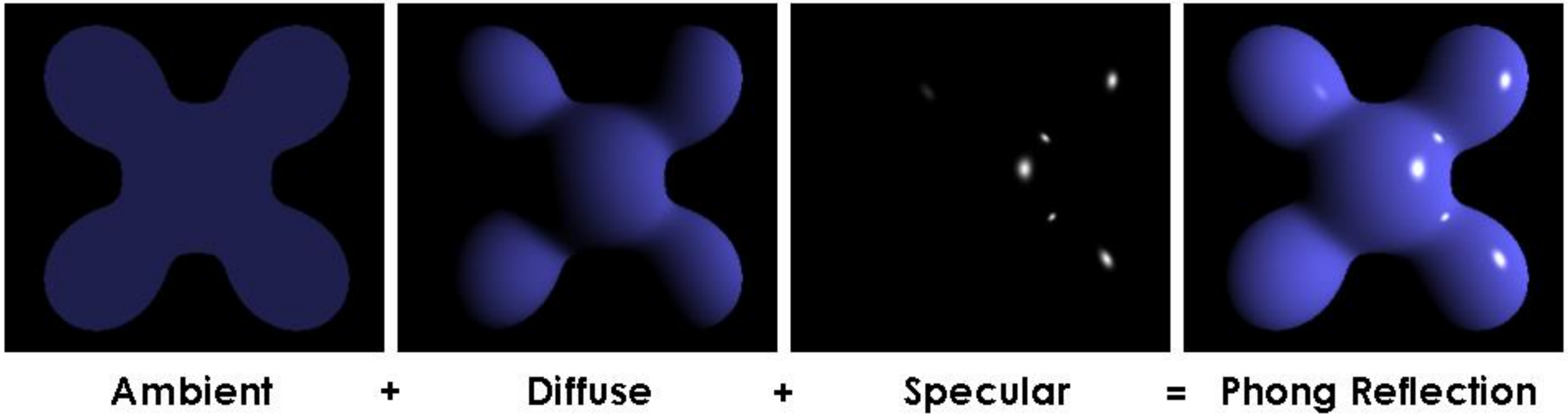
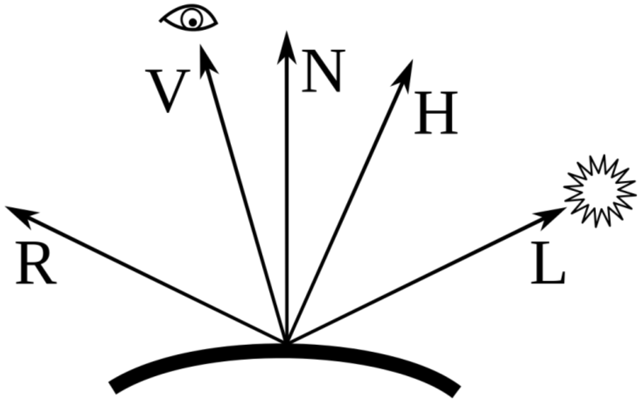
GRK 13

Dr Wojciech Palubicki

Phong model of lighting





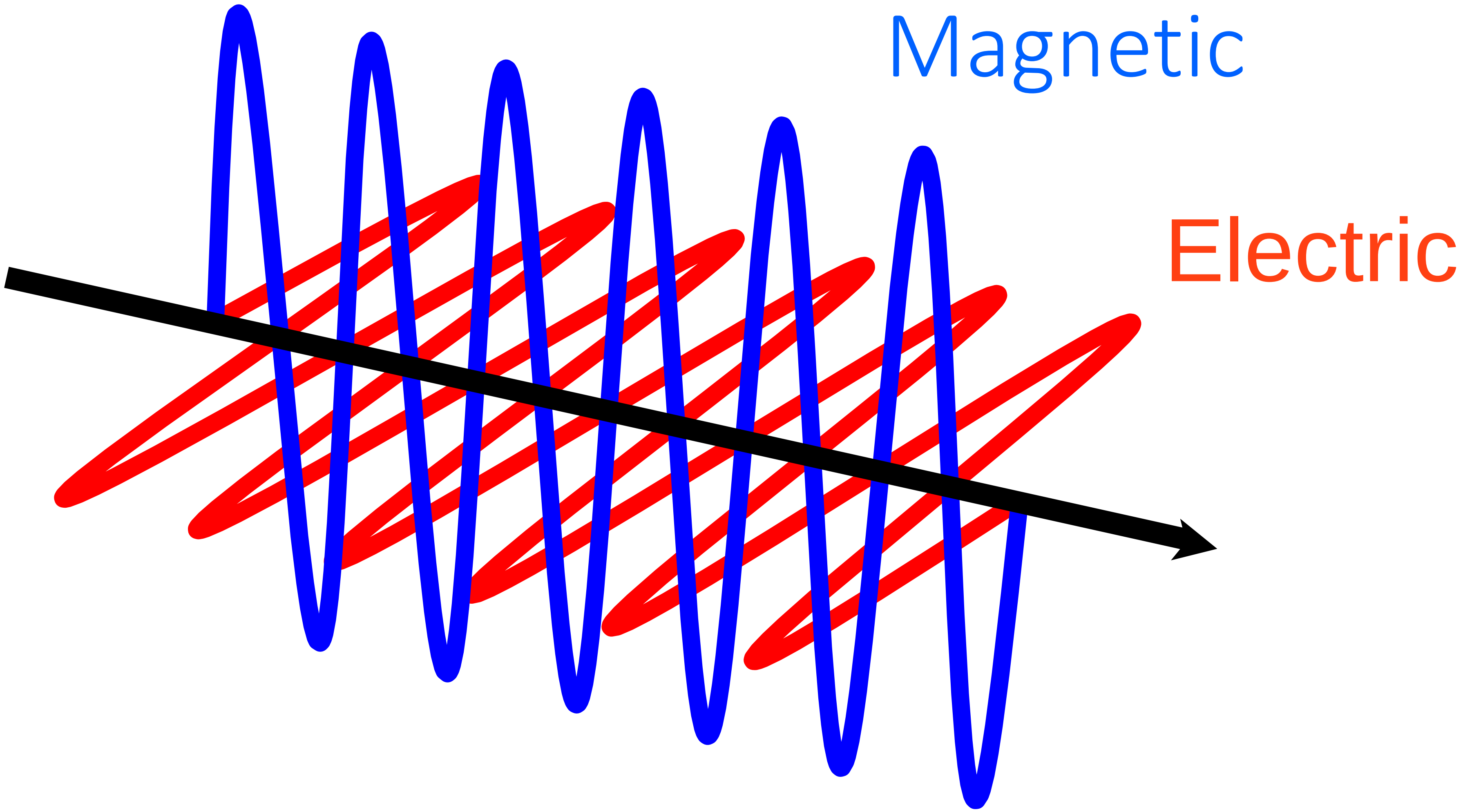

PHONG


PHONG
PBR

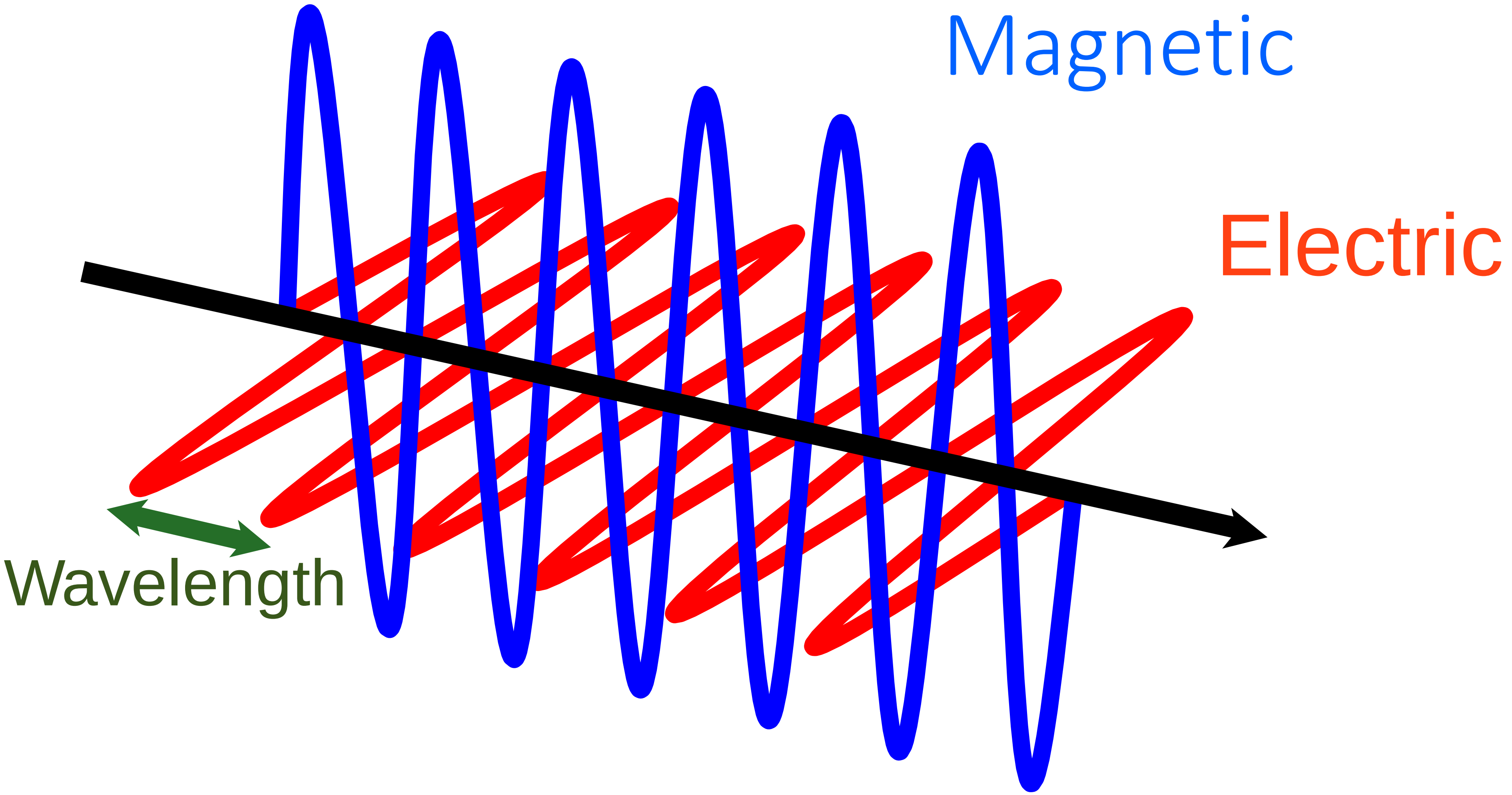
Physically based rendering (PBR)

- “Real-Time Rendering, 3rd Edition”, A K Peters 2008
- Physics of Light
- Geometric Optics
- Mathematical description for real-time lighting (micro-facet BRDF)

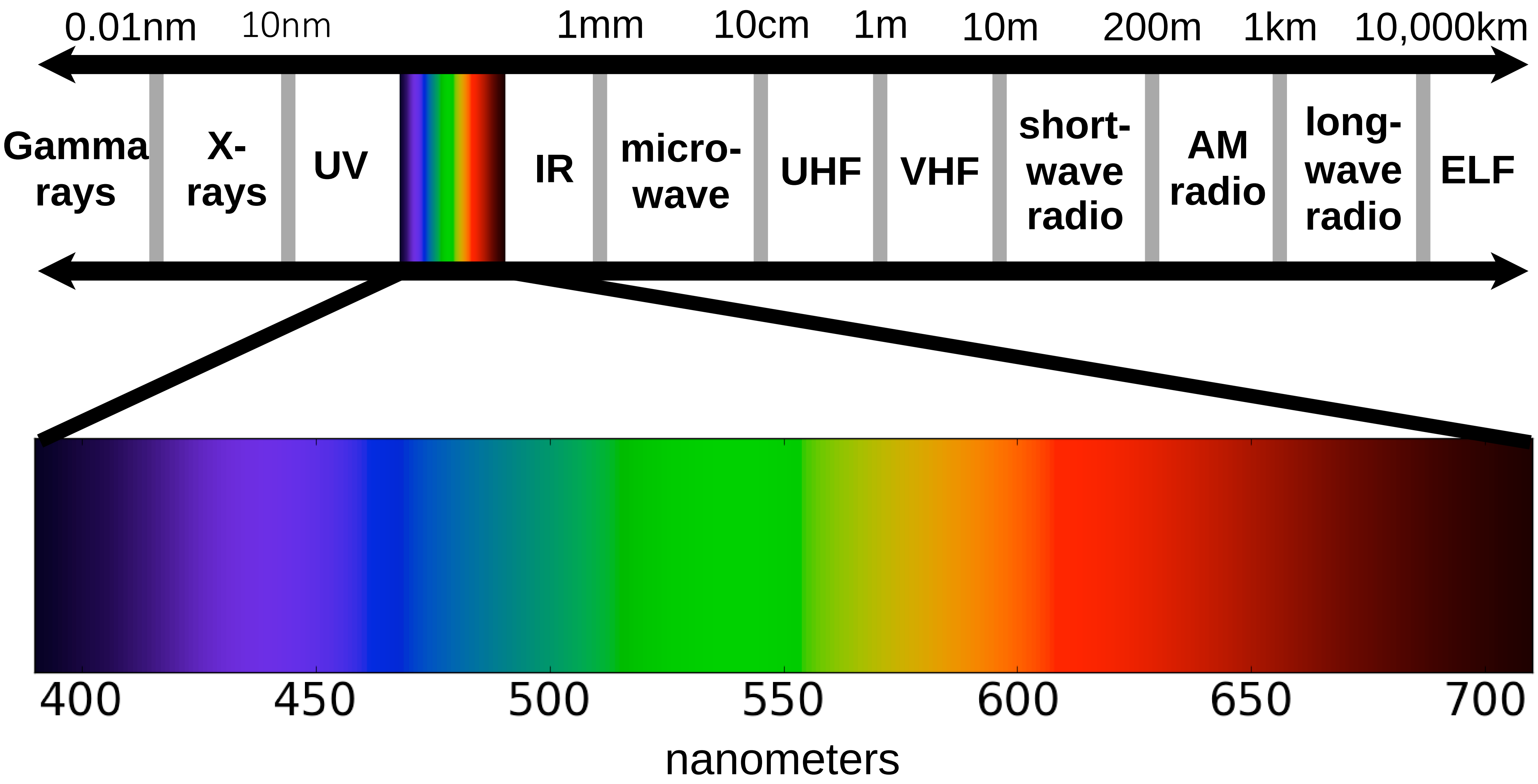
Light – physical point of view

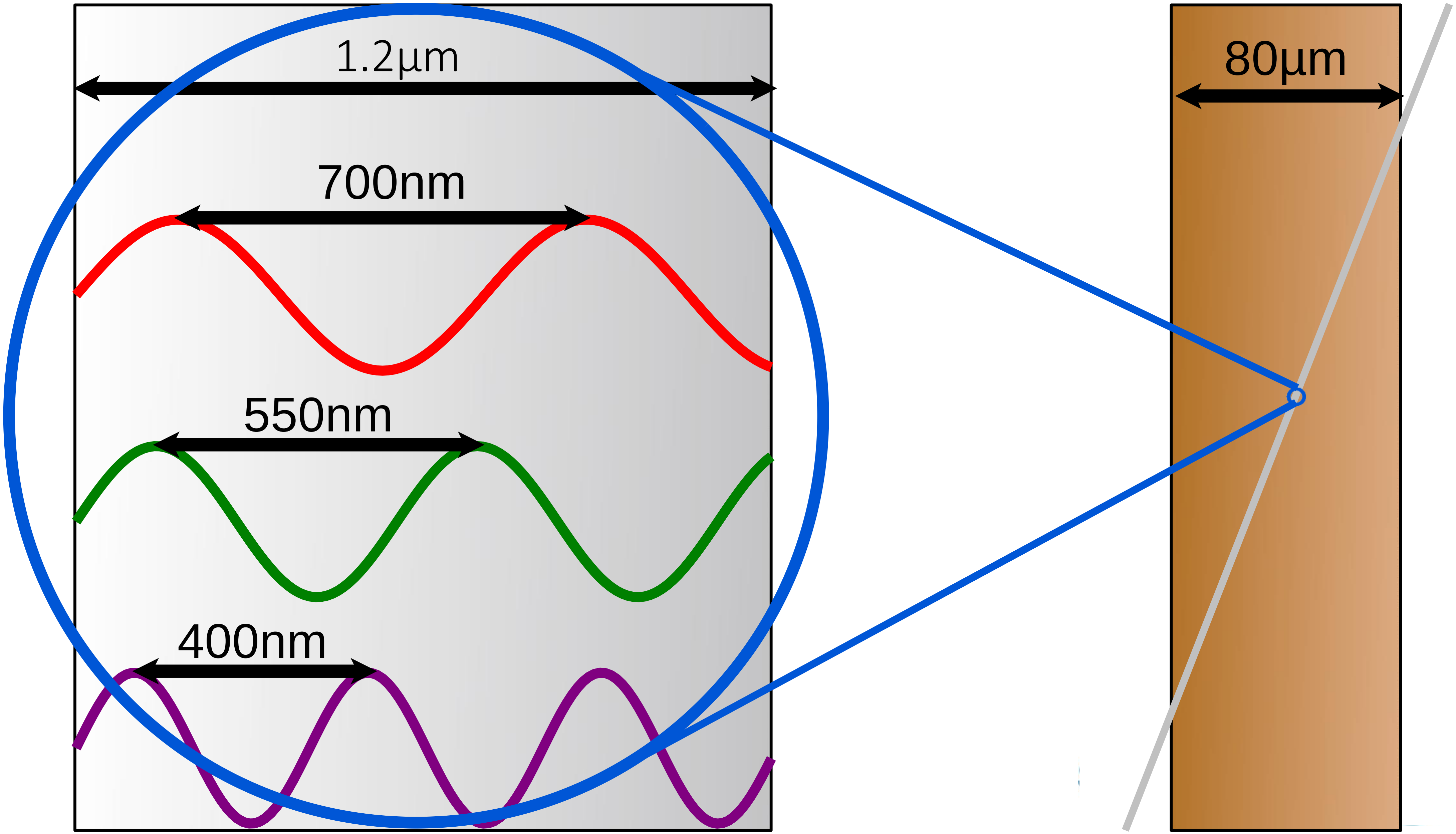


Light – physical point of view

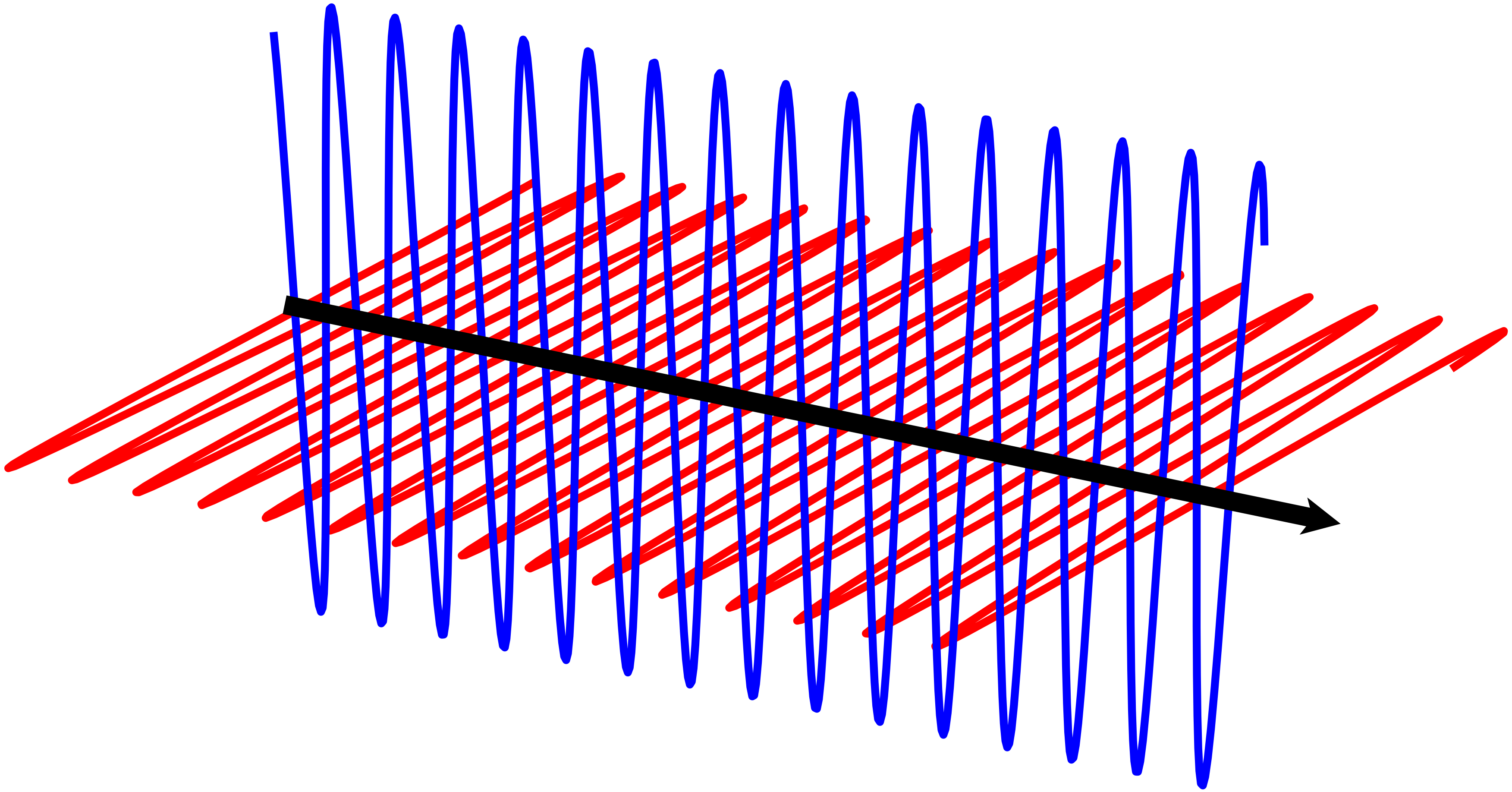


Electromagnetic wavelengths

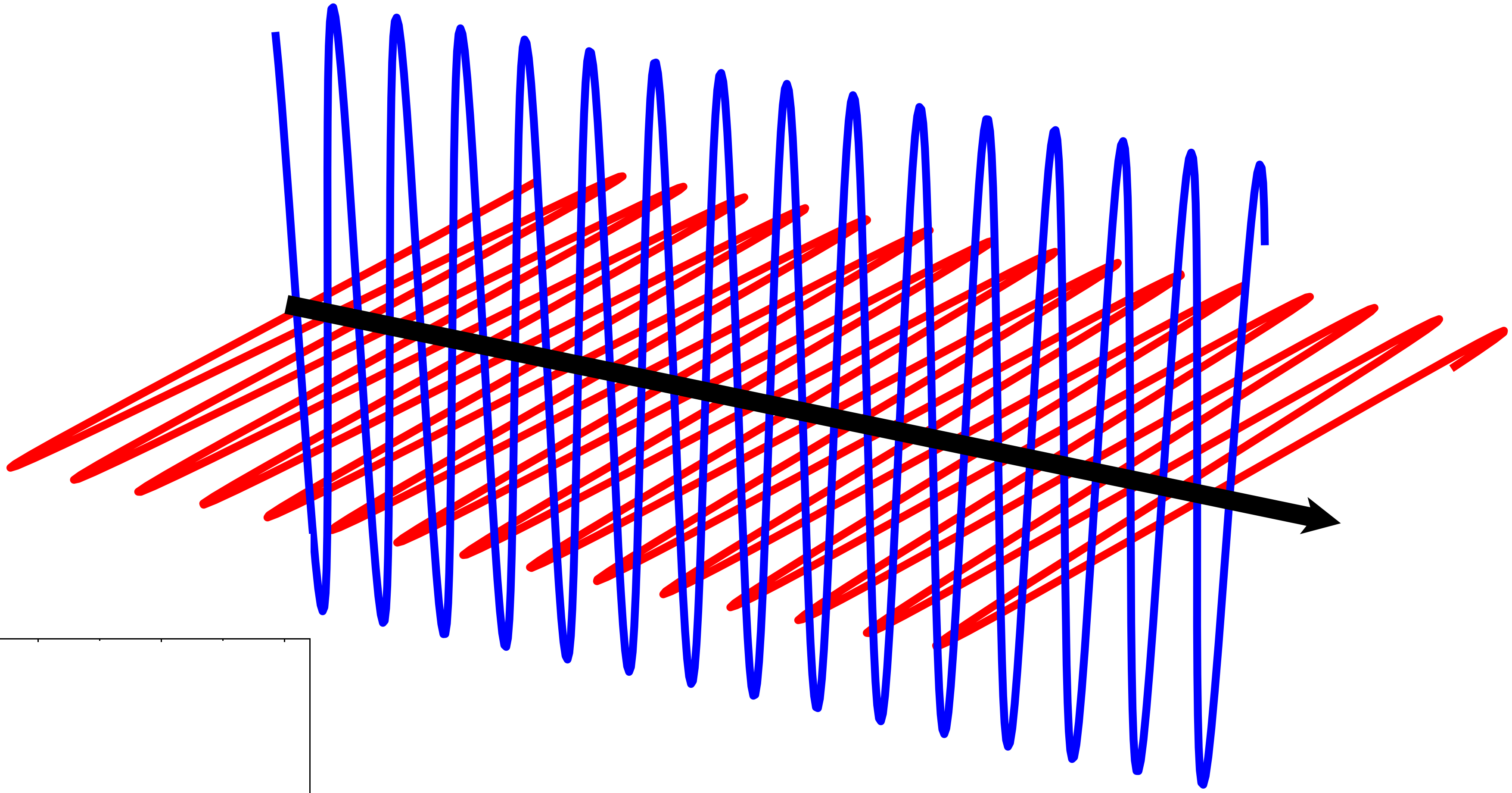


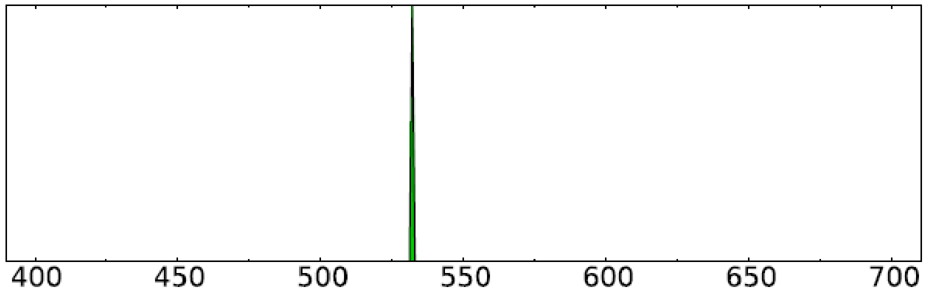

1.2µm
700nm
550nm
400nm
80µm

Wavelengths

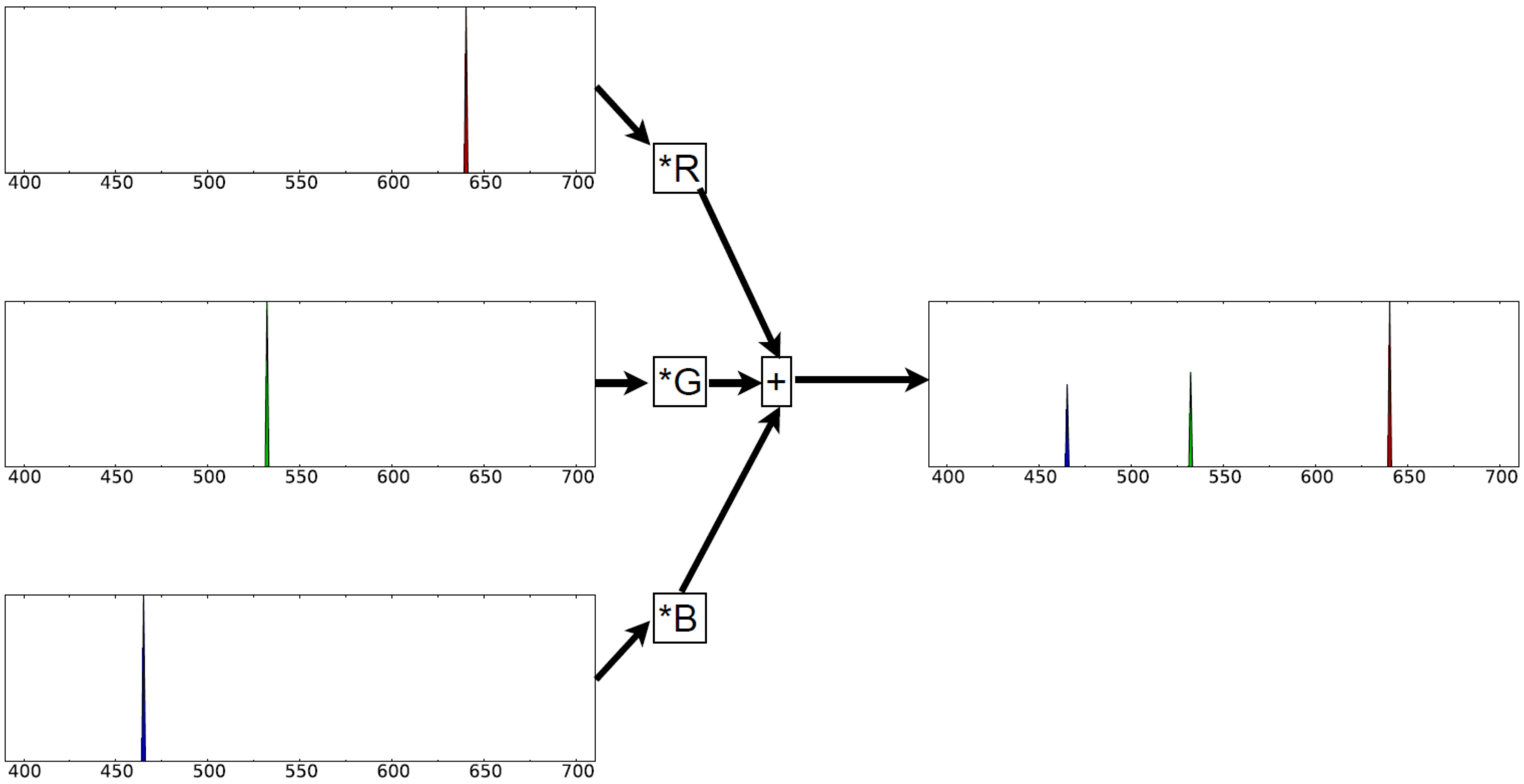


Spectral Power Distribution (SPD)

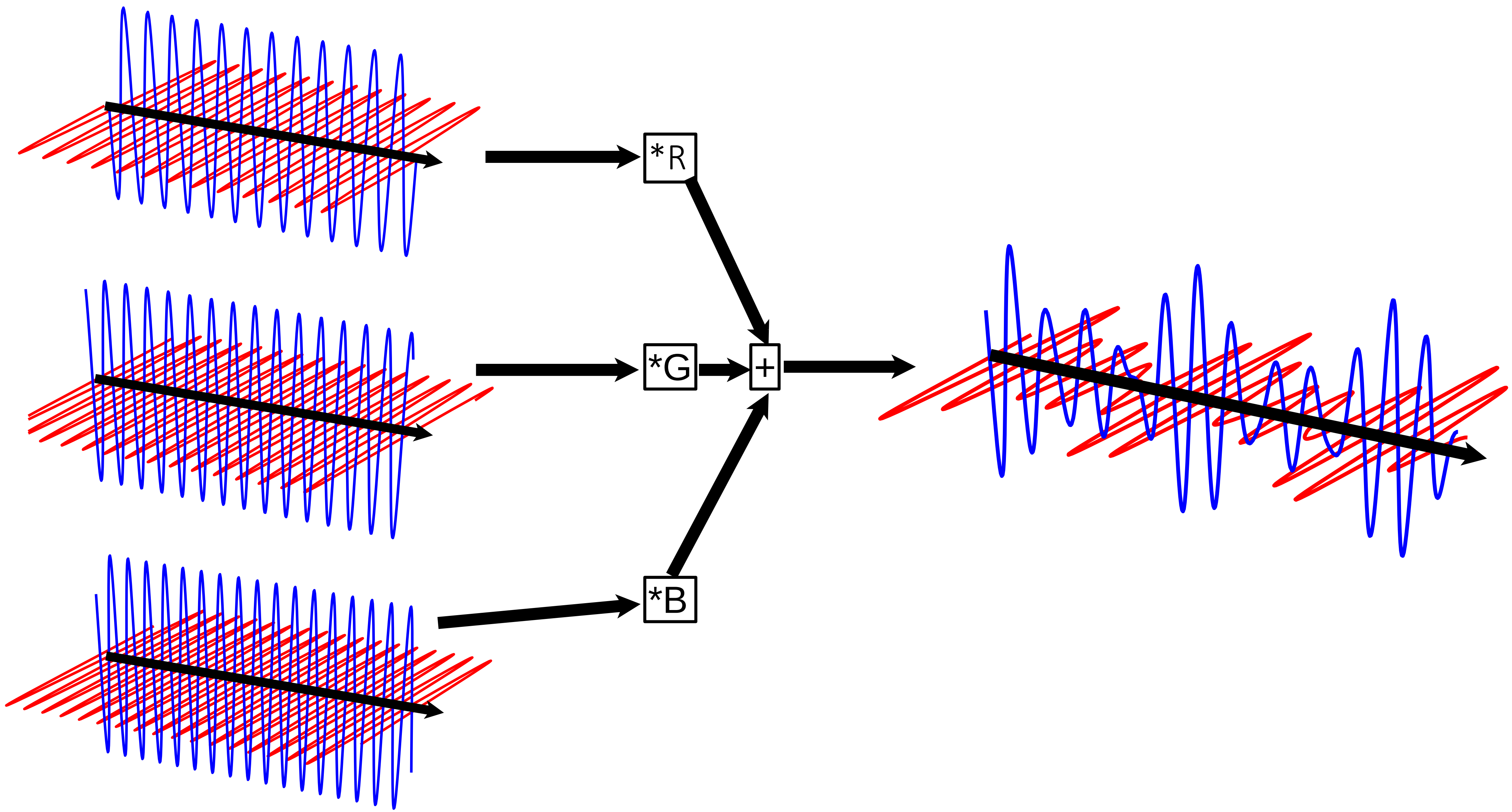




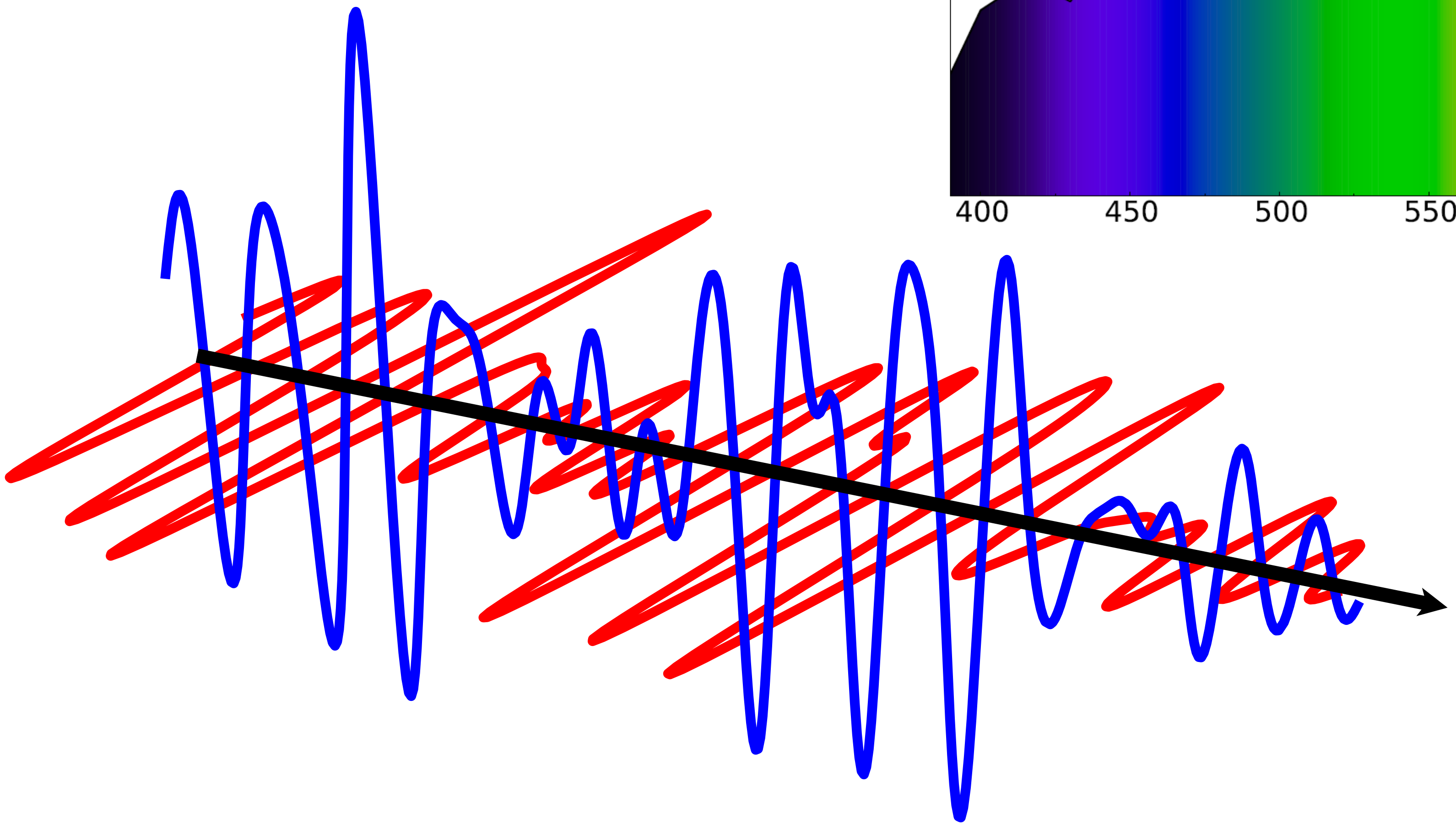
Example: RGB Laser Projector

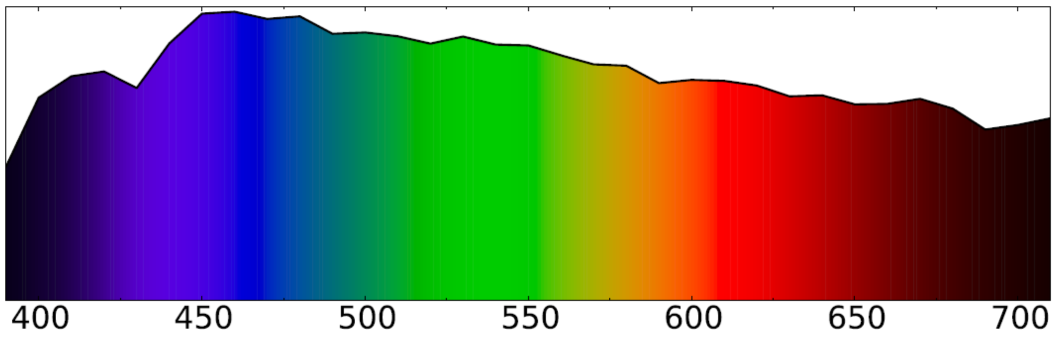


Resulting wave form

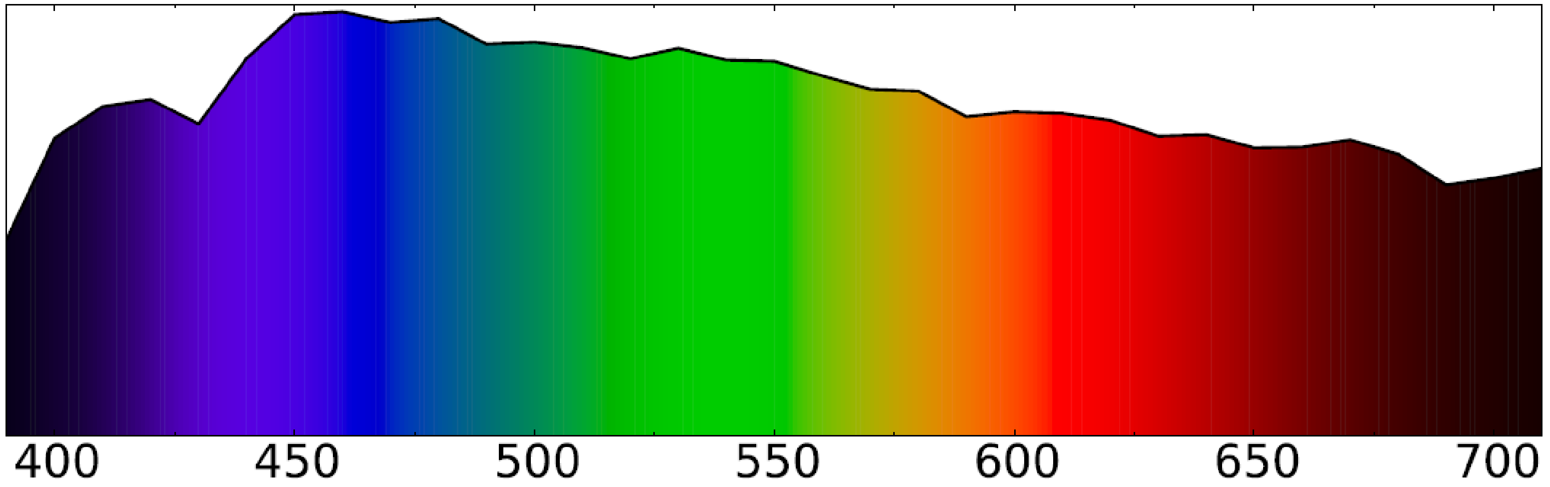


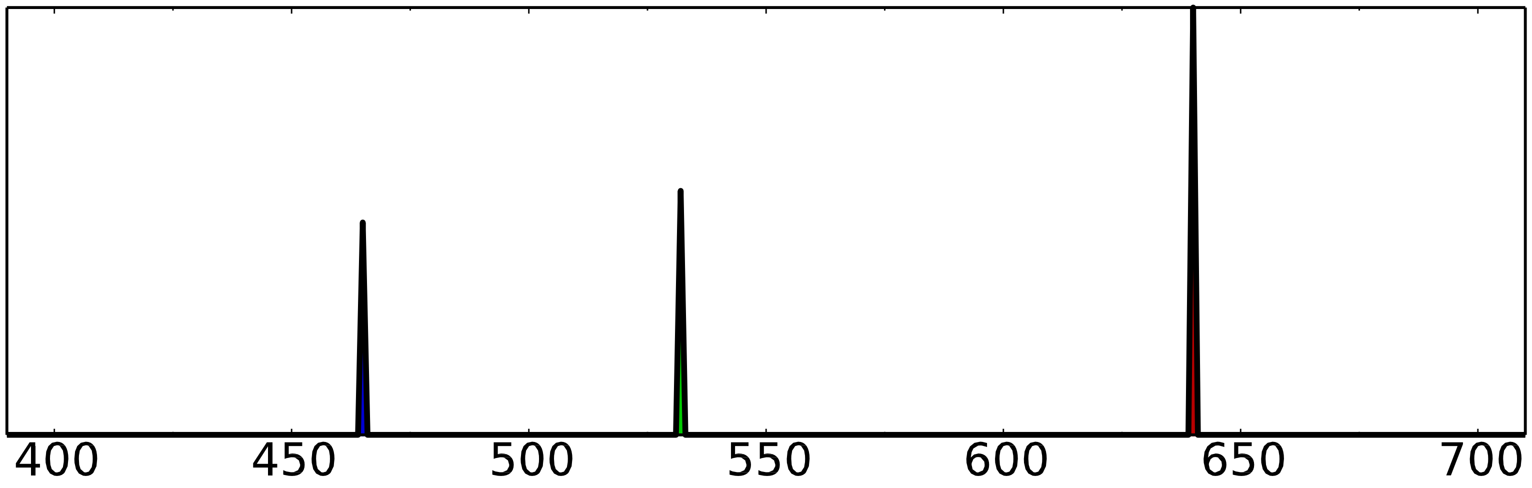
White light wave form



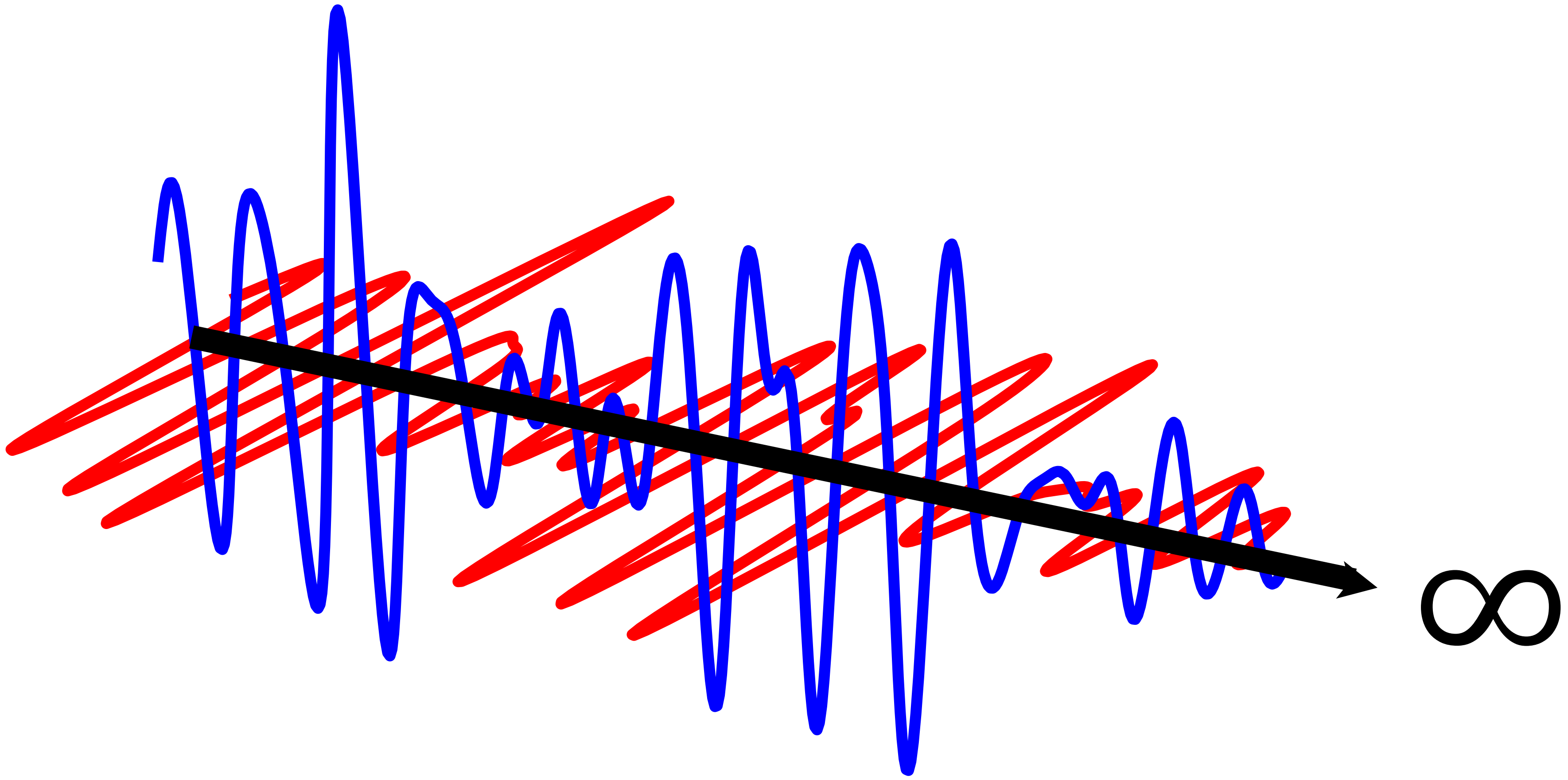


White light and laser projector light comparison

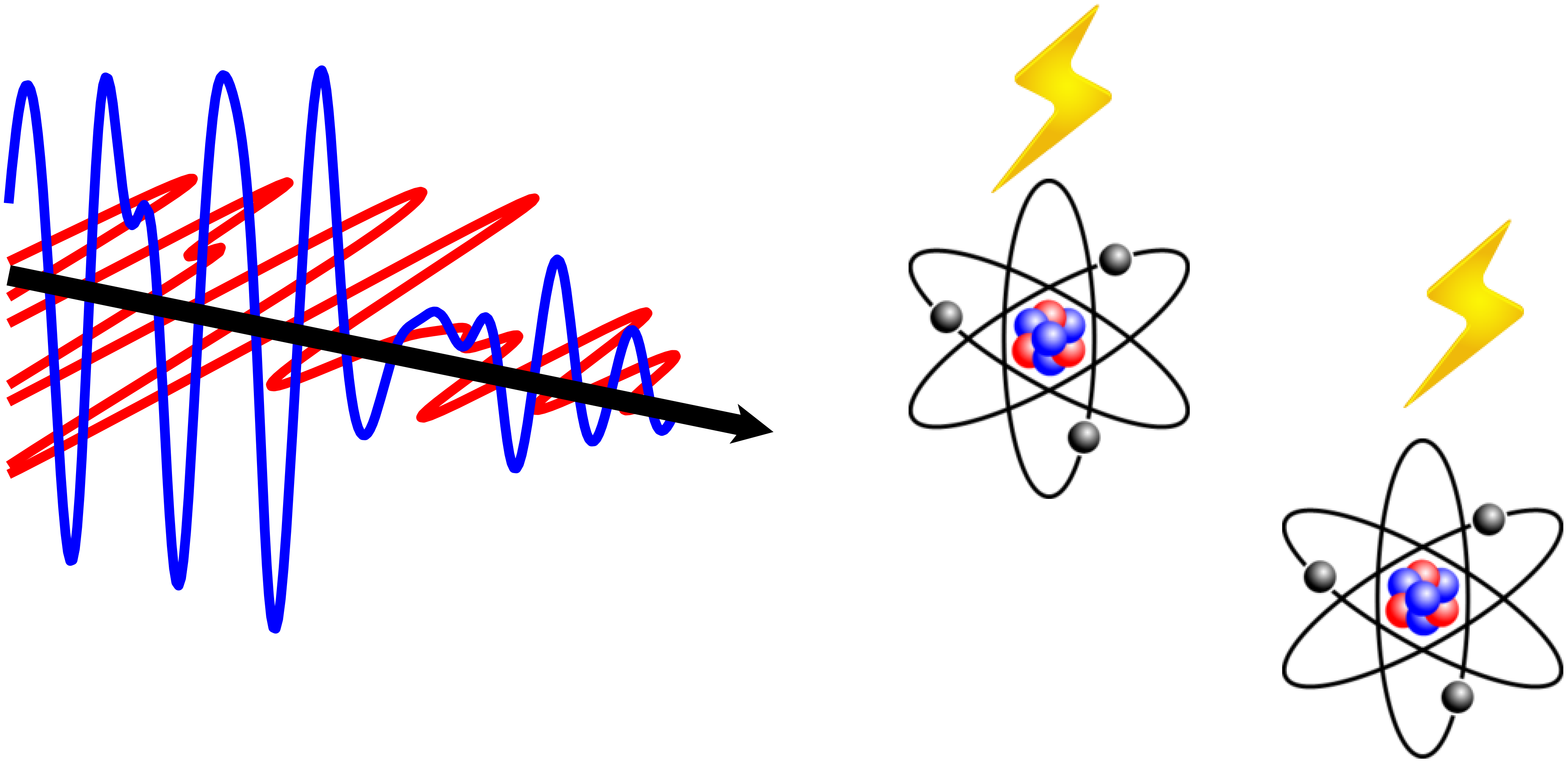




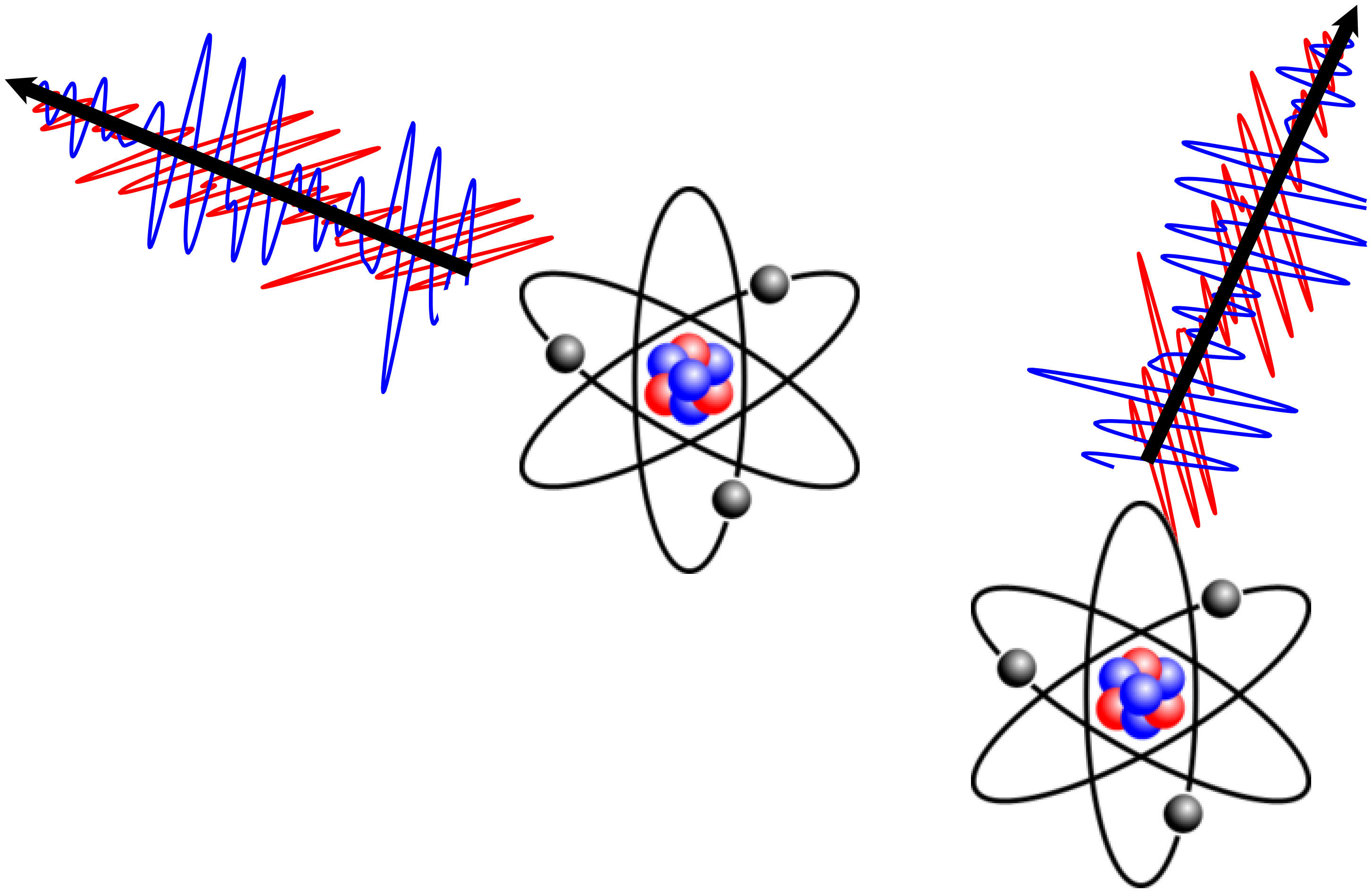
In a vacuum light propagates to infinity



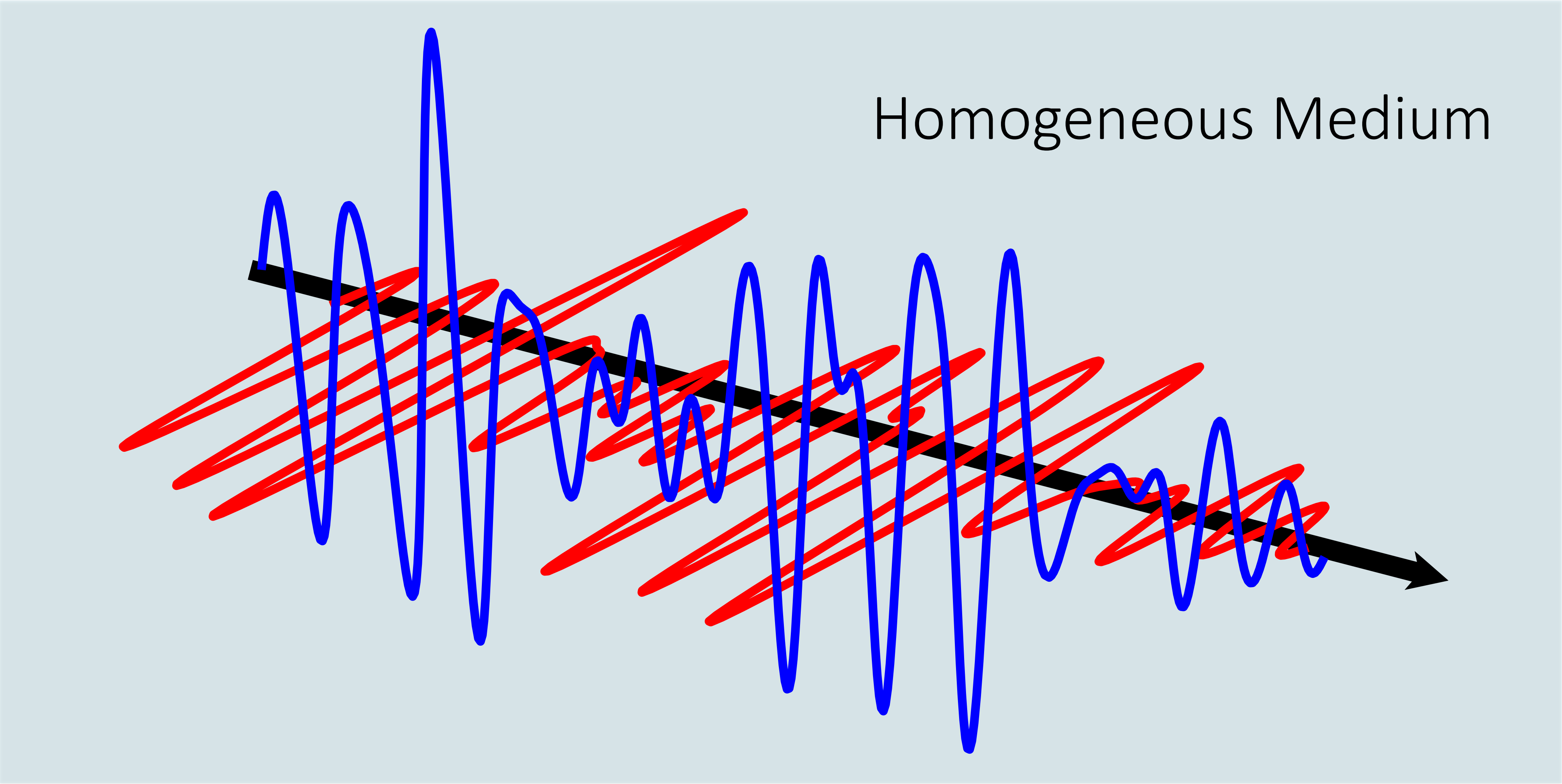
When interacting with atoms it energizes them



This energy is absorbed and re-radiated as light

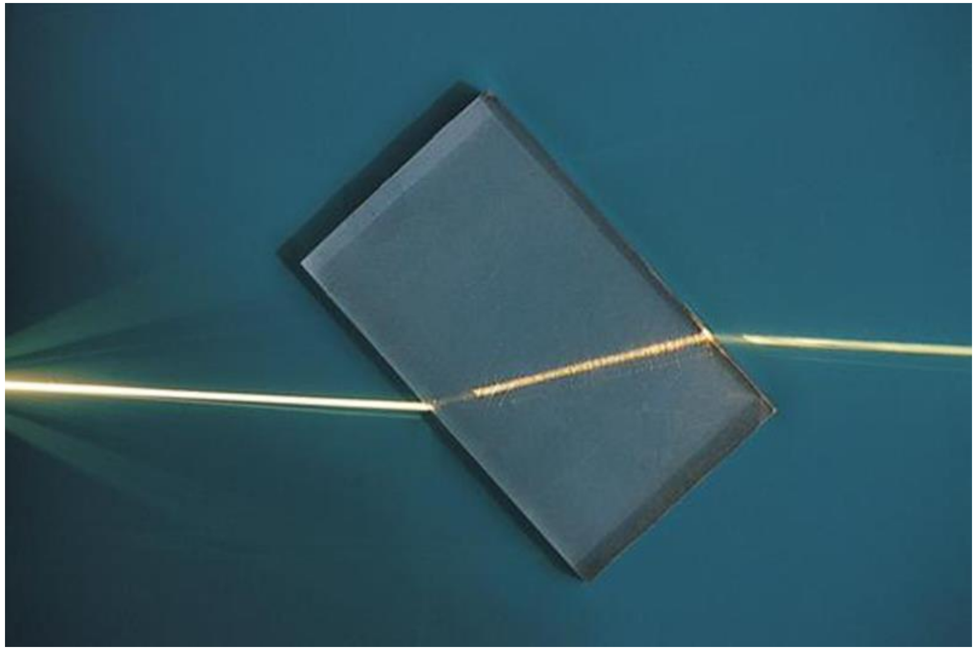


Simplification: Wave Optics

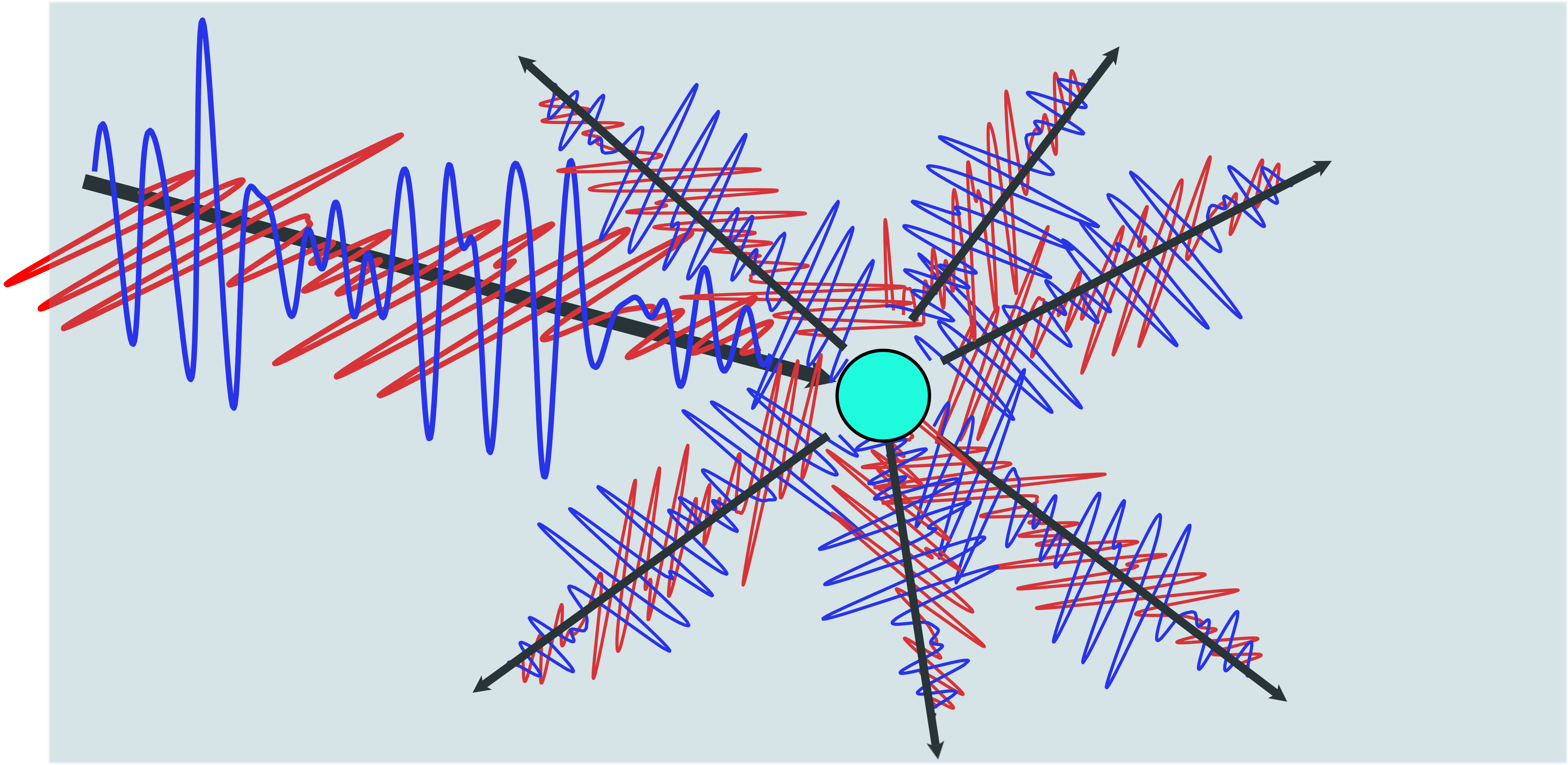


Refractive Index n (dimensionless)

- $n = \frac{c}{v}$
- c is the speed of light in vacuum
- v is the phase velocity of light in the medium
- Measures the **absorption** of light by a medium



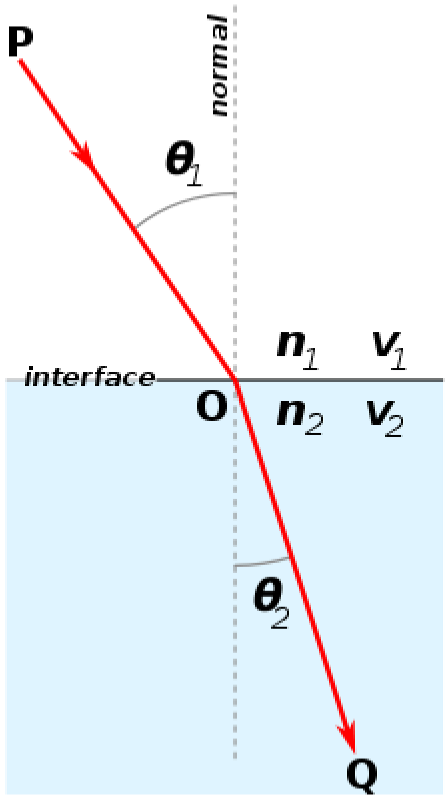
Scattering particle



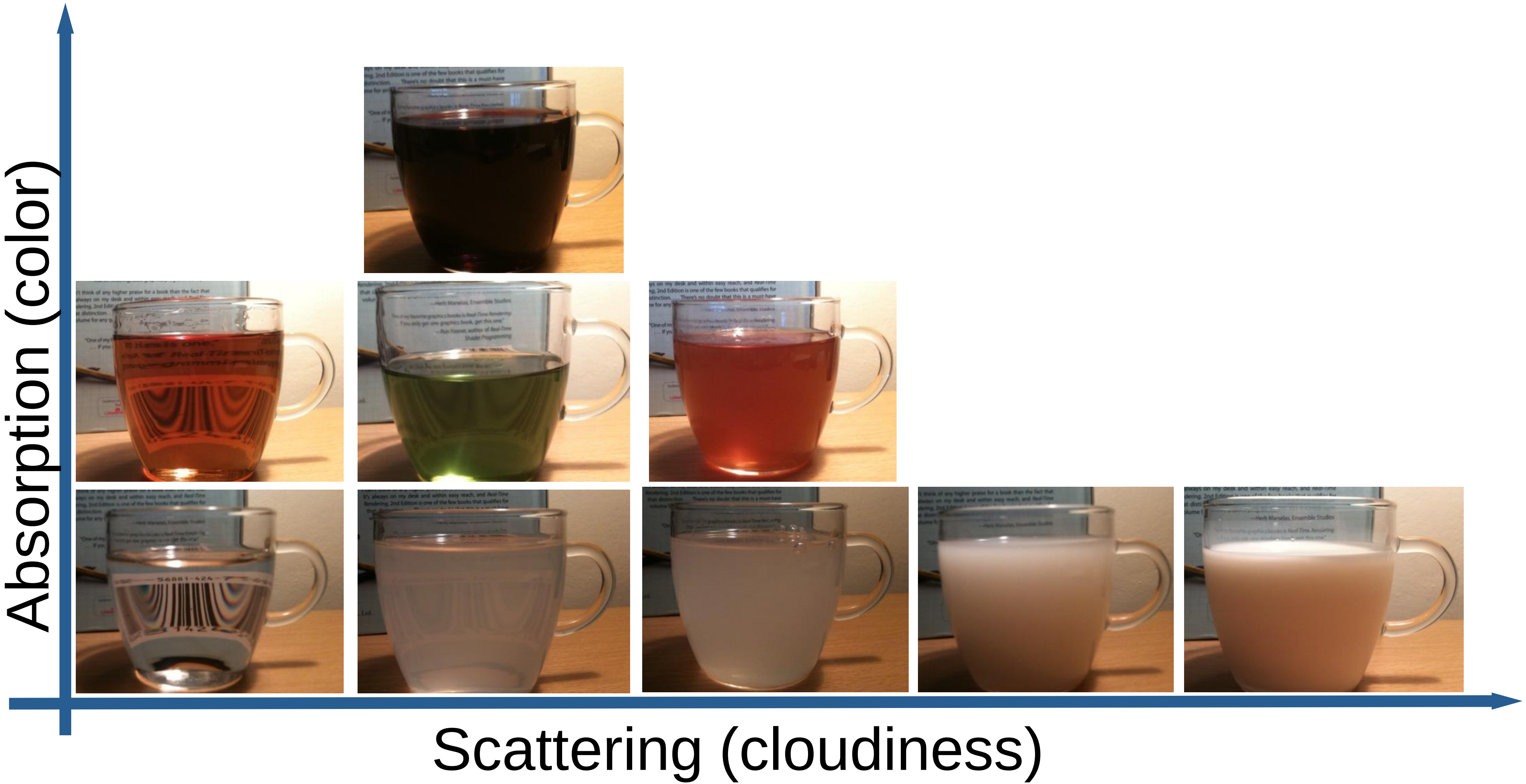
Snell's Law

- describes the relationship between the angles of incidence and refraction, when referring to light or other waves passing through a boundary between two different isotropic media, such as water, glass, or air

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \frac{n_1}{n_2}$$

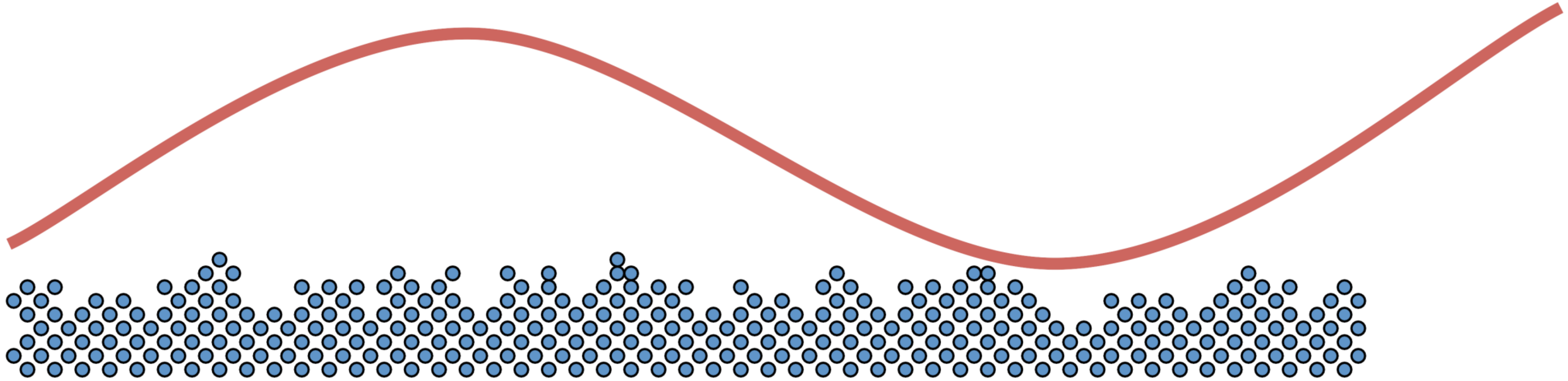


Appearance of a medium

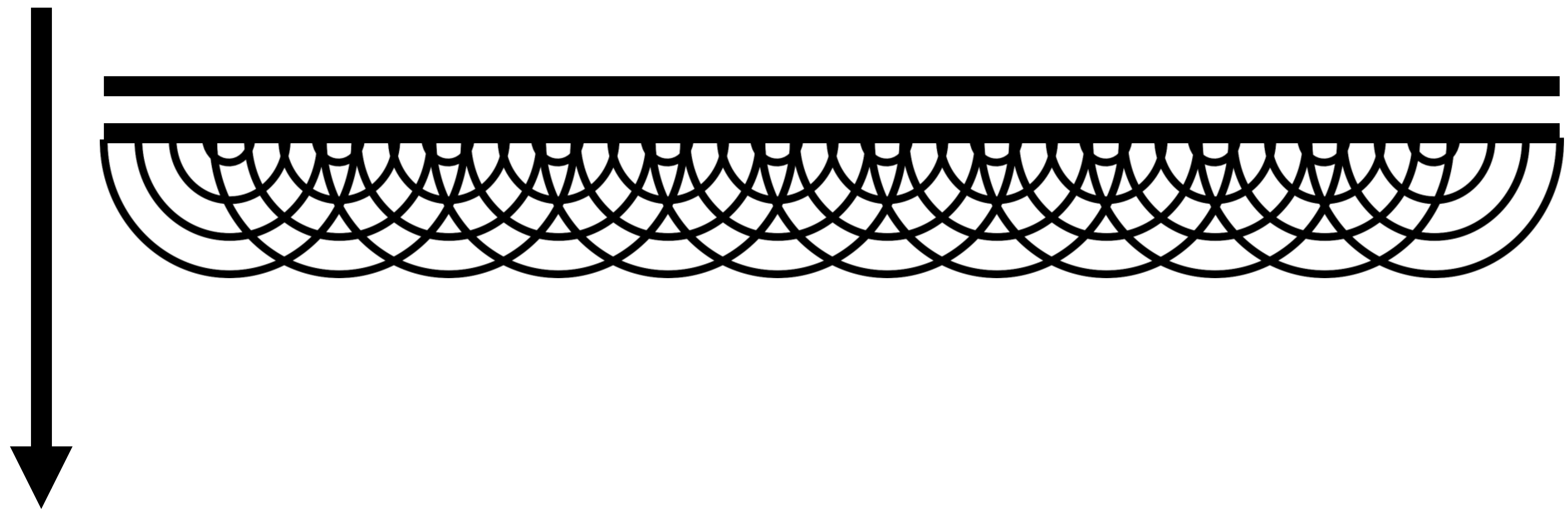


Object surfaces

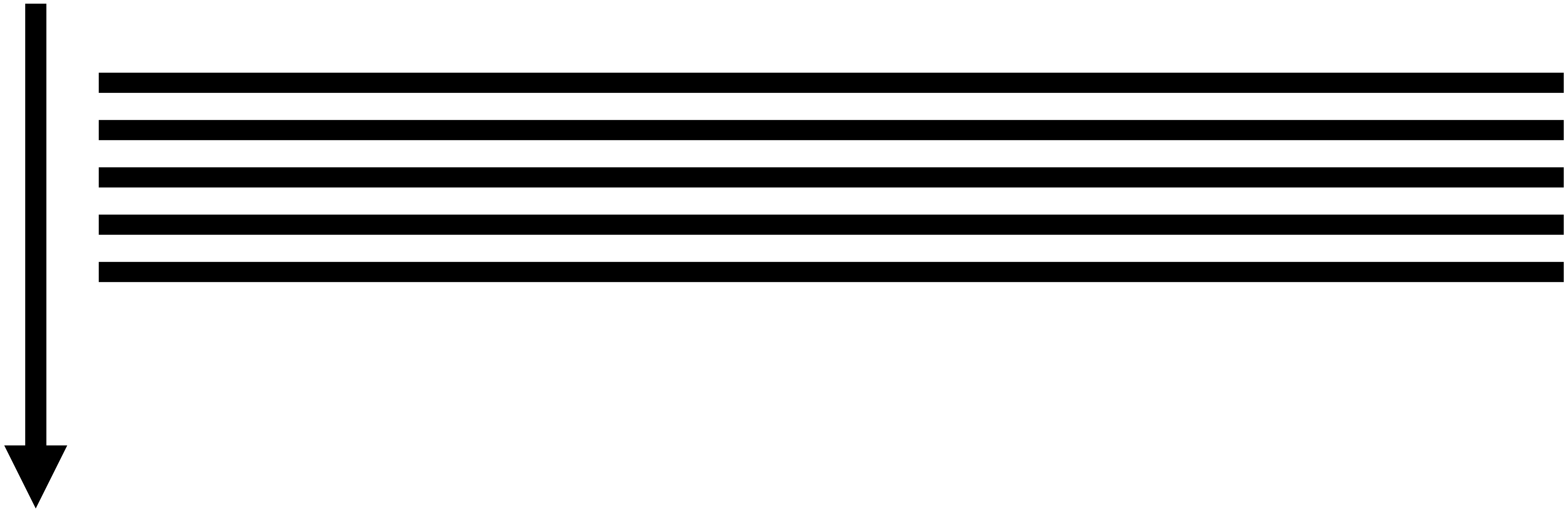
Nanogeometry



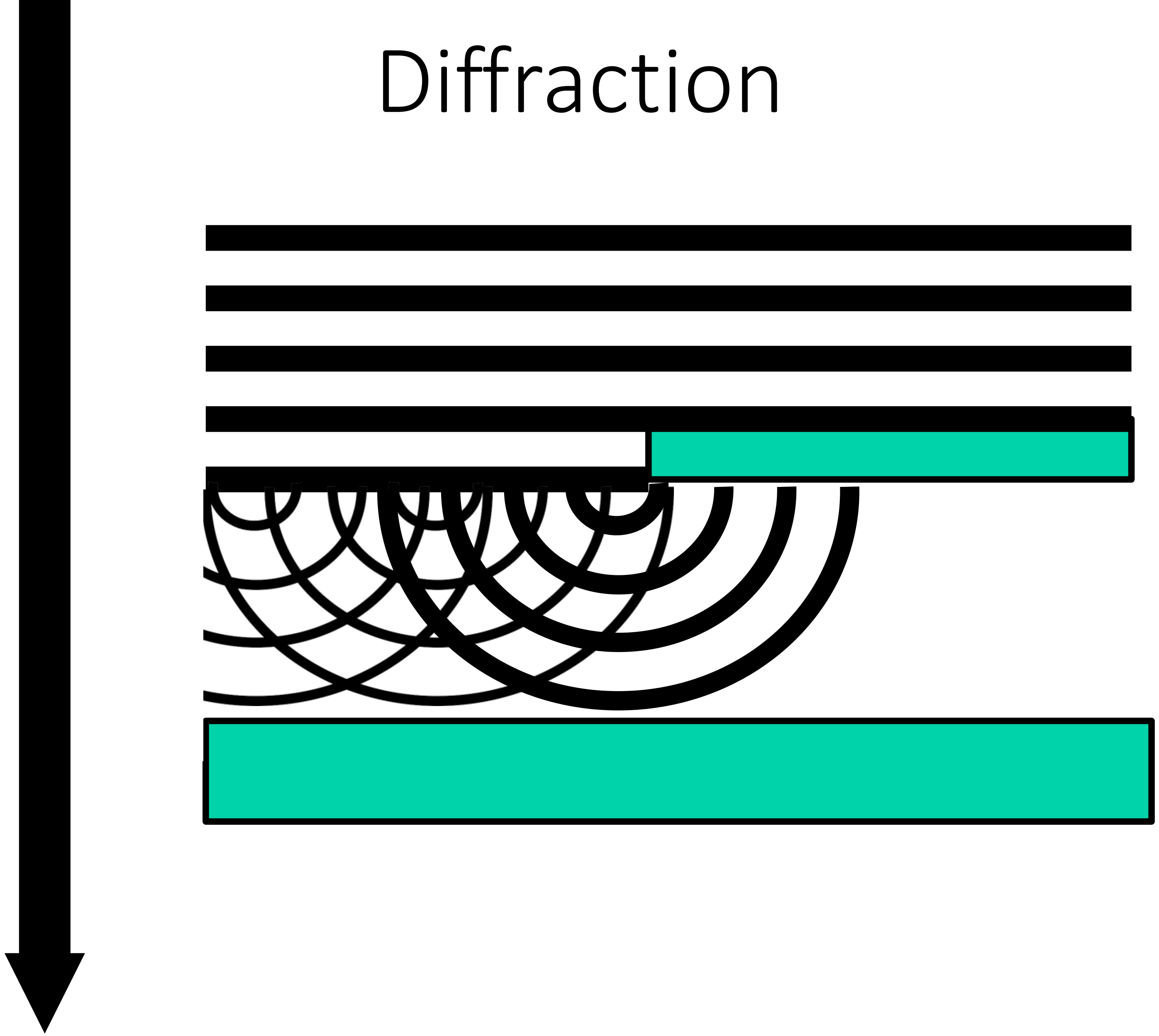
Huygens-Fresnel Principle



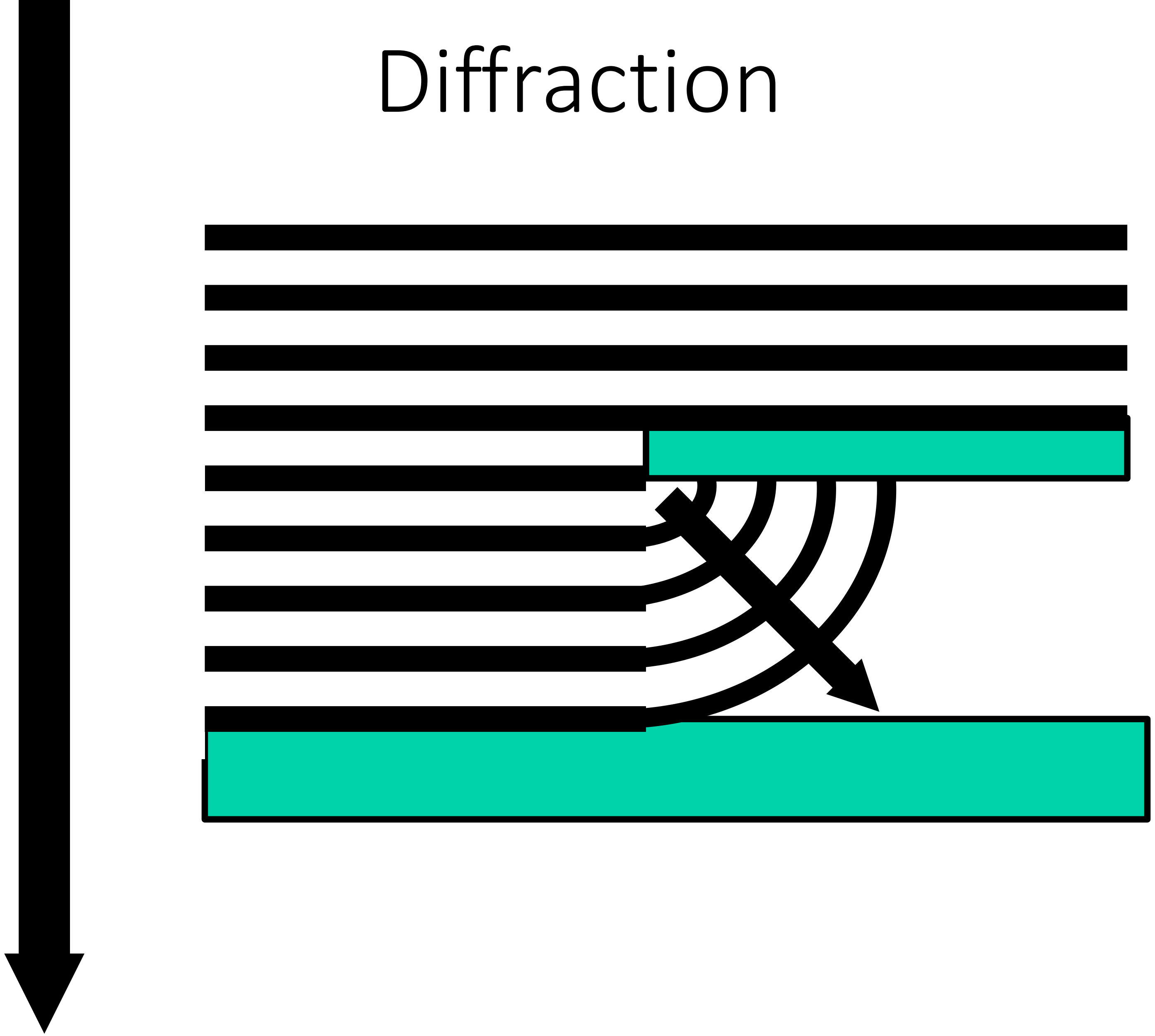
Huygens-Fresnel Principle



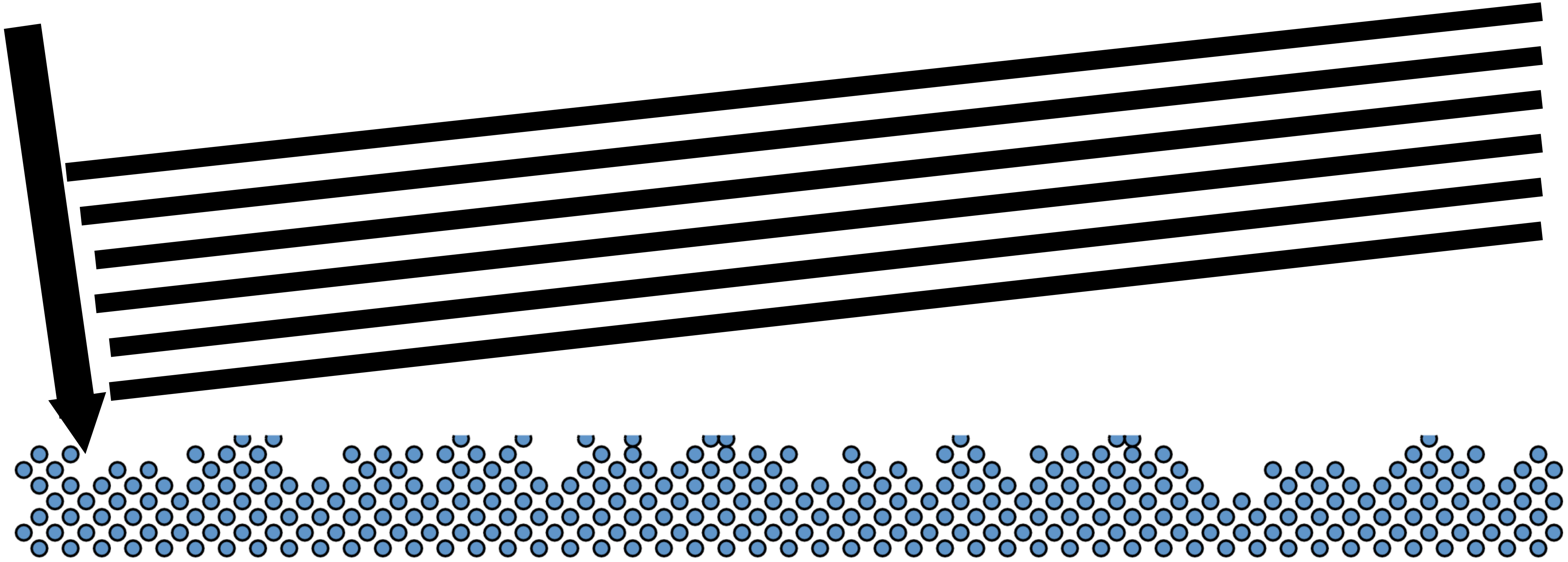
Diffraction



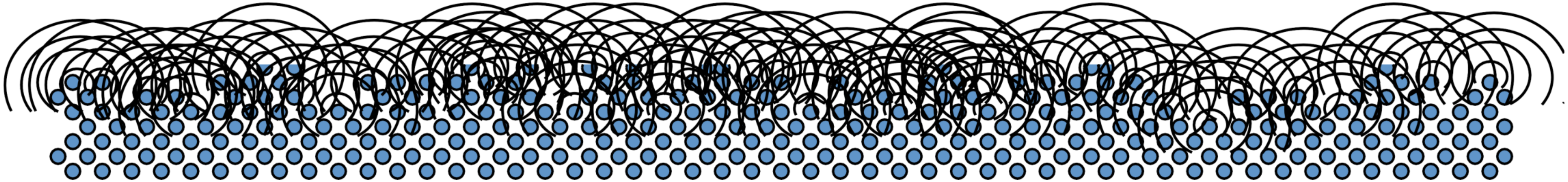
Diffraction



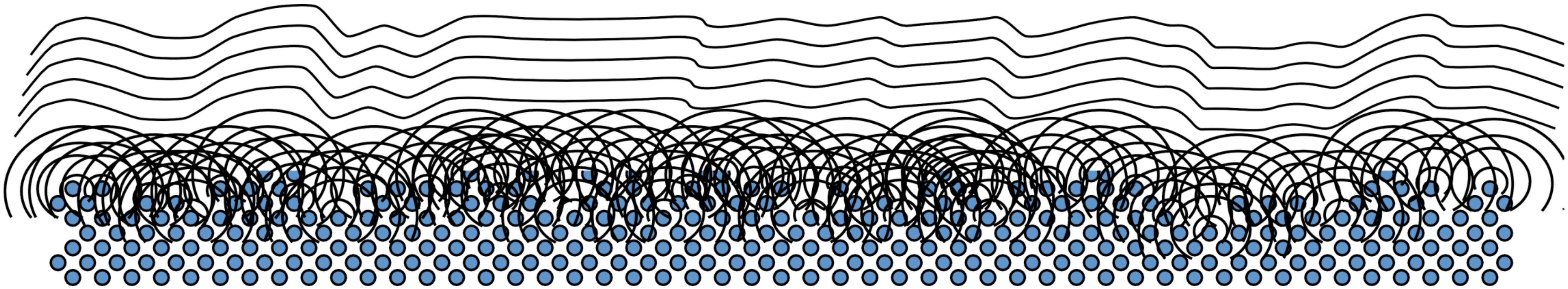
Diffraction from Optically-Smooth Surface



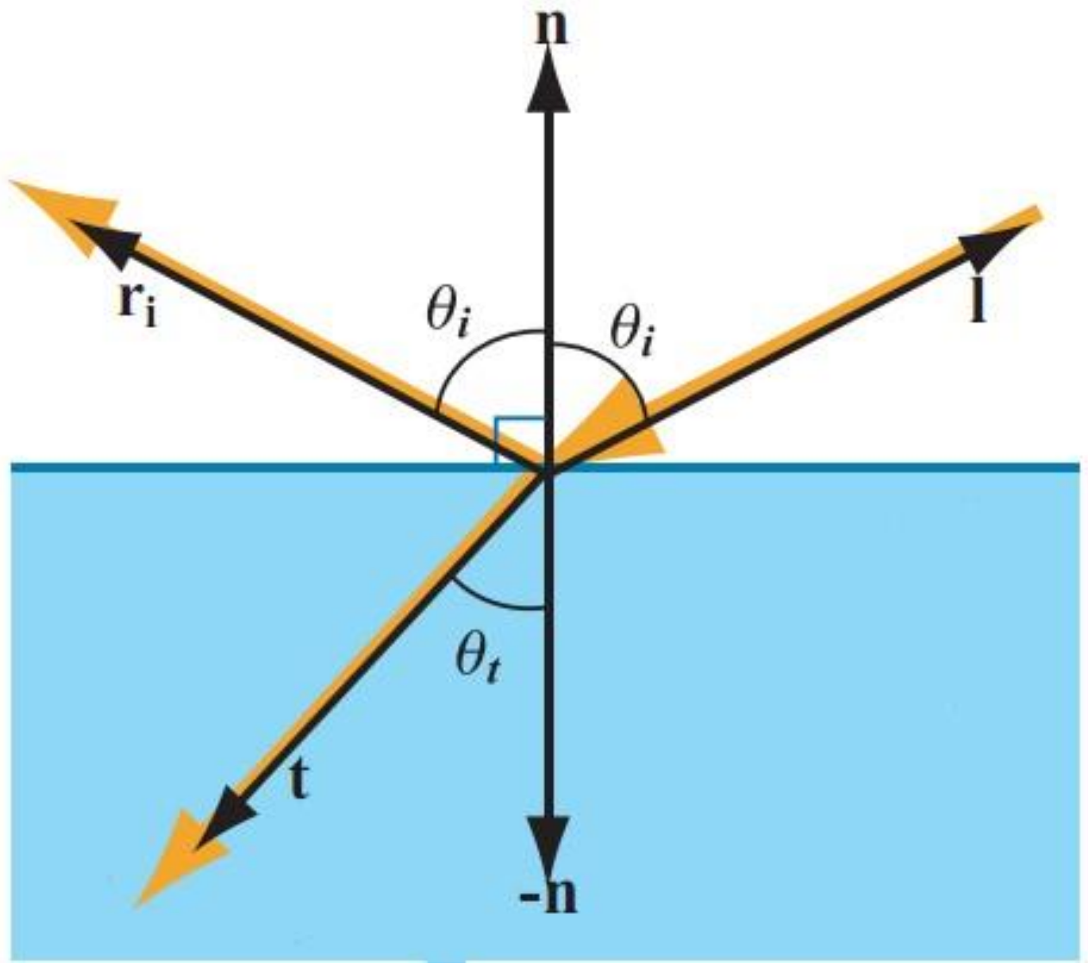
Diffraction from Optically-Smooth Surface



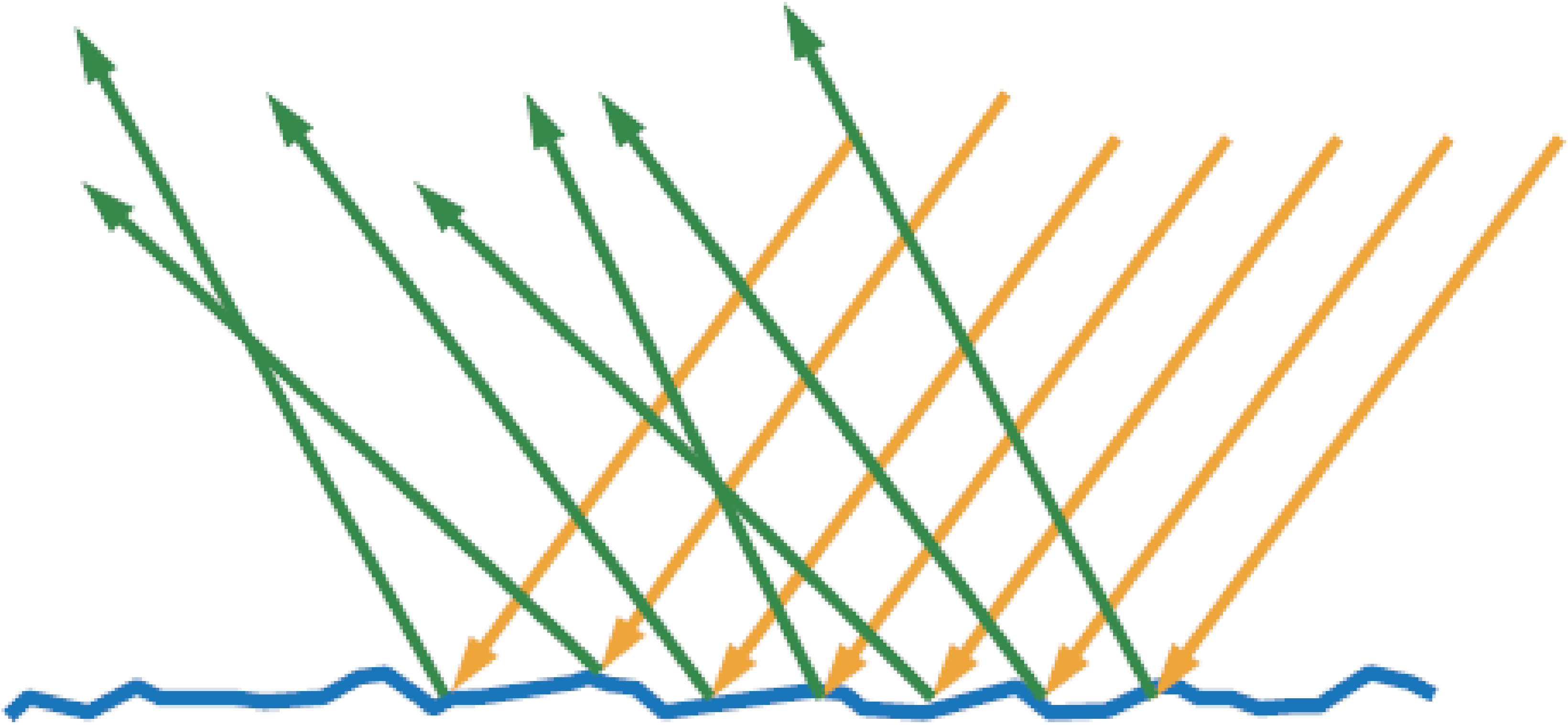
Diffraction from Optically-Smooth Surface



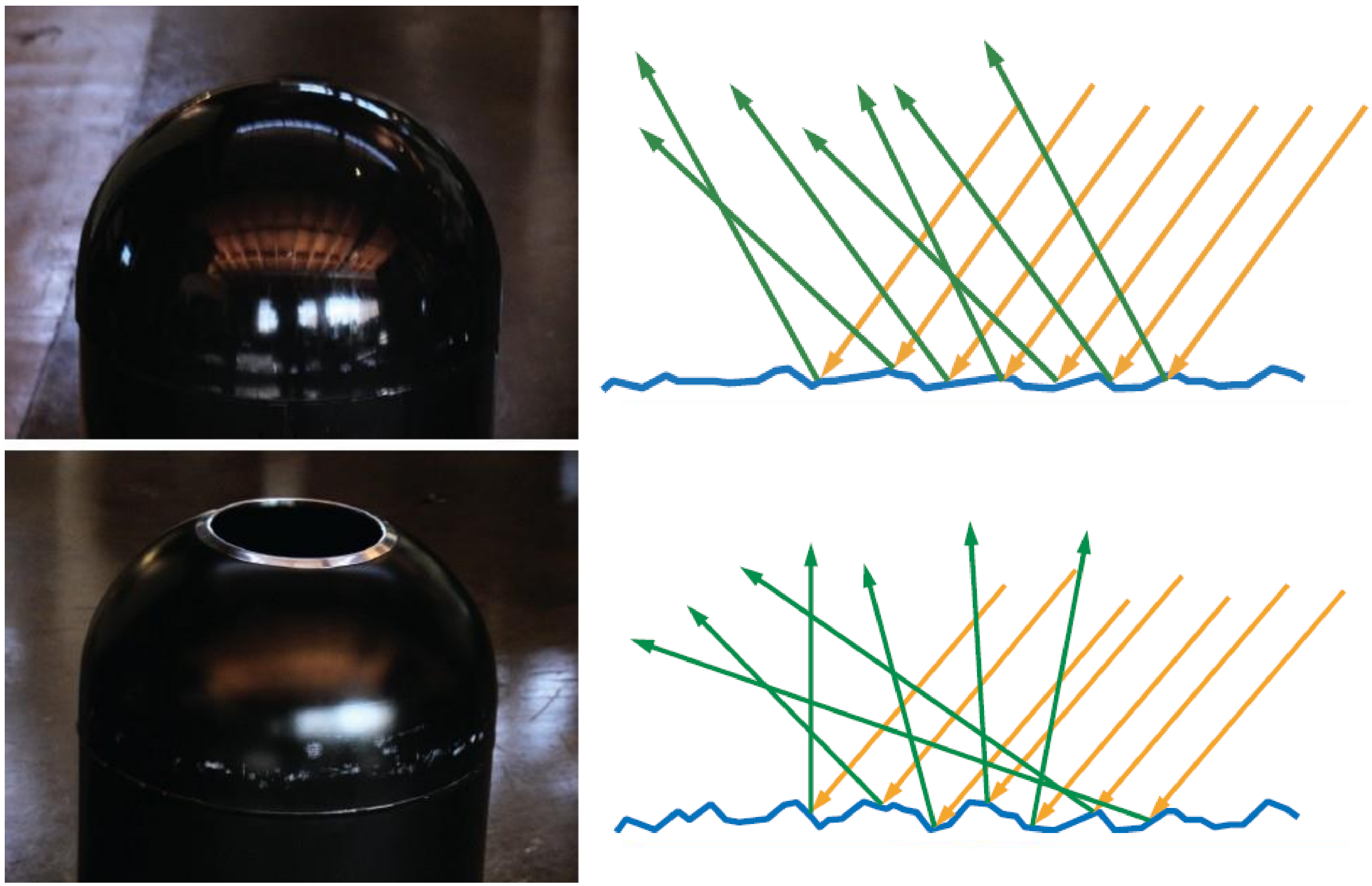
Geometric Optics



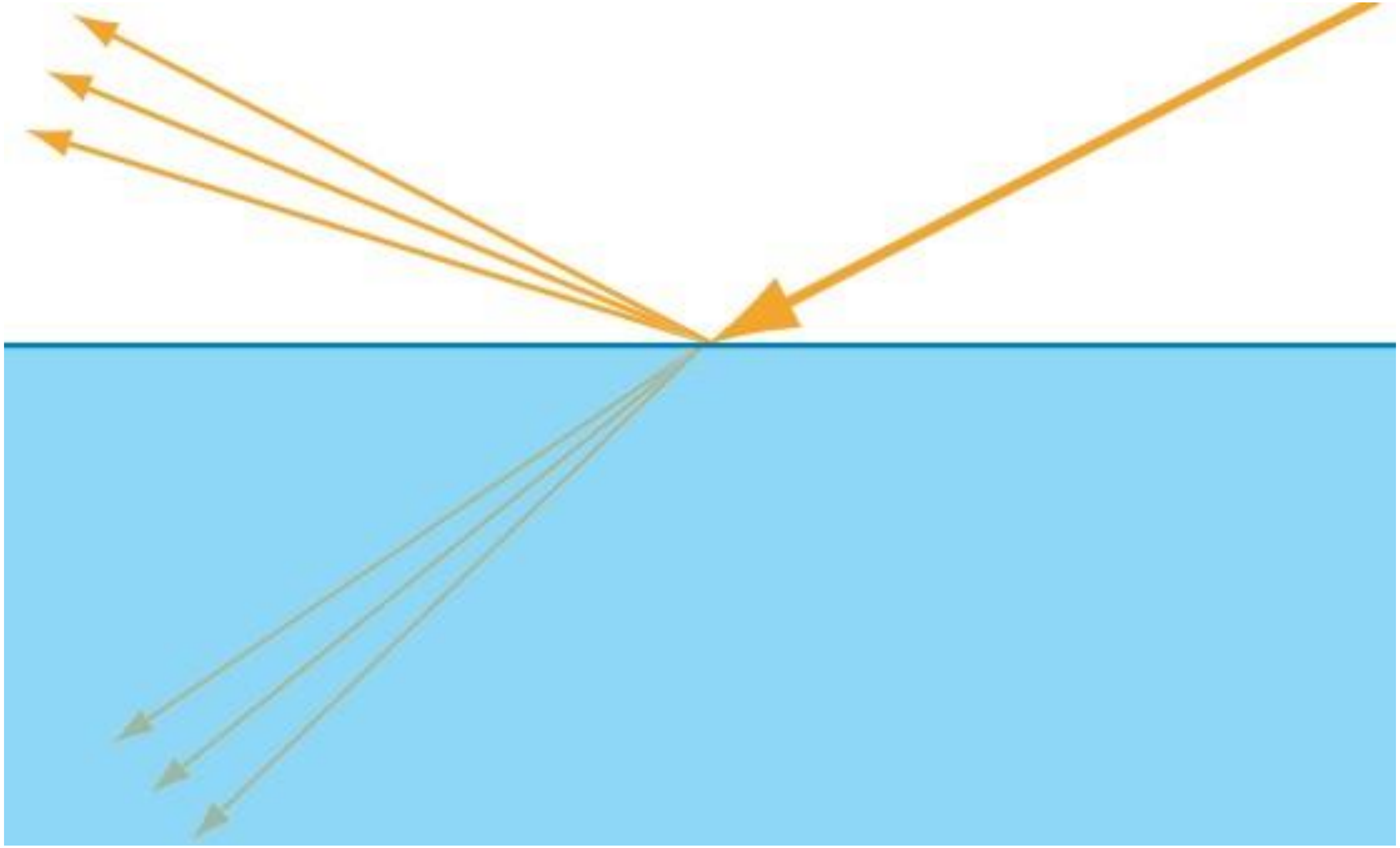
Microgeometry



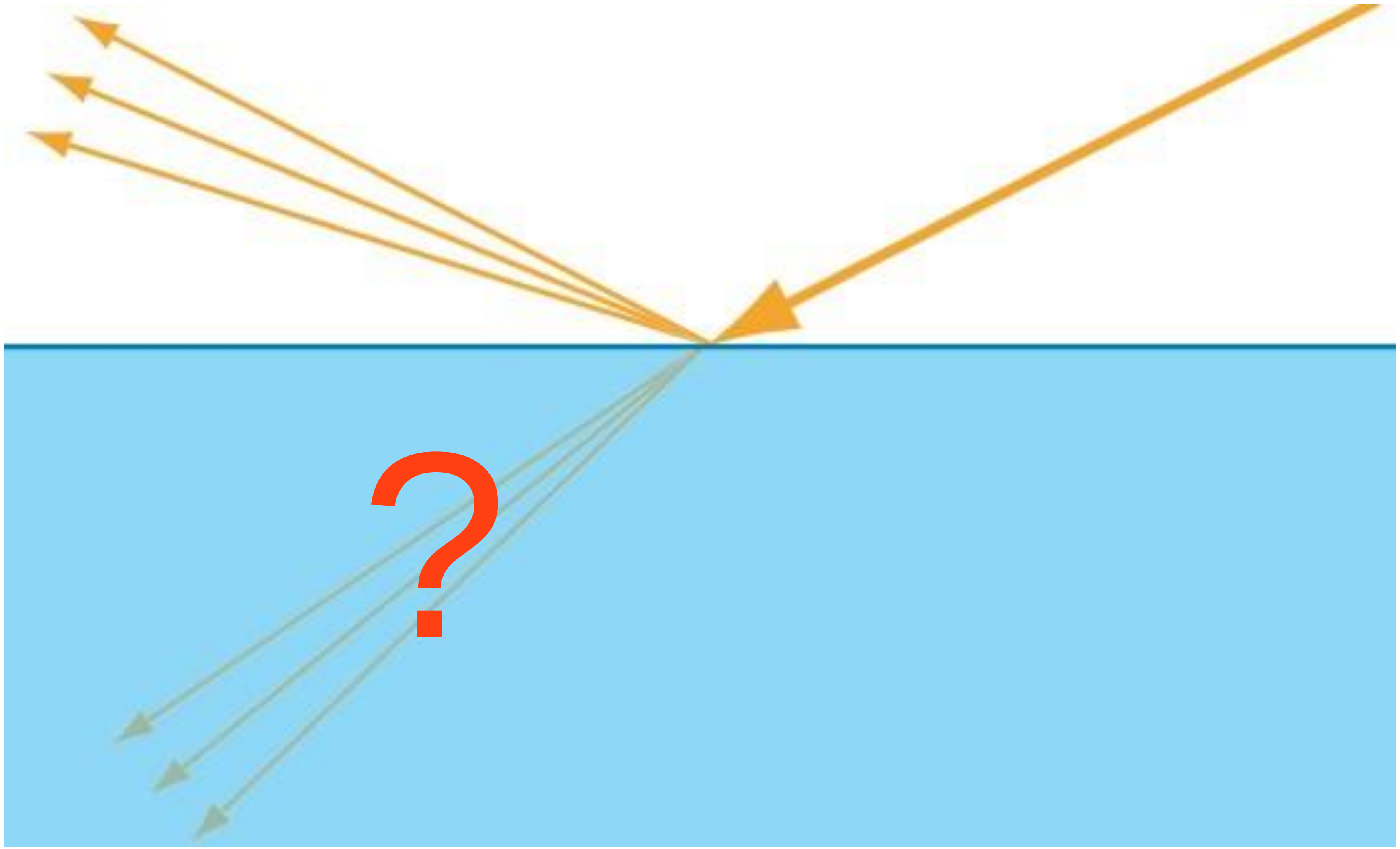
Rougher = Blurrier Reflections



Statistical macroscopic view



What happens to the refracted light?



Metals (Conductors)

Dielectrics (Insulators)

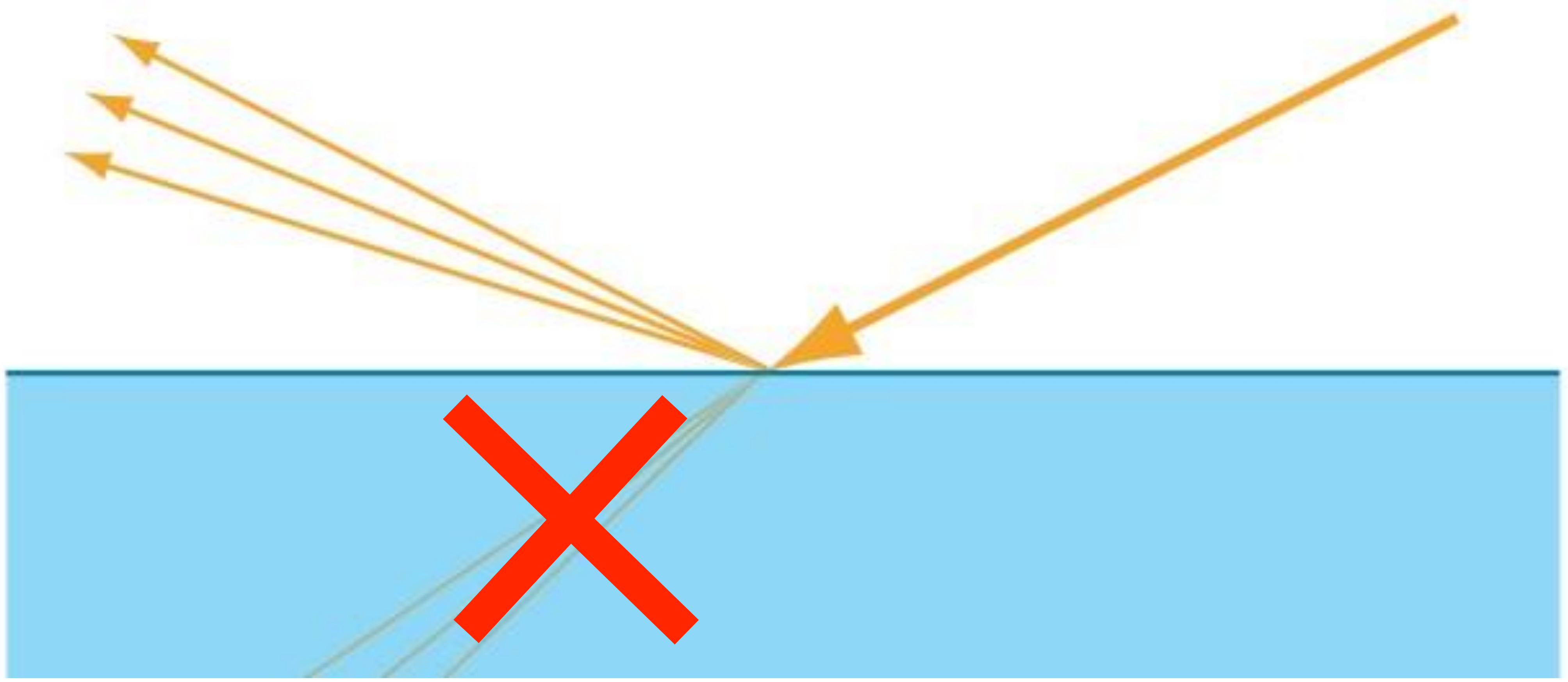
Semiconductors

Metals

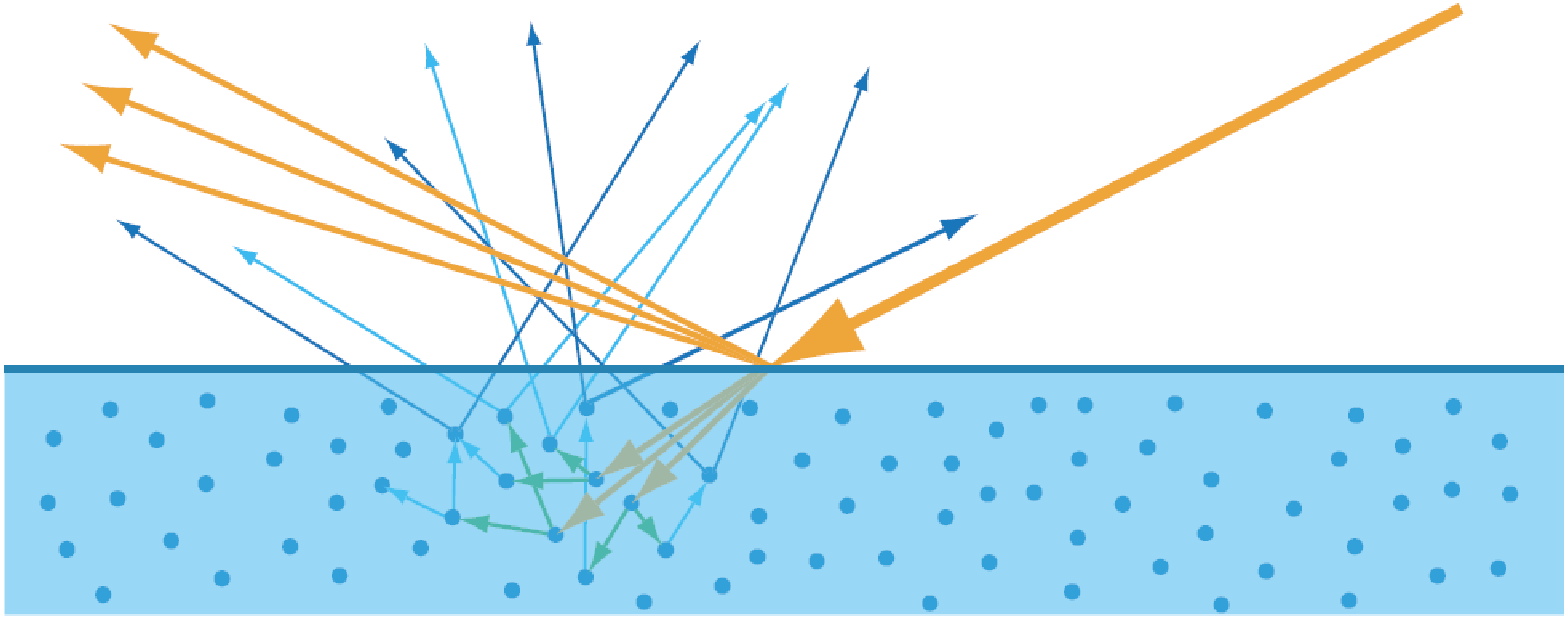
Non-Metals

~~Semiconductors~~

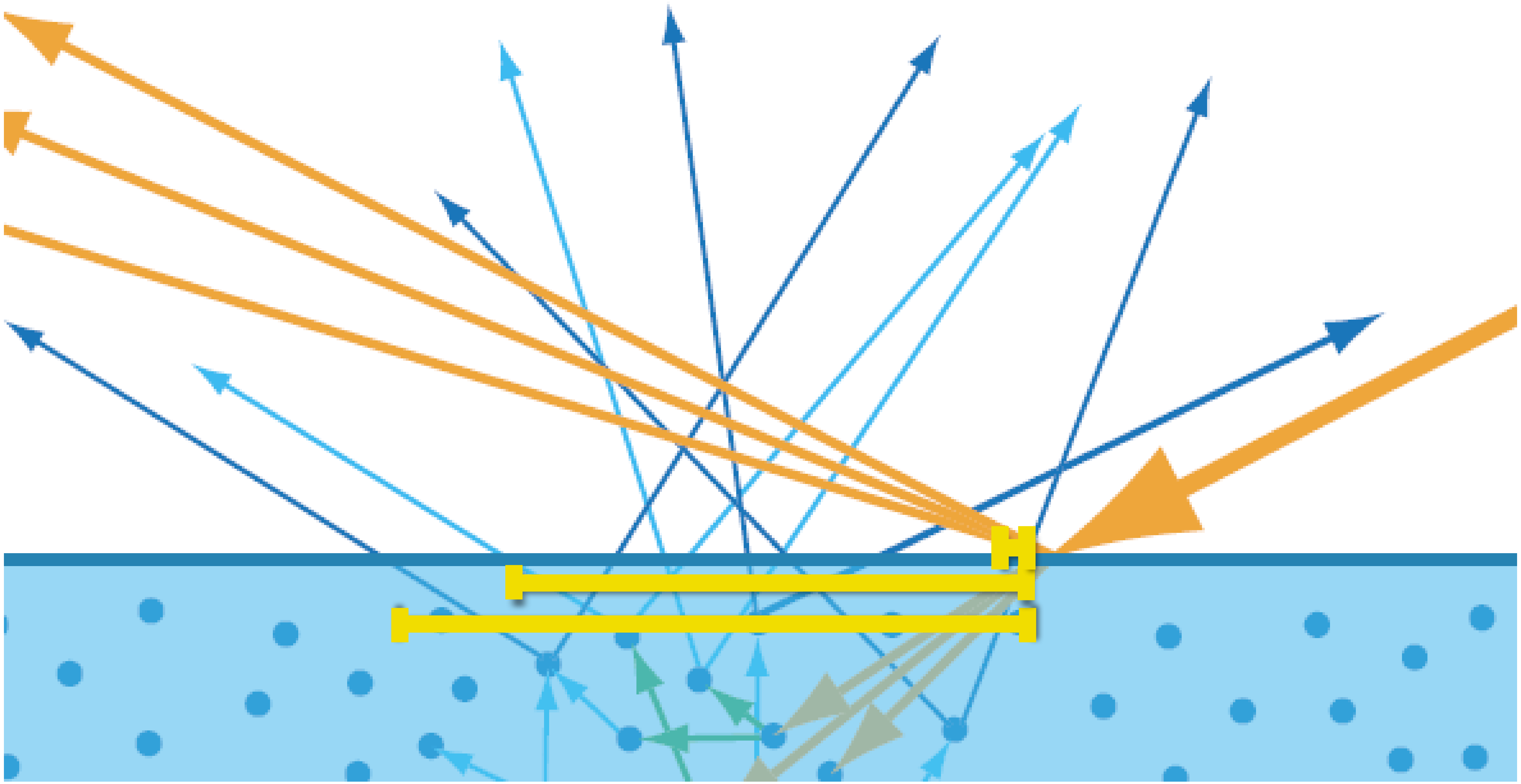
Metals



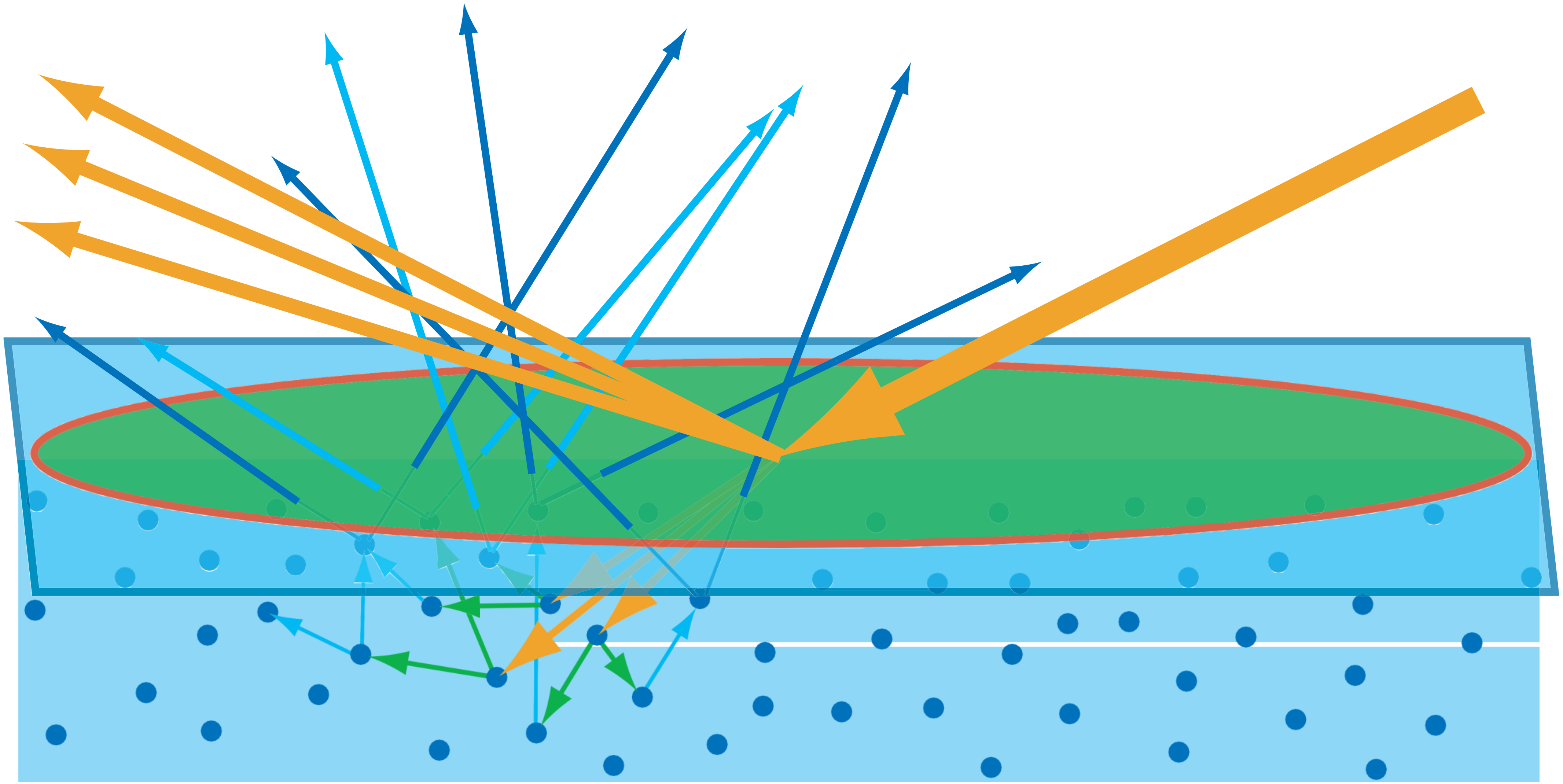
Non-Metals



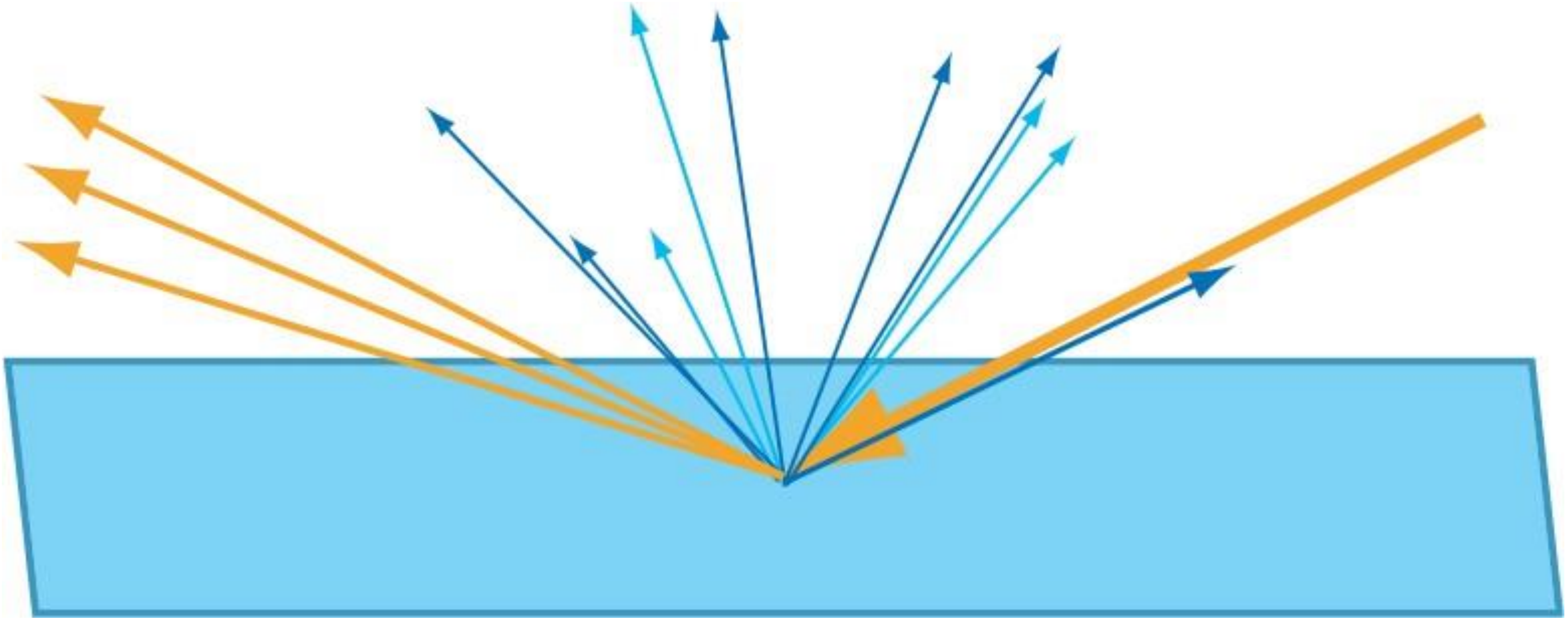
Refracted light



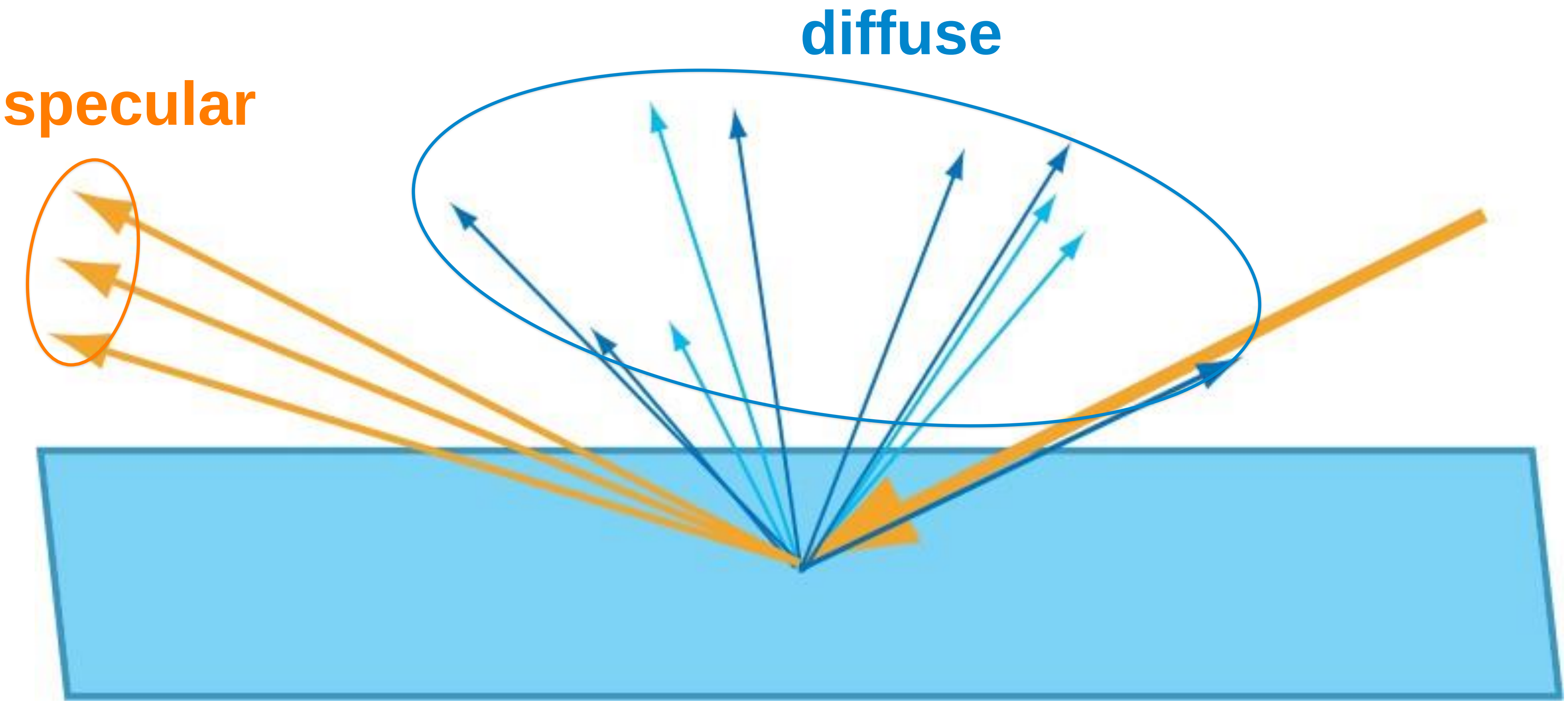
Large sub-Surface scattering area



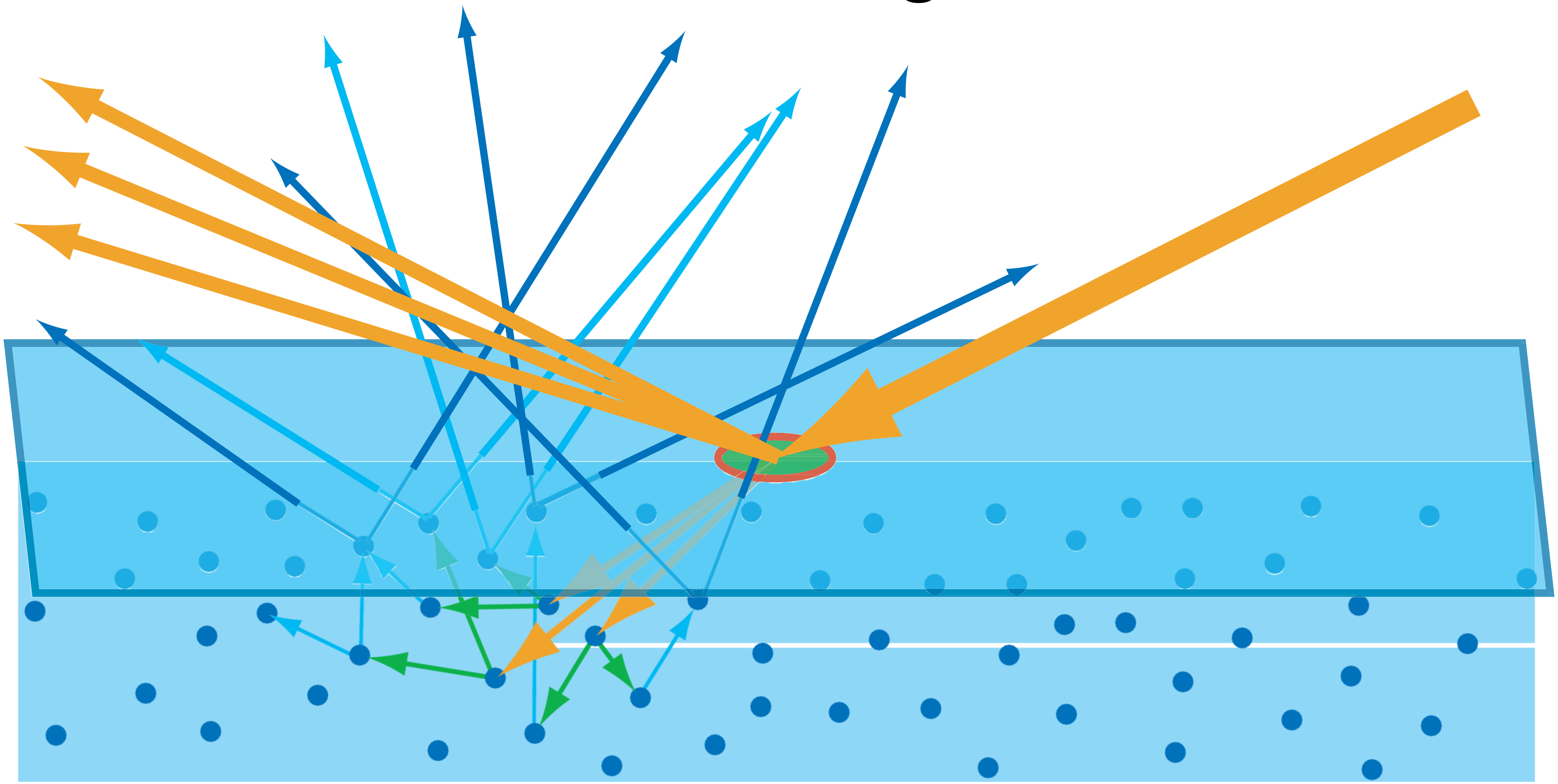
Ignoring sub-surface scattering

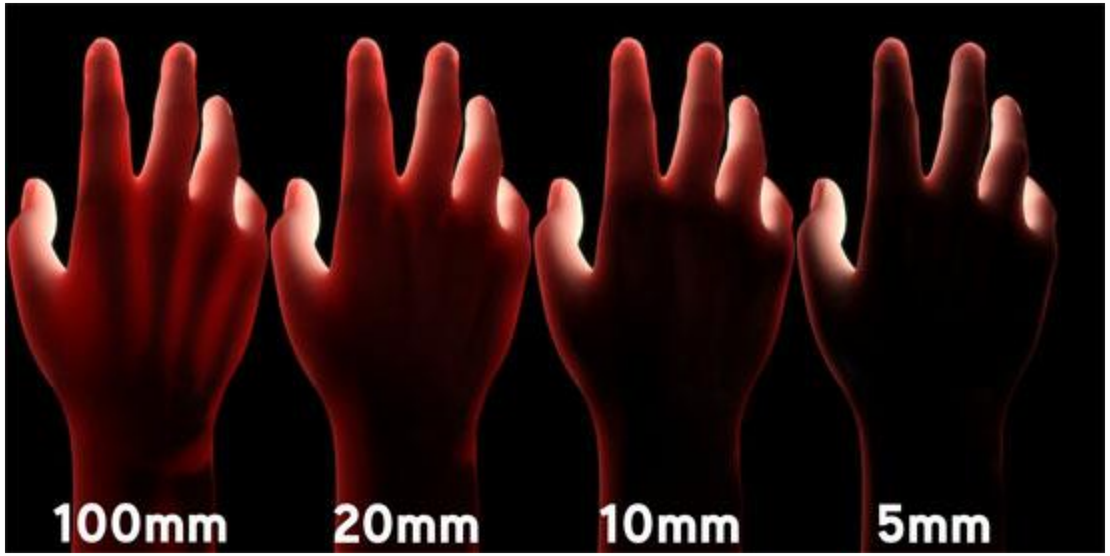


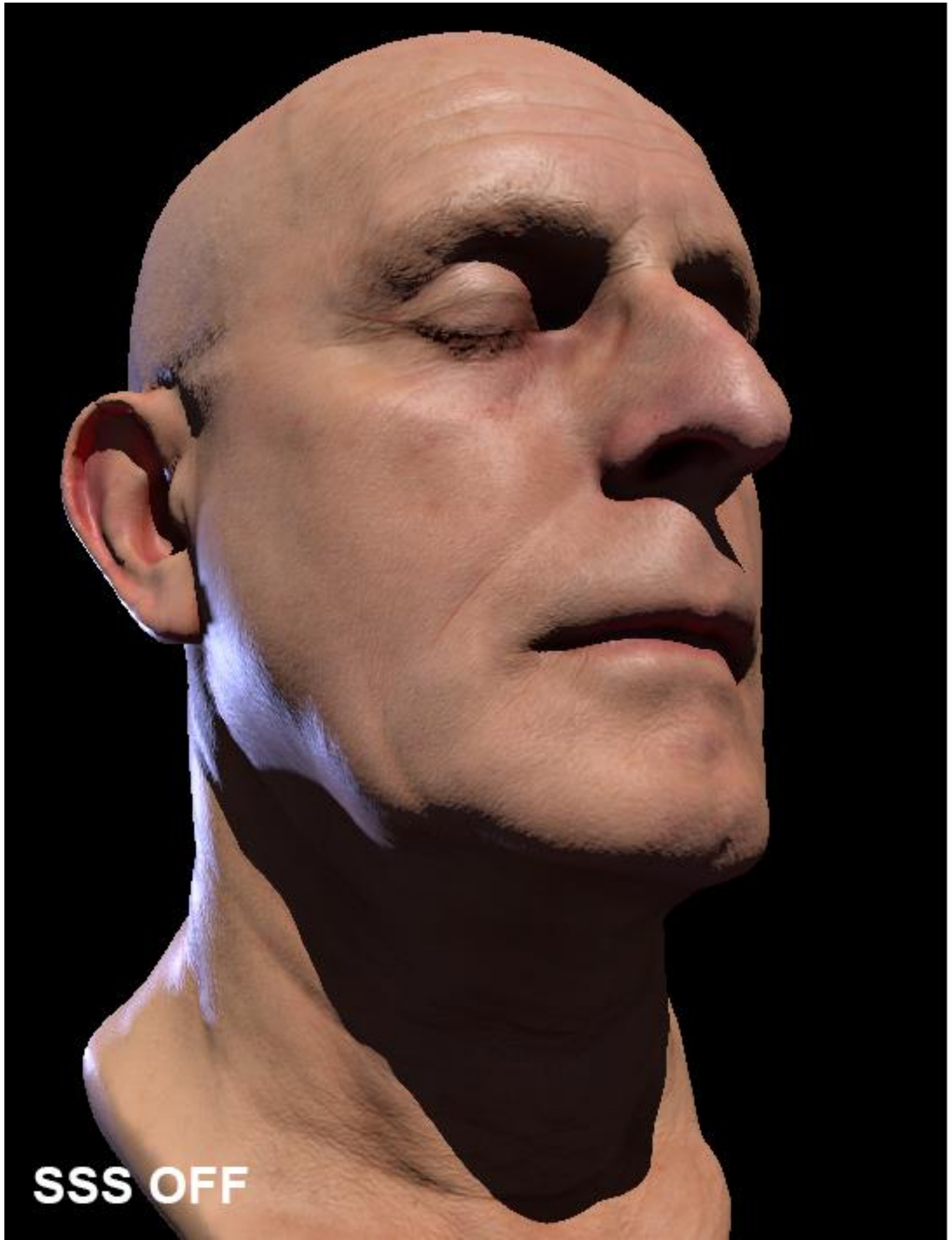
Divide into specular and diffuse light



Small sub-surface scattering area




100mm
20mm
10mm
5mm


SSS OFF


SSS ON

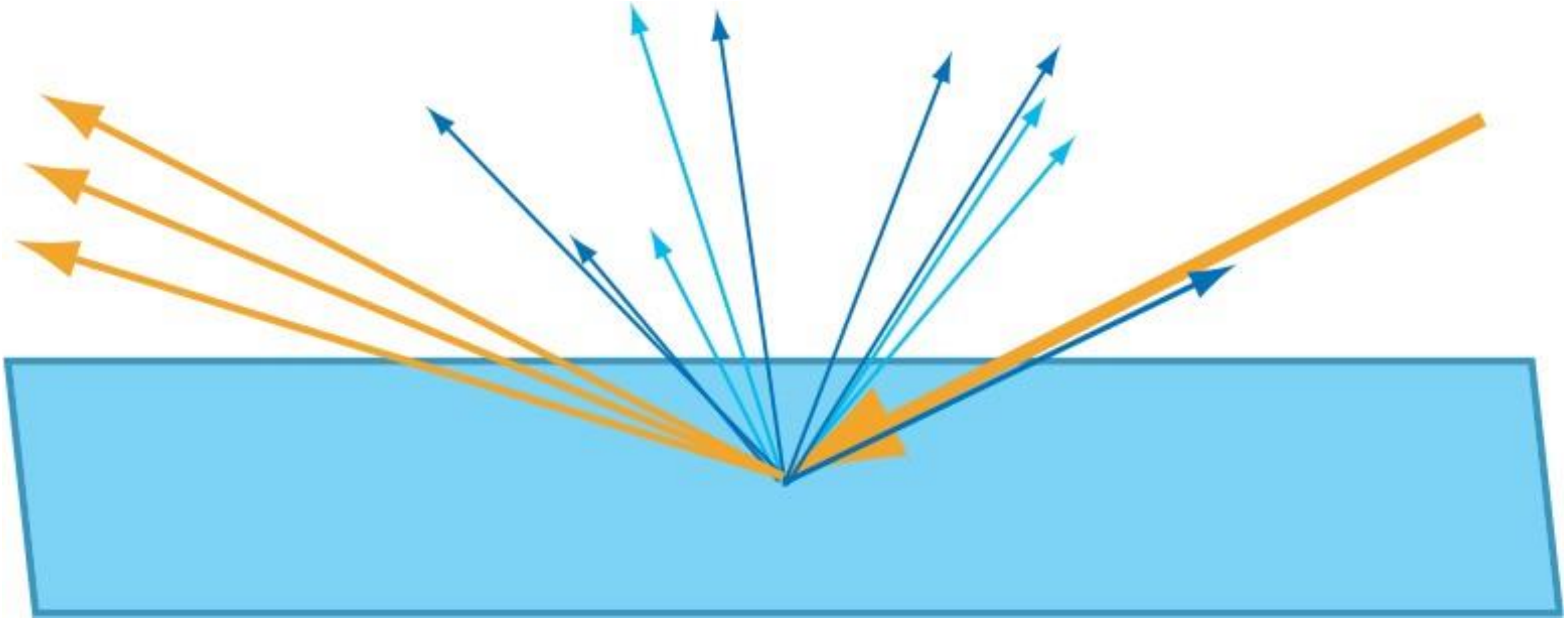
Mathematical model

Radiance

Single Ray

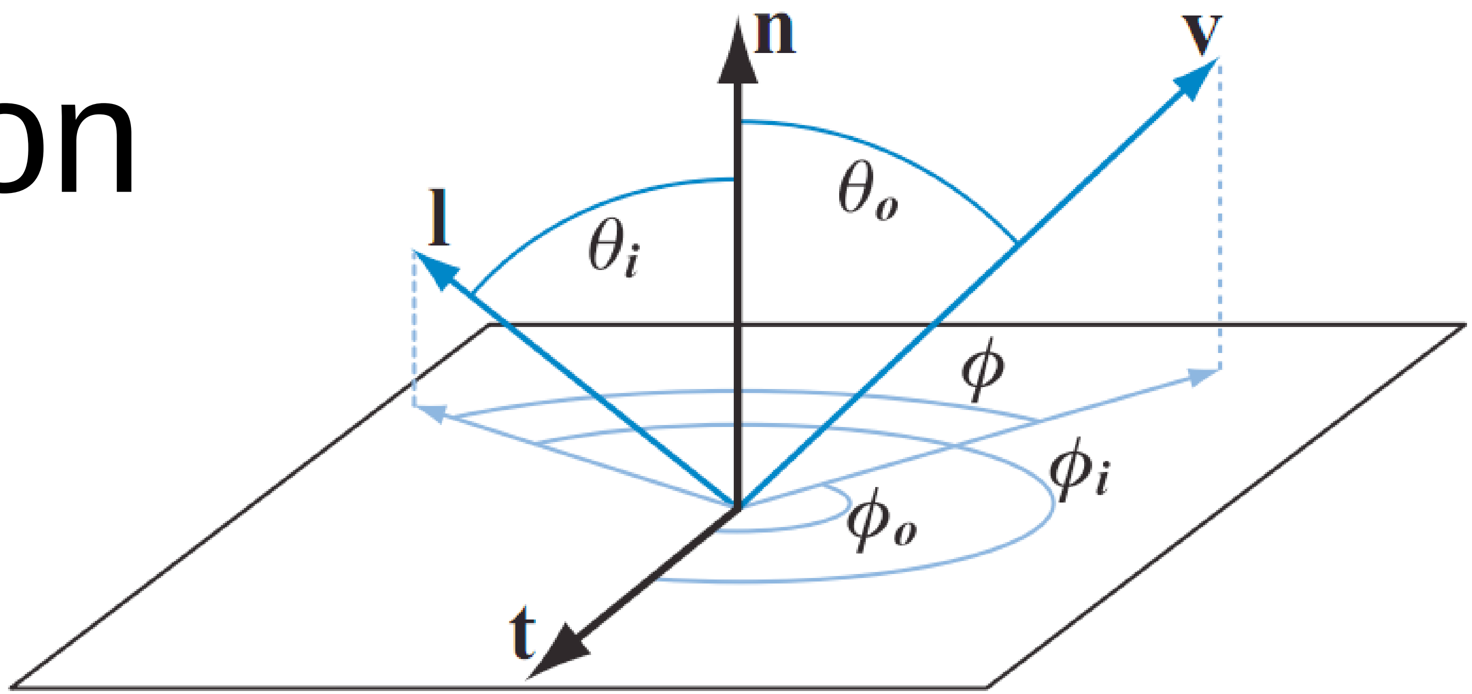
Spectral/RGB

Depends only on light and view directions



Bidirectional
Reflectance
Distribution
Function

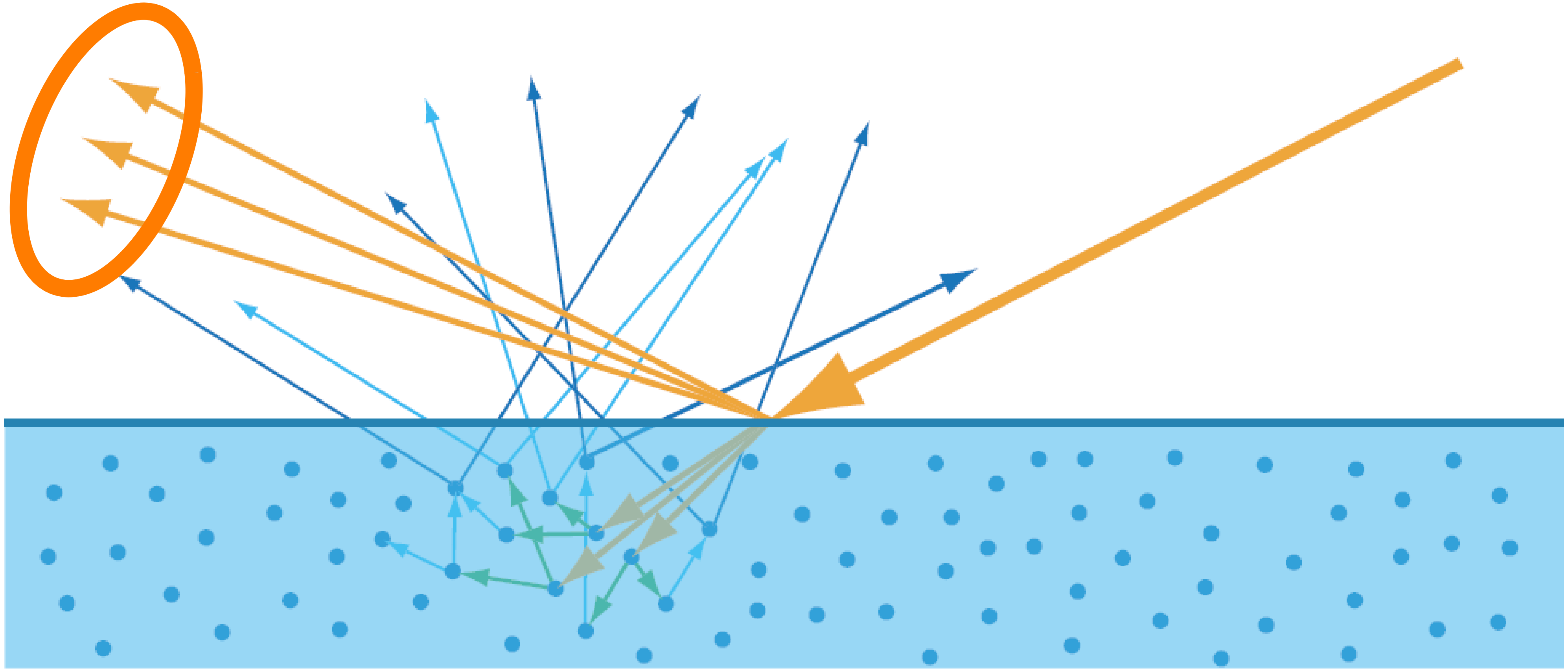
$$f(\mathbf{l}, \mathbf{v})$$



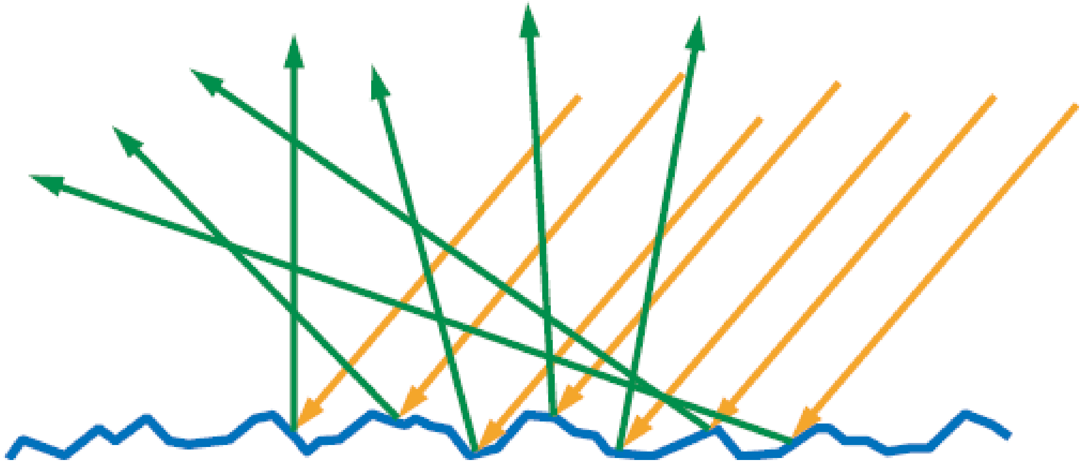
The Reflectance Equation

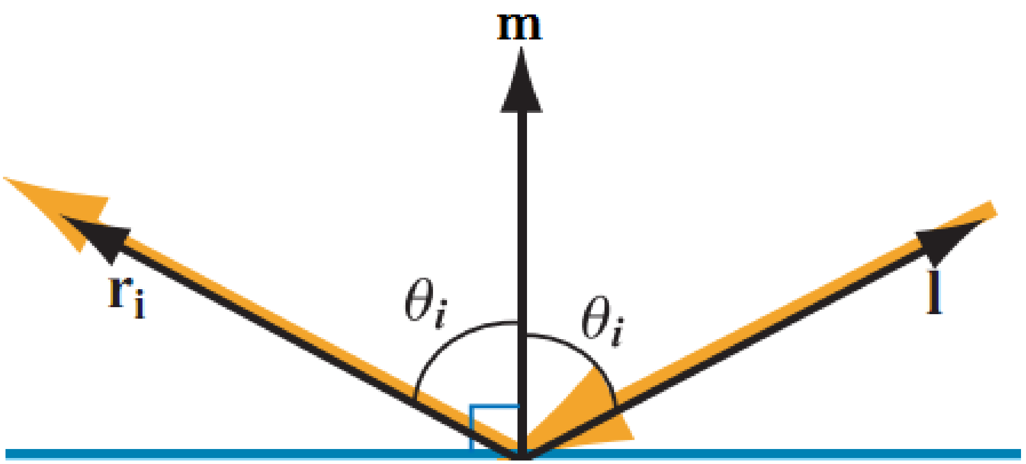
$$L_o(\boldsymbol{v}) = \int_{\Omega} f(\boldsymbol{l}, \boldsymbol{v}) \otimes L_i(\boldsymbol{l})(\boldsymbol{n} \cdot \boldsymbol{l}) d\omega_i$$

Surface Reflection (Specular Term)

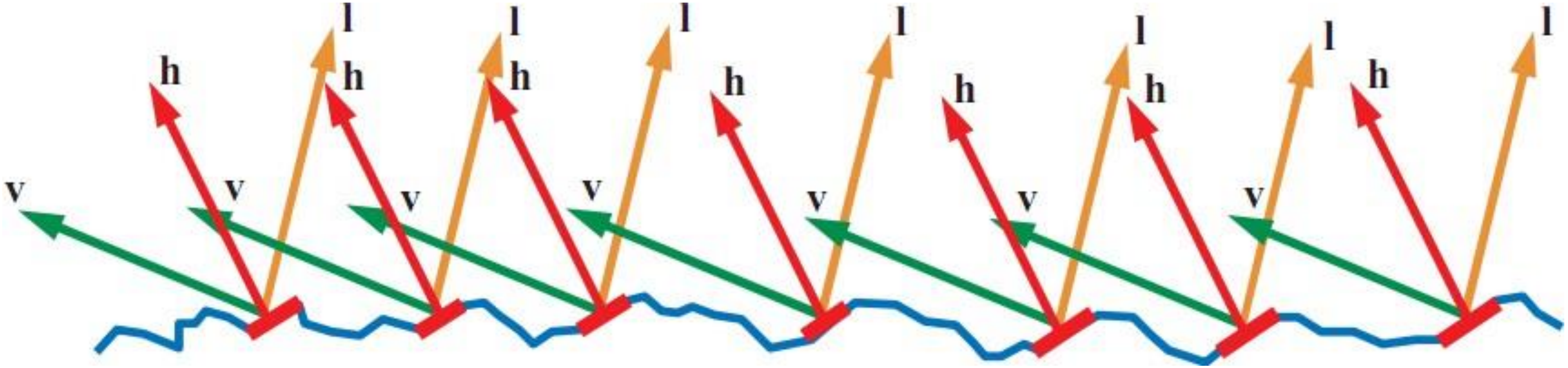


Microfacet Theory

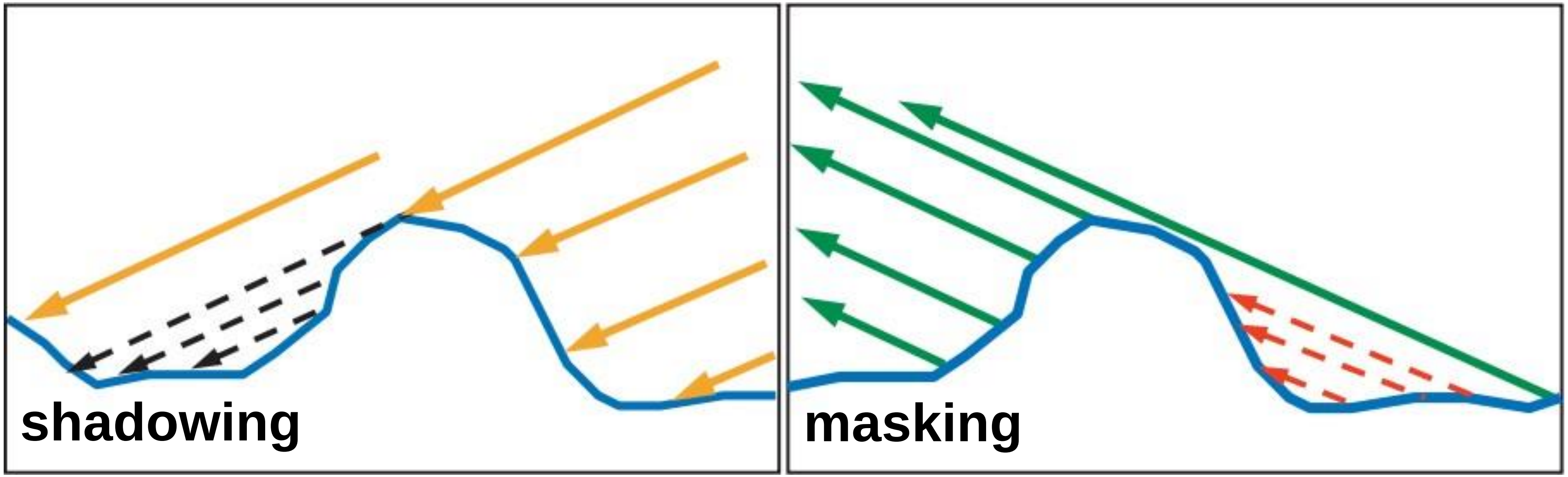




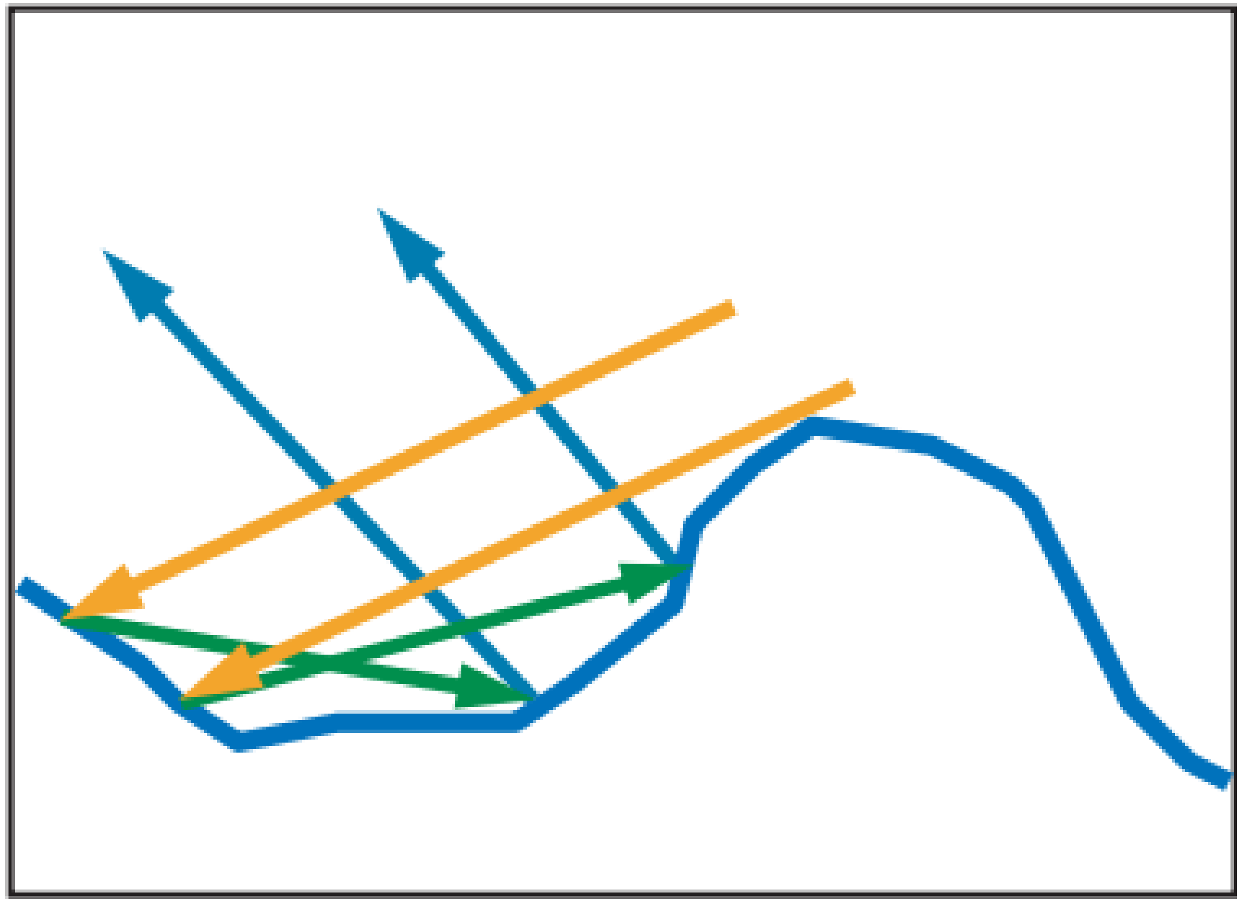
The Half Vector



Shadowing and Masking



Multiple Surface Bounces



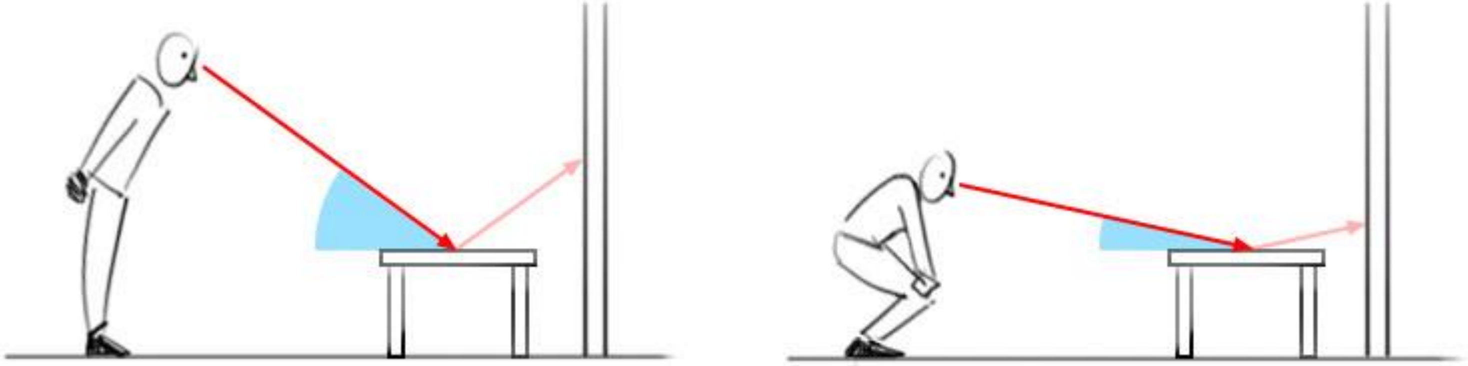
Microfacet Specular BRDF

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

Fresnel Reflectance

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

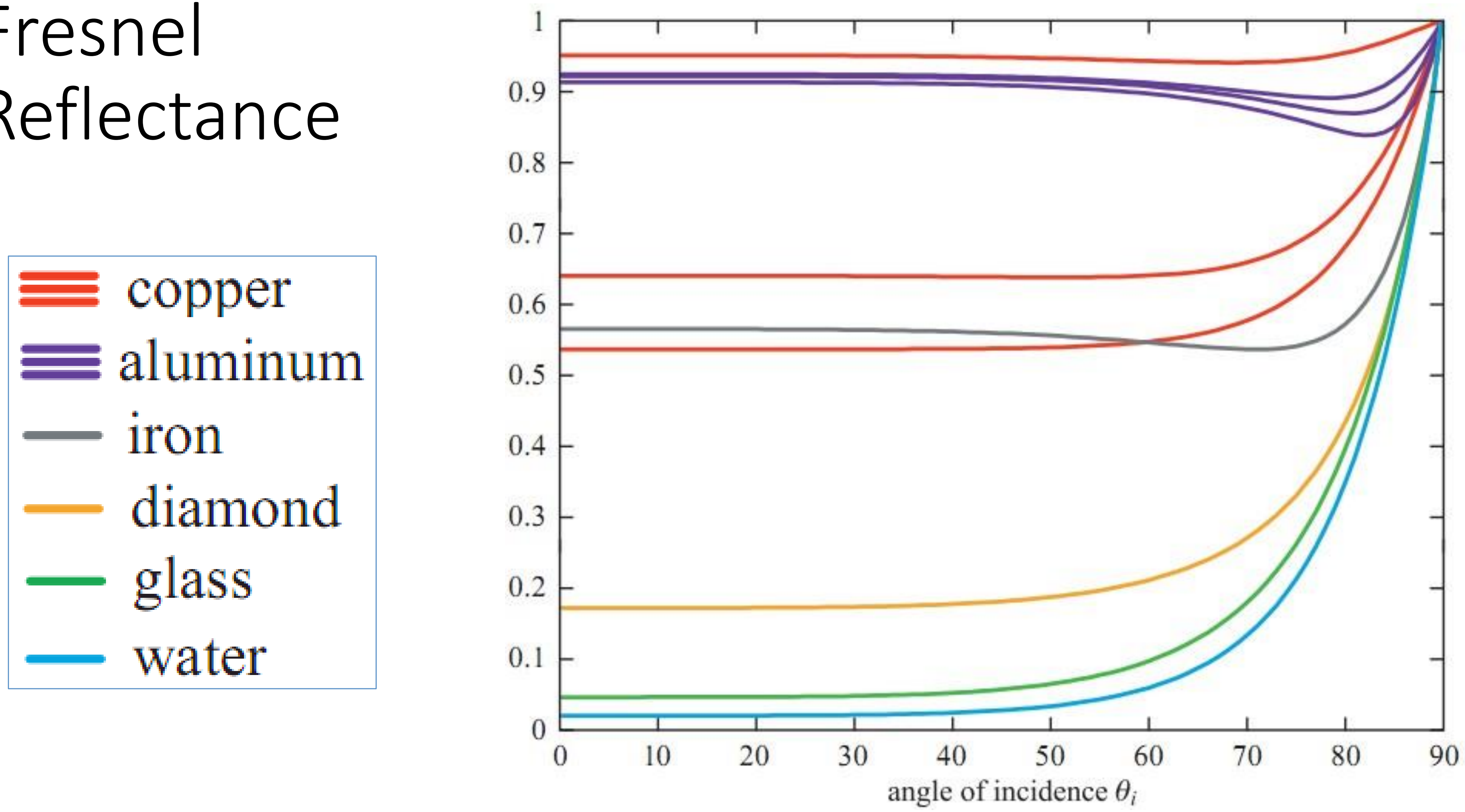
Fresnel Reflectance

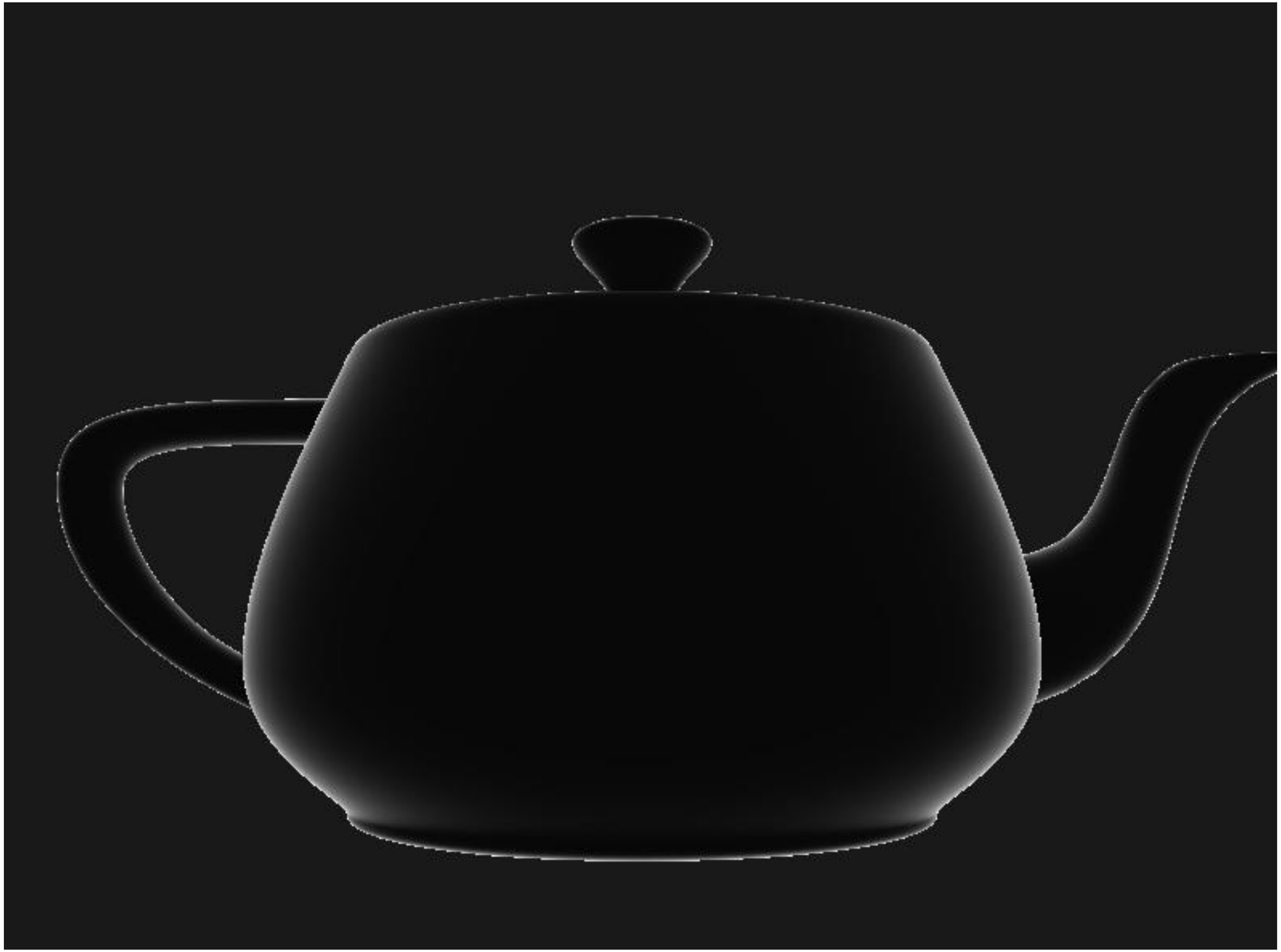


steep angle = weak reflection   shallow angle = strong reflection

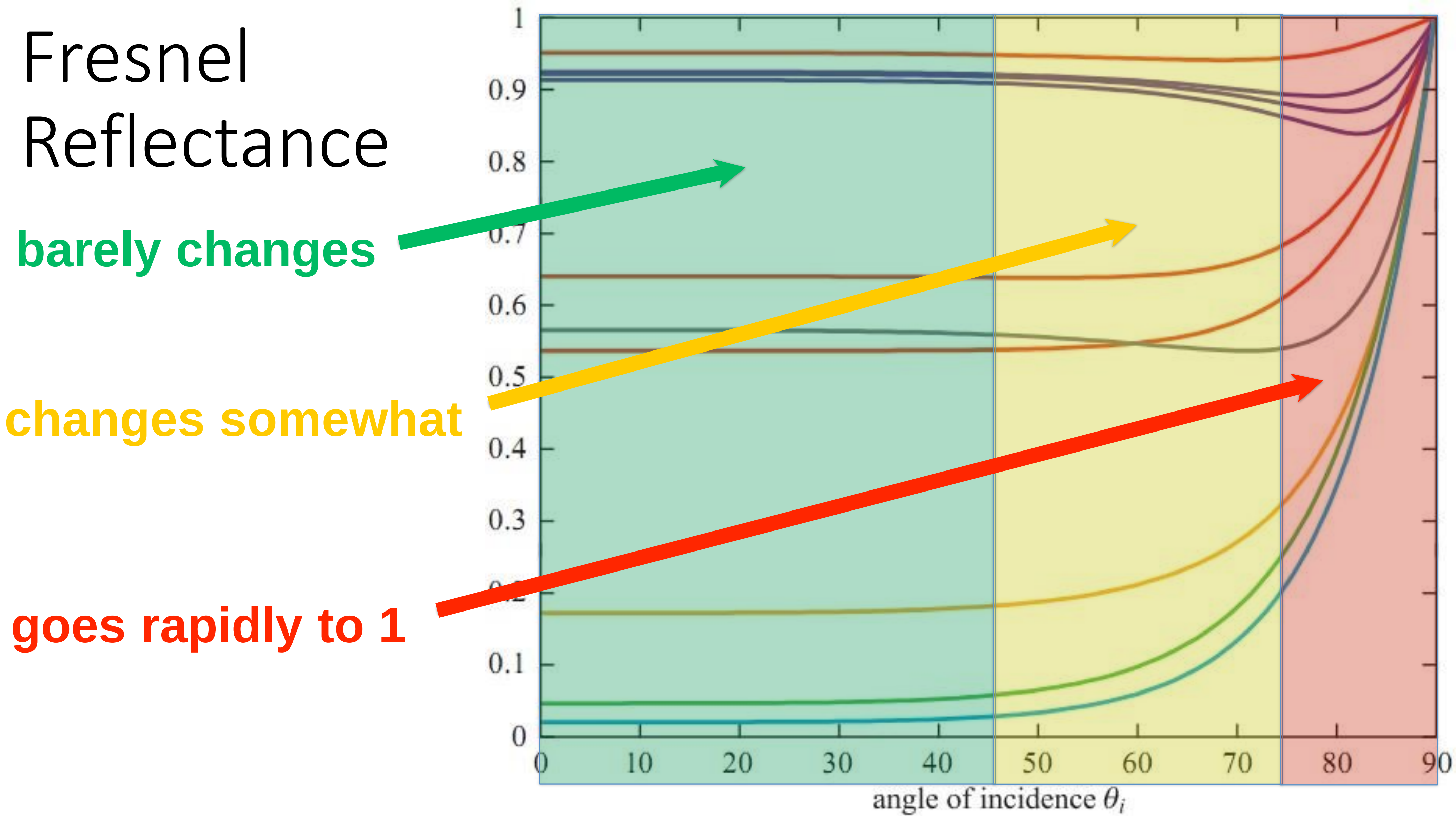
Example

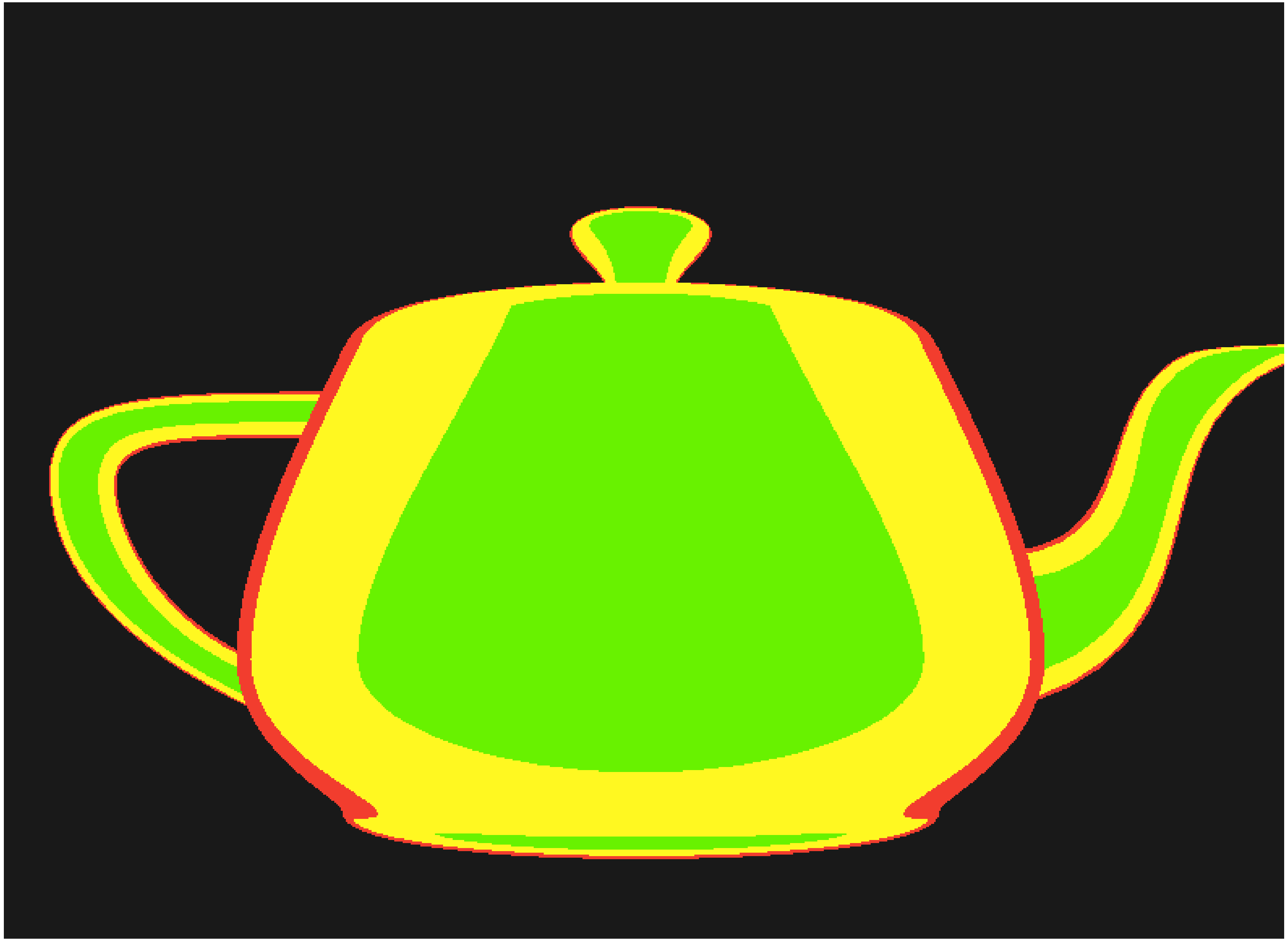
Fresnel Reflectance





Fresnel Reflectance

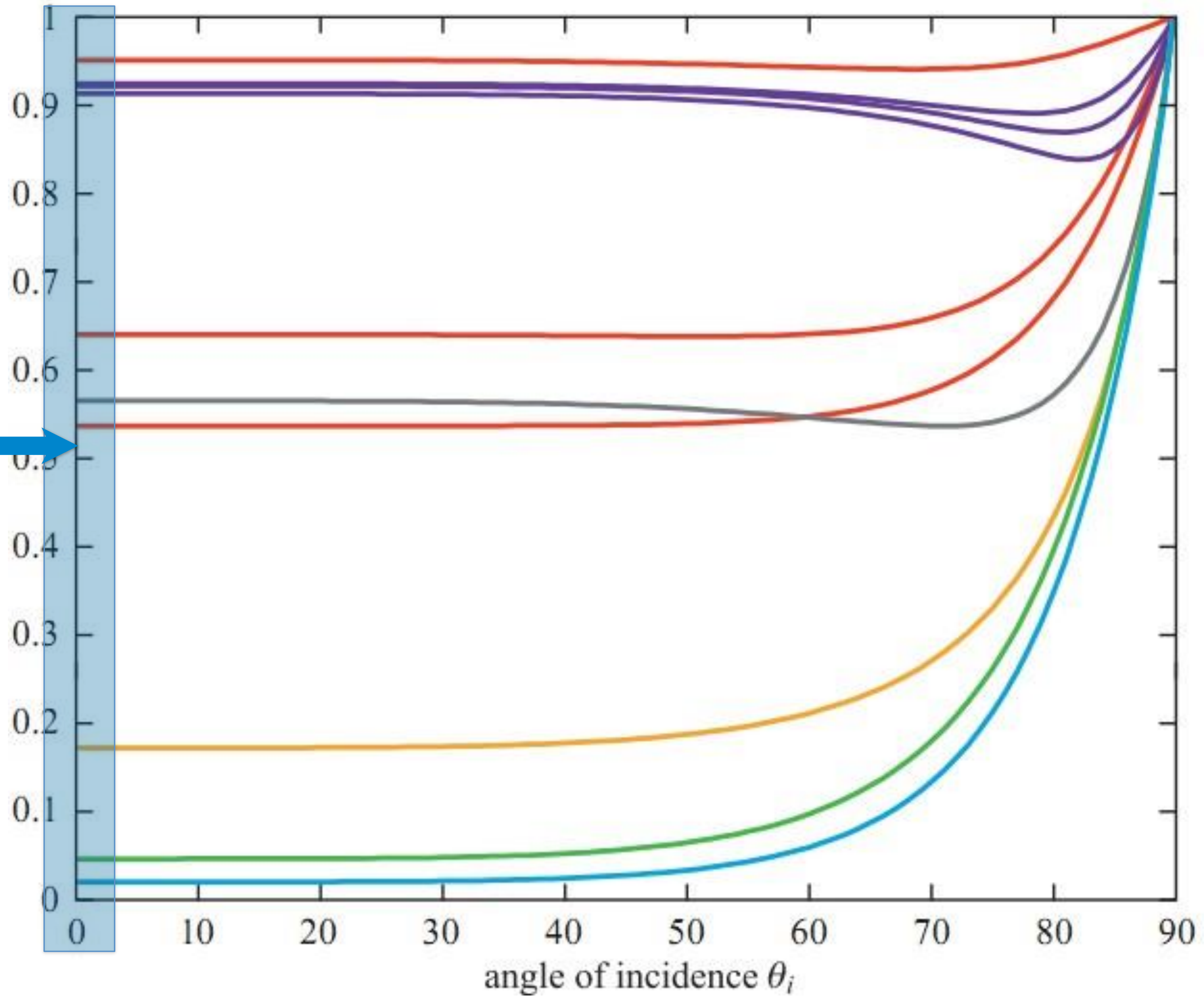




Fresnel Reflectance

$F_0 = F(0°)$

Is the surface's characteristic specular color



Metal	F_0 (Linear,Float)	F_0 (sRGB,U8)	Color
Titanium	0.542,0.497,0.449	194,187,179	
Chromium	0.549,0.556,0.554	196,197,196	
Iron	0.562,0.565,0.578	198,198,200	
Nickel	0.660,0.609,0.526	212,205,192	
Platinum	0.673,0.637,0.585	214,209,201	
Copper	0.955,0.638,0.538	250,209,194	
Palladium	0.733,0.697,0.652	222,217,211	
Zinc	0.664,0.824,0.850	213,234,237	
Gold	1.022,0.782,0.344	255,229,158	
Aluminum	0.913,0.922,0.924	245,246,246	
Silver	0.972,0.960,0.915	252,250,245	

Metal	F_0 (Linear,Float)	F_0 (sRGB,U8)	Color
Titanium	0.542,0.497,0.449	194,187,179	
Chromium	0.549,0.556,0.554	196,197,196	
Iron	0.562,0.565,0.578	198,198,200	
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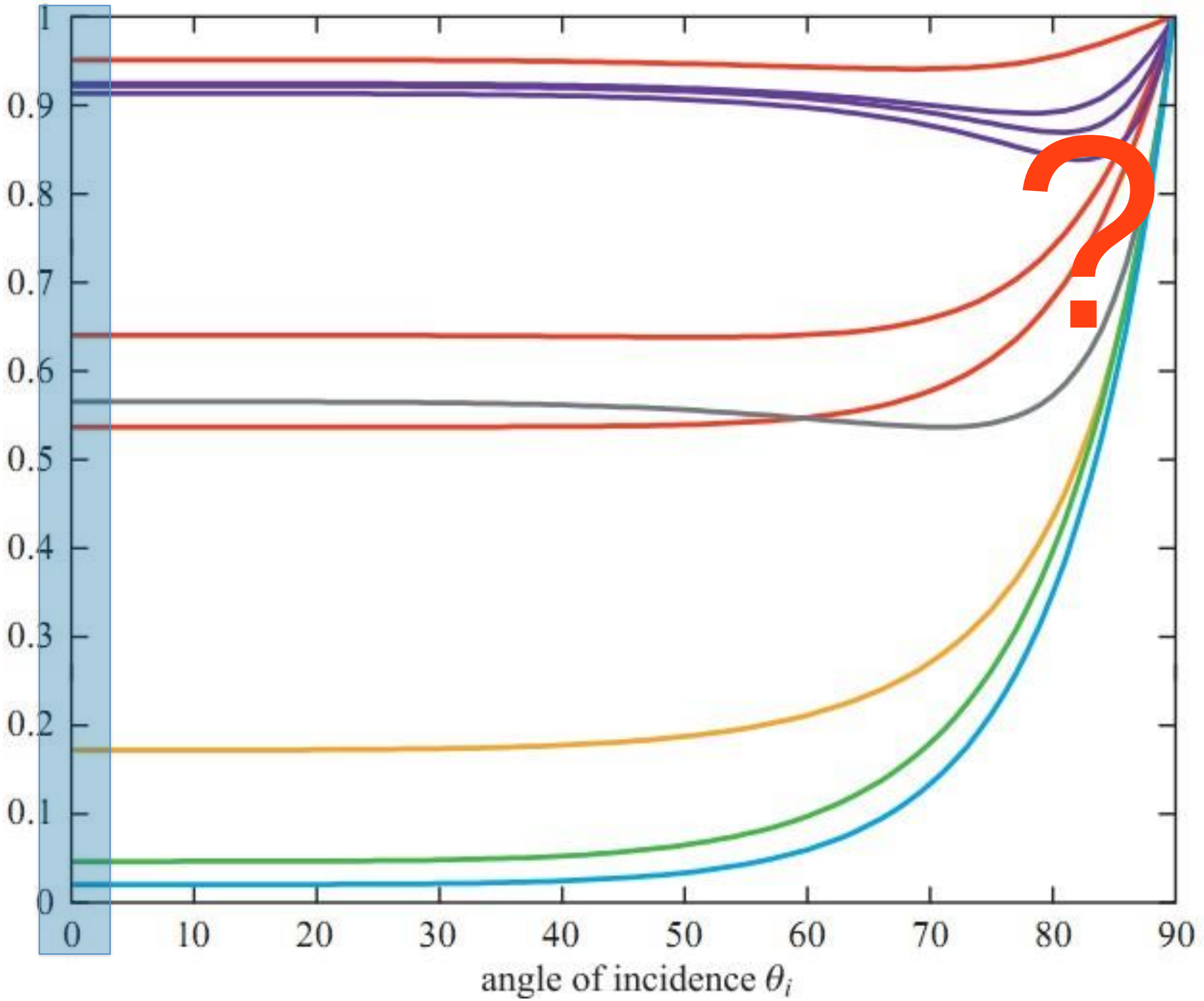
Aluminum	0.913,0.922,0.924	245,246,246	
Silver	0.972,0.960,0.915	252,250,245	

F_0 Values for Dielectrics

Dielectric	F_0 (Linear, Float)	F_0 (sRGB, U8)	Color
Water	0.020	39	
Plastic, Glass	0.040 – 0.045	56 – 60	
Crystalware, Gems	0.050 – 0.080	63 – 80	
Diamond-like	0.100 – 0.200	90 – 124	

Fresnel Reflectance



The Schlick Approximation to Fresnel

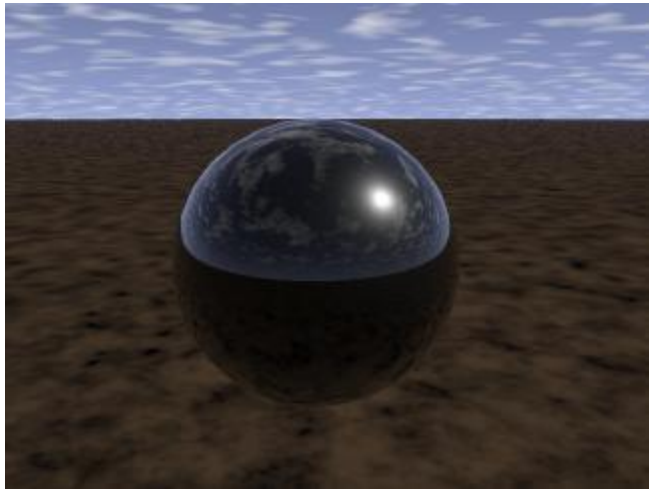
- Fairly accurate, cheap, parameterized by F_0

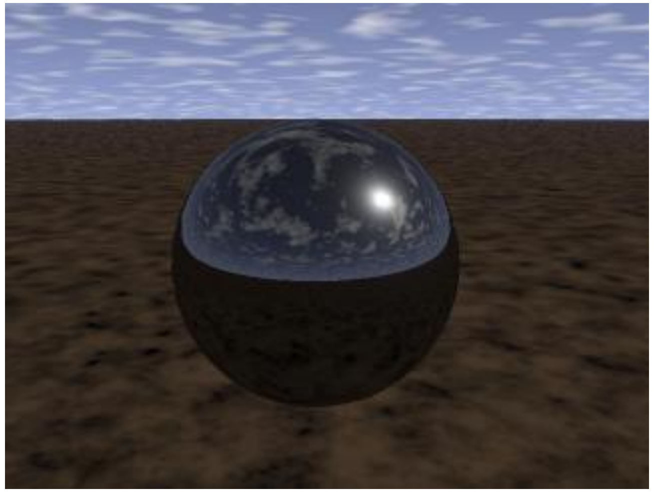
$$F_{\text{Schlick}}(F_0, \mathbf{l}, \mathbf{n}) = F_0 + (1 - F_0)(1 - (\mathbf{l} \cdot \mathbf{n}))^5$$

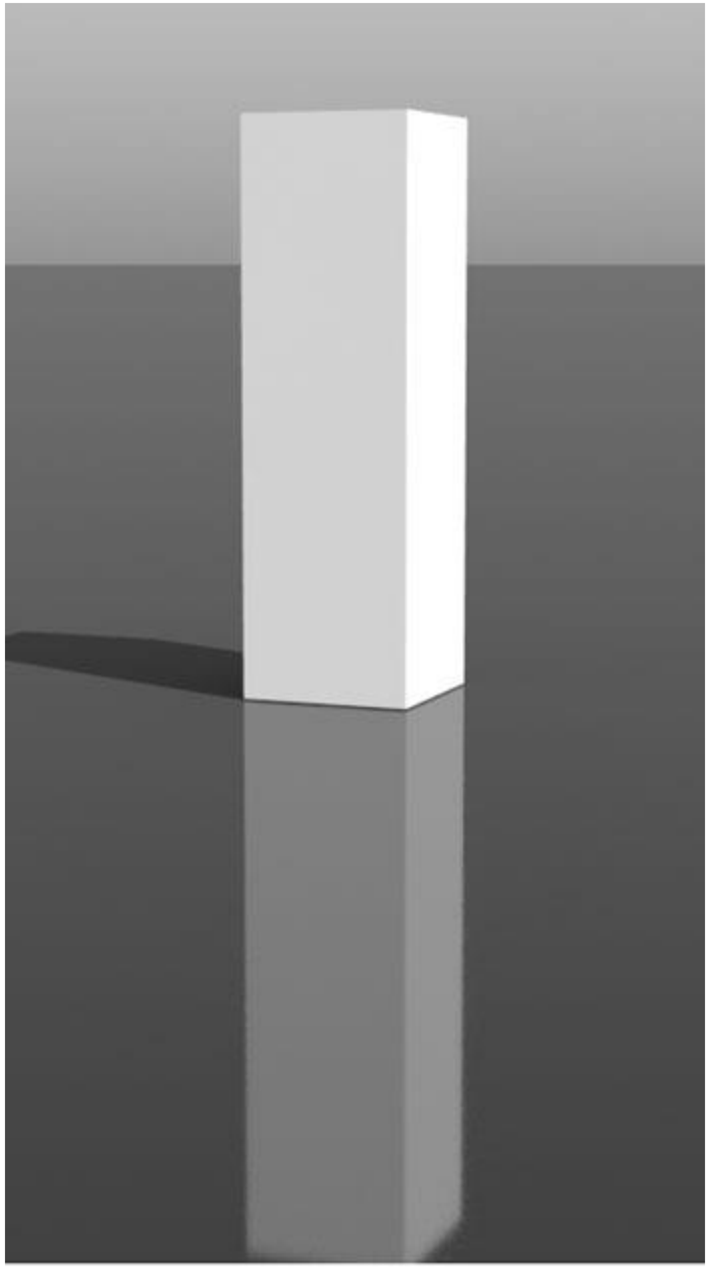
- For microfacet BRDFs ($\mathbf{n} = \mathbf{h}$):

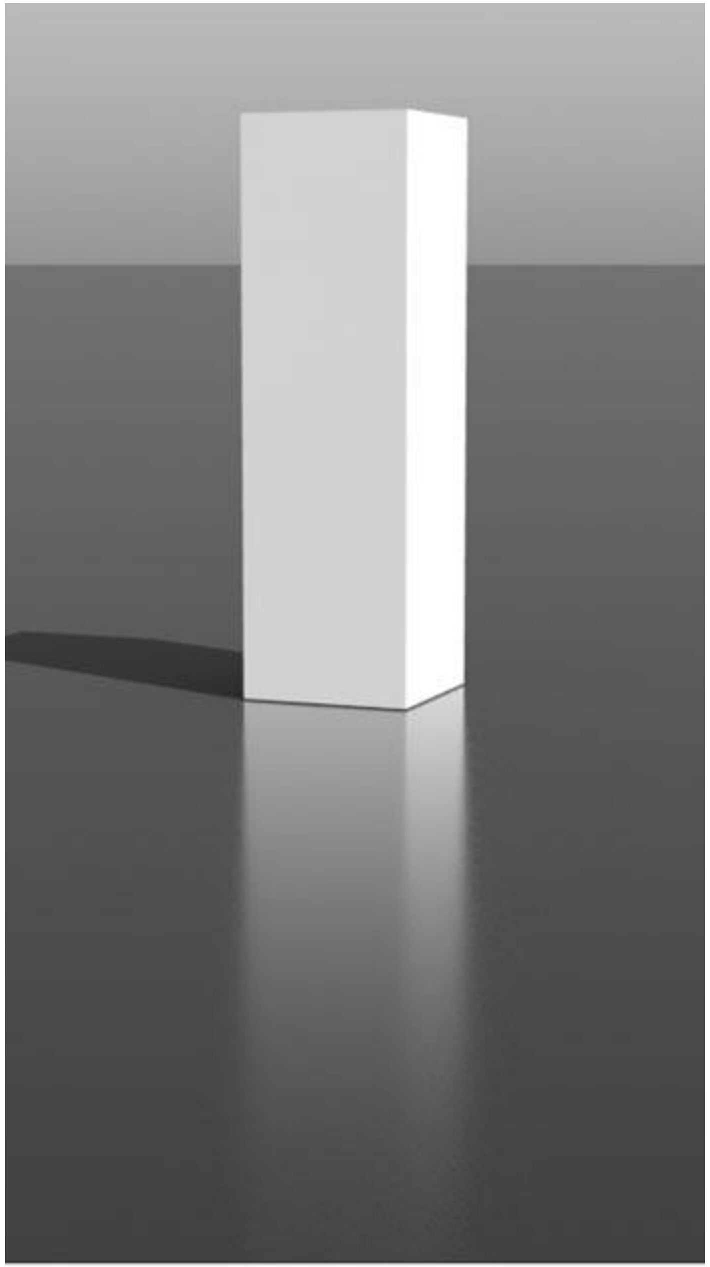
$$F_{\text{Schlick}}(F_0, \mathbf{l}, \mathbf{h}) = F_0 + (1 - F_0)(1 - (\mathbf{l} \cdot \mathbf{h}))^5$$

With and without Fresnel reflectance






without fresnel


with fresnel

Normal Distribution Function

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

Different Normal Distribution Functions

$$D_p(\mathbf{m}) = \frac{\alpha_p + 2}{2\pi}(\mathbf{n} \cdot \mathbf{m})^{\alpha_p}$$

$$D_{uabc}(\mathbf{m}) = \frac{1}{\left(1 + \alpha_{abc1}\left(1 - (\mathbf{n} \cdot \mathbf{m})\right)\right)^{\alpha_{abc2}}}$$

$$D_{tr}(\mathbf{m}) = \frac{\alpha_{tr}^2}{\pi\left((\mathbf{n} \cdot \mathbf{m})^2\left(\alpha_{tr}^2 - 1\right) + 1\right)^2}$$

$$D_b(\mathbf{m}) = \frac{1}{\pi\alpha_b^2(\mathbf{n} \cdot \mathbf{m})^4} e^{-\left(\frac{1 - (\mathbf{n} \cdot \mathbf{m})^2}{\alpha_b^2(\mathbf{n} \cdot \mathbf{m})^2}\right)}$$

Let $D_{BlinnPhong}(h) = K(\underline{n.h})^{\alpha}$

$$\int_{\Theta} D_{BlinnPhong}(h)(n.h)\,dh = 1$$

$$\int_{\Theta} K(\underline{n.h})^{\alpha}(n.h)\,dh = 1$$

$$K\int_{0}^{2\pi}\int_{0}^{\pi}(\underline{n.h})^{\alpha}(n.h)\,sin\theta\;d\theta d\varphi = 1$$

$$K\int_{0}^{2\pi}\left(\int_{0}^{\pi/2}(\underline{n.h})^{\alpha}(n.h)\,sin\theta\;d\theta + \int_{\pi/2}^{\pi}(\underline{n.h})^{\alpha}(n.h)\,sin\theta\;d\theta\right)\,d\varphi = 1$$

$$K\int_{0}^{2\pi}\left(\int_{0}^{\pi/2}(n.h)^{\alpha+1}\,sin\theta\;d\theta + \int_{\pi/2}^{\pi}0\,(n.h)\,sin\theta\;d\theta\right)\,d\varphi = 1$$

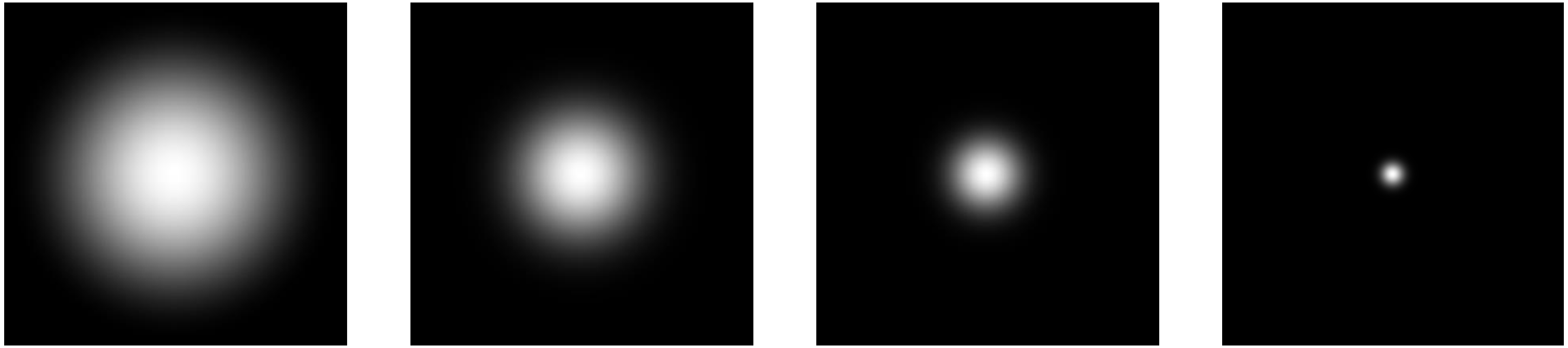
$$K\,2\pi\int_{0}^{\pi/2}(cos\theta)^{\alpha+1}\,d(-cos\theta) = 1$$

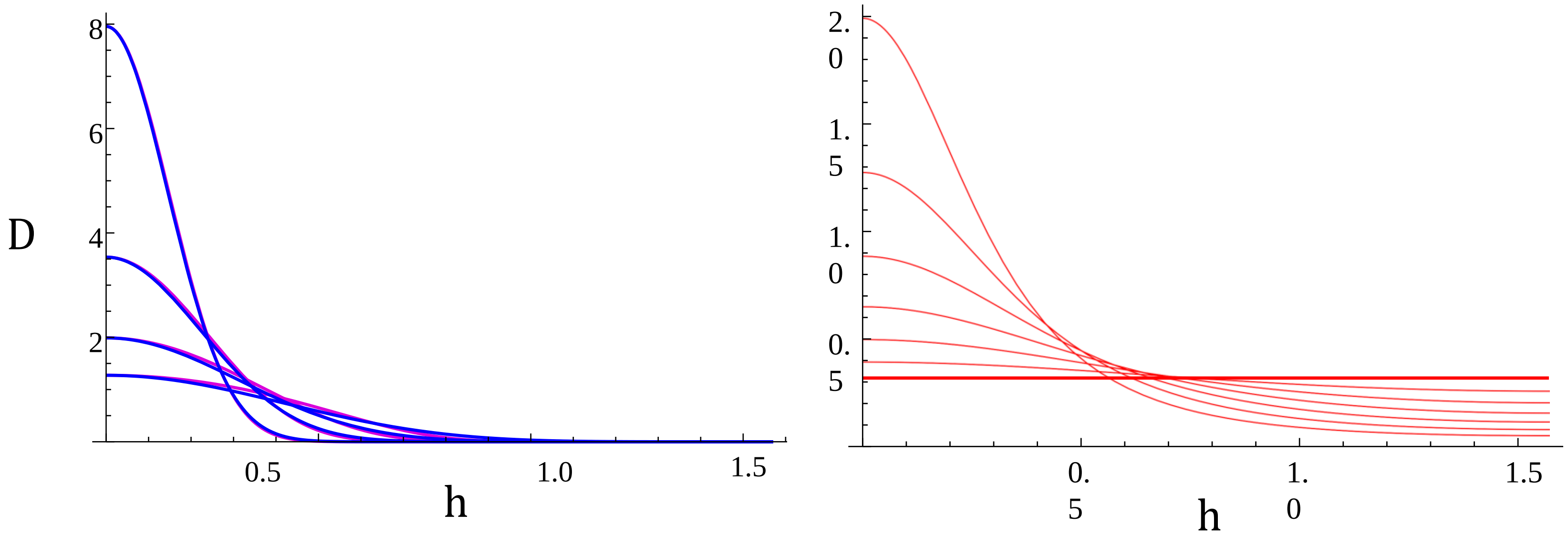
$$-K\,2\pi\left[\frac{\cos^{\alpha+2}\theta}{\alpha+2}\right]_{0}^{\pi/2} = 1$$

$$-K\,2\pi\frac{-1}{\alpha+2} = 1$$

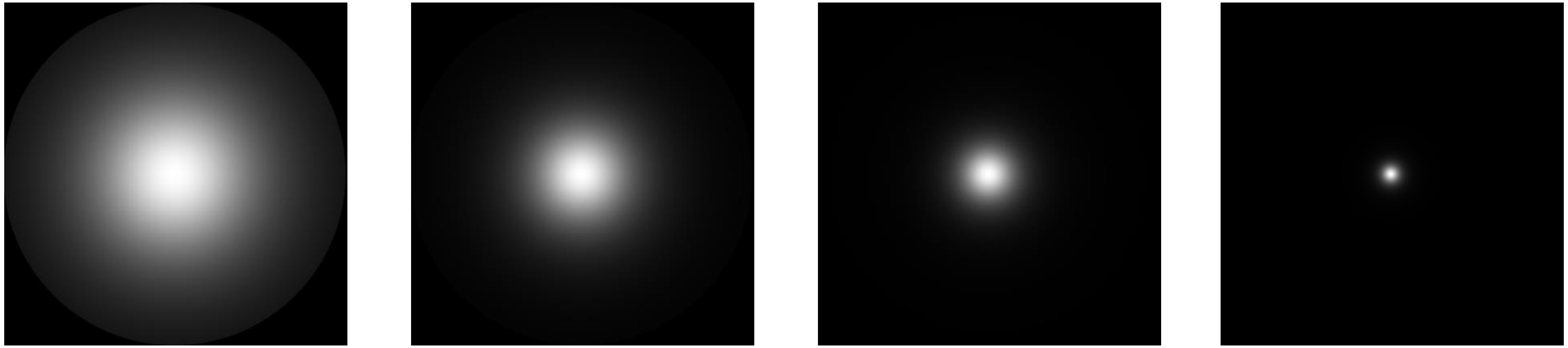
$$K = \frac{\alpha+2}{2\pi}$$

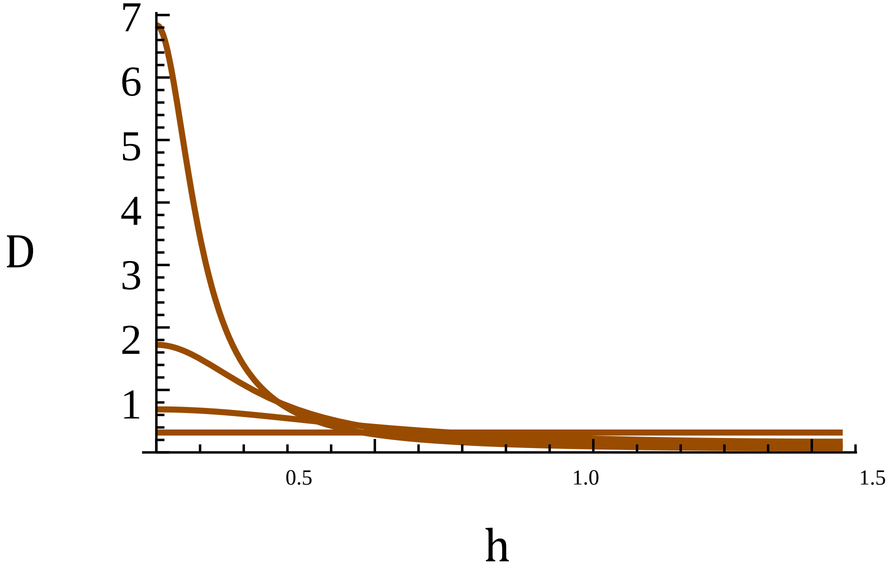
$$\therefore\; D_{BlinnPhong}(h) = \frac{\alpha+2}{2\pi}(\underline{n.h})^{\alpha}$$

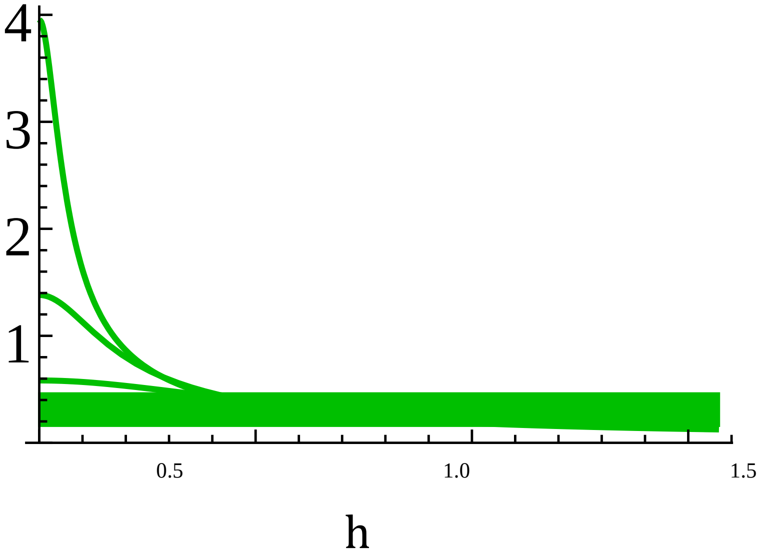




Blobby highlights: Beckmann, Phong, Blinn-Phong



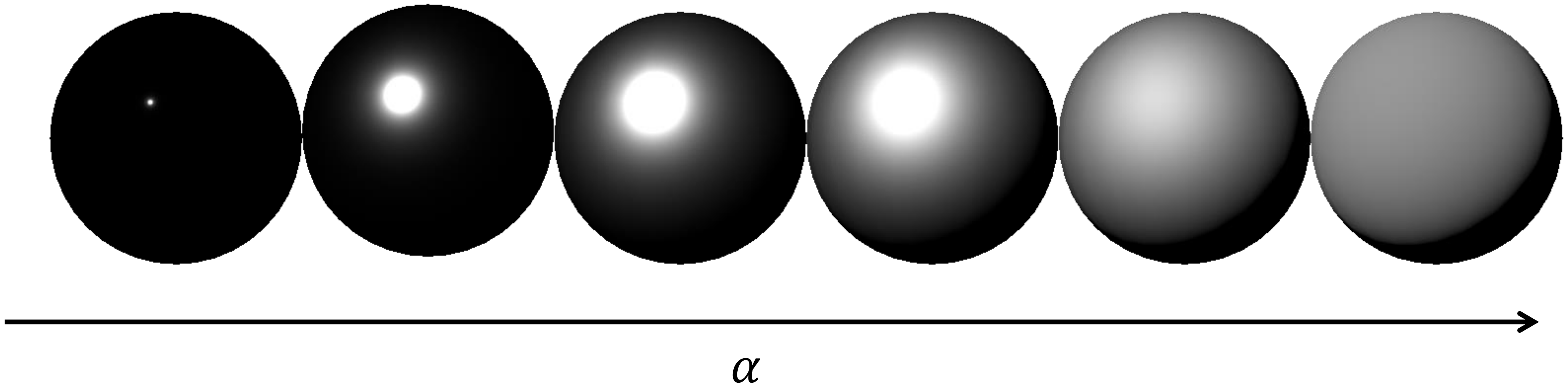




Sharp highlights: GGX

Normal Distribution Function

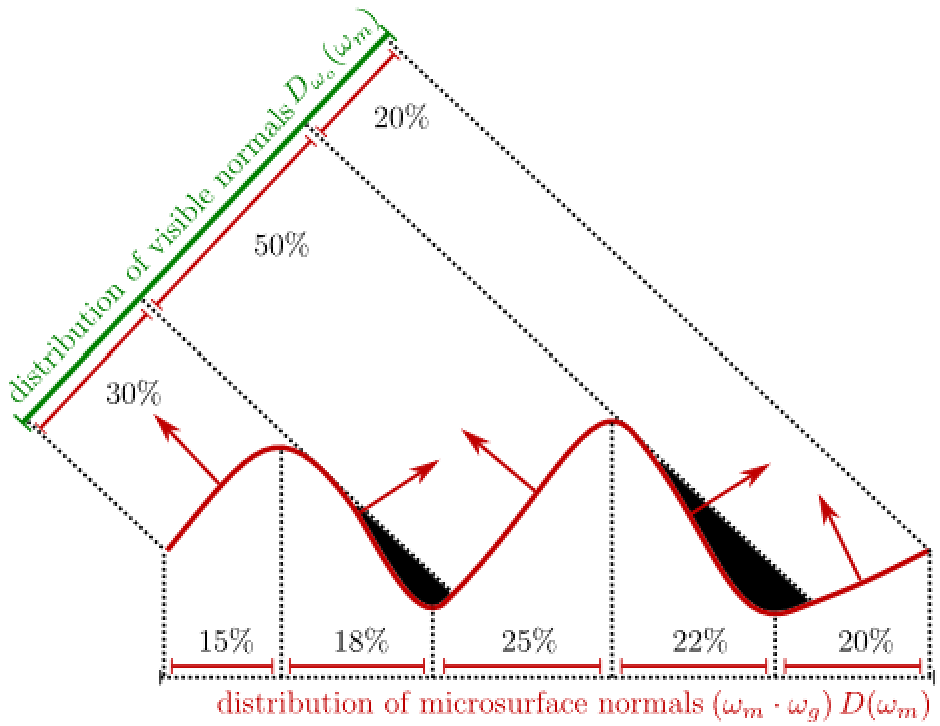
- approximates the relative surface area of microfacets aligned to the (halfway) vector
- D(n, h, α) where α indicates surface roughness



Geometry Function

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

Shadowing and Masking from View Direction



$$G_{\mathrm{ct}}(\mathbf{l}, \mathbf{v}, \mathbf{h}) = \min\left(1, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{v})}{(\mathbf{v}\cdot\mathbf{h})}, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{l})}{(\mathbf{v}\cdot\mathbf{h})}\right)$$

$$\frac{G_{\mathrm{ct}}(\mathbf{l}, \mathbf{v}, \mathbf{h})}{(\mathbf{n}\cdot\mathbf{l})(\mathbf{n}\cdot\mathbf{v})} \approx \frac{1}{(\mathbf{l}\cdot\mathbf{h})^2}$$

$$G_{\mathrm{implicit}}(\mathbf{l}, \mathbf{v}, \mathbf{m}) = (\mathbf{n}\cdot\mathbf{l})(\mathbf{n}\cdot\mathbf{v})$$

$$G_{\mathrm{s}}(\mathbf{l}, \mathbf{v}, \mathbf{h}) = G_{\mathrm{s1}}(\mathbf{l}, \mathbf{h})G_{\mathrm{s1}}(\mathbf{v}, \mathbf{h})$$

$$G_{\mathrm{ct}}(\mathbf{l},\mathbf{v},\mathbf{h}) = \min\left(1, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{v})}{(\mathbf{v}\cdot\mathbf{h})}, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{l})}{(\mathbf{v}\cdot\mathbf{h})}\right)$$

$$\frac{G_{\mathrm{ct}}(\mathbf{l},\mathbf{v},\mathbf{h})}{(\mathbf{n}\cdot\mathbf{l})(\mathbf{n}\cdot\mathbf{v})} \approx \frac{1}{(\mathbf{l}\cdot\mathbf{h})^2} \qquad G_{\mathrm{implicit}}(\mathbf{l},\mathbf{v},\mathbf{m}) = (\mathbf{n}\cdot\mathbf{l})(\mathbf{n}\cdot\mathbf{v})$$

$$\boxed{G_{\mathrm{s}}(\mathbf{l},\mathbf{v},\mathbf{h}) = G_{\mathrm{s1}}(\mathbf{l},\mathbf{h})G_{\mathrm{s1}}(\mathbf{v},\mathbf{h})}$$

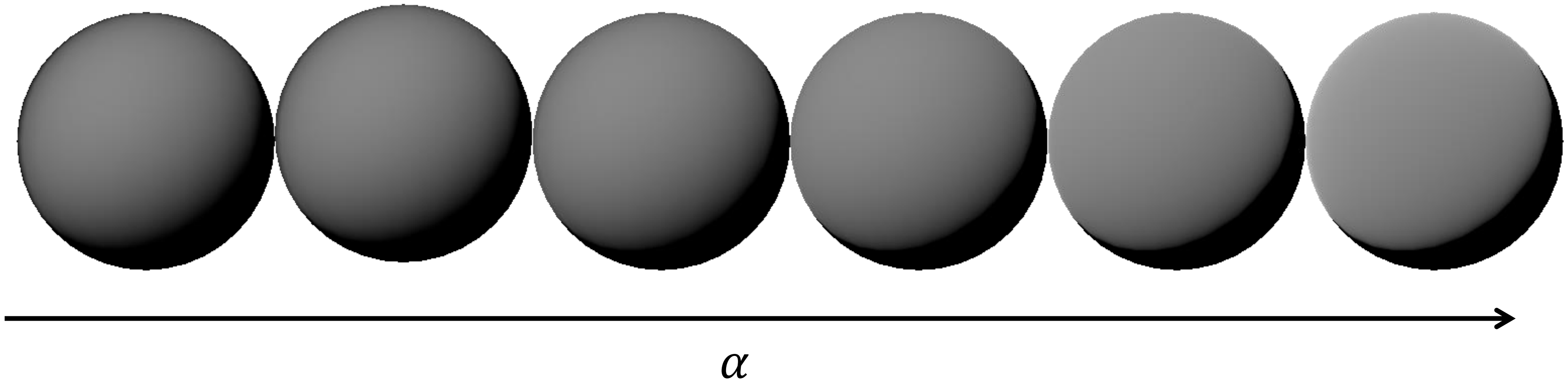
Heitz 2014, Journal of Computer Graphics Techniques Vol. 3, No. 2, 2014

G_{s1}

$$G_{1-Schlick}(v,h) = \frac{(n.v)}{(n.v)(1-k)+k}$$

$$, where\ k = m\sqrt{\frac{2}{\pi}}, m\ is\ the\ rms\ roughness$$

Schlick method results



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

Concentration of
active microfacets

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

Visibility of microfacets

Concentration of active microfacets

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

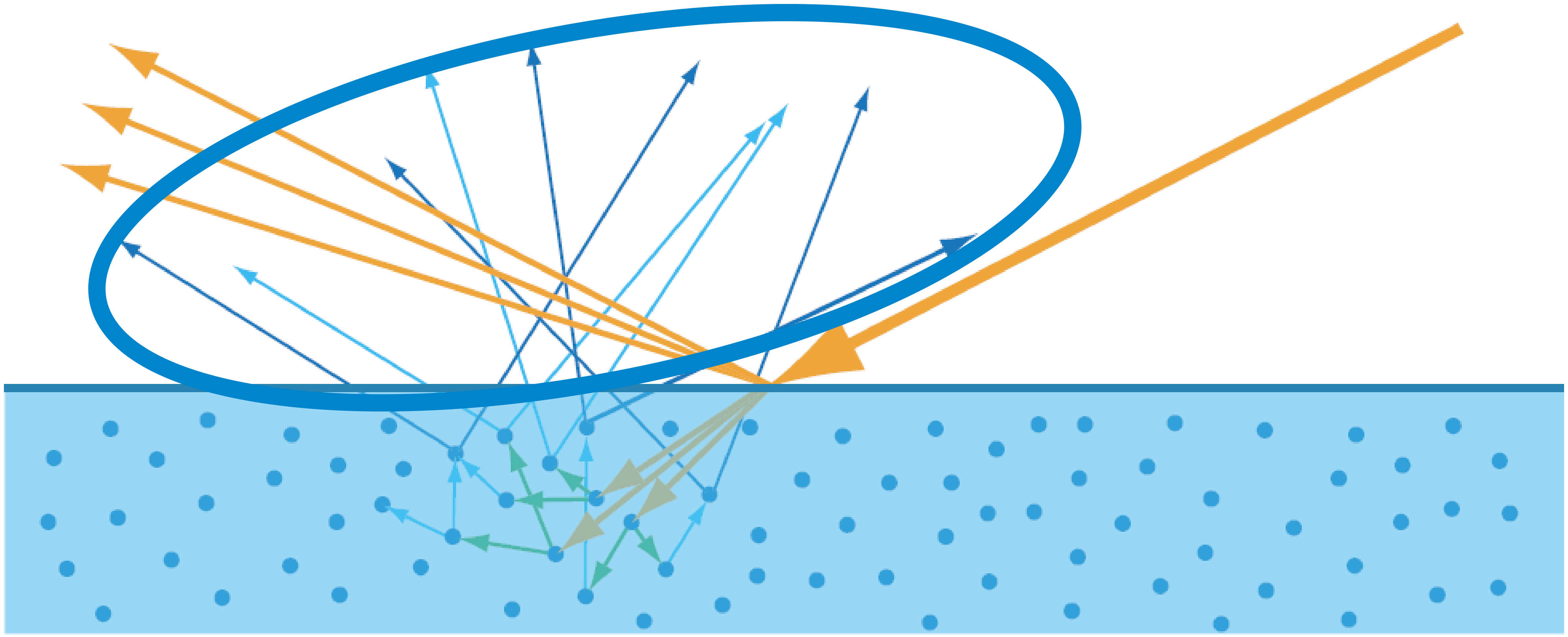
Fresnel reflectance

Visibility of microfacets

Concentration of active microfacets

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

Subsurface Reflection (Diffuse Term)



Lambert

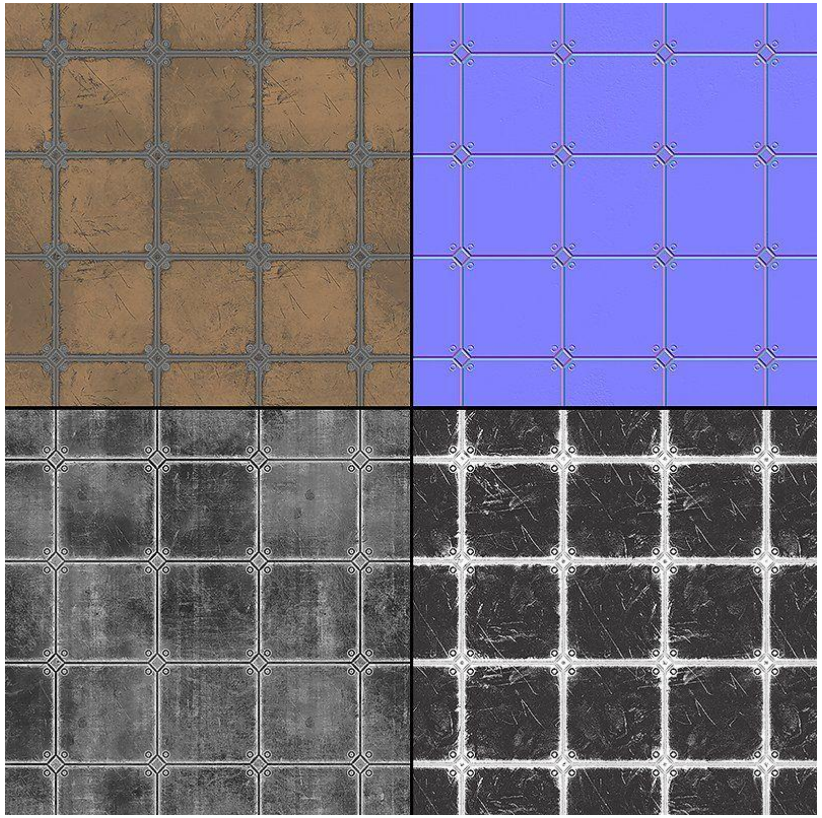
- Constant value (**n•l** is part of reflectance equation):

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

- $\mathbf{c}_{\mathrm{diff}}$: fraction of light reflected, or diffuse color, also called **albedo**

Textures

- Albedo
- Normal
- Roughness
- Metallic



Example microfacet BRDF

- http://simonstechblog.blogspot.com/2011/12/microfacet-brdf.html
- https://learnopengl.com/PBR/Theory