Game Design & Development

Lighting and Materials in Games
with Case Study: Halo3

Outline

- Motivation
- Global illumination(GI) Image
- Rendering Equation
- BRDF and related functions
- Challenges: real time GI for complex materials and complex light source
  - complex **materials** (dull concrete to shiny metal)
  - Area **light source** (sky light → expensive integral)
  - Fresnel effect (not captured in Phong model)
- Goal：better light source, GI effect, materials
- Cook-Torrance BRDF model
- Real time strategy: equation factoring into components, using different techniques

Halo 3

- Tech Info
  - Publisher: Microsoft Game Studios
  - Developer: Bungie Software
  - Genre: Sci-Fi First-Person Shooter
  - Release Date: Sep 25, 2007
- Official Site
  - www.xbox.com/en-US/games/h/halo3
- The first day sale:
  - $170 million in the U.S. (a new record within 24 hours)
- 14.5 million copies by 2012
- Award:
  - the "Best Real Time Visuals in a Video Game" (The Visual Effects Society)
- Features
  - Global illumination
  - Complex material under complex lighting
  - HDR

Lighting Examples

Motivation

- Top priority of game graphics system
  - keeping the players immersed in the virtual environment for long periods of time
- lighting and material:
  - global illumination
  - handle variety of environments
  - consistent lighting everywhere
  - render bump maps “correctly”
  - complex materials under complex lighting
  - HDR

Concepts and Topics

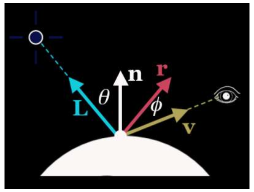
- Irradiance (light irradiance, surface irradiance)
- Radiance
- Solid angle
- Reflectance equation
- BRDF and its variants (BSSRDF, SVBRDF…)
  - Taxonomy of appearance
  - 2 characteristics of BRDF
  - Fresnel reflectance, Snell’s Law, Schlick’s approximation
  - BRDF model (acquisition, representation, implementation)
- Halo 3:
  - Cook-Torrance BRDF model
  - Spherical Harmonics

Global illumination effects

- direct illumination vs. indirect illumination
- Model indirect illumination effects and complex phenomenon
  - reflection
  - refraction
  - color bleeding
  - soft shadows
  - …
- More complexity
  - Light sources
  - Materials
  - Light transport paths

Local Illumination

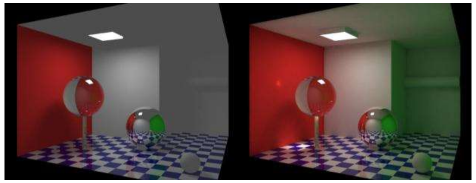
- Phong model is a local illumination model
  (shaded color depends purely on local surface configuration)
- Other surfaces have no effect
- But in reality surfaces interact a great deal!!



$$I = I_L k_d \cos\theta + I_L k_s \cos^n \phi + I_a k_a$$

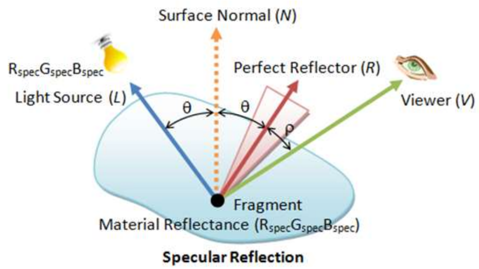
Global Illumination

- Illumination of one object depends on others
- All light reflections and transmissions are accounted for
- E.g.: Color bleeding，Caustics
- Radiosity and ray tracing are both GI algorithms



Lighting factors

- Light sources
- Materials
- Sensors

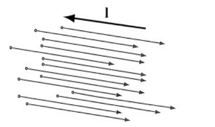


Light Sources

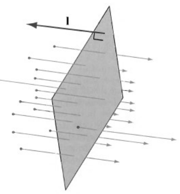
- Light is variously modeled as *geometric rays, electromagnetic waves, or photons* (quantum particles with some wave properties).
- Regardless of how it is treated, light is electromagnetic radiant energy—electromagnetic energy that travels through space.
- Light sources emit light, rather than scattering or absorbing it.

Light irradiance

- A simple type of light source: ***directional lights***
- Two factors:
  - —Light direction
    - light vector l: opposite
  - —The amount of illumination it emits
    - Can be quantified by measuring power through a unit area surface perpendicular to l. (called ***light irradiance*** E_L)
      - – *Represented as an RGB vector with 3 values (in theory can be arbitrarily large)*



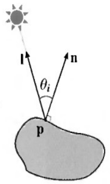
The light vector l is defined opposite to the direction the light is traveling.

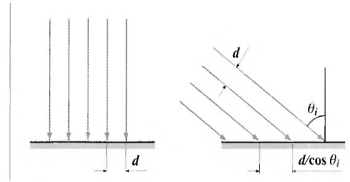


Surface irradiance

- **Light irradiance E_L tells us how bright the light is in general**
- **But to compute its illumination on a surface, we need to measure irradiance at a plane parallel to that surface (i.e., perpendicular to the surface normal n). called the *surface irradiance E***

$$E = E_L \overline{\cos}\, \theta_i$$
$$= E_L \max(\mathbf{n} \cdot \mathbf{l}, 0).$$

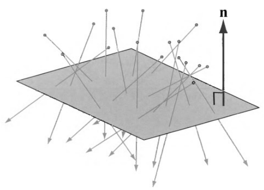




Irradiance

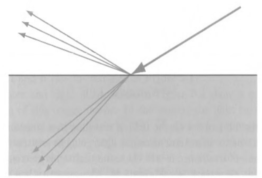
- *irradiance* in general measures light going in arbitrary directions
- Definition: light energy crossing a unit-area plane in one second
- **Irradiance is additive for multiple light sources**

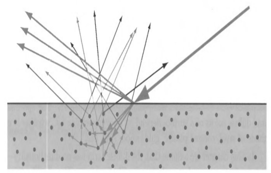
$$E = \sum_{k=1}^{n} E_{L_k} \overline{\cos}\, \theta_{i_k}$$



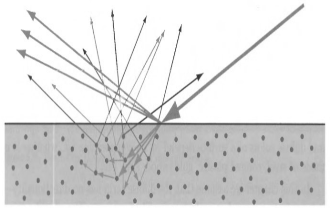
Material

- **Fundamentally, all light-matter interactions are the result of two phenomena:**
  - —**Scattering** (when light encounter optical discontinuity)
    - reflection (out of surface)
    - refraction/transmission (into surface)
  - —**Absorption** (inside matter)
    - Convert into another kind of energy or disappear
    - Reduce amount but not affect direction

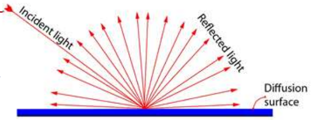




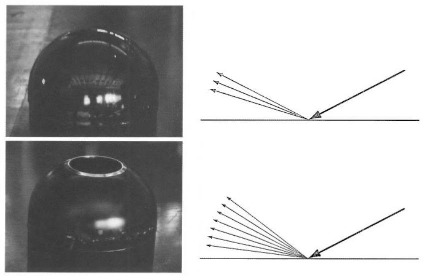
- Two common terms of shading equation (for opaque object)
  - *Specular term*
    - *light reflected at surface*
  - *Diffuse term*
    - *light transmitted, partially absorbed, finally scattered back out*



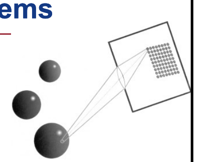
- To characterize the behavior of a material by a shading equation, we need to represent the amount and direction of outgoing light, based on the amount and direction of incoming light.
  - Incoming illumination is measured as ***surface irradiance E***.
  - outgoing light as ***exitance M,*** which similarly to irradiance is energy per second per unit area.
  - Light-matter interactions are linear: e.g. 2 E→ 2 M
  - M/E: The ratio of exitance and irradiance is a characteristic property of the material. (for non-emissive matter, the value is between [0,1].
    - Different for different colors, represented as color vector, called the ***surface color***



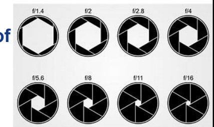
- ***diffuse color***
  - *Assume has no directionality*
- ***specular color***
  - *Has significantly directionality*



Sensor for Real imaging systems



- Sensors
  - Rods/cones in eye, photodiodes in DC,…
- Sensors detects the irradiance value over its surface and produces a color signal.
  - Irradiance sensors themselves cannot produce an image, since they average light rays from all incoming directions.
  - So a full imaging system includes a light-proof enclosure with a single small aperture (opening) that restricts the directions from which light can enter and strike the sensors.
    - A lens placed at the aperture focuses the light so that each sensor only receives light from a small set of incoming directions.

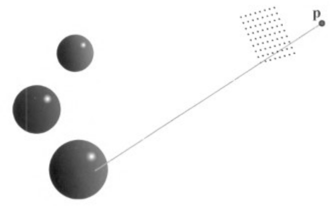


Radiance

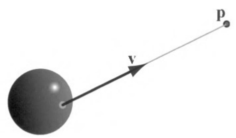
- Rather than measuring average irradiance (the density of light flow—from all directions—per surface area), these sensors measure average *radiance.*
- Radiance (L) is the density of light flow per area and per incoming direction.
  - —can be thought of as the measure of the brightness and color of *a single ray of light*.
  - —Like irradiance, radiance is represented as an RGB vector with theoretically unbounded values.

Sensors For Rendering systems

- Rendering systems:
  - —also "measure" (compute) radiance similarly to real imaging systems.
  - —However, they use a simplified and idealized model of the imaging sensor



- In this model, each sensor measures a single radiance sample, rather than an average.
- The radiance sample for each sensor is along a ray (*the normalized view vector v*) that goes through a point representing the sensor and a shared point p, which is also the center of projection for the perspective transform

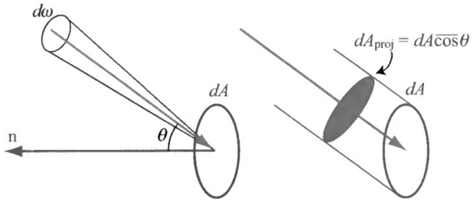


Physical sensors vs. Renderer

- Map unlimited scene radiance
  to→ limited display radiance
  (mimic physical sensors like film or human eye)
- There are important differences between physical imaging sensors and the idealized model
  - —Physical sensors measure an average value of radiance over their area, over incoming directions focused by the lens, and over a time interval;
  - —the evaluation of a shader equation computes radiance in a single ray at a single instant.
- There are problems caused by these differences, and various solutions (such as aliasing)

Radiance

- Radiance
  - —a measure of light in a single ray
  - —the density of light flux(power) w.r.t. both area and solid angle



1. Radiance is power per unit projected area per unit solid angle.

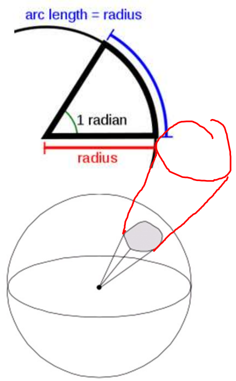
Solid Angle

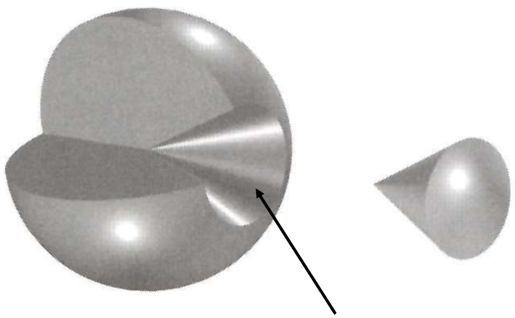
- **Angle** $\theta = \frac{l}{r}$

  $\Rightarrow$ circle has 2π radians

- **Solid angle** $\Omega = \frac{A}{R^2}$

  $\Rightarrow$ sphere has 4π steradians





从一个球面上去除1球面度立体角的圆锥

Irradiance, Radiosity

- Irradiance E is radiant power per unit area
  - —a measure of light incoming to a surface point from all directions
  - —the density of light flux w.r.t. area (perpendicular to surface normal n)
- Integrate incoming radiance over hemisphere
  - —Projected solid angle (cos θ dω)
  - —Uniform illumination: Irradiance = π
  - —Units: W/m^2
- Radiant Exitance M (radiosity)
  - —Power per unit area leaving surface (like irradiance)

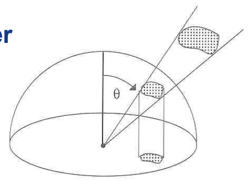


Figure 2.8: *Projection of differential area.*

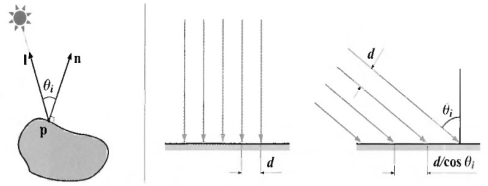
Units

Radiometric Quantity: Units
radiant energy: joule (J)
radiant flux: watt (W)
irradiance: $\mathrm{W/m^2}$
radiant intensity: W/sr
radiance: $\mathrm{W/m^2}$-sr

irradiance (remind)

- ***Surface irradiance: E***
- ***Light irradiance： E_L***

$$E = E_L \overline{\cos}\,\theta_i = E_L \max(\mathbf{n}\cdot\mathbf{l}, 0).$$

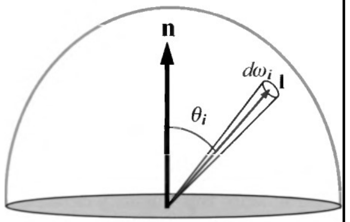


Irradiance and Radiance

- Irradiance E is the cosine-weighted integral of radiance L_i over the hemisphere above a surface point.

$$dE = L_i(\mathbf{l})d\omega_i \overline{\cos}\,\theta_i$$

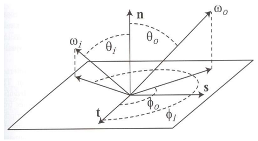
$$E = \int_\Omega L_i(\mathbf{l}) \cos\theta_i d\omega_i.$$



Reflectance Equation

- **Radiance is the final quantity computed by the rendering process**
- **Computing the outgoing radiance L_o in the view direction v. Lo determines the shaded pixel color.**
- **Use the BRDF(bidirectional reflectance distribution function)**

$$f(\mathbf{l},\mathbf{v}) = \frac{dL_o(\mathbf{v})}{dE(\mathbf{l})}$$



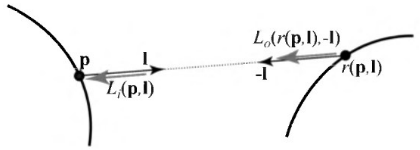
and Reflectance Equation

$$L_o(\mathbf{p},\mathbf{v}) = \int_\Omega f(\mathbf{l},\mathbf{v}) \otimes L_i(\mathbf{p},\mathbf{l}) \cos\theta_i d\omega_i,$$

Full GI rendering equation

- Extend the reflectance equation
- Consider the inter-reflections between surfaces
- Usually, one bounce is enough for game

$$L_o(\mathbf{p},\mathbf{v}) = L_e(\mathbf{p},\mathbf{v}) + \int_\Omega f(\mathbf{l},\mathbf{v}) \otimes L_o(r(\mathbf{p},\mathbf{l}),-\mathbf{l}) \cos\theta_i d\omega_i,$$



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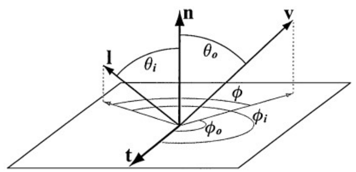
Material: BRDF

BRDF

- bidirectional reflectance distribution function (BRDF)
- The precise definition of the BRDF is the ratio between differential outgoing radiance and differential irradiance:

$$f(\mathbf{l},\mathbf{v}) = \frac{dL_o(\mathbf{v})}{dE(\mathbf{l})}$$



for non-area light sources

- When shading with non-area light sources such as point or directional lights, a non-differential form:

$$f(\mathbf{l},\mathbf{v}) = \frac{L_o(\mathbf{v})}{E_L \overline{\cos}\,\theta_i}$$

- straightforward to fit BRDF into a general shading equation with n non-area lights:

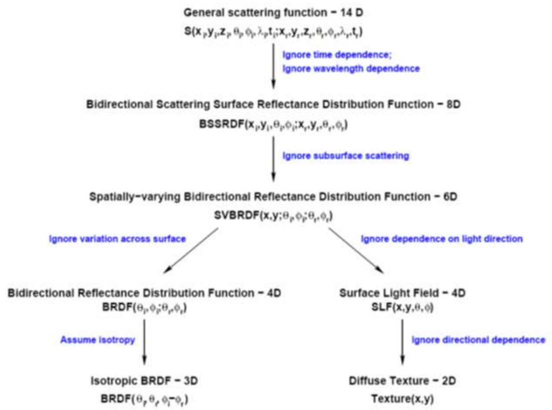
$$L_o(\mathbf{v}) = \sum_{k=1}^{n} f(\mathbf{l}_k,\mathbf{v}) \otimes E_{L_k} \overline{\cos}\,\theta_{i_k}$$

- BRDF: a function of four scalar variables

Variants of BRDFs

- Isotropic BRDF
- BSSRDF
- Spatially varying BRDF (SVBRDF or SBRDF)
- To handle transmission (2 BRDFs + 2 BTDFs) ➔ BSDF (rarely needed)

Taxonomy of Appearance

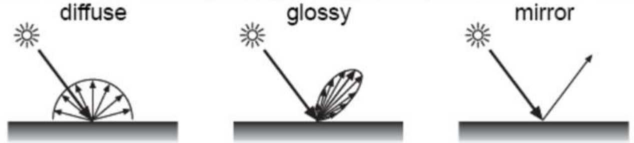


Material Samples

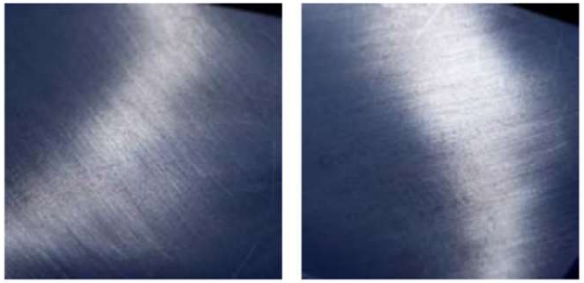
diffuse glossy mirror

Material Samples

diffuse glossy mirror



Material Samples

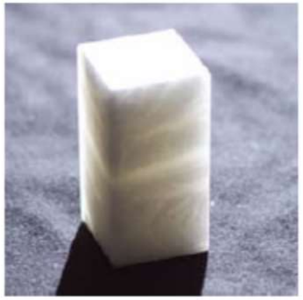


anisotropic

Material Samples

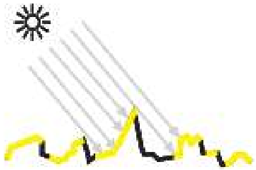
translucent

Material Samples



translucent

Material Samples



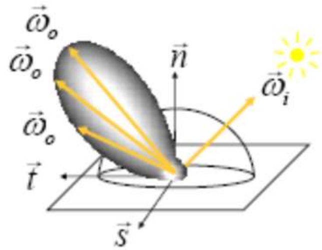
complex surface structure

How to describe materials?

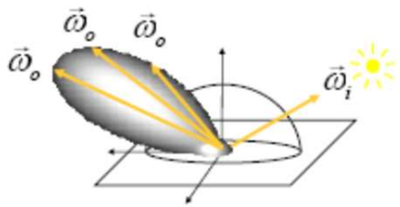
- mechanical, chemical, electrical properties
- reflection properties
- surface roughness
- geometry/meso-structure

- **relightable** representation of appearance

Reflection of an Opaque Surface



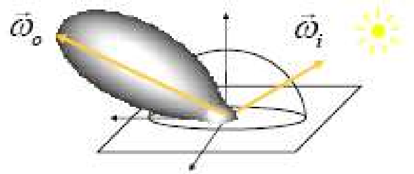
Reflection of an Opaque Surface



BRDF – 4D

(bidirectional reflectance distribution function)

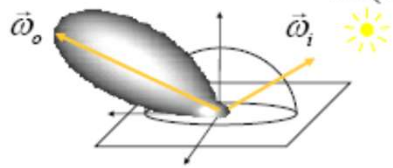
$$f_r(\vec{\omega}_i \rightarrow \vec{\omega}_o)$$



BRDF – 4D

(bidirectional reflectance distribution function)

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

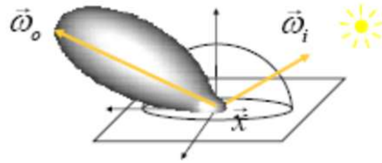


ratio of reflected radiance to incident irradiance

Spatially Varying BRDF – 6D

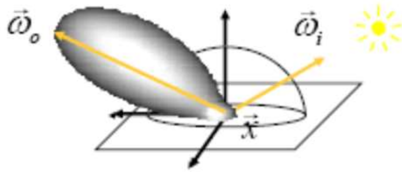
- heterogeneous materials

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

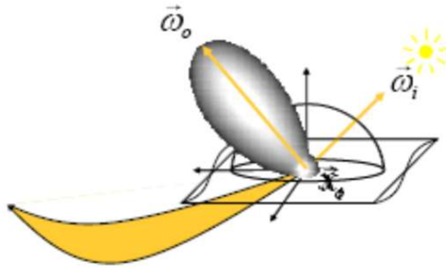


Isotropic BRDF – 3D

- invariant with respect to rotation about the normal



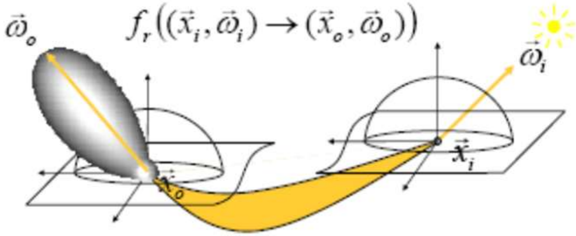
Subsurface Scattering



BSSRDF – 8D

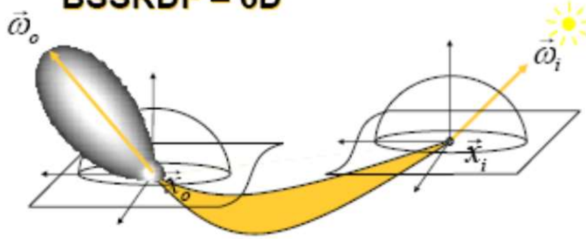
(bidirectional scattering surface reflectance distribution function)

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



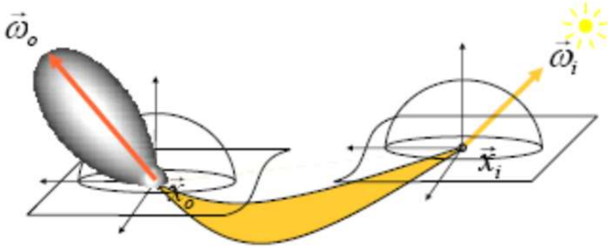
Subsurface Scattering Homogeneous Material

BSSRDF – 6D



Generalization – 9D

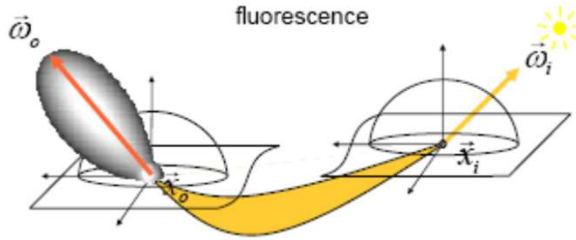
$$f_r(\lambda; (\vec{x}_i, \vec{\omega}_i) \rightarrow (\vec{x}_o, \vec{\omega}_o))$$



Generalization – 10D

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

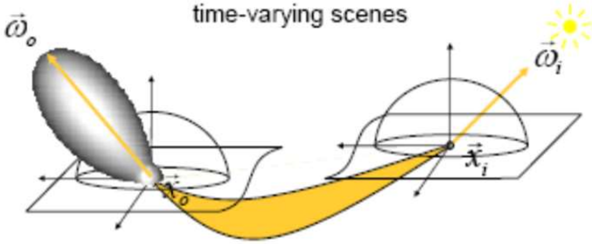
fluorescence



Generalization – 11D

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

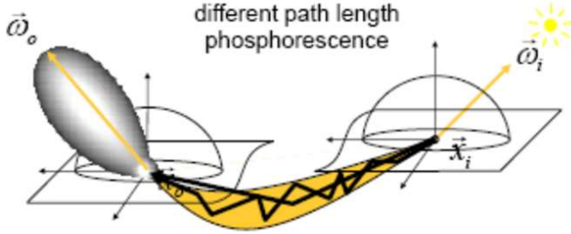
time-varying scenes



Generalization – 12D

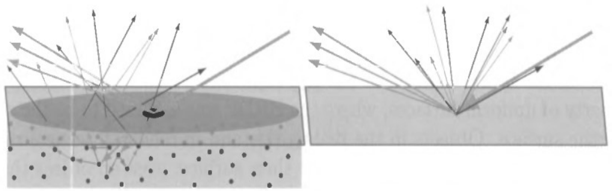
$$f_r((\vec{x}_i,\vec{\omega}_i,t_i,\lambda_i)\rightarrow(\vec{x}_o,\vec{\omega}_o,t_o,\lambda_o))$$

different path length
phosphorescence



BRDF approximation

- **BRDF approximation depend on**
  - —The surface material
  - —The scale of observation



- **In practice, BRDF or SVBRDF is often sufficient for most surface behavior**

BRDF characteristics

Two physics constrains：

1. Helmholtz reciprocity $f(\mathbf{l},\mathbf{v}) = f(\mathbf{v},\mathbf{l})$

- —in practice often violate without noticeable artifacts;
- —useful tool to determine if a BRDF is physically plausible

2. Conservation of energy

- — e.g. some offline ray tracing require this
- —real time rendering often not necessary for strict conservation
  - approximate energy conservation is desirable
  - otherwise might look much too bright

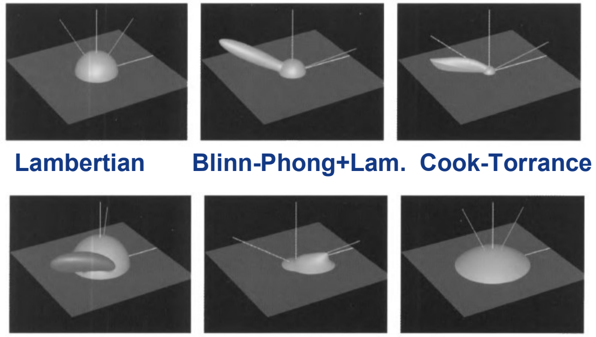
Lambertian BRDF

- The simplest possible BRDF: Lambertian BRDF
  - Has a constant value

$$R(\mathbf{l}) = \pi f(\mathbf{l}, \mathbf{v})$$

  - Diffuse color $f(\mathbf{l}, \mathbf{v}) = \dfrac{\mathbf{c}_{\text{diff}}}{\pi}$
  - $1/\pi$ term
    - – factored into the light's radiance in real time applications
    - – Need to be careful when adapting academic papers BRDF to real-time shading equations :
      - » multiply by pi before use

Visualize BRDF

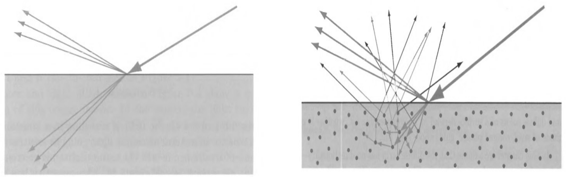


Lambertian Blinn-Phong+Lam. Cook-Torrance

anisotropic retro-reflection scattering

Surface and body reflectance

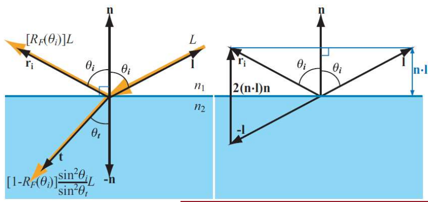
- Two phenomena of reflectance:
  - —Surface reflectance: modeled with specular BRDF terms
  - —Body reflectance: modeled with diffuse BRDF terms



Surface Reflectance: Fresnel Reflectance

- Fresnel equations (19th century)
- Require a perfect flat plane
  - — Not possible even at atomic level (atom forms bumps)
  - — In practice: Surface irregularities < smallest wavelength of light spectrum (~400nm, visible light)
- Scatter to two directions:
  - — Ideal reflection direction
  - — Ideal refraction direction

Augustin-Jean Fresnel
1788-1827



Fresnel Reflectance

- *Fresnel reflectance R_F*
  - —the amount of light reflected
  - —depends on incoming angle
- the proportion of transmitted flux to incoming flux is *$1 - R_F$*
- the proportion of transmitted-to-incident radiance (due to projected area and solid angle differences)

$$L_t = (1 - R_F(\theta_i)) \frac{\sin^2\theta_i}{\sin^2\theta_t} L_i.$$

Snell's Law

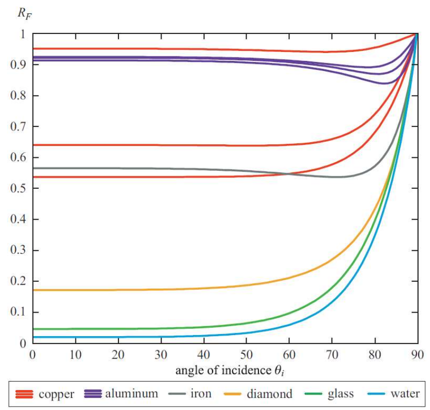
- R_F and transmission angle both depend on
  - incoming angle
  - *n: refractive index* (an optical property of the two substances)
  - *Snell's Law:* $n_1 \sin(\theta_i) = n_2 \sin(\theta_t).$
- Thus

$$L_t = (1 - R_F(\theta_i)) \frac{n_2^2}{n_1^2} L_i$$

External Reflectance

- External Reflectance: A transition from low refractive index to higher one (e.g. air to water)
- When $\theta_i = 0°$
  - — $R_F(0°)$ is a property of the substance
  - —the characteristic specular color of the substance
  - —*Normal incidence*
- As θ_i increase → 90 degree, the value $R_F(\theta_i)$ → 1 for all frequencies (white)
- called *Fresnel Effect in rendering*

Fresnel Effect



Schlick's approximation

- **Fresnel equations are difficult to use**
- **A simpler approach: Schlick's approximation**

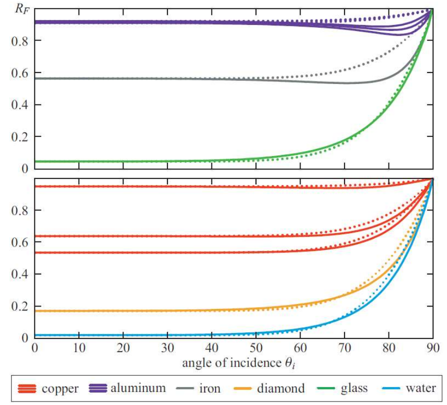
$$R_F(\theta_i) \approx R_F(0^\circ) + (1 - R_F(0^\circ))(1 - \overline{\cos}\,\theta_i)^5$$

— $R_F(0^\circ)$ **is the only controlling parameter**

- **Easy to set and can be textured**
- **available for many real-world materials**
- **The refractive index can be used to compute it**

$$R_F(0^\circ) = \left(\frac{n-1}{n+1}\right)^2$$

Schlick's approximation



Typical Fresnel Reflectance Values

- **Typical Fresnel Reflectance Values**
  - —Different types of substances have different ranges of values of $R_F(0^\circ)$
  - —Three main groups of substances:
    - Insulators (dielectrics)
    - Metals (conductors)
    - Semiconductors (between above two, rarely found in rendered scenes)

Insulators

- **most commonly materials**
  - —Water, glass, skin, wood, hair, leather, plastic, stone, etc.
  - —Usually $R_F(0^\circ)$ <= 0.05 (Fresnel effect particularly visible)
  - —Uniform in the spectrum (colorless reflectance values)
- **Light transmitted into Insulators:**
  - further scattered or absorbed or "internal reflection"

Insulator	$R_F(0^\circ)$ (Linear)	$R_F(0^\circ)$ (sRGB)	Color
Water	0.02,0.02,0.02	0.15,0.15,0.15	
Plastic / Glass (Low)	0.03,0.03,0.03	0.21,0.21,0.21	
Plastic High	0.05,0.05,0.05	0.24,0.24,0.24	
Glass (High) / Ruby	0.08,0.08,0.08	0.31,0.31,0.31	
Diamond	0.17,0.17,0.17	0.45,0.45,0.45	

Metals

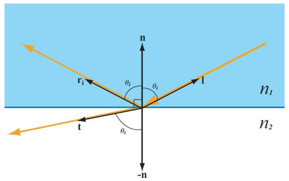
- High values of $R_F(0°)$ (>=0.5)
- Some metals have optical properties vary over the visible spectrum → colored reflectance values
- Metal immediately absorb any transmitted light:
  - *no subsurface scattering or transparency !!!*

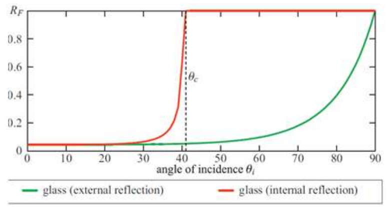
Metal	$R_F(0°)$ (Linear)	$R_F(0°)$ (sRGB)	Color
Gold	1.00,0.71,0.29	1.00,0.86,0.57	
Silver	0.95,0.93,0.88	0.98,0.97,0.95	
Copper	0.95,0.64,0.54	0.98,0.82,0.76	
Iron	0.56,0.57,0.58	0.77,0.78,0.78	
Aluminum	0.91,0.92,0.92	0.96,0.96,0.97	

Internal Reflection

- A transition from high refractive index to lower one (e.g. water to air) $\sin\theta_t > \sin\theta_i$
- total internal reflection: when θ_i > *a critical angle*
- Why air bubbles underwater is highly reflective ?
- Only for insulators

$$\sin\theta_c = \frac{n_2}{n_1} = \frac{1-\sqrt{R_F(0°)}}{1+\sqrt{R_F(0°)}}.$$





Body reflectance

- Insulators must include body reflectance (metals don't present)
- Local subsurface scattering (only for insulators)
- If insulator is *homogeneous* → few internal discontinuities → transparent
  - E.g. glass, gemstones, crystals, clear liquids (water, oil, wine)
  - Partially absorb light but do not change its direction
  - Transmitted light: straight line until internal reflection and transmitted out of the object

Heterogeneous insulator

- If *heterogeneous*
  - Most insulators (wood, stone, snow, earth, skin, opaque plastic, -- any opaque non-metal)
  - Numerous discontinuities (air bubbles, foreign particles, density variations, structural changes)
  - Cause light to scatter inside
  - Transmitted light completely absorbed or partially absorbed (remaining is re-emitted from the surface)
  - To model it use BRDF
    - Assume re-emitted from the same point where it entered
      - Called *local subsurface scattering*

Local subsurface scattering

- Most often modeled as a Lambertian diffuse term in the BRDF
- Trade-off between surface and body reflectance terms
- Fresnel effect implies that the trade-off changes with incoming angle
- A simple way

$$f_{\text{diff}}(\mathbf{l}, \mathbf{v}) = (1 - R_F(\theta_i))\frac{\rho}{\pi}.$$

BRDF models

- BRDF models:
  - Two groups:
    - Physical theory
    - Empirical BRDF models (simpler, more commonly used in Real time rendering)
      - Lambertian or constant BRDF
      - Phong Specular model (transformed to Phong BRDF)
      - The normalized Phong BRDFs
      - Blinn-Phone BRDF
      - …

BRDF acquisition and representation

- BRDF acquisition and representation
  - Match to real ones
  - Or Save authoring time
- Two problems:
  - Capture (using goniometers, reflectometers, image based methods)
  - Representation:
    - parametric (analytic BRDFs)
    - vs. non-parametric (basis, factorization?))

Representations

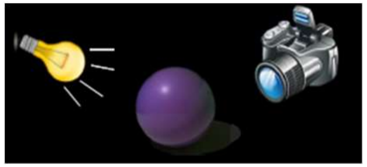
- Raw data : large, densely sampled, noise
- *Analytic BRDF:* select an analytic BRDF and fit its parameters to the measured data
  - Very compact representation
  - Rendering is reasonably fast
  - Easy to edit manually
  - Not always simple to choose a BRDF and fitting (complex and time-consuming optimization process)
- A weighted sum of *multiple BRDF* terms
- *Basis Projections* : project BRDFs onto *orthornormal bases, such as spherical harmonics*
- *Factorization: factor the 4D function into a sum of products of lower-dimensional functions (1D or 2D → textures → GPU hardware)*

Implementing BRDFs in a rendering system

- ***The BRDF be evaluated as part of a shading equation***
- **Analytic BRDF**
  - —**Pixel shader (best quality)**
  - —**Vertex shader (pre-evaluated subexpressions)**
  - —**Texture reads**
- **Projection Basis BRDF**
  - —**Straightforward: evaluate the basis function**
  - —**Large number of coefficients: expensive computation**
  - —**If SVBRDF, very large number of texture reads**
- **Factorized BRDF**
  - —**Easier to render：relatively small number of textures read（usually 2）**
  - —**Not suitable for measured SVBRDFs; not easy to edit**

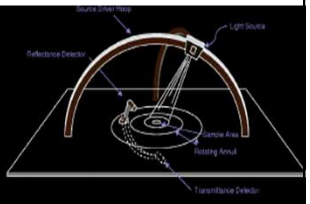
REFLECTANCE ACQUISITION

- A typical measurement setup includes
  - —a light source to uniformly illuminate a large area of a surface
  - —a detector to measure a small area within the illuminated region



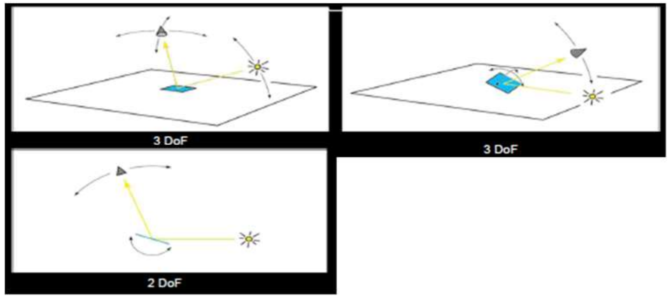
BRDF ACQUISITION-GONIOREFLECTOMETERS

- Typically consists of:
  - a light source
  - a sample material placed on the sample holder
  - a turntable which rotates around the vertical axis
  - a detector which captures data about reflected light from the sample
- Several variations
  - Number of Degrees of Freedom
  - Moving / fixed parts
- Main drawback: only one BRDF value is measured at a time

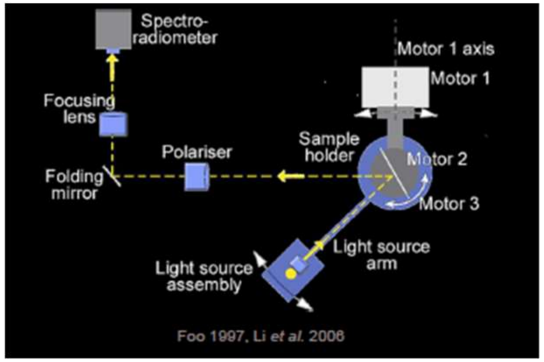


Cornell University
(also NIST, CUReT)

GONIOREFLECTOMETERS - DOF



GONIOREFLECTOMETERS (2)



GONIOREFLECTOMETERS (3)

BRDF ACQUISITION – IMAGE BASED SETUPS

+ Makes use of photographs of an object
+ Requires only general-purpose equipment
+ Lowers the cost and the time of the process
− To include the wavelength spectrum of the BRDF requires more time per measurement

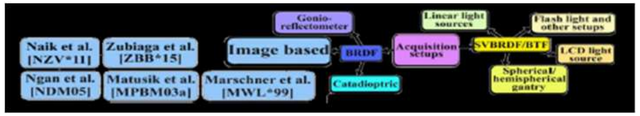
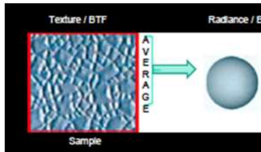
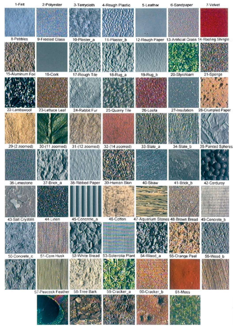


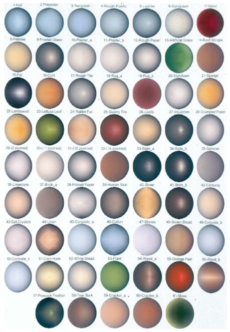
IMAGE BASED



	Surface Appearance	
	Coarse scale	Fine scale
Fixed view / Illumination	Reflectance	Texture
Varied view / Illumination	BRDF	BTF

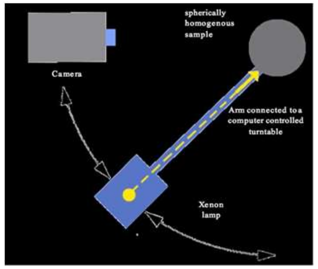
DANA K. J., VAN GINNEKEN B., NAYAR S. K., KOENDERINK J. J.: Reflectance and texture of real-world surfaces. ACM Transactions on Graphics (TOG) 18, 1 (1999), 1–34.

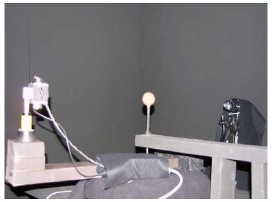




DANA K. J., VAN GINNEKEN B., NAYAR S. K., KOENDERINK J. J.: Reflectance and texture of real-world surfaces. ACM Transactions on Graphics (TOG) 18, 1 (1999), 1–34.

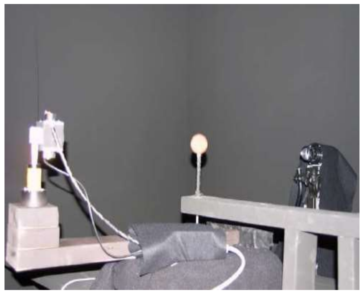
IMAGE BASED (3)





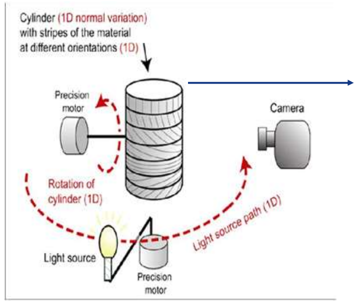
MATUSIK W., PFISTER H., BRAND M., MCMILLAN L.: A data-driven reflectance model. ACM Trans. Graph. 22, 3 (July 2003), 759–769.

IMAGE BASED (3) – 100 ISOTROPIC BRDFS



MATUSIK W., PFISTER H., BRAND M., MCMILLAN L.: A data-driven reflectance model. ACM Trans. Graph. 22, 3 (July 2003), 759–769.

IMAGE BASED (4) – ANISOTROPIC FABRICS



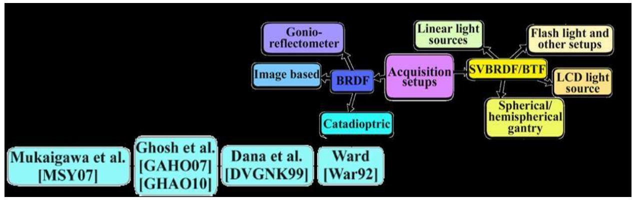
Anisotropic BRDF acquisition

Strips of materials at different orientations

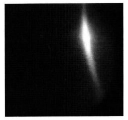
NGAN A., DURAND F., MATUSIK W.: Experimental analysis of brdf models. In Proceedings of the Sixteenth Eurographics Conference on Rendering Techniques (Aire-la-Ville, Switzerland, Switzerland, 2005), EGSR'05, Eurographics Association, pp. 117–126. doi: 10.2312/EGWR/EGSR05/117-126.

BRDF ACQUISITION – CATADIOPTRIC SETUPS

- Make use of both reflected and refracted light
  - – reduce aberrations
- Generally they are efficient image based BRDF acquisition devices
- Usually without any moving parts

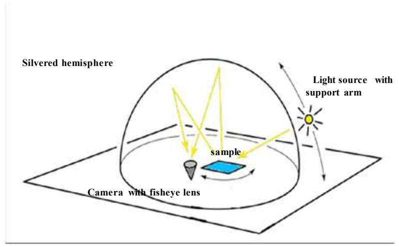


CATADIOPTRIC

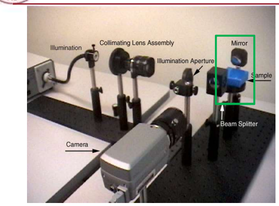


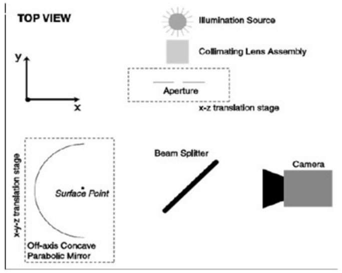
Anisotropic brushed aluminium

Gregory J. Ward. 1992. Measuring and Modeling Anisotropic Reflection. SIGGRAPH Comput. Graph. 26, 2 (July 1992), 265–272.



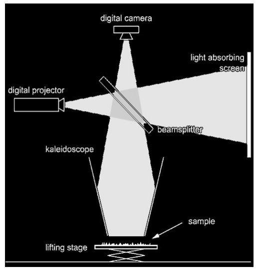
CATADIOPTRIC (2)

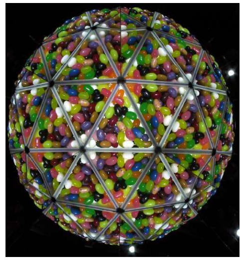




K. J. Dana, "BRDF/BTF measurement device," Computer Vision, 2001. ICCV 2001. Proceedings. Eighth IEEE International Conference on, Vancouver, BC, 2001, pp. 460-466 vol.2. 65

CATADIOPTRIC (3)

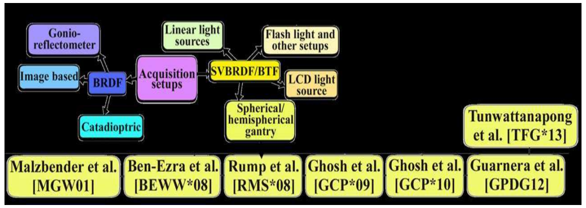




- HAN J. Y., PERLIN K.: Measuring bidirectional texture reflectance with a kaleidoscope. ACM Trans. Graph. 22, 3 (July 2003), 741–748

SVBRDF ACQUISITION - SPHERICAL AND HEMISPHERICAL GANTRY

- Single viewpoint
- Multiple light directions
  - Moving light source
  - Light source arrays



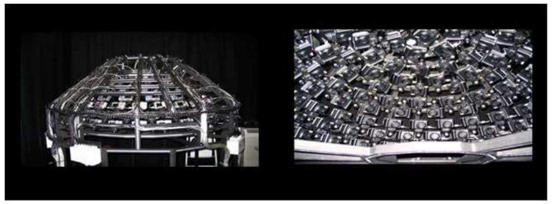
SPHERICAL AND HEMISPHERICAL GANTRY

$$L(u,v;l_u,l_v) = a_0(u,v)l_u^2 + a_1(u,v)l_v^2 + a_2(u,v)l_u l_v + a_3(u,v)l_u + a_4(u,v)l_v + a_5(u,v)$$

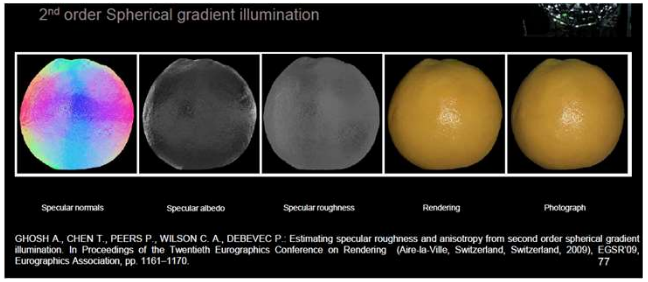
. (lu,lv) are projections of the normalized light vector into the local texture coordinate system (u,v)
. L is the resultant surface luminance at that coordinate.
. Coefficients (a0-a5) are fit to the photographic data per texel and stored as a spatial map referred to as a Polynomial Texture Map

- MALZBENDER T., GELB D., WOLTERS H.: Polynomial texture maps. In Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques (NewYork,NY,USA,2001), SIGGRAPH '01, ACM, pp. 519–528.

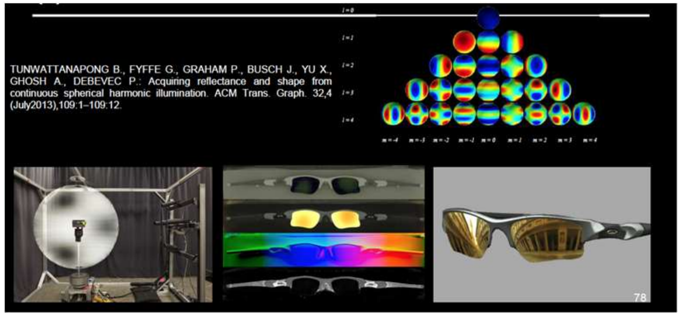
SPHERICAL AND HEMISPHERICAL GANTRY



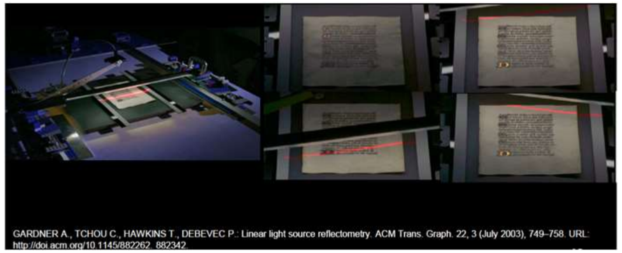
SPHERICAL AND HEMISPHERICAL GANTRY



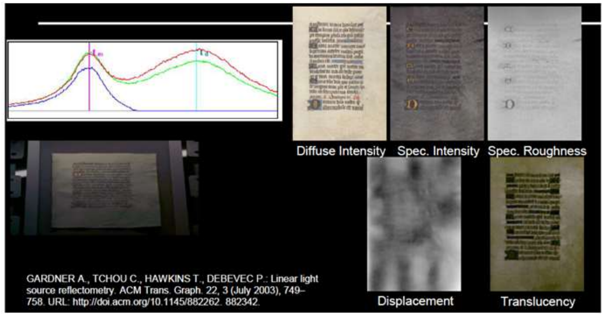
SPHERICAL AND HEMISPHERICAL GANTRY



LINEAR LIGHT SOURCE



LINEAR LIGHT SOURCE



LINEAR LIGHT SOURCE (2)

- hand-held linear light source device
- a BRDF chart

REN P., WANG J., SNYDER J., TONG X., GUO B.: Pocket reflectometry. ACM Trans. Graph. 30, 4 (July 2011), 45:1–45:10.

Figure 1: We capture spatially-varying, isotropic reflectance in about half a minute of casual scanning using three simple tools shown on the far left. Rendered results from four captured examples are shown on the right.

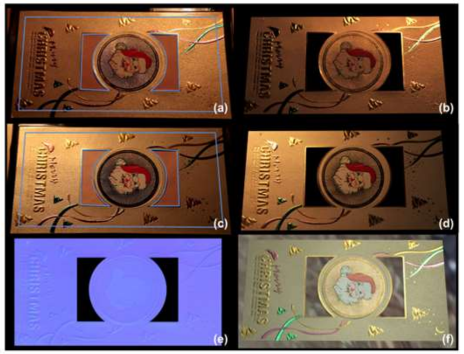
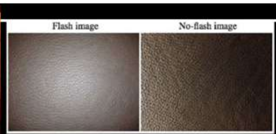
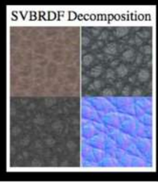


Figure 11: *Results for a bumpy example: (a/c) real photo, (b/d) rendered result of reconstructed SVBRDF with normal map in (e), (f) rendered result under natural environmental lighting.*

FLASH ILLUMINATION





- Two shot capture!
  - Ambient + flash image
  - Repeating texture/material
  - Statistical appearance sharing

AITTALA M., WEYRICH T., LEHTINEN J.: Two-shot SVBRDF capture for stationary materials. ACM Trans. Graph. 34, 4 (July 2015), 110:1–110:13. URL: http://doi.acm.org/10.1145/2766967.

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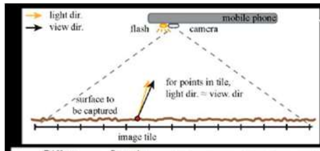
FLASH ILLUMINATION



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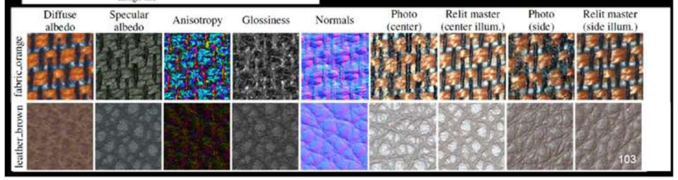

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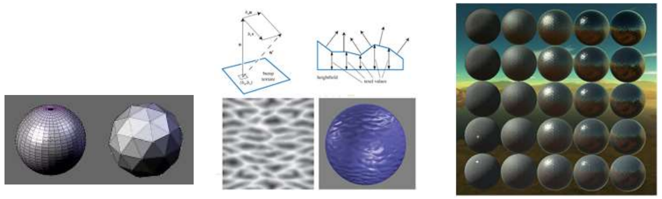
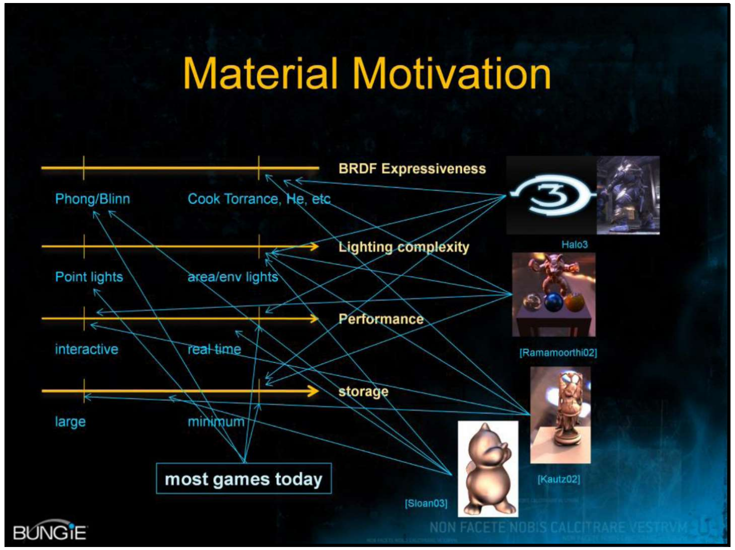
Halo3

Concepts

- Light map → irradiance map
- Bump mapping
- Details on an object:
  - —Macro-scale: many pixels → vertices and triangles
  - —Meso-scale: a few pixels → … (bump mapping…)
  - —Micro-scale: subpixels → shading model





Definitions

- Radiance
  - —*L(ω)*: density of light energy through a given point in a given direction.
- Irradiance
  - —*I:* incident radiance integrated over the hemisphere of the surface normal with the cosine lobe.
- BRDF
  - —*f(V, L):* Bidirectional reflectance distribution function.
- Fresnel
  - —*F:* Predicts ratio of reflected and transmitted light when light travels between different mediums.
  - —F_0: Reflectance at near normal incident angle.

Halo 3

- how the Equation can be factored into separate components, which can each be rendered in real time using different techniques,
- how the parts are combined together in the end for final shading
- BRDF for Cook-Torrence reflectance model

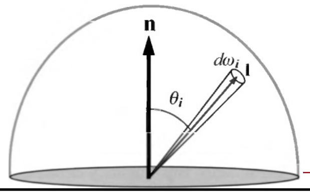
$$f(V,L) = k_d R_d + k_s F R_m(V,L)$$

- Plugging the BRDF into rendering equation

$$I(V) = k_d R_d \left[\int \cos(\theta)\ell(\omega)d\omega + k_s\left[\int F R_m(V,L)\cos(\theta)\ell(\omega)d\omega\right.\right.$$

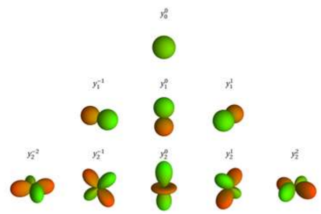
Arbitrary light sources

- Both the diffuse and specular components in Equation involve an integral that is expensive to compute directly in real time.
- However, if the light sources are point lights only, the integral becomes a sum of (*N.L) terms for diffuse illumination.*
- the restriction of point light sources (and direct illumination only) is one of the main reasons that many games look unrealistic
- To handle arbitrary light sources
  - — need to find a way to evaluate the integrals in equation efficiently
  - — turn to spherical harmonics



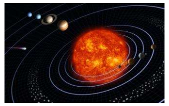
Spherical Harmonics

- Spherical harmonics (SH) basis over the sphere
  - —analogous to the Fourier basis over the line or the circle
- for Lambertian surfaces, a small number of spherical harmonics terms are sufficient to approximate the original lighting to high accuracy



Harmonic Functions?

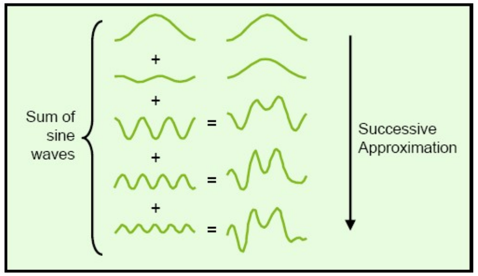
- Solutions of Laplace equation
  - —Divergence of gradient = 0



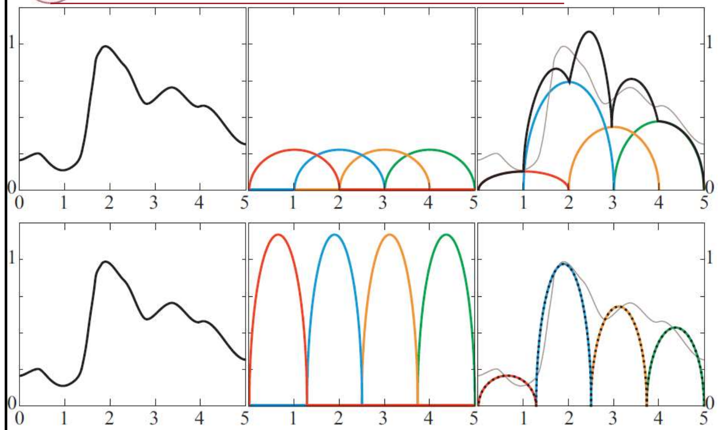
$$\Delta f = \frac{df^2}{dx^2} + \frac{df^2}{dy^2} + \frac{df^2}{dz^2}$$

  - —Potential theory: fluids, e&m, gravity
- Fourier basis is solution on unit circle
- Spherical Harmonics are solution on the sphere
  - —Also eigenfunctions of Angular Momentum operators in Quantum Chemistry/Physics

Fourier Theory



- it is possible to represent any 1D signal as a sum of appropriately scaled and shifted sine waves
- Spherical harmonics are the same idea on a sphere!



Concepts

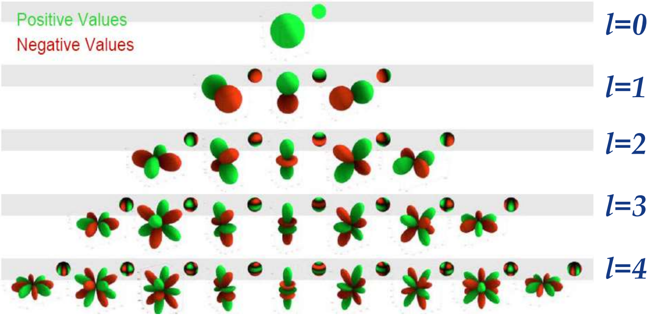
- Basis functions: weighted and summed
- Orthogonal set of basis functions
- Inner product of two functions $\langle f_i(x), f_j(x)\rangle \equiv \int f_i(x) f_j(x) dx,$
- inner product of SH functions $\langle f_i(\mathbf{n}), f_j(\mathbf{n})\rangle \equiv \int_\Theta f_i(\mathbf{n}) f_j(\mathbf{n}) d\omega,$
- Orthonormal set $\langle f_i(), f_j()\rangle = \begin{cases} 0, & \text{where } i \neq j, \\ 1, & \text{where } i = j. \end{cases}$
- Basis projection

$$k_j = \langle f_{\text{target}}(), f_j()\rangle,$$

$$f_{\text{target}}() \approx \sum_{j=1}^{n} k_j f_j().$$

Spherical Harmonic Basis

- The first 5 frequency bands of SH basis



SH in Halo3

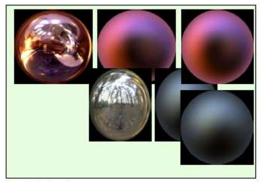
- Chose spherical harmonics basis for Halo3 lighting and material methods:
  - —SH is suitable for approximating smooth changing signals using a small number of coefficients which makes it ideal for lighting, transfer and material purposes;
  - —SH can be rotated easily in a shader;
  - —there are a number of algorithms such as PRT(Precomputed Radiance Transfer) that are compatible with the SH representation which use in game.

Spherical Harmonics Irradiance Environment Maps

- *Spherical Harmonics Irradiance Environment Maps,*
  - —encode the irradiance distribution function (IDF) as a vector of SH coefficients
  - —Un-shadowed diffuse transfer can then be computed in a shader using a quadratic polynomial approximation.
  - —for shadowed transfer and inter-reflections, the *Pre-computed Radiance Transfer (PRT) method pre-computes* the transfer function as a SH vector, which is then combined with incoming lighting using a SH dot product.
- Glossy materials are also possible in the SH representation
  - —although none of the previous methods can meet the stringent performance and storage requirements of a real time game

Spherical Projection: Storage and Computation

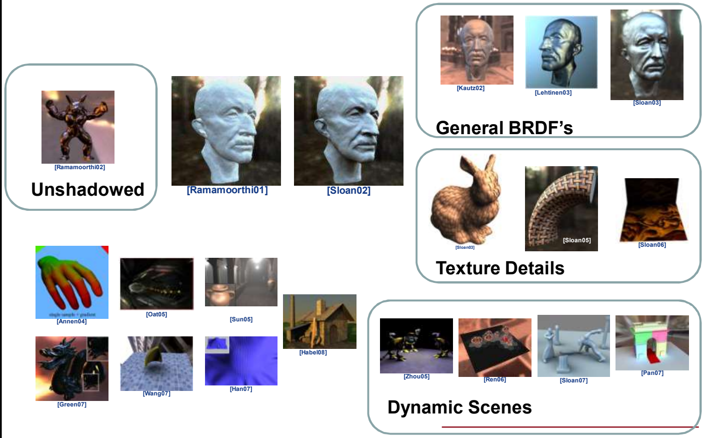
- Projecting an environment map into 3rd order SH effectively gives you the irradiance distribution function
  - —not only a storage win, but a preprocessing win too
    - SH projection is much faster than convolving an environment map with a cosine kernel for all possible normal orientations



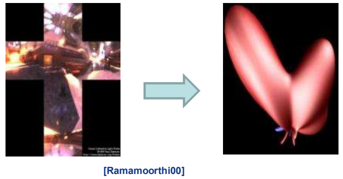
[Ramamoorthi]

Original Environment Map | Filtered Environment Map | SH Representation

SH for Interactive Graphics



SH Irradiance Env Map



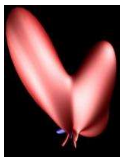
$$L_{lm} = \iint_{\theta,\phi} L(\theta,\phi) Y_{lm}(\theta,\phi) \sin(\theta) d\theta d\phi$$

distant radiance at given direction

SH basis evaluated at given direction

diff solid angle

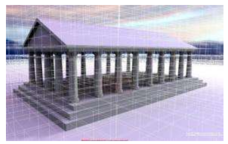
SH Irradiance Env Map



$$E(n) = n^t M n$$

- Irradiance distribution as SH vector.
- <3% error with just 9 terms
- Evaluate normal to get irradiance.
- Only represent a single point in space.
- Only for infinite lighting environment.
- What about local lighting?

Irradiance Volumes

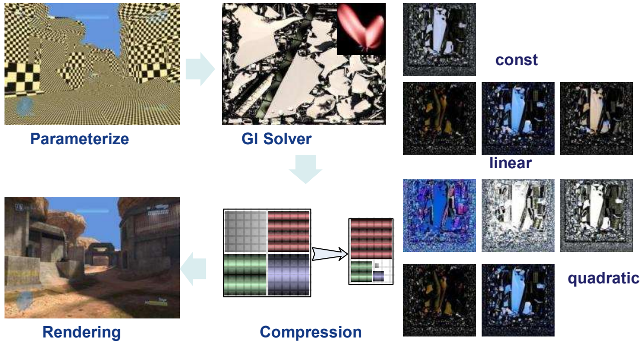



[Greger 98] [ATI 05]

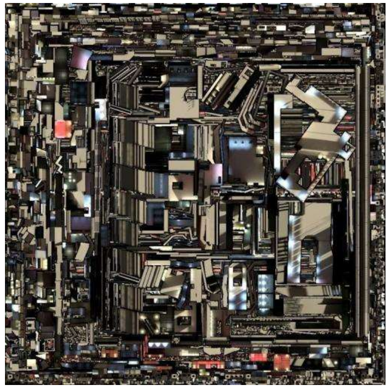
- Spatially divide volume into cells.
- Irradiance volume per cell.
- Interpolate between samples.

SH Light Map

Store a SH Irradiance environment map per pixel over the surface

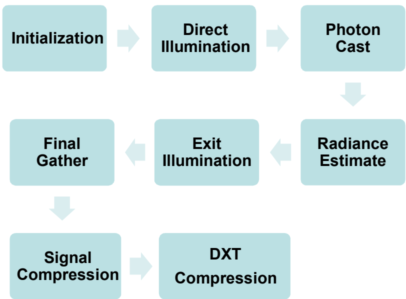


Parameterization



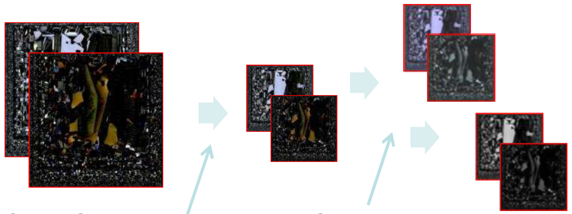
- **UVAtlas (DirectX SDK)**
  - Minimize distortion
  - Efficient Packing
  - Input "importance"
- **Halo3 improvements:**
  - small charts placement.
  - long and thin charts.
- **> 80% texel utilization**
  - Halo2: < 50%

Photon Mapping Farm



256 servers; 456 Processors; 1GB memory per proc

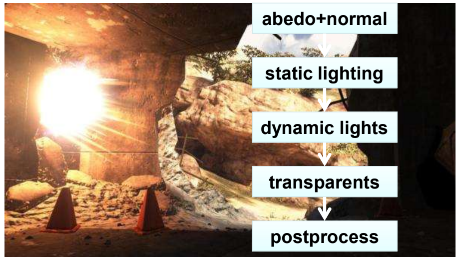
Compression



Signal Optimization:
- Compute signal gradient
- Resample to half dim.
- Preserve high freq charts
- Squeeze low freq charts

DXT Compression
- Use 2 DXT5 for each FP16
- Color space conversion
- 12 bits (2 DXT5 alpha) luminance
- 3:1 compression ratio

Scene Rendering



Object Lighting

sample surface

PRT

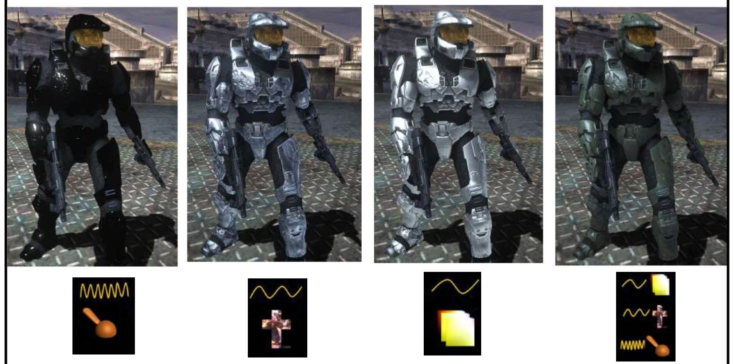
VS:
PRT/Unshadowed

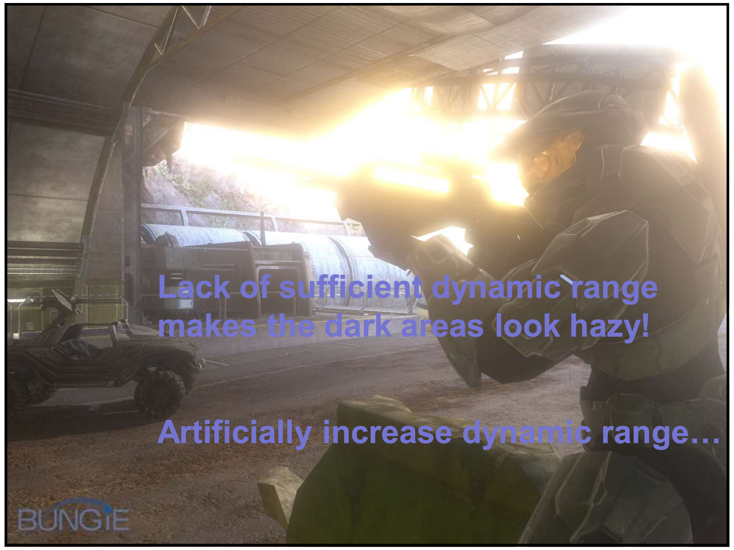
PS:
Unshadowed * ratio

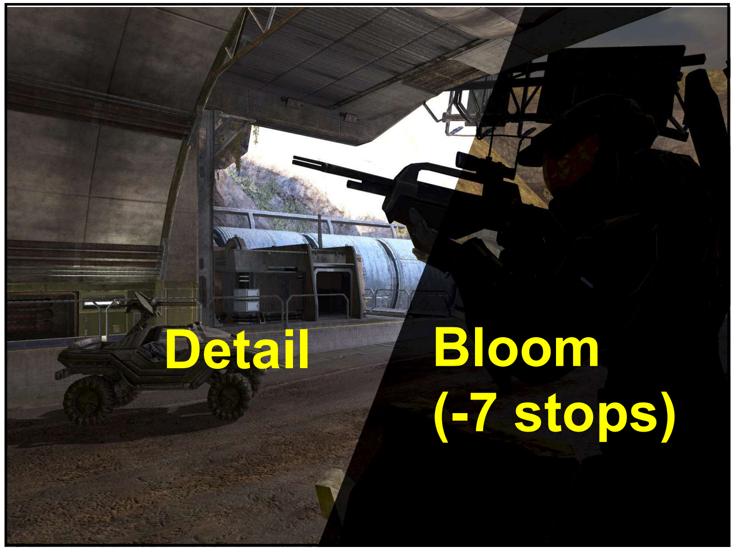
Lighting Examples

Lighting Examples

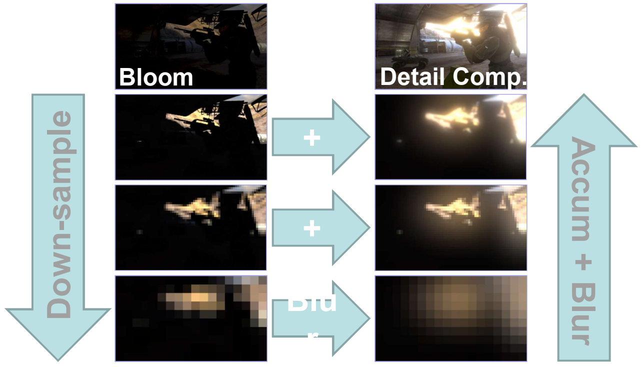
Lighting Examples



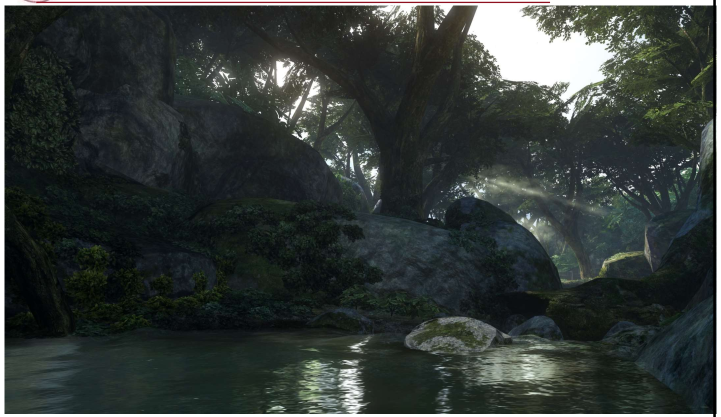


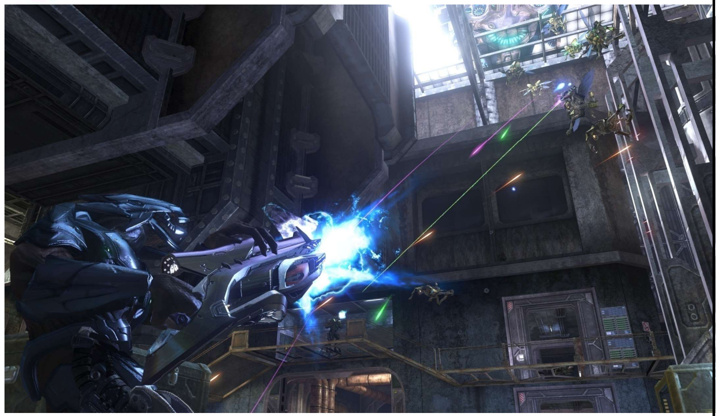


Bloom Postprocessing



(Weighted Average for Auto-Exposure)





Readings

- Chen, Hao, and Xinguo Liu. "Lighting and material of Halo 3." In *ACM SIGGRAPH 2008 Games*, pp. 1-22. ACM, 2008.
- Kautz, Jan, John Snyder, and Peter-Pike J. Sloan. "Fast Arbitrary BRDF Shading for Low-Frequency Lighting Using Spherical Harmonics." *Rendering Techniques* 2 (2002): 291-296.
- Chapter 7-8: Tomas Akenine-Möller, Eric Haines, and Naty Hoffman, Real Time Rendering, A.K. Peters Ltd., 3rd edition, ISBN 978-1-56881-424-7, 2008.
- Siggraph 2017 Course notes on Material Acquisition and Representation for Virtual Reality