SIGGRAPH2010

The People Behind the Pixels

Physically Based Shading Models for Film and Game Production

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Course website (shortened URL)

http://bit.ly/s10shaders

- Course materials will be available on this website shortly after the conference

Schedule (Note Recent Change)

- 2:00-2:30 *Background: Physically Based Shading* (Hoffman)
- 2:30-3:00 *Practical Implementation of Physically Based Shading Models at tri-Ace* (Gotanda)
- 3:00-3:00 *Crafting Physically Motivated Shading Models for Game Development* (Hoffman)
- 3:30-3:45 Break
- 3:45-4:30 *Terminators and Iron Men: Image-Based Lighting and Physical Shading at ILM* (Snow)
- 4:30-5:00 *Faster Photorealism in Wonderland: Physically Based Shading and Lighting at Sony Pictures Imageworks* (Martinez)
- 5:00-5:15 Conclusion, Q&A (All)

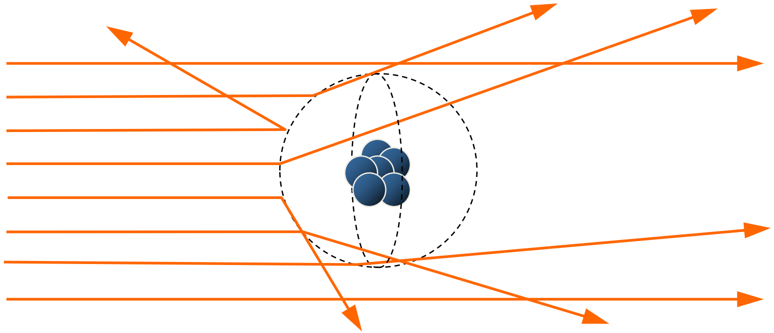
Background: Physically Based Shading

Naty Hoffman

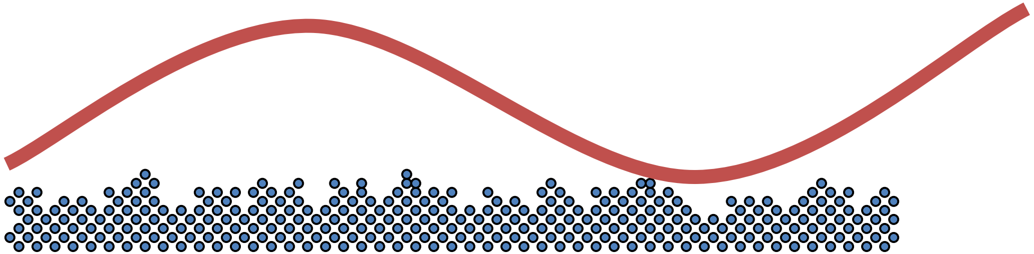
Activision

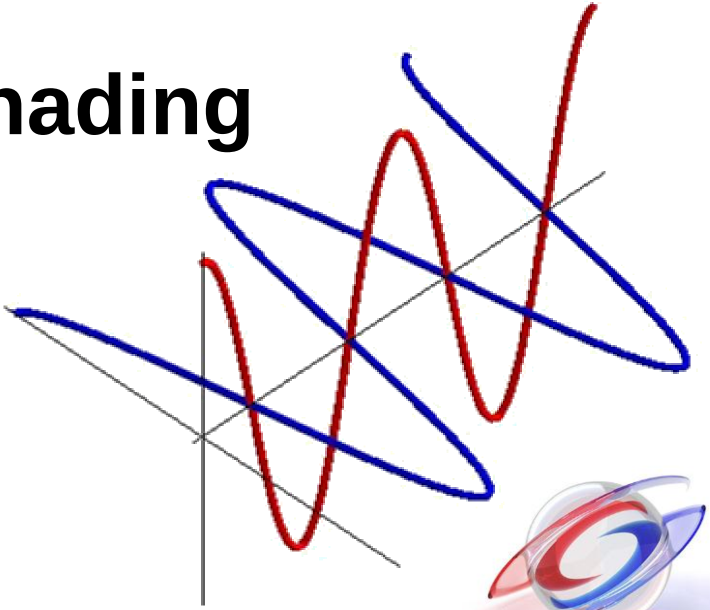
Background

- The Physics of Shading
- The Mathematics of Shading
- Implementing Shading



The Physics of Shading

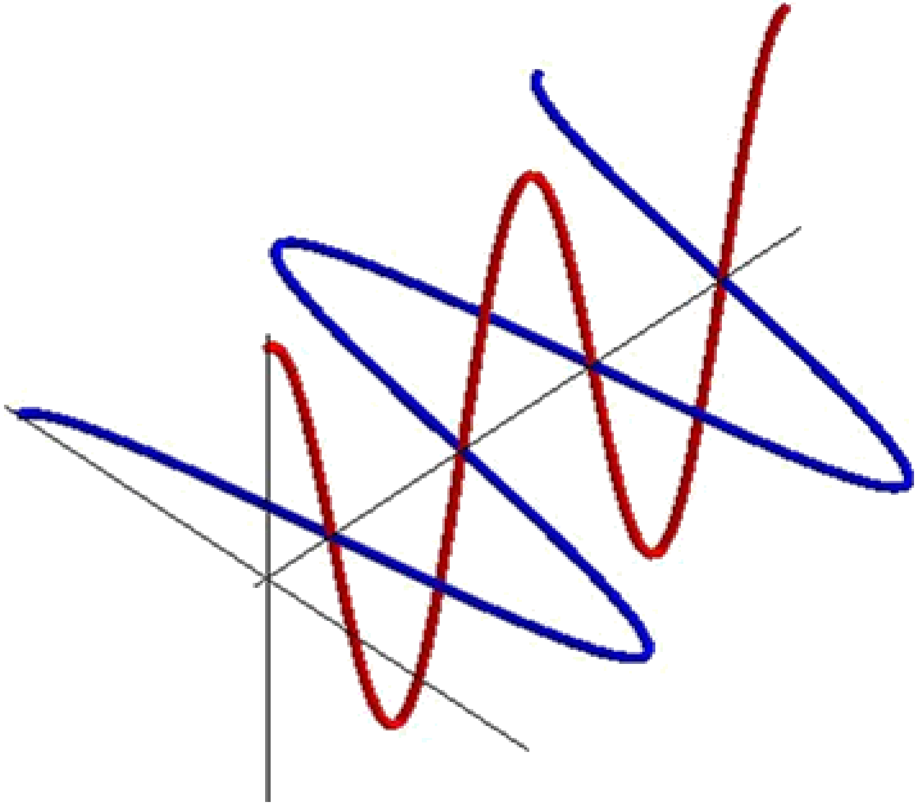




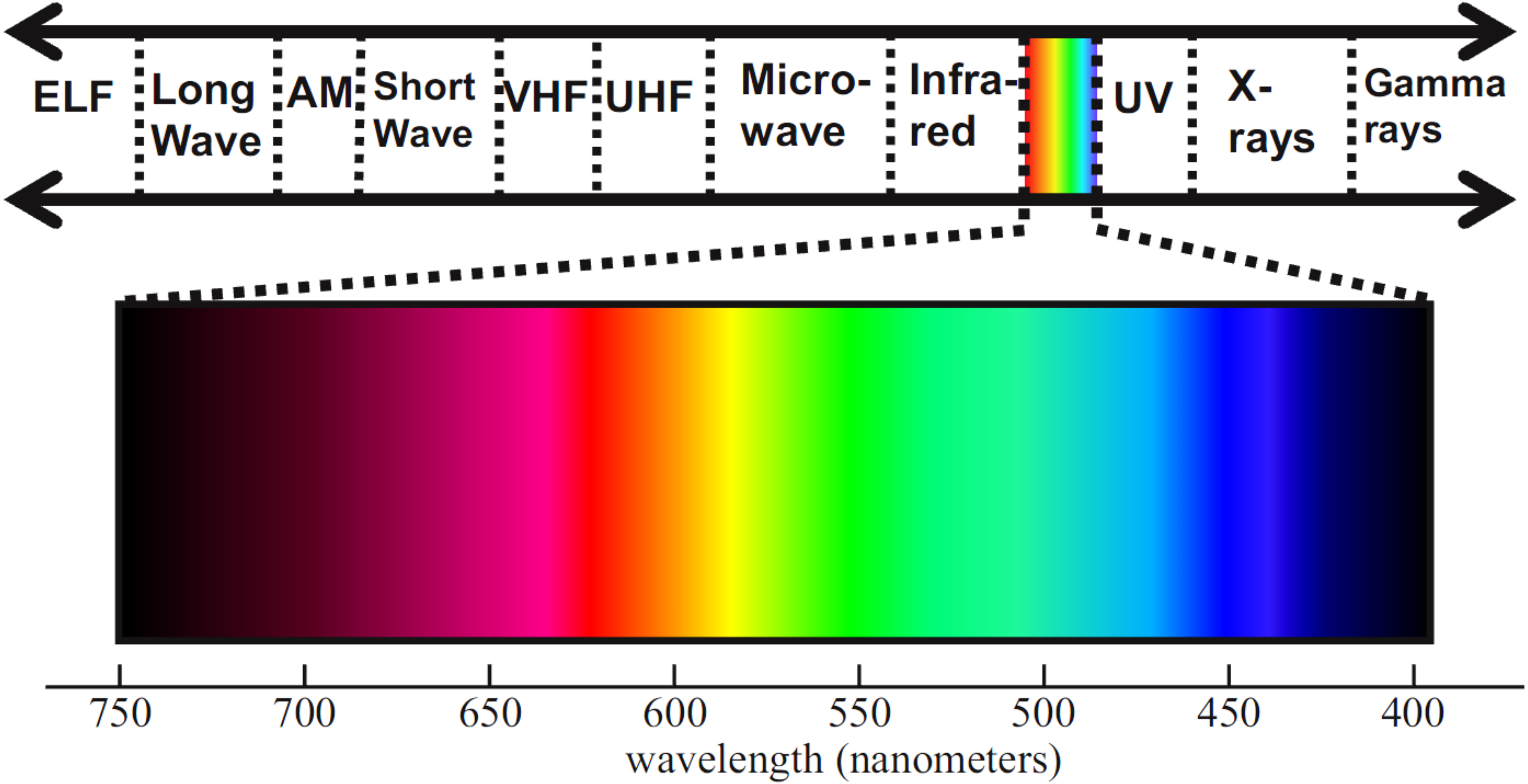
The Physics Behind Shading

- The physical phenomena that occur when light interacts with matter

What is Light? EM Transverse Wave



What is Visible Light? ~400-700nm

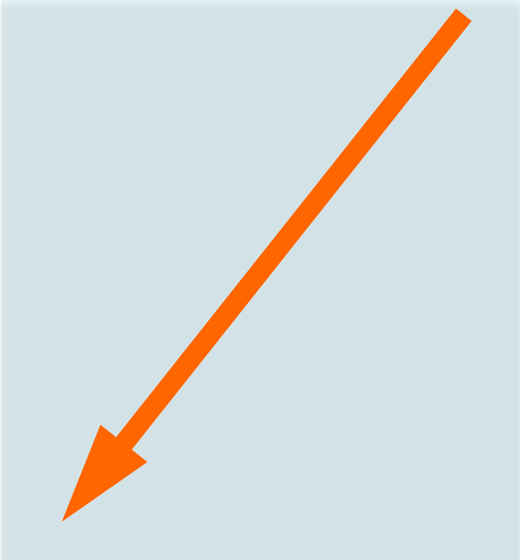


Light Propagating Through Matter

- Light propagating through a homogeneous medium is affected by medium's *refractive index*
- In the general case, it's a complex number
  - The real part affects the speed of propagation
  - The imaginary part affects whether the light is absorbed as it propagates
- Refractive index may vary with wavelength

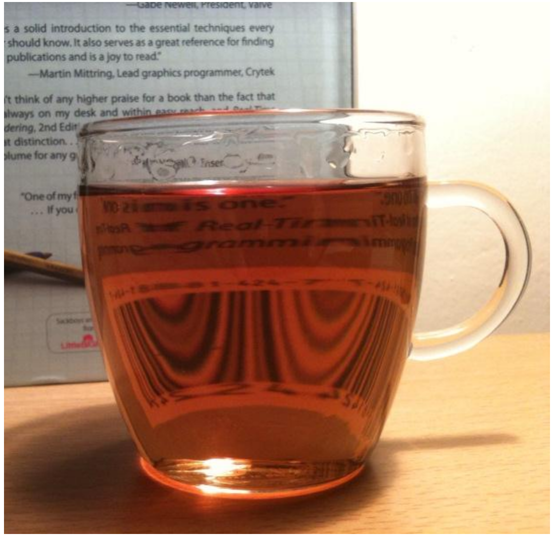
Transparent media

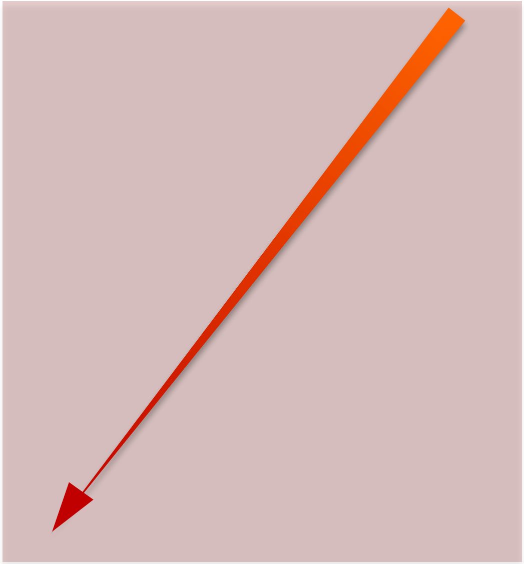
- E.g. water, glass – absorption in the visible spectrum is very low



Clear Absorbent Media

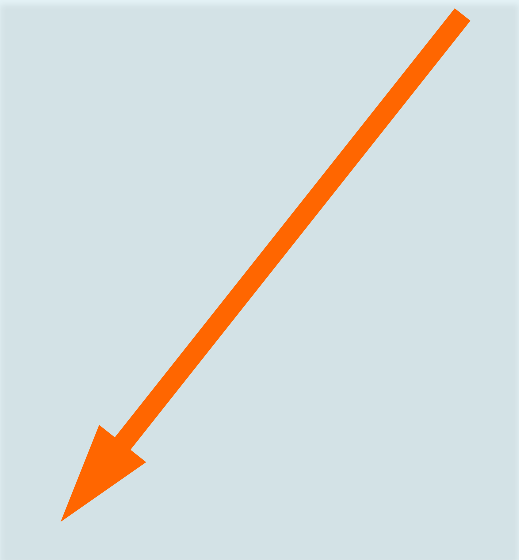
- Significant absorption over all or part of the visible spectrum





Scale

- Scale important – absorption negligible over inches...



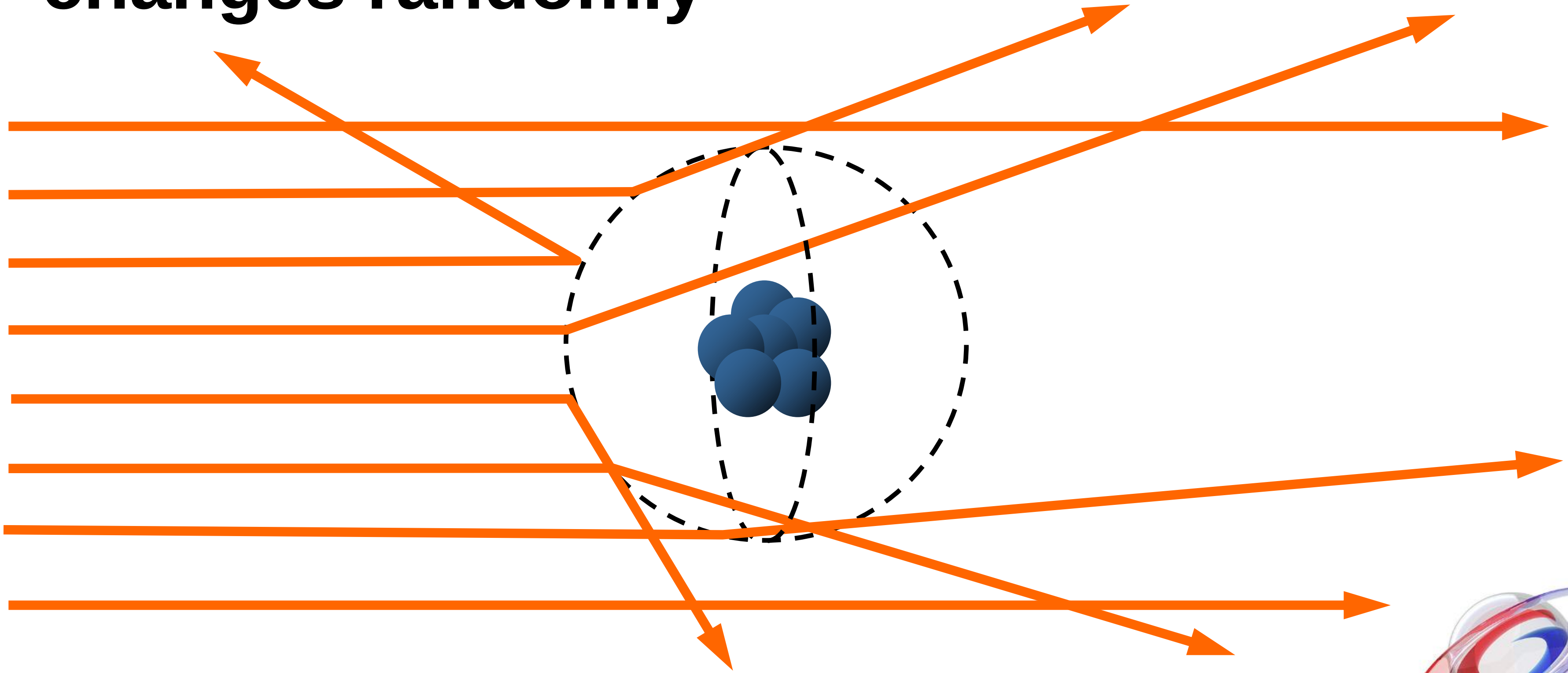
Scale

- …may be significant over yards

What if the medium isn't homogeneous?

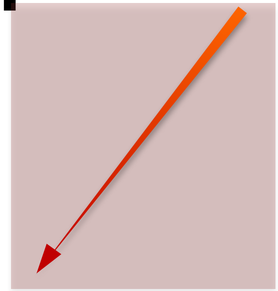
- Index of refraction changes
  - If it changes slowly and continuously, light bends
  - If it changes abruptly, over a small distance (compared to the wavelength), then light ***scatters***
- Direction of light changes abruptly; amount of light stays the same

Scattering by a particle: light direction changes randomly

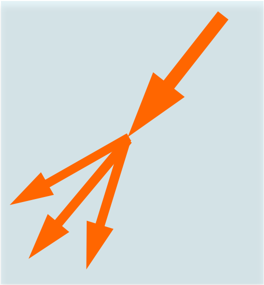


Interactions of Light and Matter

- Absorption: intensity decrease / color change, direction unchanged



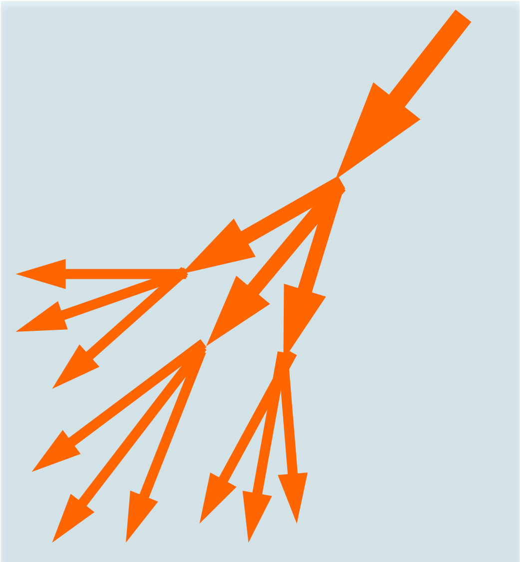
- Scattering: direction of light changes, intensity unchanged



- Emission (new light created; doesn't come up often in shading)

Cloudy Media

- Scattering somewhat randomizes light propagation direction

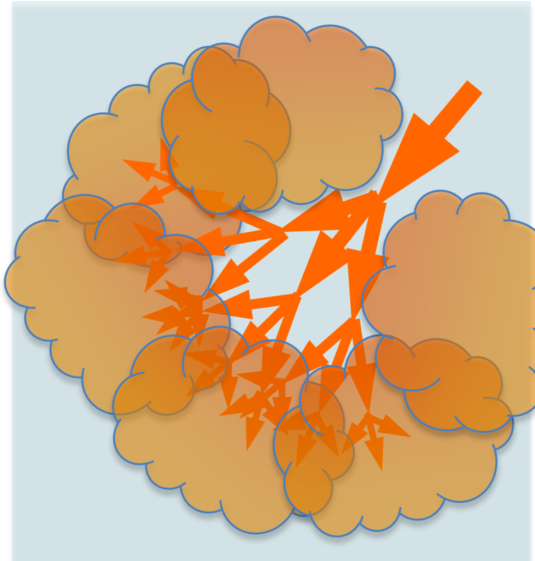


Scattering and Scale

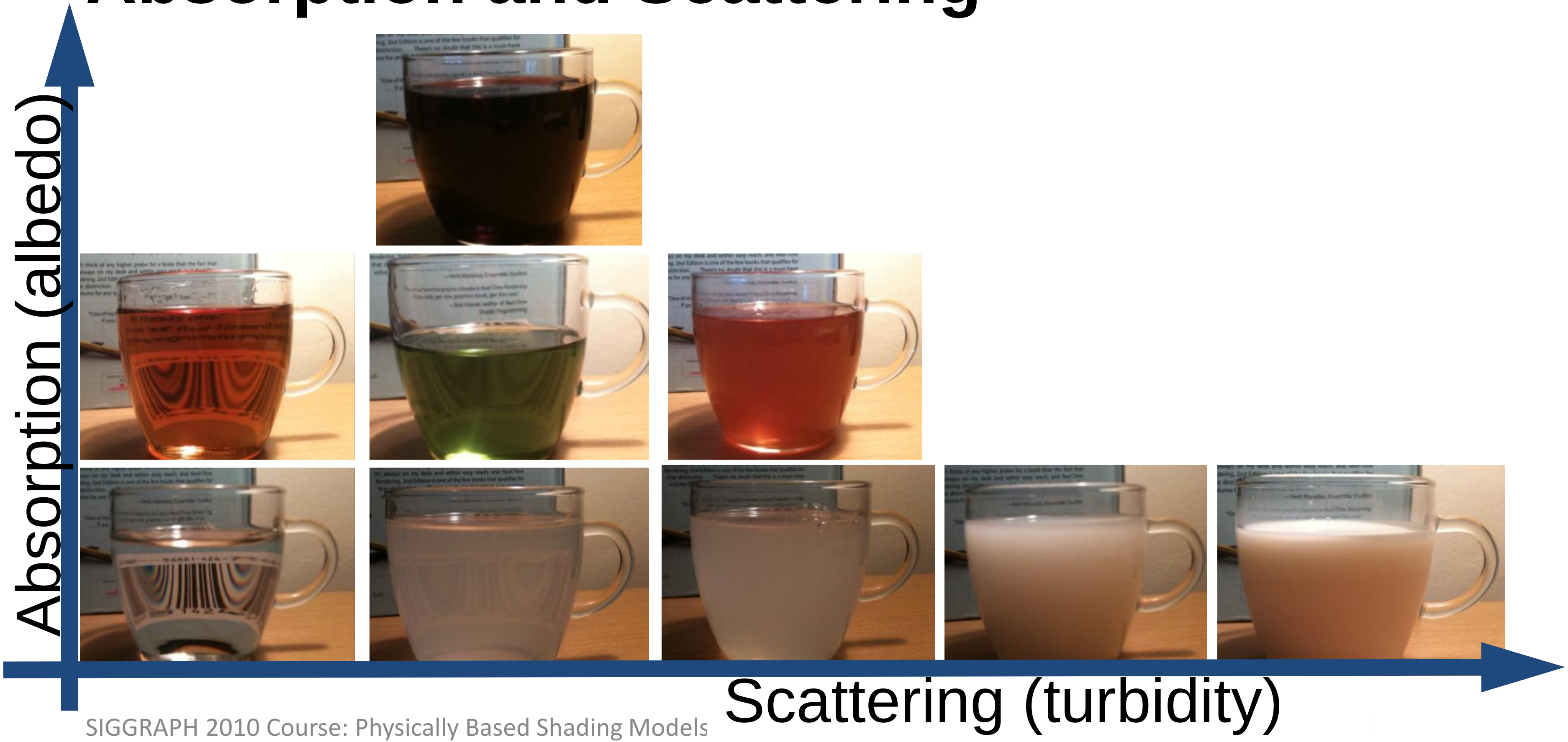
- Scale matters here too

Opaque or Translucent Media

- Scattering completely randomizes light propagation direction



Absorption and Scattering



Scattering at a Planar Boundary

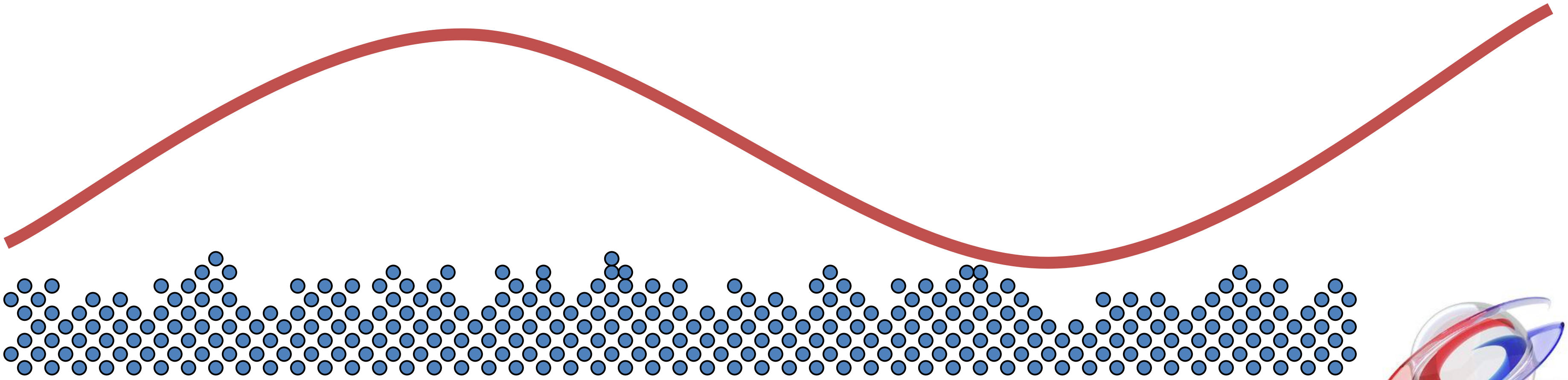
- Abrupt changes in refractive index cause light direction to change
- There is an important special case:
  - Infinite, perfectly flat planar boundary between two volumes with different refractive indices
  - Object surface; refractive index of air on one side of the boundary, refractive index of object on the other

Wait a Moment, “Infinite”?

- The relevant scale is the wavelength of visible light (400-700nm)
- At this scale surface effectively infinitely large

“Perfectly Flat”? What About Atoms?

- It is possible to be perfectly flat at this scale
  - Bumps much smaller than wavelength don’t count



Planar Boundary: Reflection & Refraction

- Light splits into two directions: reflection and refraction
- Refracted light may be absorbed and/or scattered under the surface

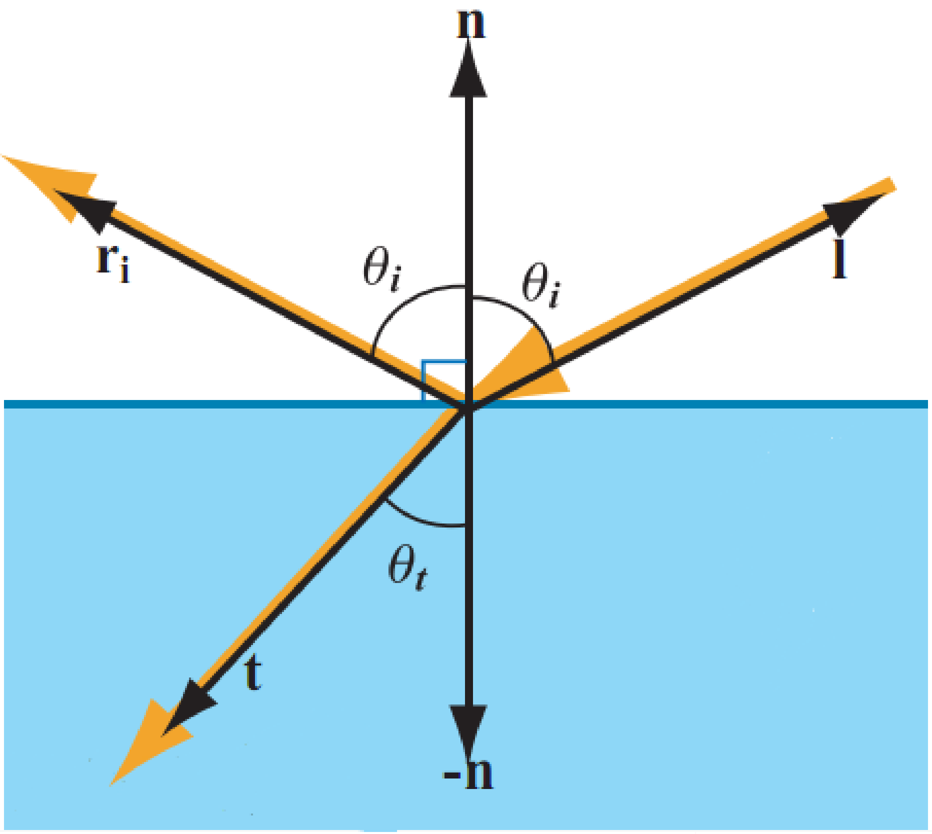


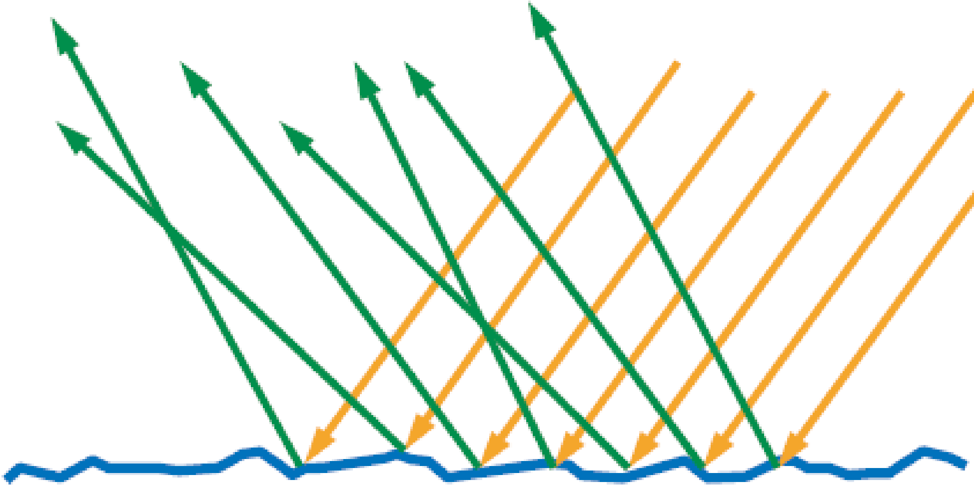
Image from “Real-Time Rendering, 3rd Edition”, A K Peters 2008

Surfaces That Aren't Optically Flat

- Few surfaces (mostly high-quality optical mirrors and lenses) are *optically flat* (all irregularities are much smaller than visible light wavelengths)
- Most surfaces have irregularities which are larger than light wavelengths but smaller than the *scale of observation* (e.g. subpixel size)

Microgeometry

- At surface point, light reflected in one direction
- Surface appearance is aggregate result of many points with different surface orientations



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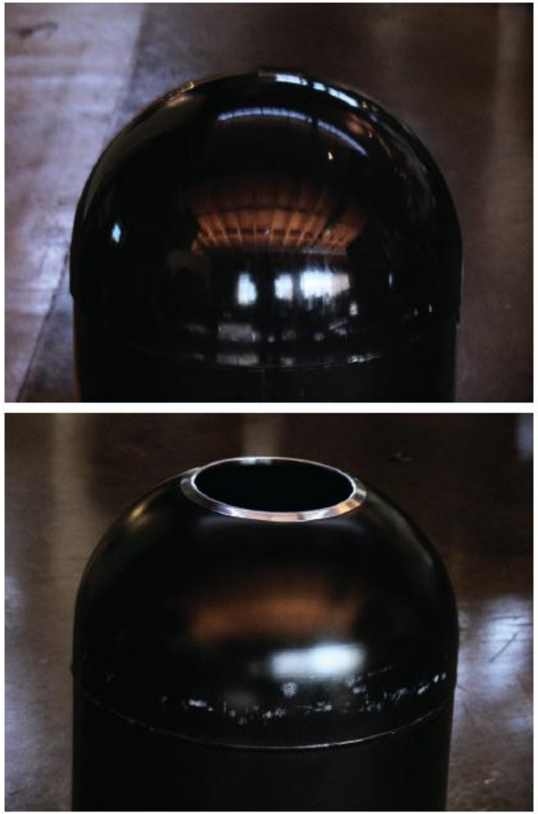
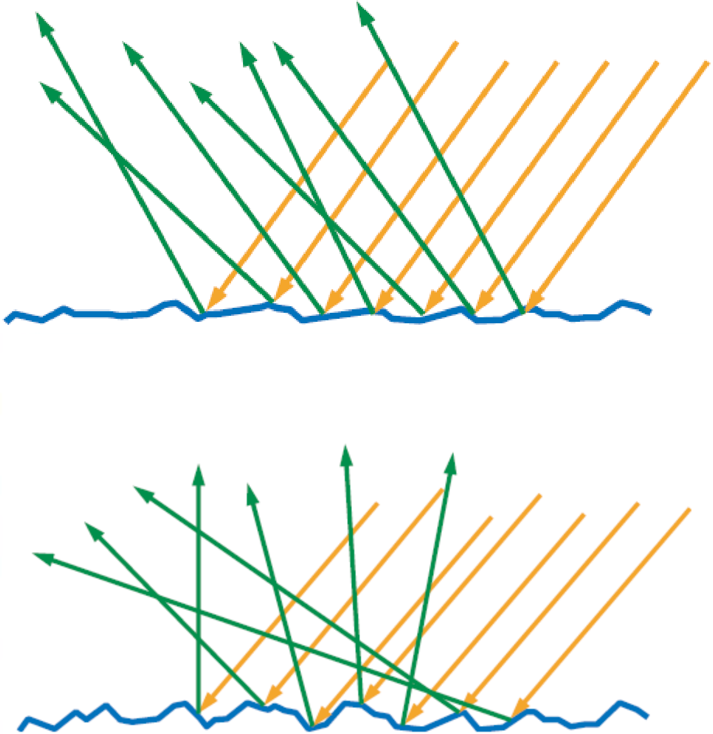
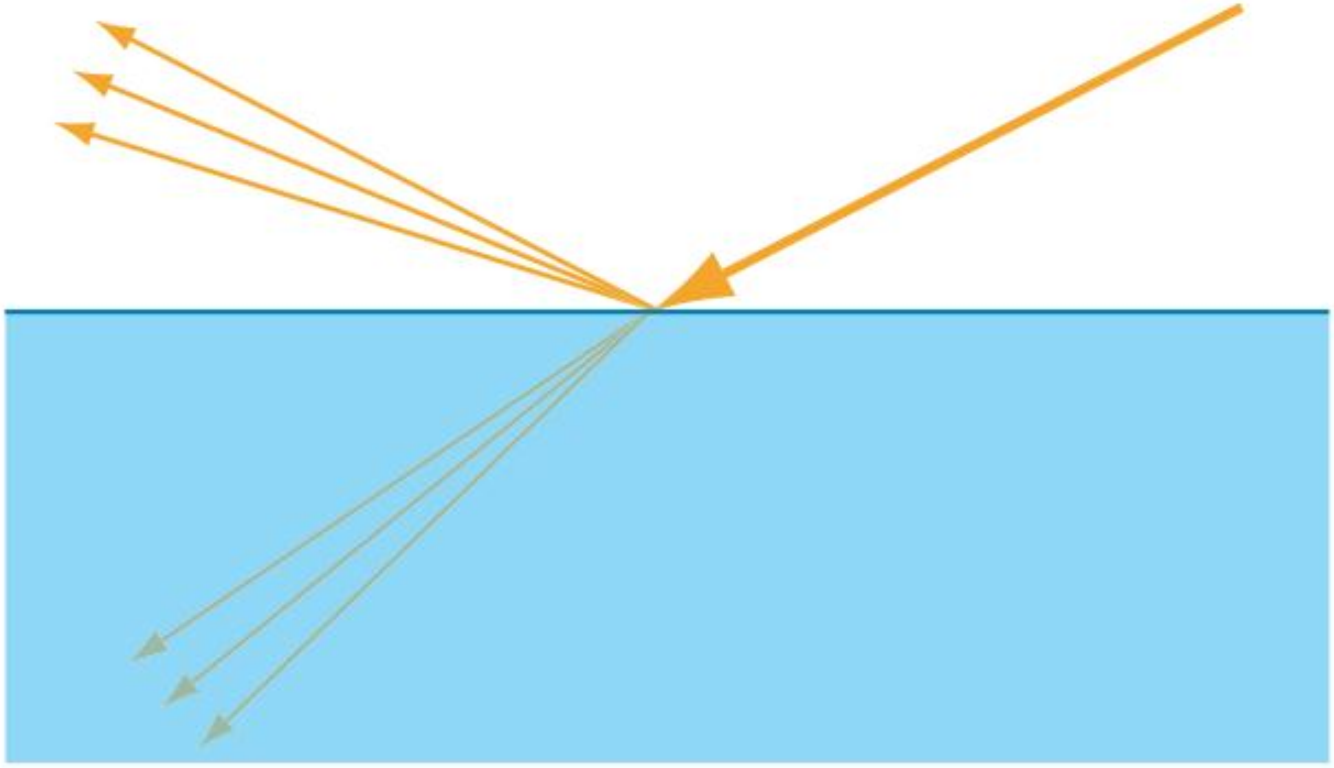
Rougher = Blurrier Reflections





Images from “Real-Time Rendering, 3rd Edition”, A K Peters 2008

Macroscopic View



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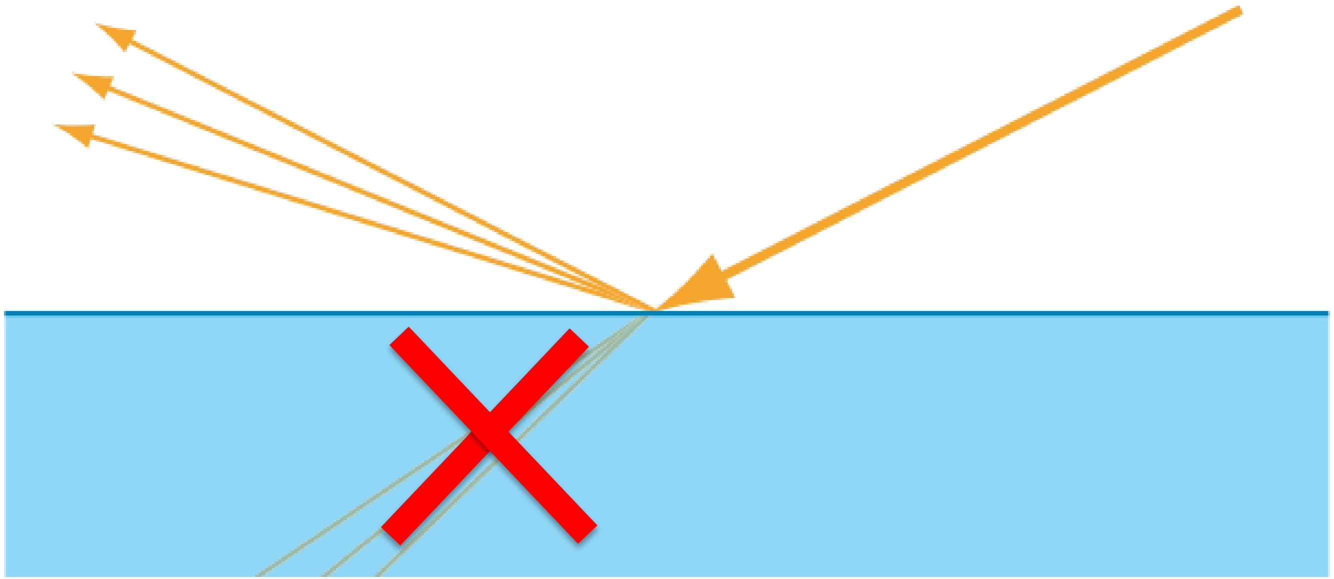
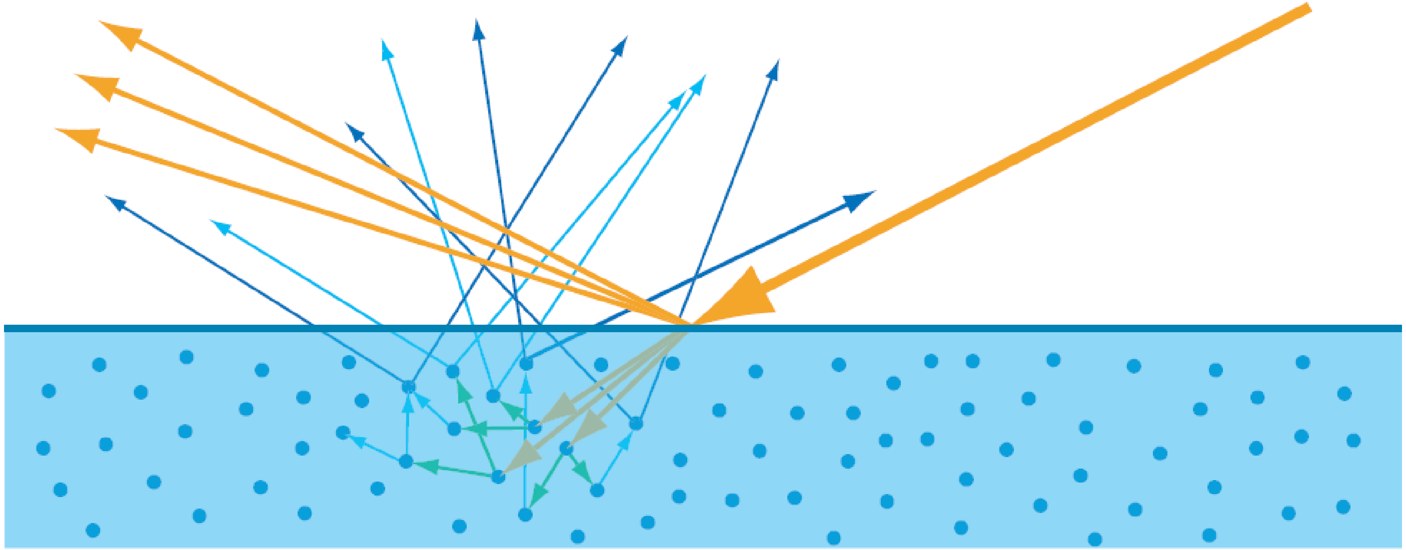
Metals

- All refracted light is immediately absorbed



Non-Metals (Insulators, Dielectrics)

- Refracted light undergoes scattering and/or absorption, often re-emerging from the surface



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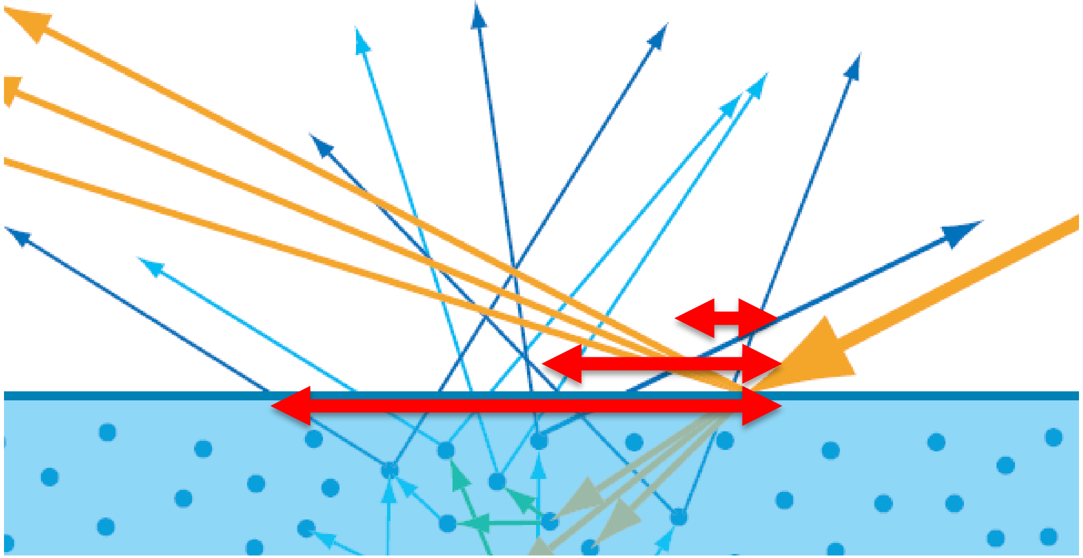
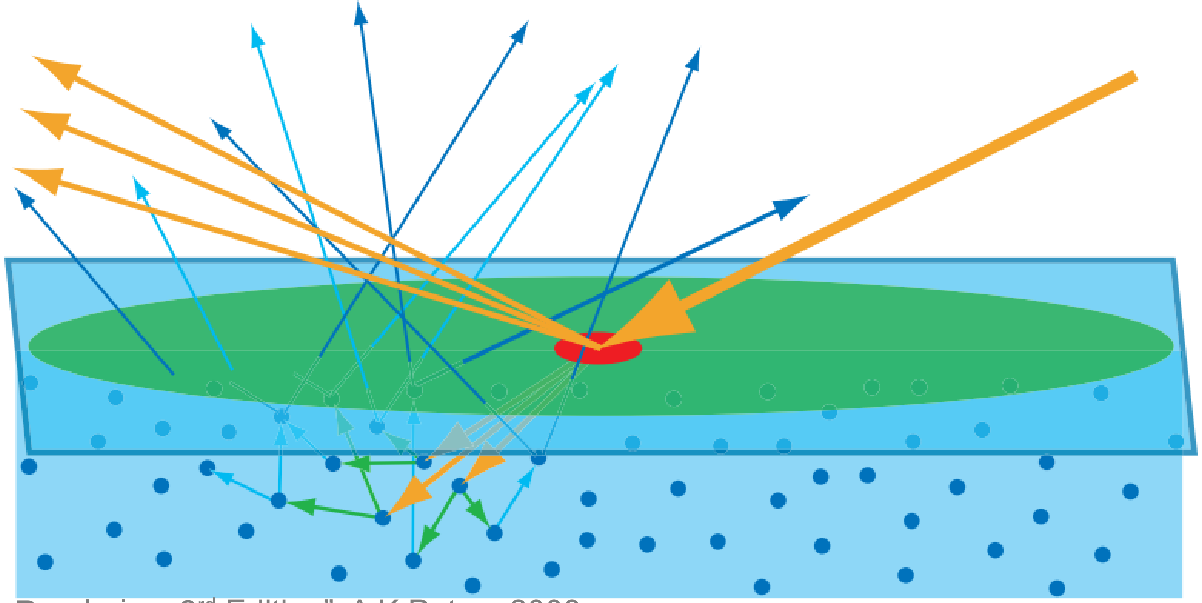
Scale and Subsurface Scattering

- Distribution of entry-exit distances depends on density and properties of scattering particles



Scale and Subsurface Scattering

- If pixel is large (green circle) compared to entry-exit distances, can assume distances are zero



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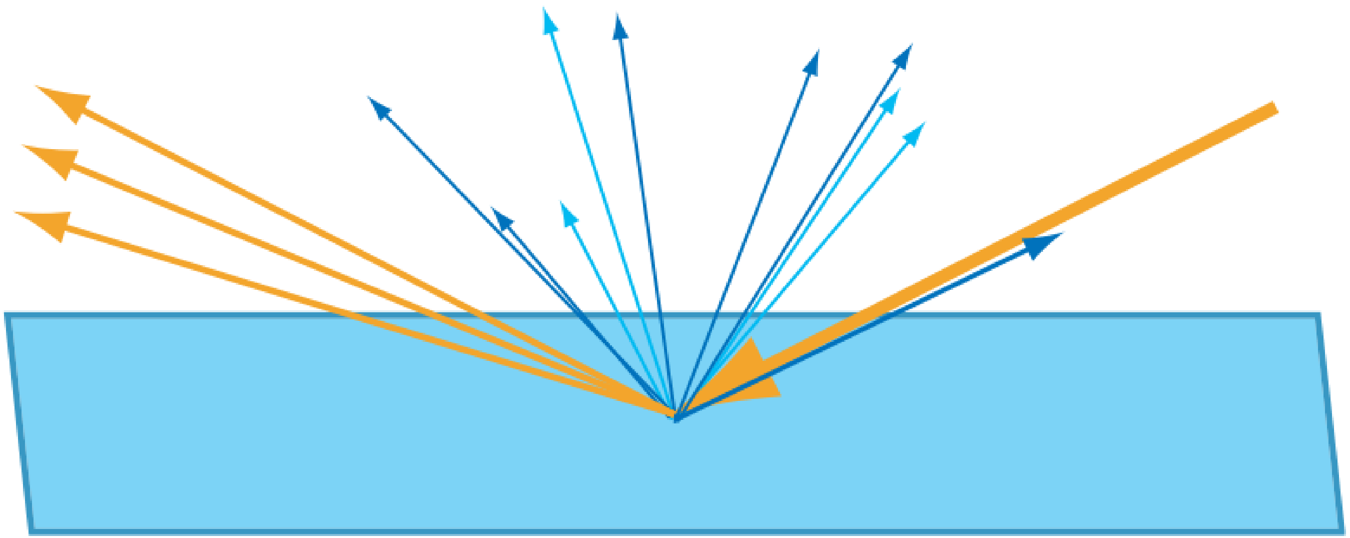
Scale and Subsurface Scattering

- By ignoring entry-exit distance, all shading can be computed locally, at a single point



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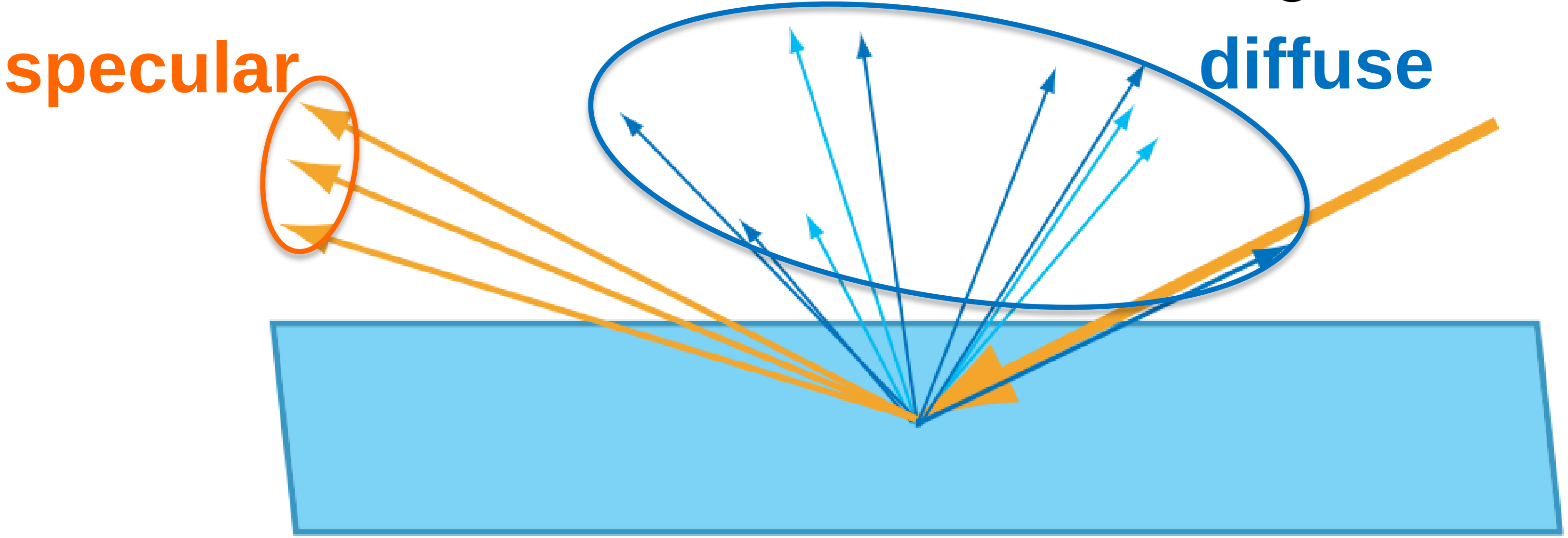
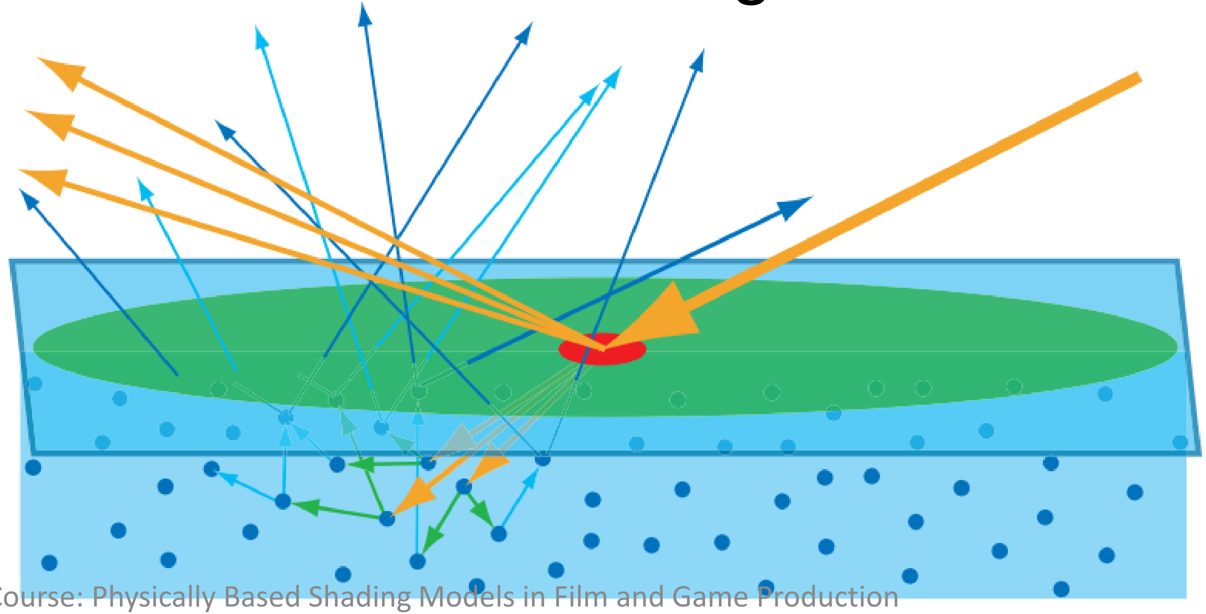
Shading Terms

- Surface reflection modeled as “specular” and refraction with subsurface scattering as “diffuse”



Scale and Subsurface Scattering

- If pixel is small (red circle) compared to entry-exit distances, local shading does not suffice



$$L_o(\mathbf{v}) = \int_\Omega f(\mathbf{l}, \mathbf{v}) \otimes L_i(\mathbf{l})(\mathbf{n} \cdot \mathbf{l}) d\omega_i$$

The Mathematics of Shading

$$L_o(\mathrm{v}) = \pi f(\mathbf{l_c}, \mathbf{v}) \otimes \mathbf{c}_{\text{light}} \underline{(\mathbf{n} \cdot \mathbf{l_c})}$$

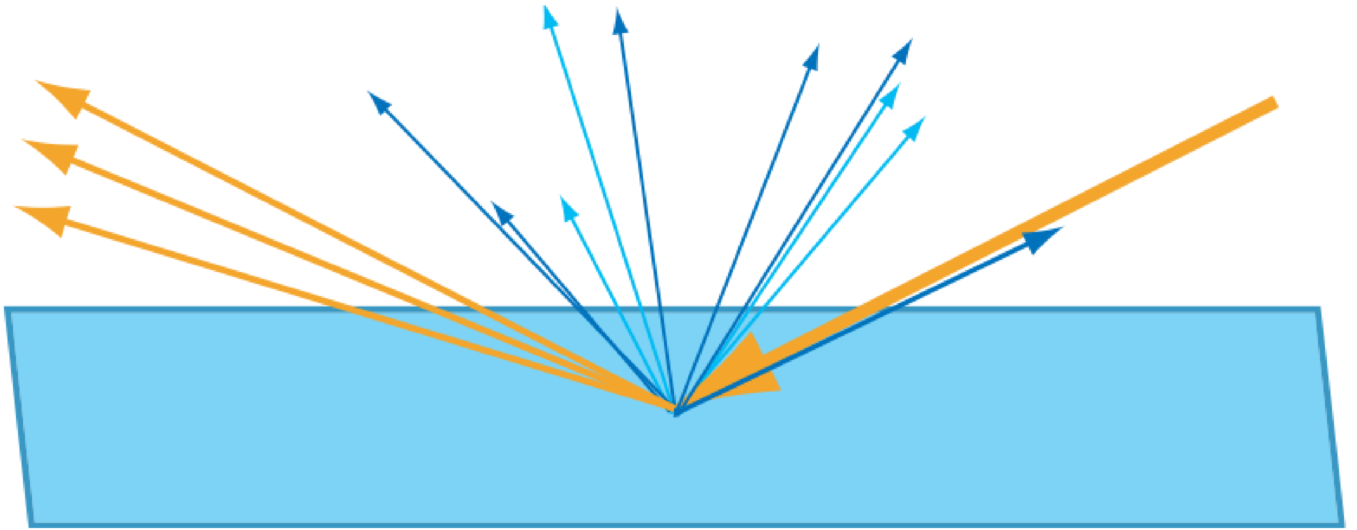
$$f(\mathbf{l}, \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{h}) G(\mathbf{l}, \mathbf{v}, \mathbf{h}) D(\mathbf{h})}{4(\mathbf{n} \cdot \mathbf{l})(\mathbf{n} \cdot \mathbf{v})}$$

Radiometry – The Measurement of Light

- There is a variety of radiometric quantities
- We will use *radiance*, which measures the intensity of light along a single ray
- Radiance varies with light wavelength
  - Technically requires a continuous spectral distribution
  - Production graphics use tristimulus values like RGB

Local Shading

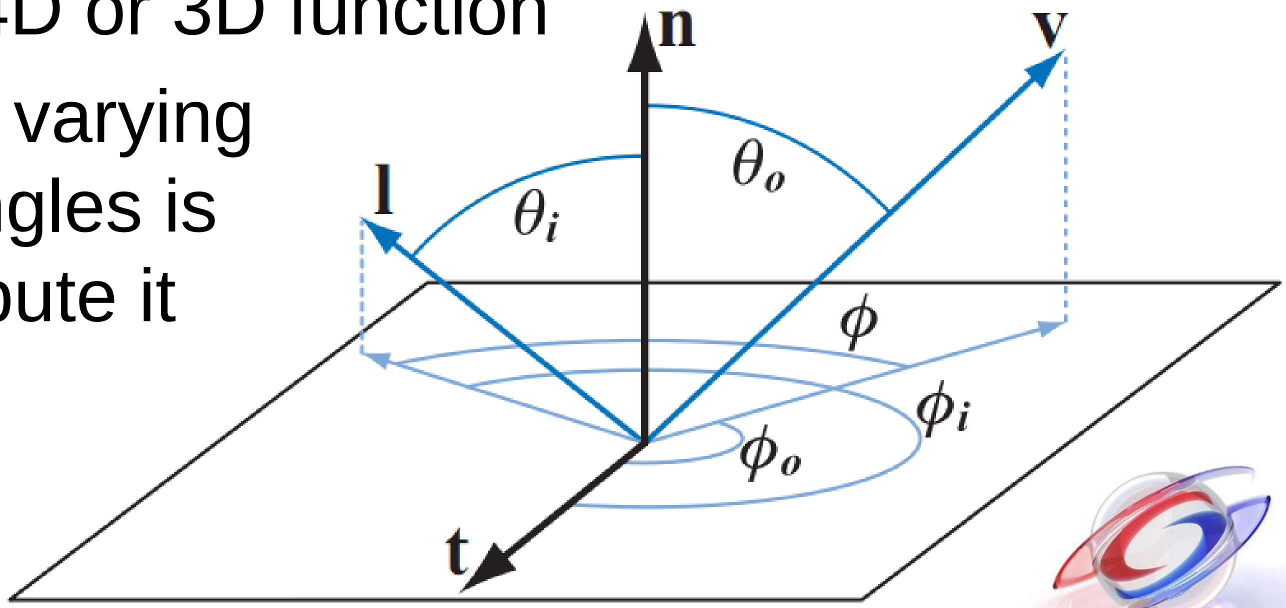
- Given the assumption that shading can be handled locally, light response at a surface point only depends on the light and view directions



BRDF: Function of View & Light Direction

- **B**idirectional **R**eflectance **D**istribution **F**unction
- In principle, 4D or 3D function
- In practice, a varying number of angles is used to compute it

$$f(\mathbf{l}, \mathbf{v})$$



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Domain of the BRDF

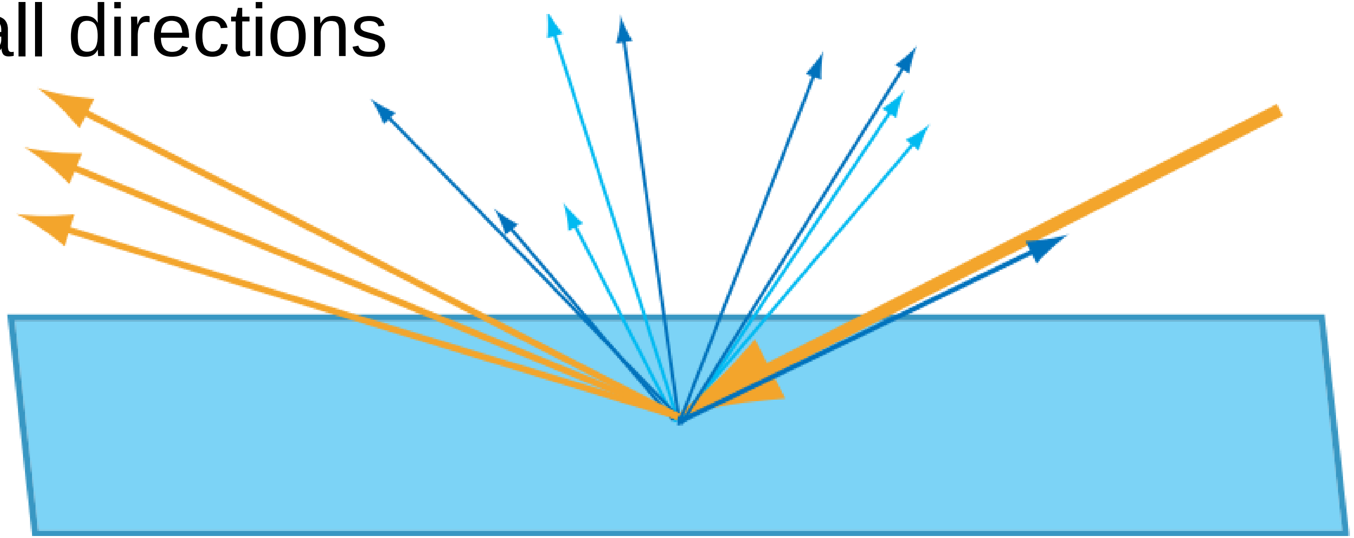
- In principle, reflection is only defined for light and view directions above the surface

$$(\mathbf{n} \cdot \mathbf{l}) > 0, (\mathbf{n} \cdot \mathbf{v}) > 0$$

- In practice, sometimes other situations need to be handled (e.g., normal mapping) – this will be discussed in the course notes

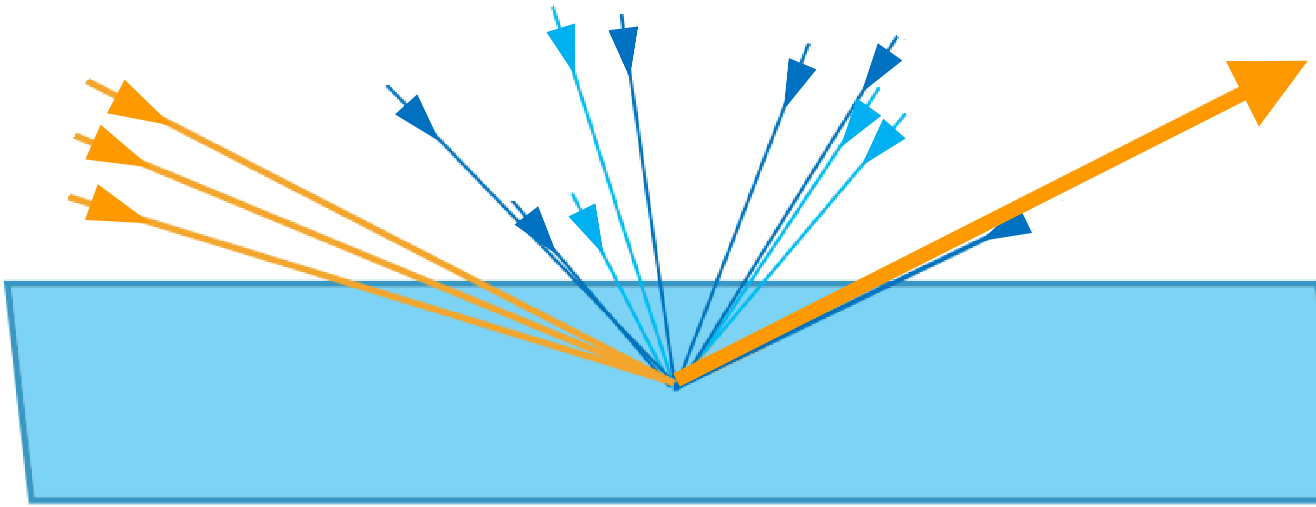
BRDF: One Interpretation

- For a ray of incoming light from a given direction, the BRDF gives the distribution of outgoing light in all directions



BRDF: Another Interpretation

- For a given view direction, the BRDF gives the relative contribution of each incoming direction



The BRDF Varies by Light Wavelength

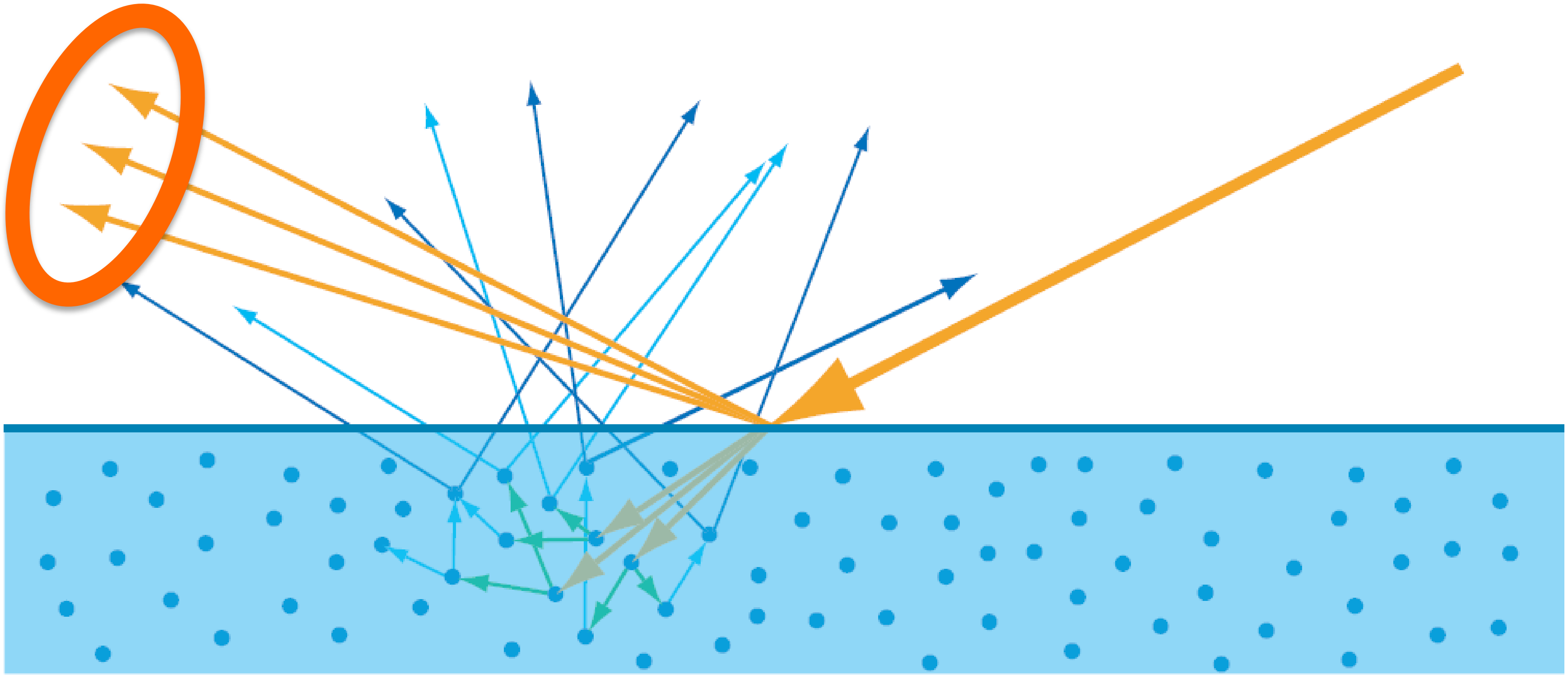
- But there is no cross-talk between frequencies
- BRDF can be treated as an RGB-valued function that gets multiplied with RGB-valued light colors

The Reflectance Equation

$$L_o(\mathbf{v}) = \int_\Omega f(\mathbf{l}, \mathbf{v}) \otimes L_i(\mathbf{l})(\mathbf{n} \cdot \mathbf{l}) d\omega_i$$

- Outgoing radiance equals the integral (over all directions above the surface) of incoming radiance times BRDF and cosine factor
- “X in circle” denotes component-wise vector (RGB) multiplication

Surface Reflection (Specular Term)

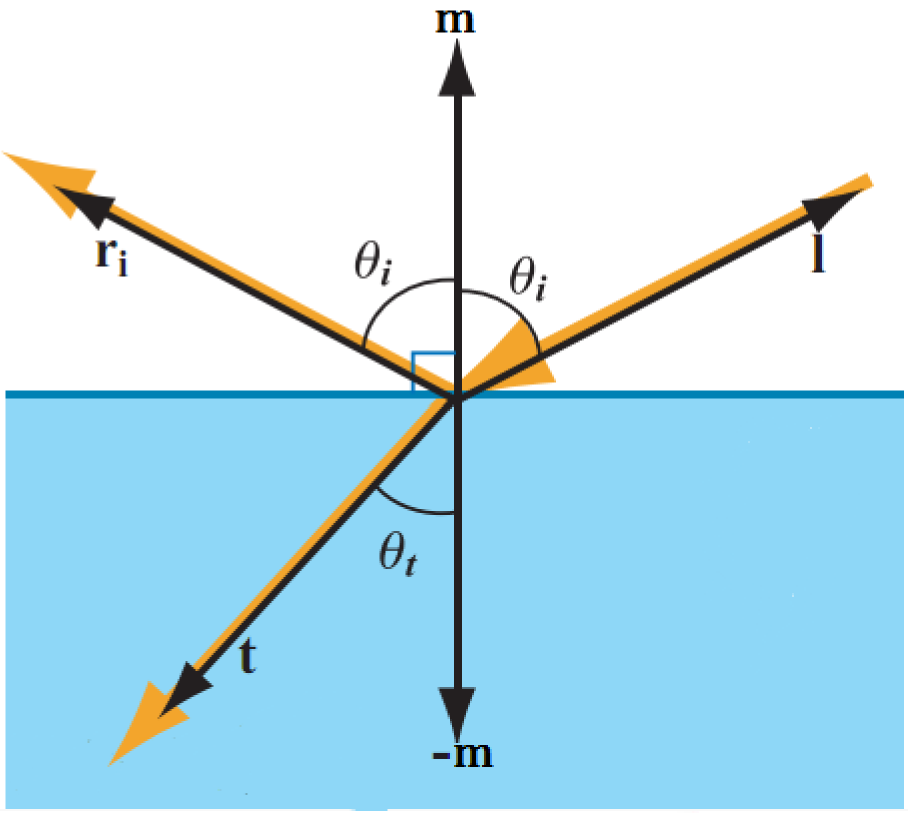


Microfacet BRDF

- BRDF derived for surface reflection from general (non-optically flat) surfaces
- Assumes surface is composed of many microfacets – individual optically flat surfaces too small to be seen

Microfacets Are Optically Flat

- Each one reflects an incoming ray of light in only one outgoing direction



The Half Vector

- Only those microfacets which happen to have their surface normal **m** oriented exactly halfway between **l** and **v** will reflect visible light

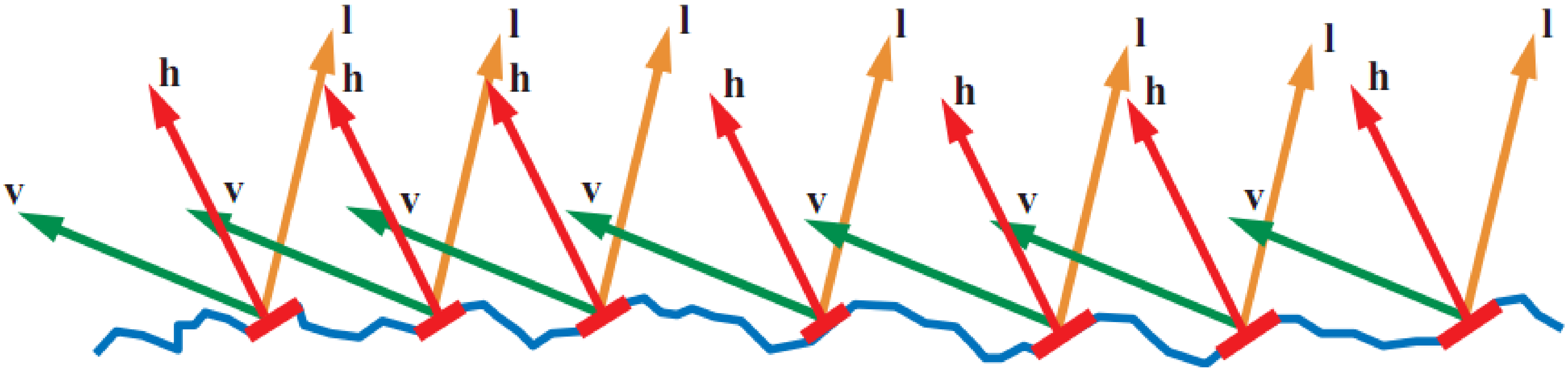
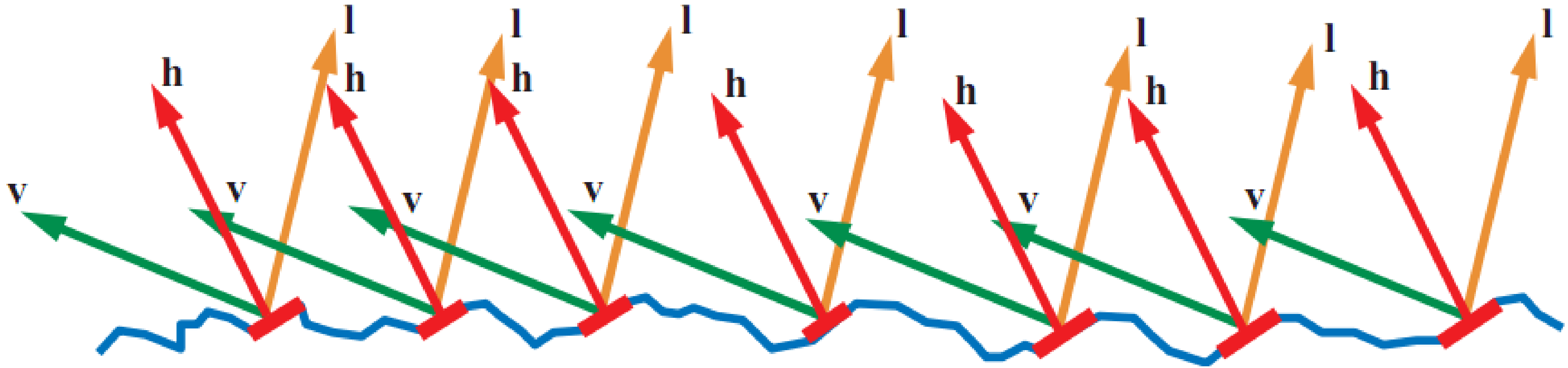


Image from "Real-Time Rendering, 3rd Edition", A K Peters 2008

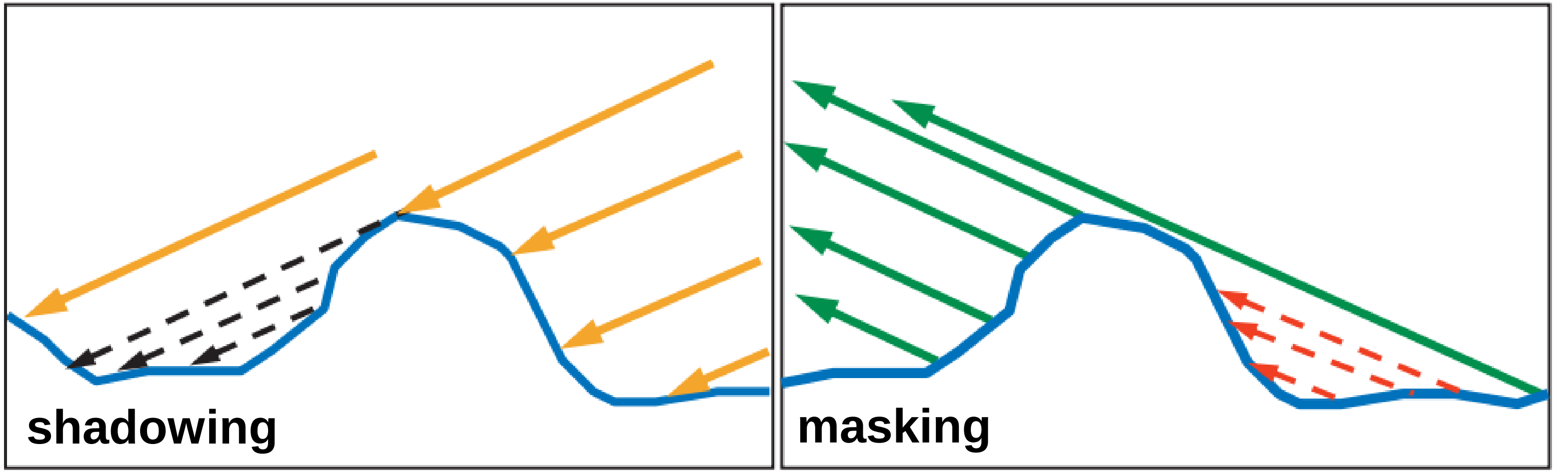
The Half Vector

- This vector which is halfway between $\mathbf{l}$ and $\mathbf{v}$, is called the *half-vector* (or *half-angle vector*) $\mathbf{h}$



Shadowing and Masking

- Not all microfacets with $\mathbf{m} = \mathbf{h}$ will contribute
- Some will be blocked by other microfacets from either $\mathbf{l}$ (*shadowing*) or $\mathbf{v}$ (*masking*)



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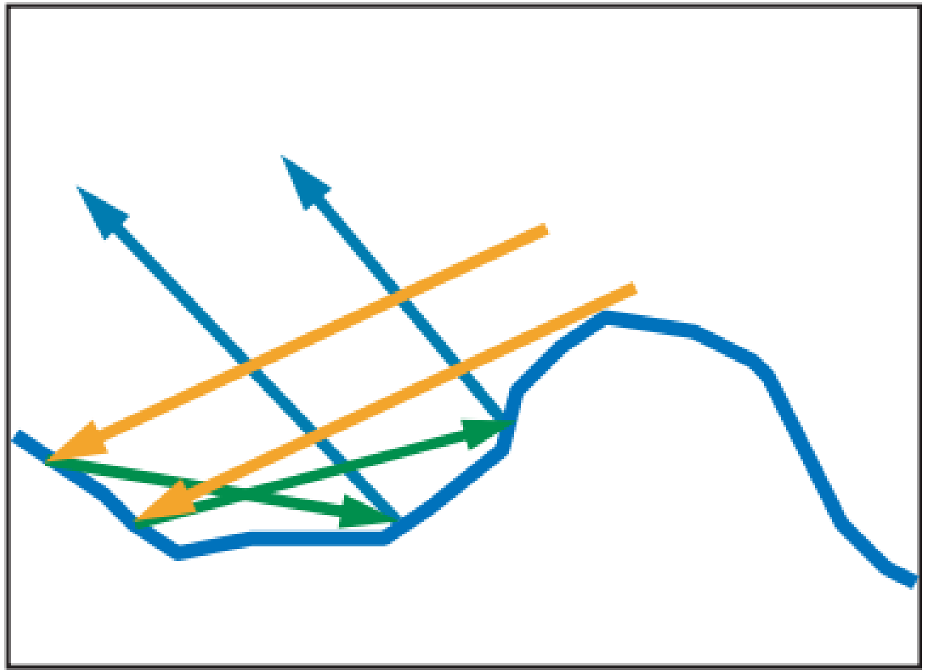
Multiple Surface Bounces

- In reality, blocked light continues to bounce; some will eventually contribute to the BRDF
- Microfacet BRDFs ignore this – blocked light is lost



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Microfacet BRDF

$$f(\mathbf{l}, \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{h})G(\mathbf{l}, \mathbf{v}, \mathbf{h})D(\mathbf{h})}{4(\mathbf{n} \cdot \mathbf{l})(\mathbf{n} \cdot \mathbf{v})}$$

Fresnel Reflectance

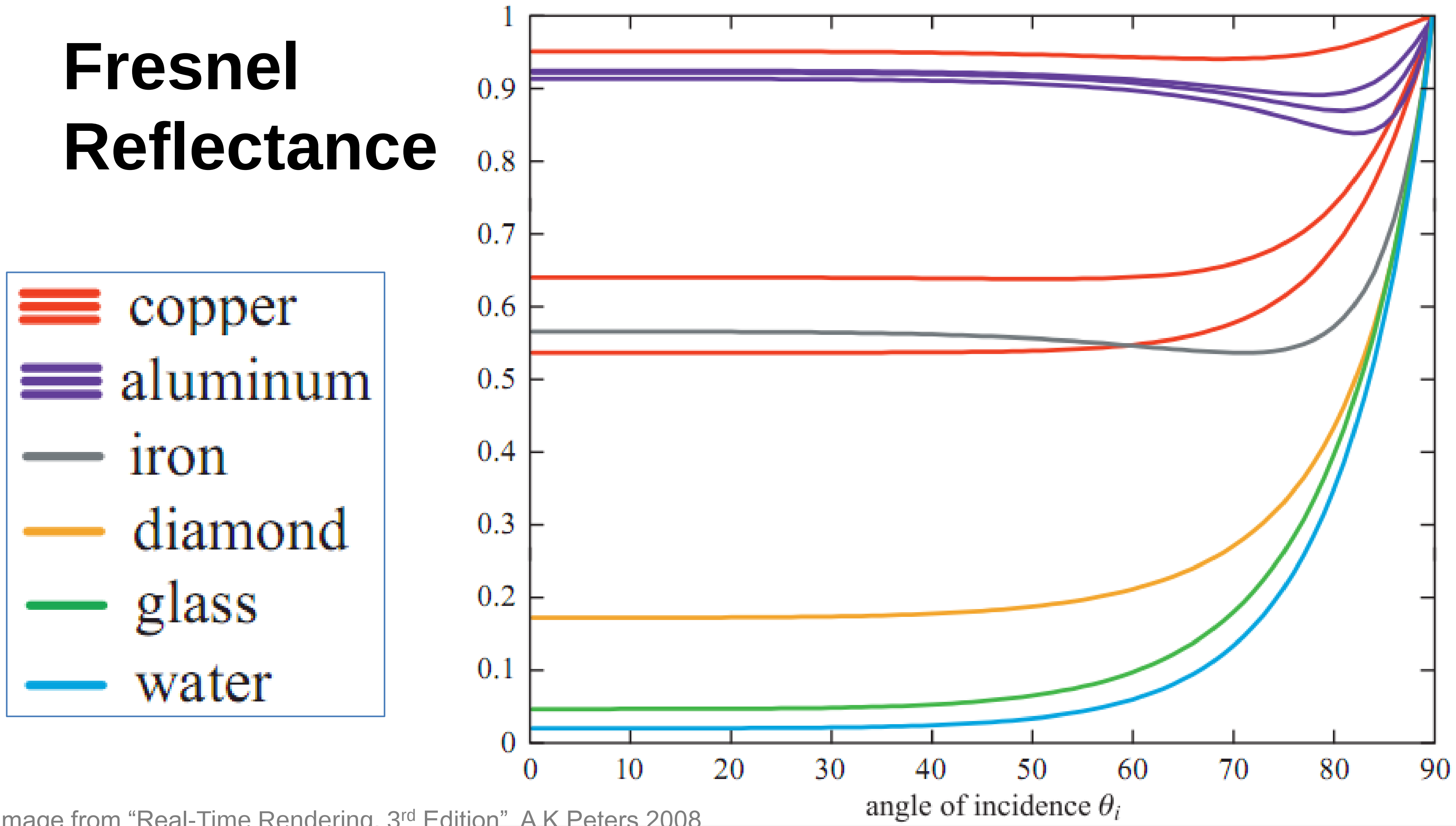
$$f(\mathbf{l}, \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{h}) G(\mathbf{l}, \mathbf{v}, \mathbf{h}) D(\mathbf{h})}{4(\mathbf{n} \cdot \mathbf{l})(\mathbf{n} \cdot \mathbf{v})}$$

- Value range: 0 to 1, spectral (RGB)
  - Fraction of light reflected (vs. refracted) from optically flat surface given light direction $\mathbf{l}$ and surface normal $\mathbf{h}$ ($\mathbf{m} = \mathbf{h}$ for participating facets)

Fresnel Reflectance

- Depends on refraction index (in other words, the substance of the object) and light angle
- As angle increases, at first the reflectance barely changes, then for very glancing angles goes to 1 at all wavelengths

Fresnel Reflectance



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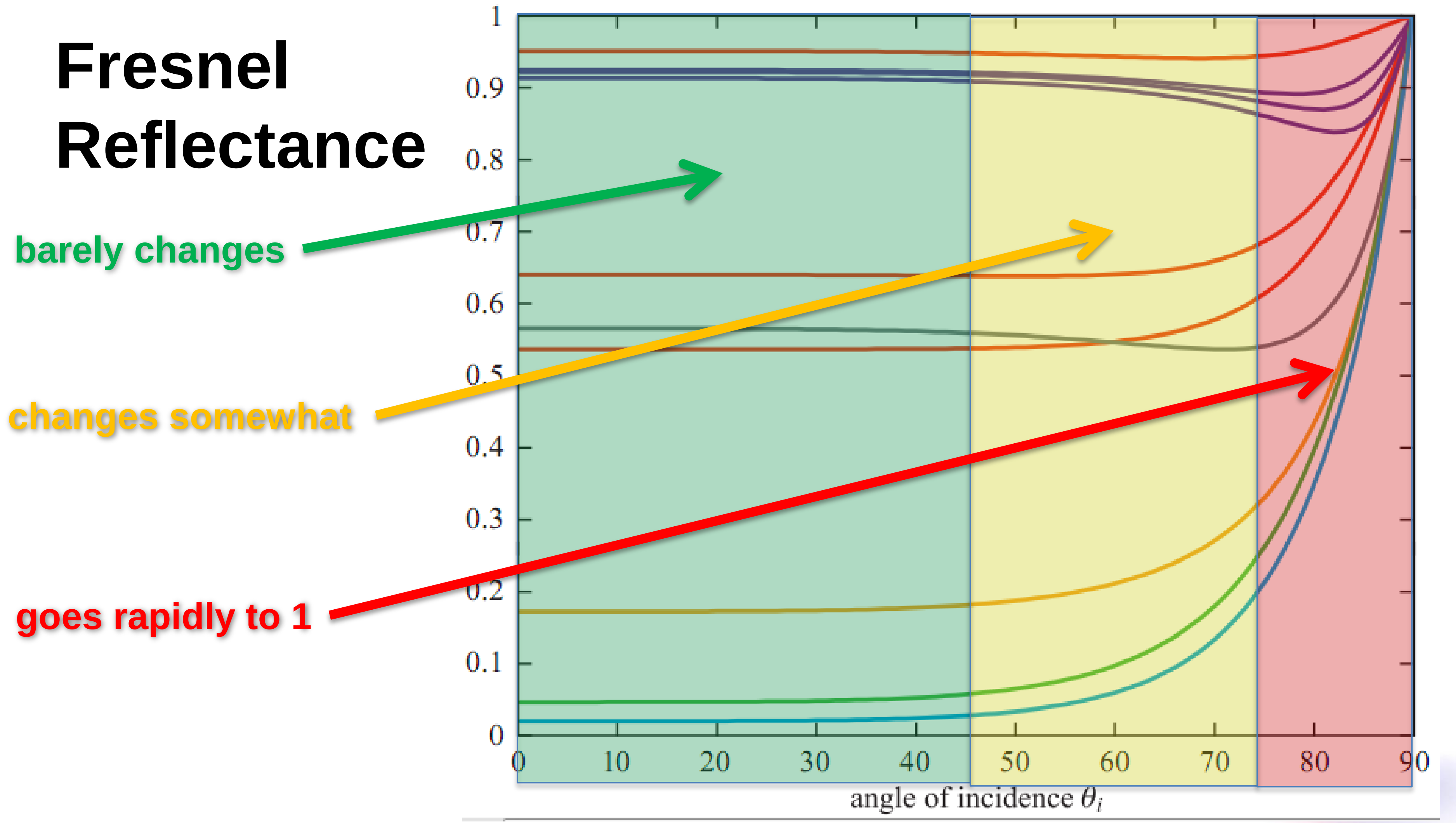
Fresnel Reflectance



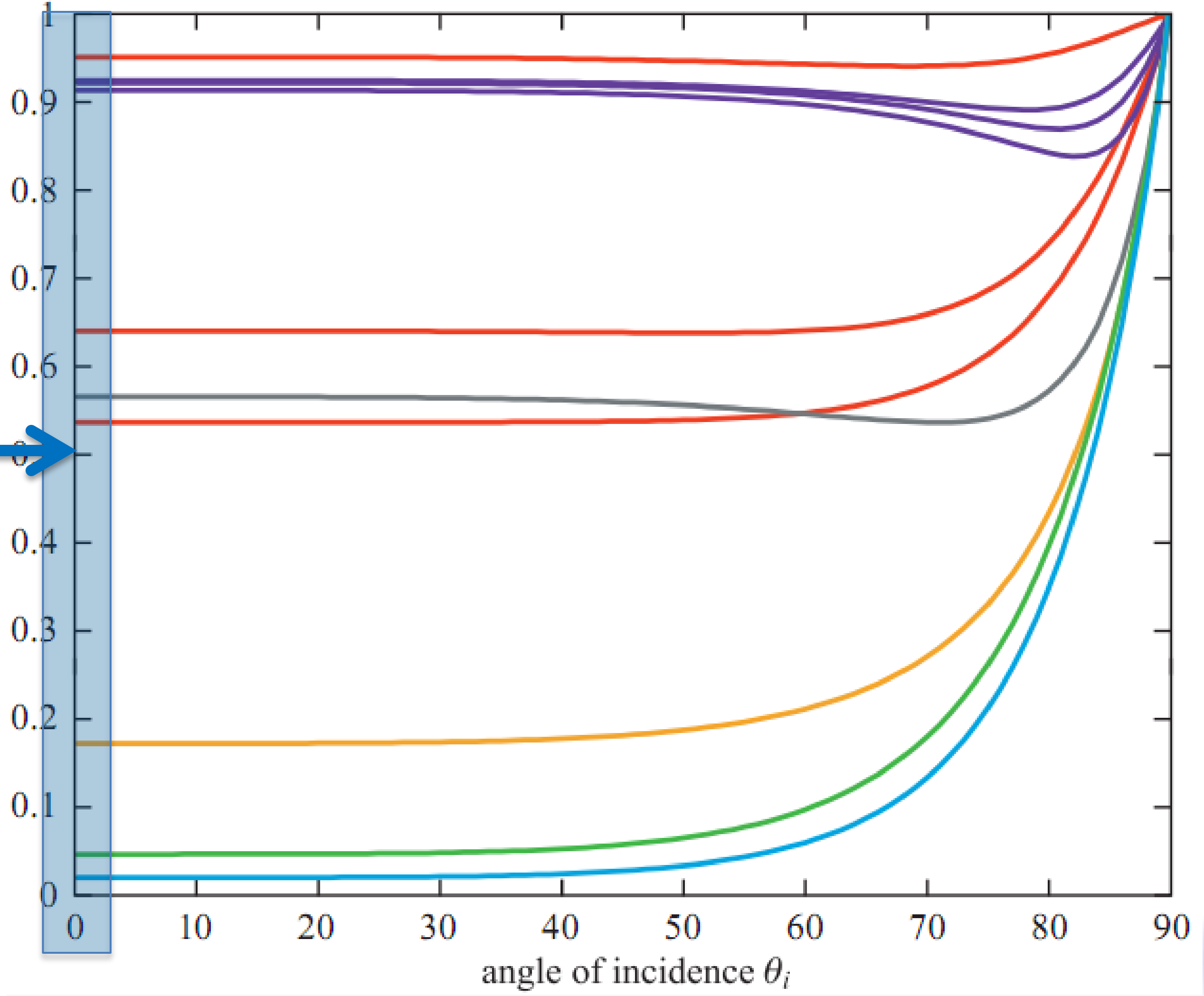
Fresnel Reflectance

The normal-incidence Fresnel reflectance:

$$F(0°)$$

Is the surface's characteristic specular color :

$$\mathbf{c}_{\text{spec}}$$



Normal-Incidence Fresnel for Metals

- No subsurface term; this is only source of color

Metal	$F(0°)$ (Linear)	$F(0°)$ (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	

Table from "Real-Time Rendering, 3rd Edition", A K Peters 2008

Normal-Incidence Fresnel for Non-Metals

- Subsurface term (diffuse) usually also present in addition to this Fresnel reflectance

Insulator	$F(0°)$ (Linear)	$F(0°)$ (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	

Table from "Real-Time Rendering, 3rd Edition", A K Peters 2008

The Schlick Approximation to Fresnel

- Pretty accurate, cheap, parameterized by $\mathbf{c}_{\text{spec}}$

$$F_{\text{Schlick}}(\mathbf{c}_{\text{spec}}, \mathbf{l}, \mathbf{n}) = \mathbf{c}_{\text{spec}} + (1 - \mathbf{c}_{\text{spec}})(1 - (\mathbf{l} \cdot \mathbf{n}))^5$$

- For microfacet BRDFs ($\mathbf{m} = \mathbf{h}$):

$$F_{\text{Schlick}}(\mathbf{c}_{\text{spec}}, \mathbf{l}, \mathbf{h}) = \mathbf{c}_{\text{spec}} + (1 - \mathbf{c}_{\text{spec}})(1 - (\mathbf{l} \cdot \mathbf{h}))^5$$

Microfacet Normal Distribution

$$f(\mathbf{l}, \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{h}) G(\mathbf{l}, \mathbf{v}, \mathbf{h}) D(\mathbf{h})}{4(\mathbf{n} \cdot \mathbf{l})(\mathbf{n} \cdot \mathbf{v})}$$

- Value range: unbounded, scalar
  - $D(\mathbf{m})$: concentration of microfacets with normal $\mathbf{m}$
  - $D(\mathbf{h})$: concentration of microfacets with normal $\mathbf{h}$

Microfacet Normal Distribution

- Determines the size and shape of the highlight
- Several (Gaussian-like) functions available
- All have some kind of “roughness” or variance parameter (anisotropic ones have two)
- As roughness decreases, concentration of microfacets around $\mathbf{n}$ increases; values of D() can get very high for smooth surfaces

Geometry Factor

$$f(\mathbf{l},\mathbf{v}) = \frac{F(\mathbf{l},\mathbf{h})G(\mathbf{l},\mathbf{v},\mathbf{h})D(\mathbf{h})}{4(\mathbf{n}\cdot\mathbf{l})(\mathbf{n}\cdot\mathbf{v})}$$

- Value range: 0 to 1, scalar
  - Chance that a microfacet of the given orientation is shadowed and/or masked
  - Various functions available in the literature; typically have no parameters or use the D() roughness

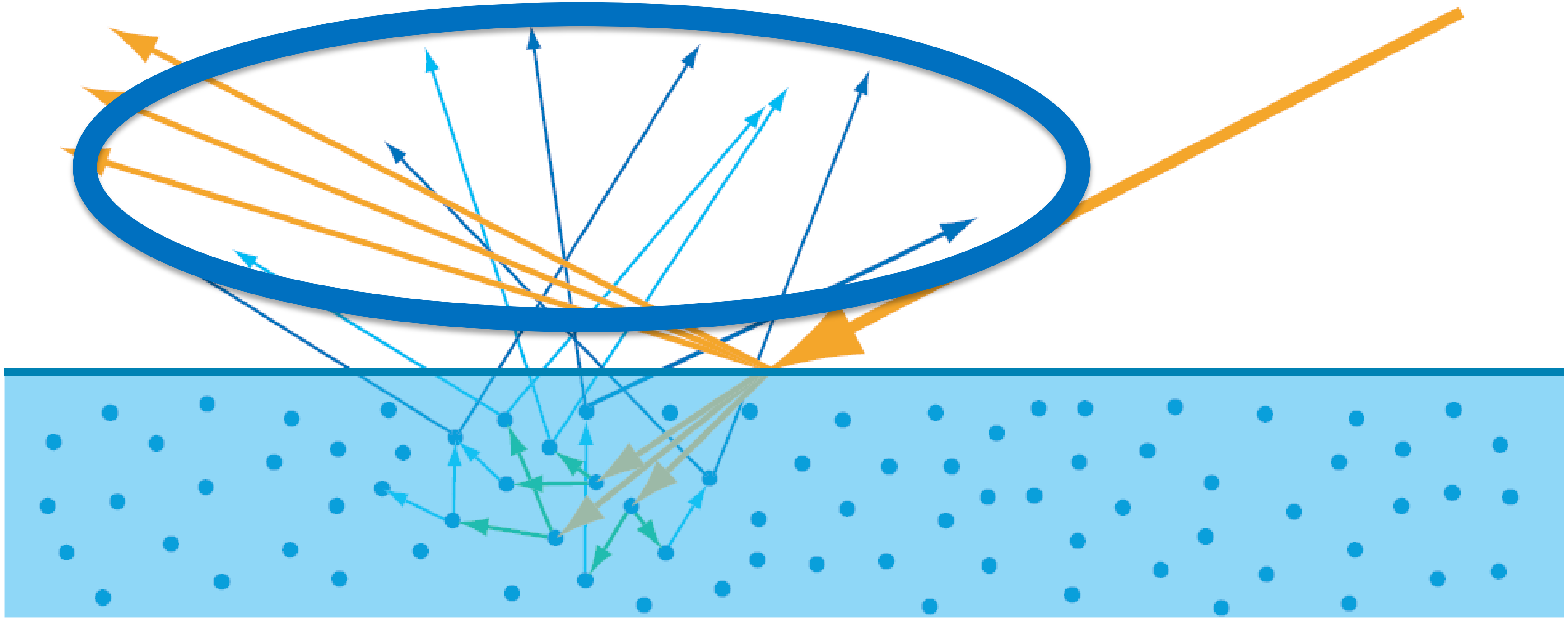
Modular Nature of Microfacet Models

- The choice of D() and G() are independent; you can mix and match from different models
- Most papers proposing a new BRDF model are really introducing a new D() or a new G()

Compact Parameterization

- Once distribution & geometry functions chosen, most microfacet BRDFs have just 2 parameters:
  - $F(0°) = \mathbf{c}_{\text{spec}}$: (RGB)
  - Roughness: 1 scalar (2 for anisotropic)
- However, this only describes surface reflection…

Subsurface Reflection (Diffuse Term)



Lambert: The Simplest BRDF

- Many models for subsurface local reflection in the literature; Lambert by far the most common
- Constant value ($\mathbf{n} \bullet \mathbf{l}$ is part of reflection equation):

$$f_{\text{Lambert}}(\mathbf{l}, \mathbf{v}) = \frac{\mathbf{c}_{\text{diff}}}{\pi}$$

- $\mathbf{c}_{\text{diff}}$: fraction of light reflected, or diffuse color
  - Value range 0 to 1, spectral (RGB)

Implementing Shading

General Lighting

- In the general case, the BRDF must be integrated against the incoming light from all different directions
  - Primary light sources, skylight, indirect reflections
- Requires global Illumination algorithms
- Course on Thursday, *Global Illumination Across Industries*, 2:00 to 5:15 PM, Room 502 A

Punctual Light Sources

- Production lighting models often use punctual (point / directional / spot / etc.) light sources
  - Infinitely small, infinitely bright
- Not physically realizable or realistic, but computationally convenient

Punctual Light Sources

- Parameterized by light color $\mathbf{c}_{\text{light}}$ and direction to the light center l_c
- $\mathbf{c}_{\text{light}}$ equals radiance from a white Lambertian surface illuminated by the light at 90 degrees
  - Value range: unbound, spectral (RGB)

Punctual Light Reflection Equation

$$L_o(\mathrm{v}) = \pi f(\mathbf{l_c}, \mathbf{v}) \otimes \mathbf{c}_{\text{light}} \underline{(\mathbf{n} \cdot \mathbf{l_c})}$$

- Derivation in the course notes
- Underbar denotes clamping to 0: $\underline{x} = \max(x, 0)$

Image Based Lighting

- Such as environment maps
- Production experiences with environment maps in *Terminators and Iron Men* talk, later in this course

Image Based Lighting

- For correct solution, need to do many samples
  - Importance sampling helps
  - *Faster Photorealism in Wonderland* talk in this course and *Importance Sampling for Production Rendering* course on Tuesday (9:00 to 10:30 AM, Room 406 AB)
- Prefiltering alone or with importance sampling

Course Notes Go Into More Detail

- And include references to relevant books and papers

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