growth patterns, including leaves, bark, wood, [Bloomenthal, 1985], [Prusinkiewicz *et al.*, 1988],[Vogelmann, 1993], [Baranoski and Rokne, 1997],[Baranoski and Rokne, 2001], [Franzke and Deussen, 2003], [Wang *et al.*, 2005], [Fowler *et al.*, 1989; 1992], [Fuhrer *et al.*,], [Lefebvre and Neyret, 2002], [Buchanan, 1998], [Lefebvre and Poulin, 2000], [Terraz *et al.*, 2009]
    * birds: structure of feathers, forming coats, [Dai *et al.*, 1995], [Streit and Heidrich, 2002] [Chen *et al.*, 2002]
    * insects: iridescence, [Sun, 2006]
  - Natural Materials – Inorganic
    * porous : modification of reflectance, [Merillou *et al.*, 2000]
    * wet: darkening and transparency effects for water or oil permeated materials, [Jensen *et al.*, 1999], [Nakamae *et al.*, 1990]
    * snow:internal scattering, visual particles, [Nishita *et al.*, 1997]
    * water: scattering from suspended particles, [Gutierrez *et al.*, 2008], [Narasimhan *et al.*, 2006]
  - Manufactured/Processed Materials
    * finished wood: sense of depth, [Marschner *et al.*, 2005]
    * textiles: individual fibers, threads and formation of fabrics, [Rubin, 1998],[Groeller *et al.*, 1995],[Xu *et al.*, 2001],[Adabala *et al.*, 2003]
    * automotive paint: color flop, depth, sparkle, orange peel, [Takagi *et al.*, 1990], [Günther *et al.*, 2005], [Dumont-Bècle *et al.*, 2001],[Shimizu *et al.*, 2003], [Ershov *et al.*, 2001] [Rump *et al.*, 2008]
    * artistic paints and inks: pigmentation and flow effects, [Cockshott *et al.*, 1992],[1997], [Chu and Tai, 2005]
    * gems: light phenomena requiring simulation of wave effects, [Yuan *et al.*, 1988] , [Sun *et al.*, 2001],[Guy and Soler, 2004],[Nagata *et al.*, 1997], [Weidlich and Wilkie, 2008b],[Weidlich and Wilkie, 2008a], [Weidlich and Wilkie, 2009],[Weidlich, 2009]
- Aging and Weathering Processes

– Simulation Methods:

  * patination: [Dorsey and Hanrahan, 1996],[Chang and Shih, 2000]
  * rust: [Merillou *et al.*, 2001b], [Chang and Shih, 2003]
  * erosion: [Dorsey *et al.*, 1999],[Wojtan *et al.*, 2007][Beardall *et al.*, 2007]
  * cracking: [Hirota *et al.*, 1998],[Hirota *et al.*, 2000], [Gobron and Chiba, 2001b] ,[Aoki *et al.*, 2002][Paquette *et al.*, 2002]
  * peeling: [Gobron and Chiba, 2001a]
  * scratching:[Merillou *et al.*, 2001a], [Bosch *et al.*, 2004]
  * denting and impacts: [Eric Paquette, 2001]
  * dust accumulation: [chi Hsu and tsin Wong, 1995]
  * lichen growth: [Desbenoit *et al.*, 2004]
  * general effects and survey: [Chen *et al.*, 2005],[Mérillou and Ghazanfarpour, 2008]

– Capture Approaches: Methods that use photography and/or 3D scanning to capture instances of aging effects that can be generalized

  * capturing context [Lu *et al.*, 2005],[Lu *et al.*, 2007]
  * temporal variation of BTF's and BRDF's [Koudelka, 2004] [Gu *et al.*, 2006], [Sun *et al.*, 2007]
  * models from single examples of materials: [Wang *et al.*, 2006] [Xuey *et al.*, 2008]

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