CS 563 Advanced Topics in Computer Graphics
Spectral Rendering

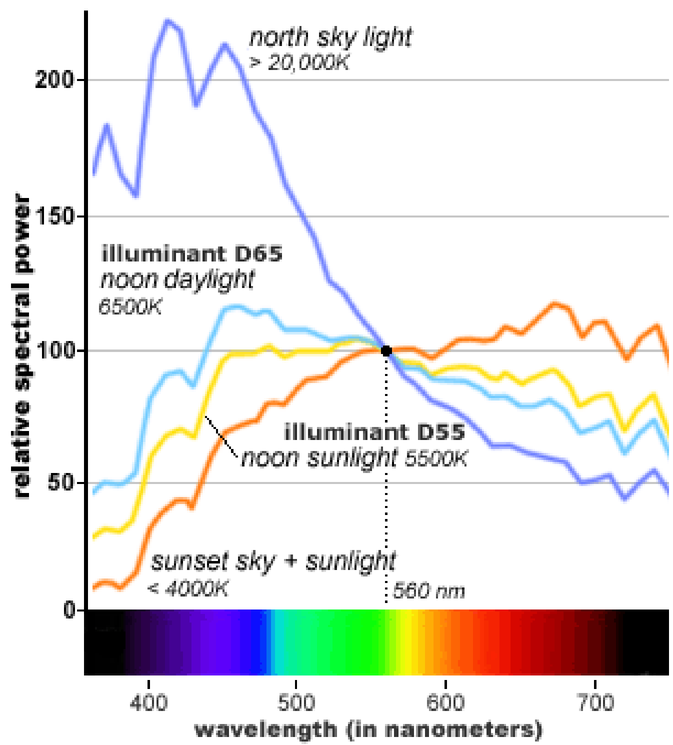
by Emmanuel Agu

Iridescent Colors

- Colors seen change with viewer angle
- Kurt Nassau classic book, *Physics and Chemistry of Color*: 15 color-causing mechanisms
- 4 of those mechanisms produce iridescent colors
  - Dispersive refraction: prism
  - Scattering: Rainbow
  - Interference: oil slicks
  - Diffraction: CD ROMs

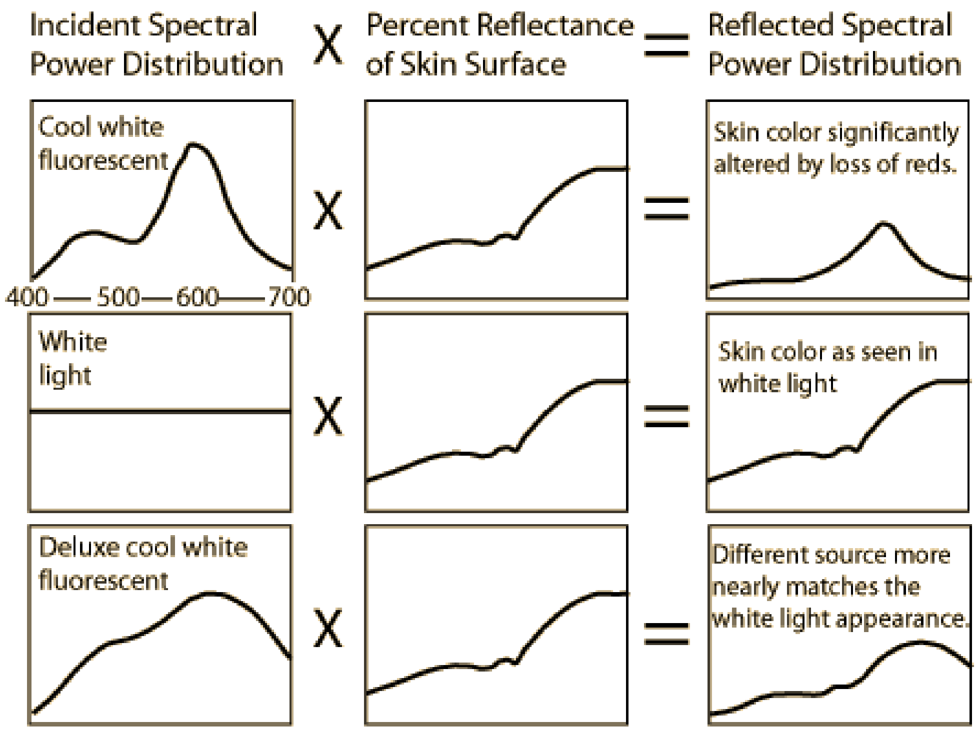
Light wavelengths

- **White light:** equal amount of all light wavelengths
- Different light types: different wavelengths in it
- **Visible spectra:** 380nm – 720nm wavelengths
  - **Red** - 680nm**, Green** – 550nm**, Blue** – 450 nm
  - RGB rendering samples only 3 wavelengths

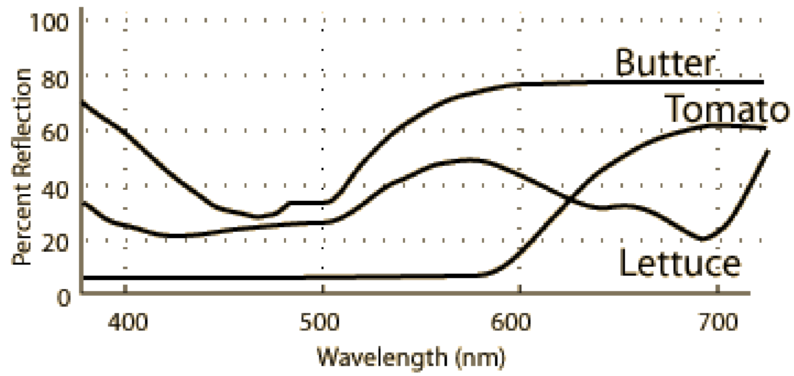


Iridescence Mechanisms

- **Non-iridescent materials:** All wavelengths reflected/refracted same paths.
  - Red surface: suppresses most wavelengths except red
  - Wavelength variations slow.
  - RGB rendering okay

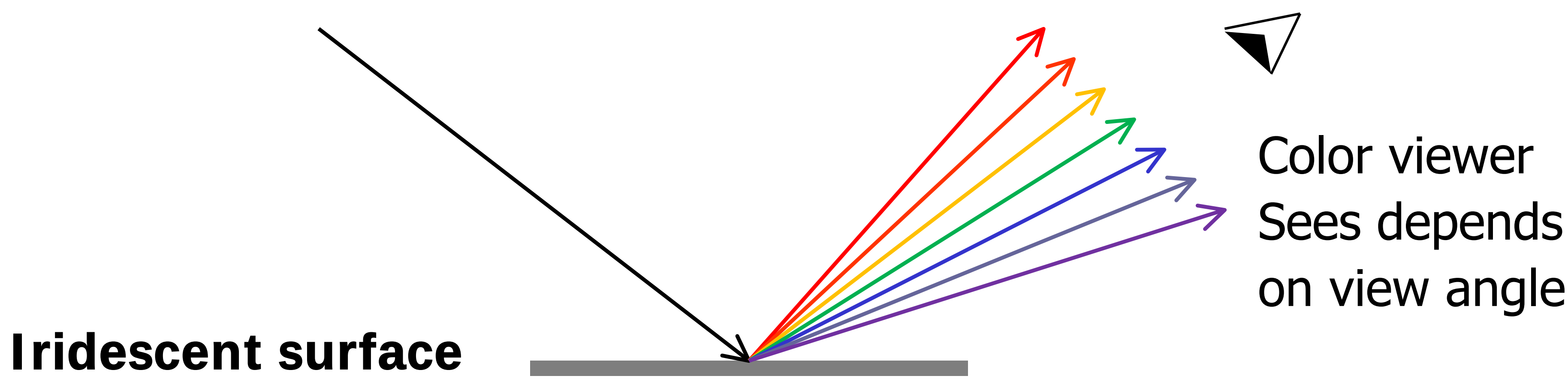


After Williamson and Cummins



Iridescence Mechanisms

- **Iridescent mechanisms:** different wavelengths = different paths.
- Each wavelength has **different** SPD
- Undersampling gives wrong final color
- RGB sampling **inadequate!!**
- Sample more wavelengths



Spectral Rendering

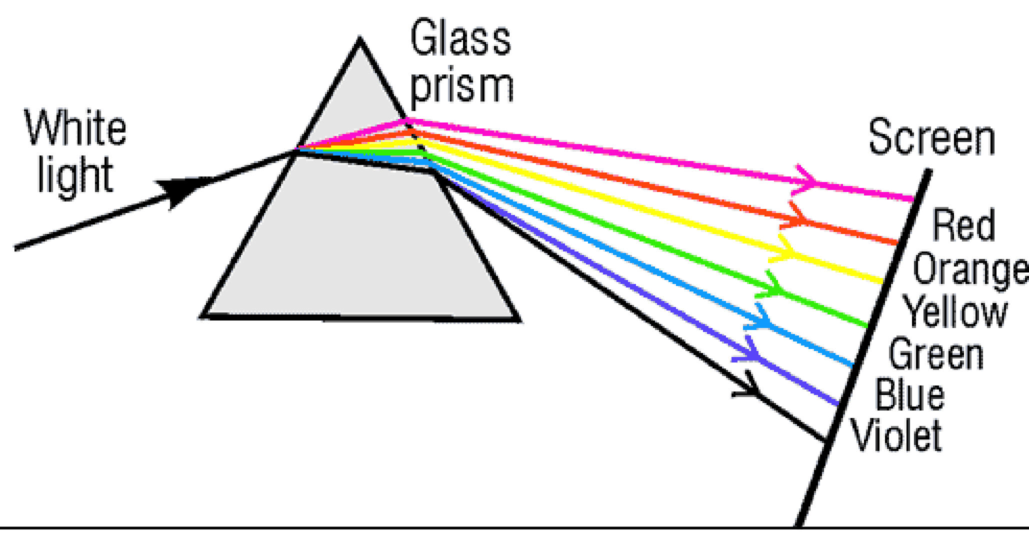
- Optics models describe per-wavelength behavior *f(λ)*
- RGB rendering samples only three wavelengths
- General approach:
  - Generate sample wavelengths
  - Cast rays at sampled wavelengths
  - **Evaluate reflectance function at sampled wavelength**
  - Convert each sample to its RGB value
  - Sum reflectance function at sampled wavelengths
- Spectral rendering same for all iridescent phenomena
- Function evaluated at surface is different though

Iridescence Mechanisms

- **Optics models** at different levels of accuracy
  - **Ray optics:** Draw lines depicting light paths
  - **Geometric optics:** Add simple interactions at surfaces
  - **Wave optics:** Model light as a wave - polarization
  - **Electromagnetic optics:** Model light as wave, add polarization
  - **Quantum optics:** Quantum physics, over-kill for graphics
- Today: mostly geometric optics, a bit of wave optics

Dispersive Refraction

- (e.g. glass prism) index of refraction varies with wavelength. i.e. $\eta \Rightarrow \eta(\lambda)$
  - 1.54 for blue wavelength, 1.5 for red wavelength
- Differences in index of refraction causes bending of wavelengths different angles
- Result: different view angles, different colors
- Musgrave, Graphics Interface 1989, Prisms & Rainbows

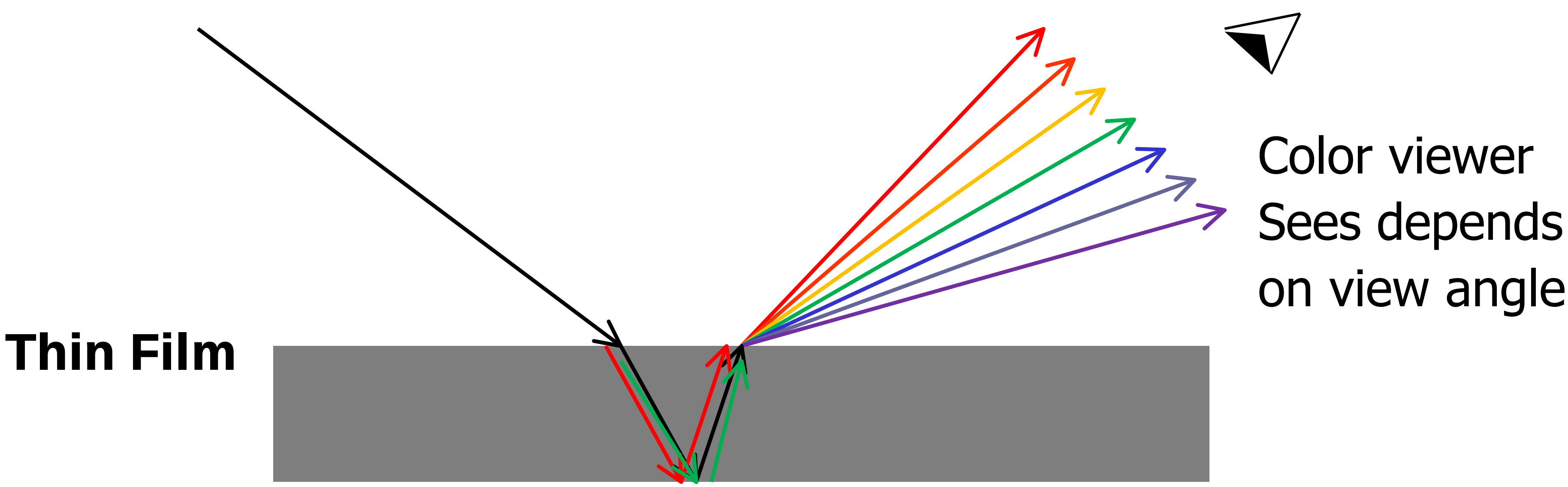


Refraction

- Refraction in diamonds

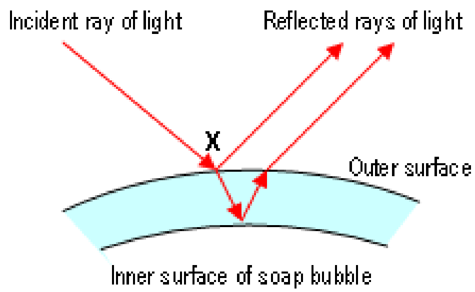
Interference

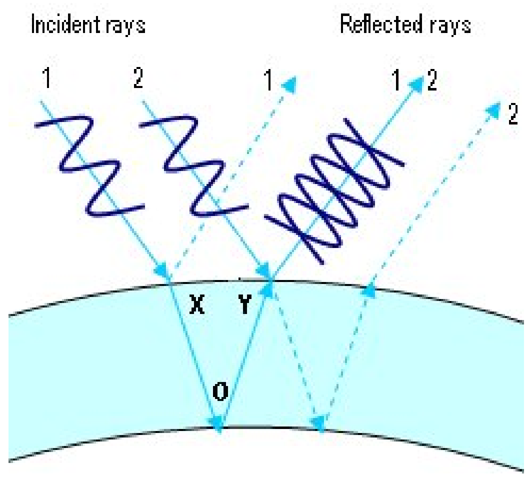
- Oil slicks
- Ski visors
- Soap bubbles
- Car windshields
- Thin film layer: different wavelengths interfere constructively in different directions



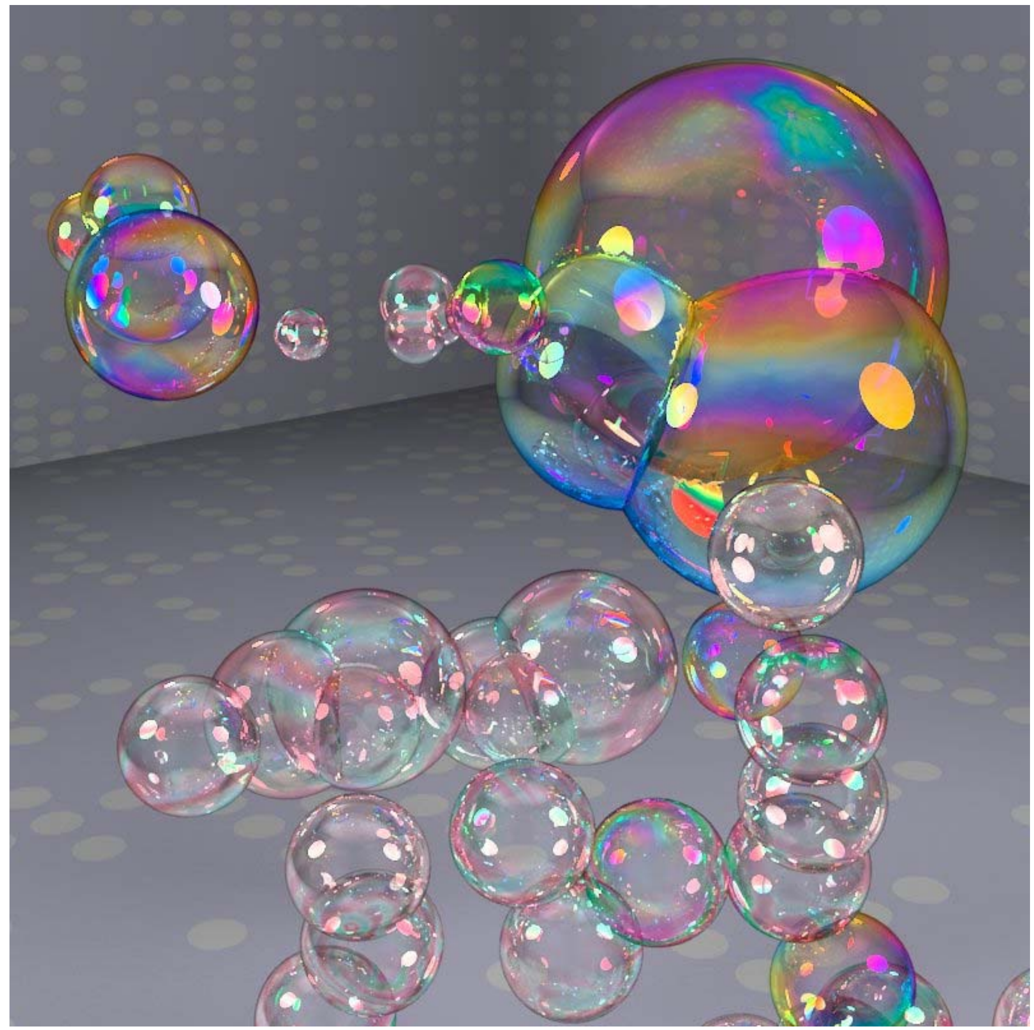
Thin film: soap bubbles

- David Harju's and Simon Que's, Stanford rendering contest '08
- Based on Andrew Glassner, IEEE CG&A 2000 paper



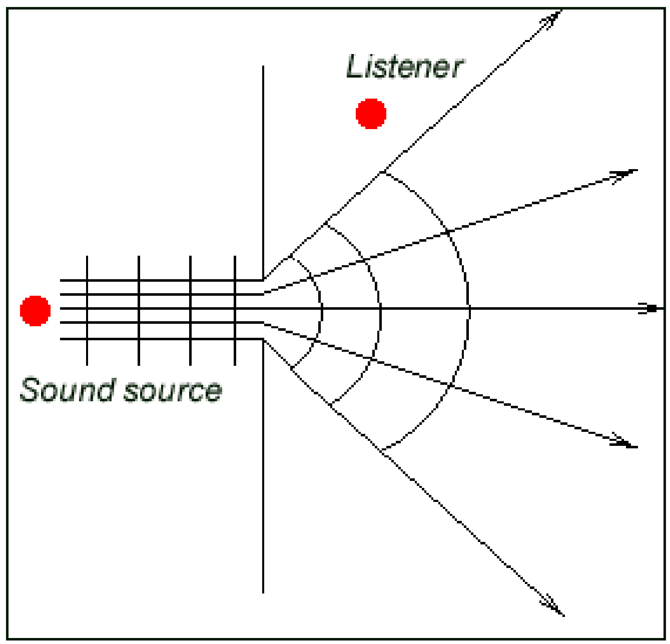


$$I_r = 4 I_i R_f \sin^2\left(\frac{2\pi}{\lambda} w \eta \cos\theta_t\right)$$



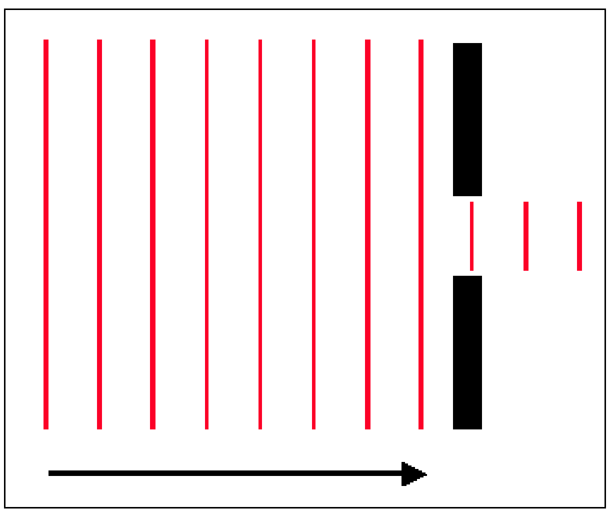
What is diffraction?

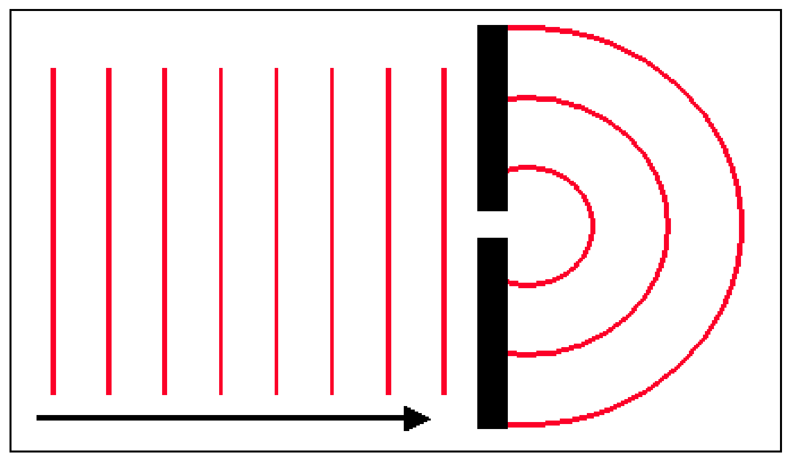
- Diffraction is the ability of waves to “bend” around objects
  - The most accessible occurrence of this is sound



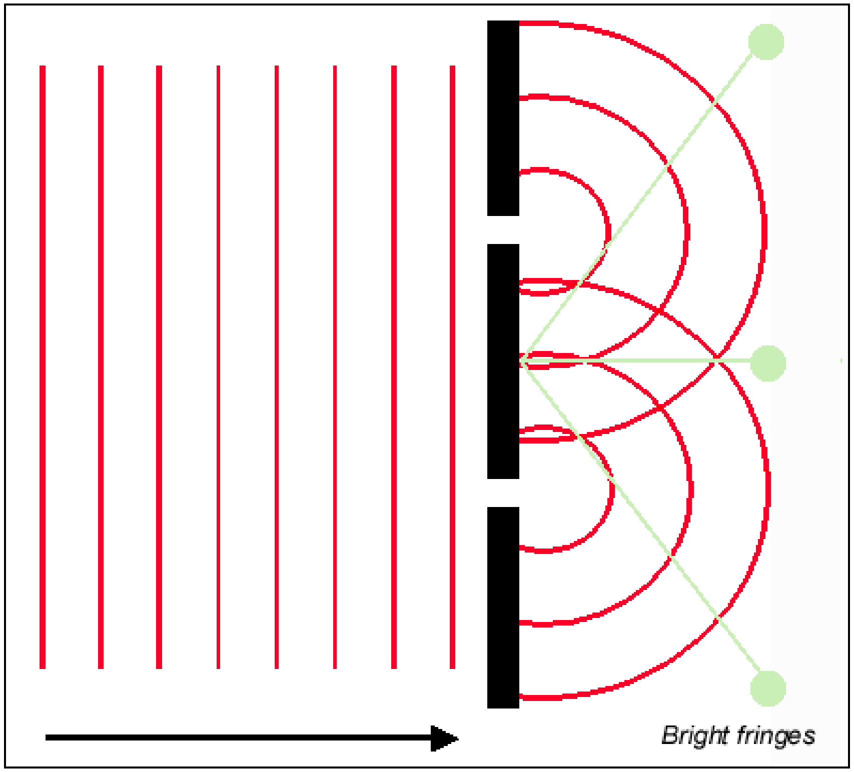
Single-slit interference

- Large slit: no effect
- If slit width small (compared to wavelength), bends incident light, passes one Huygen wavelet





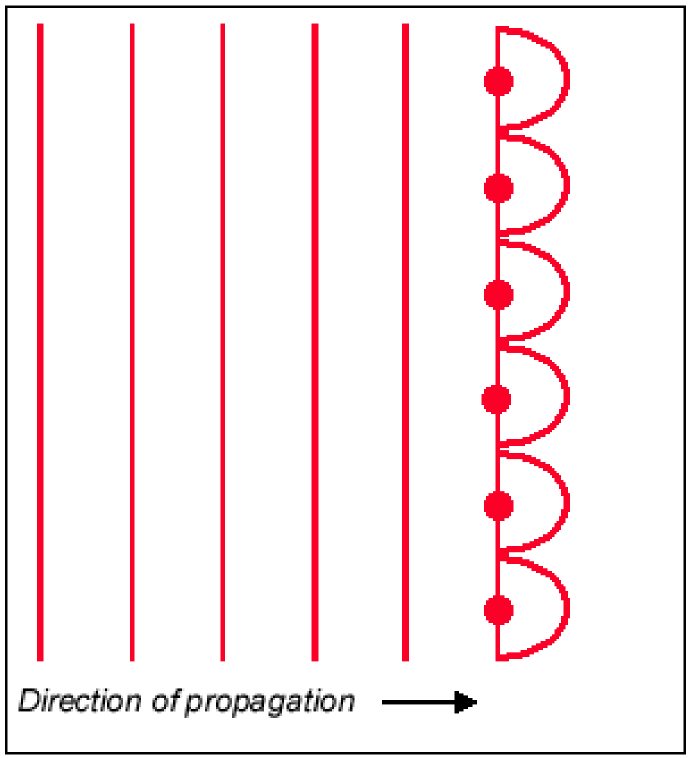
Double-slit interference



- Bent waves from slits interfere:
  - Constructive where the crests meet
  - Destructive where the troughs meet
  - Doesn’t follow simple linear super-position

Huygen's Principle(1678)

- States that points along a planar wave-front act as secondary point sources themselves(spherical wavelets)



Diffraction

- Two general cases
  - Fraunhofer diffraction: viewer many wavelengths away
  - Fresnel diffraction: viewer a few wavelengths away
- Agu and Hill
  - Geometric optics solution, fraunhofer diffraction, N slits
  - Huygens Fresnel allows superposition, find closed form formula of intensity of each wavelength as function of view angle
  - Also use Blinn’s halfway vector formula

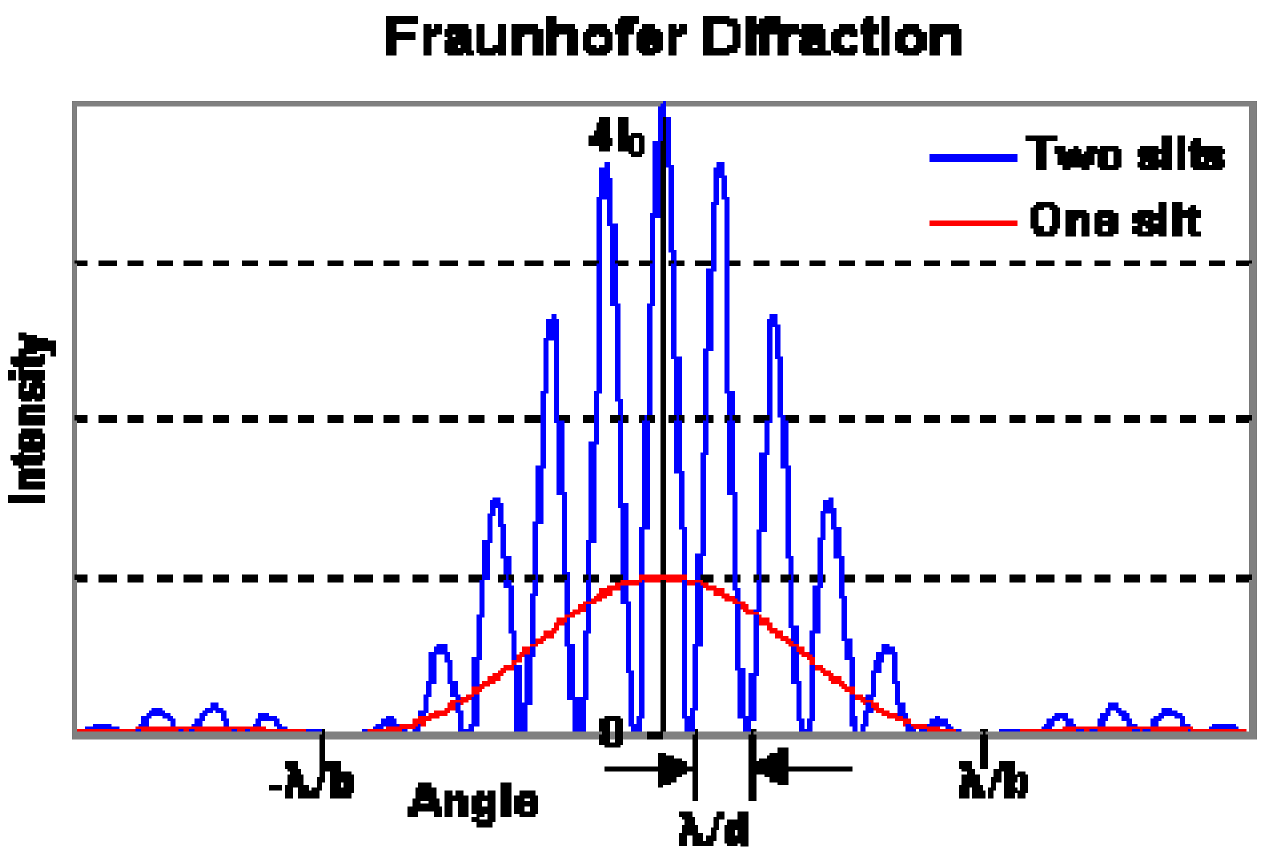
$$I = I_0 \frac{1}{N^2}\left(\frac{\sin(\beta)}{\beta}\right)^2 \left(\frac{\sin^2(N\alpha)}{\sin^2(\alpha)}\right)$$

$$\beta = \frac{kb}{2}\left(\sin(\Theta) - \sin(\Theta_i)\right)$$

$$\alpha = \pi d \frac{\left(\sin(\Theta) - \sin(\Theta_i)\right)}{\lambda}$$

$$b = \text{width between the slits}$$

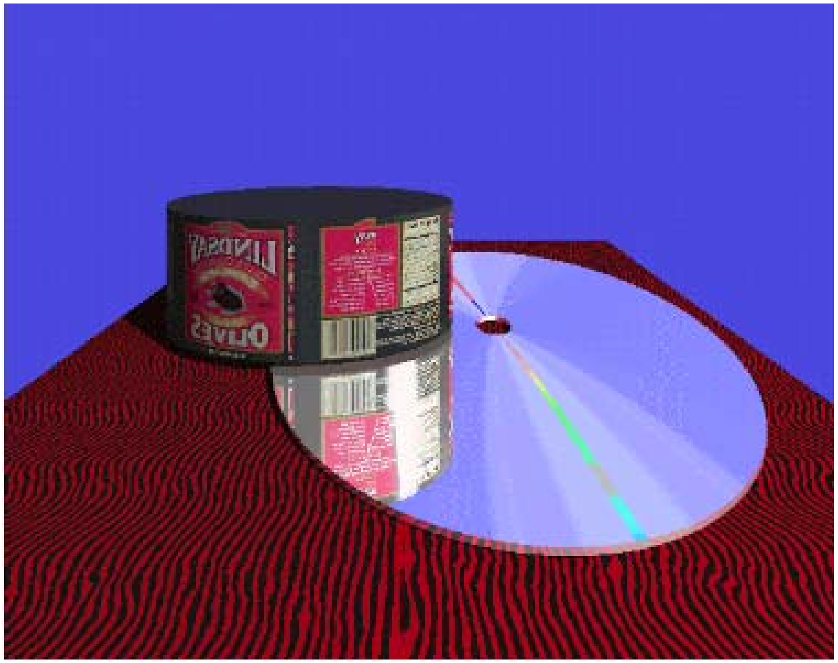
Intensity of Fraunhofer diffraction

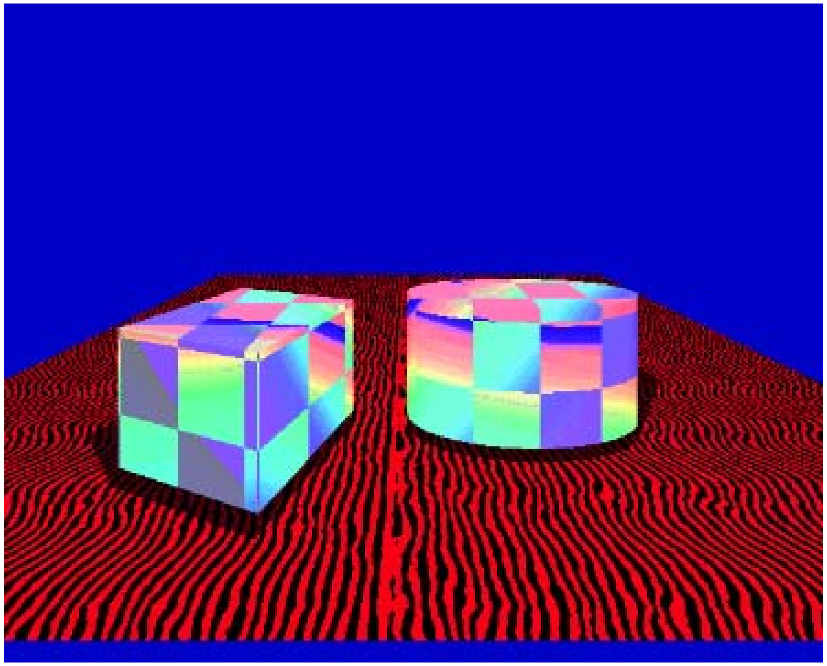


- From http://physics.nad.ru/Physics/English/stri_txt.htm

Agu and Hill

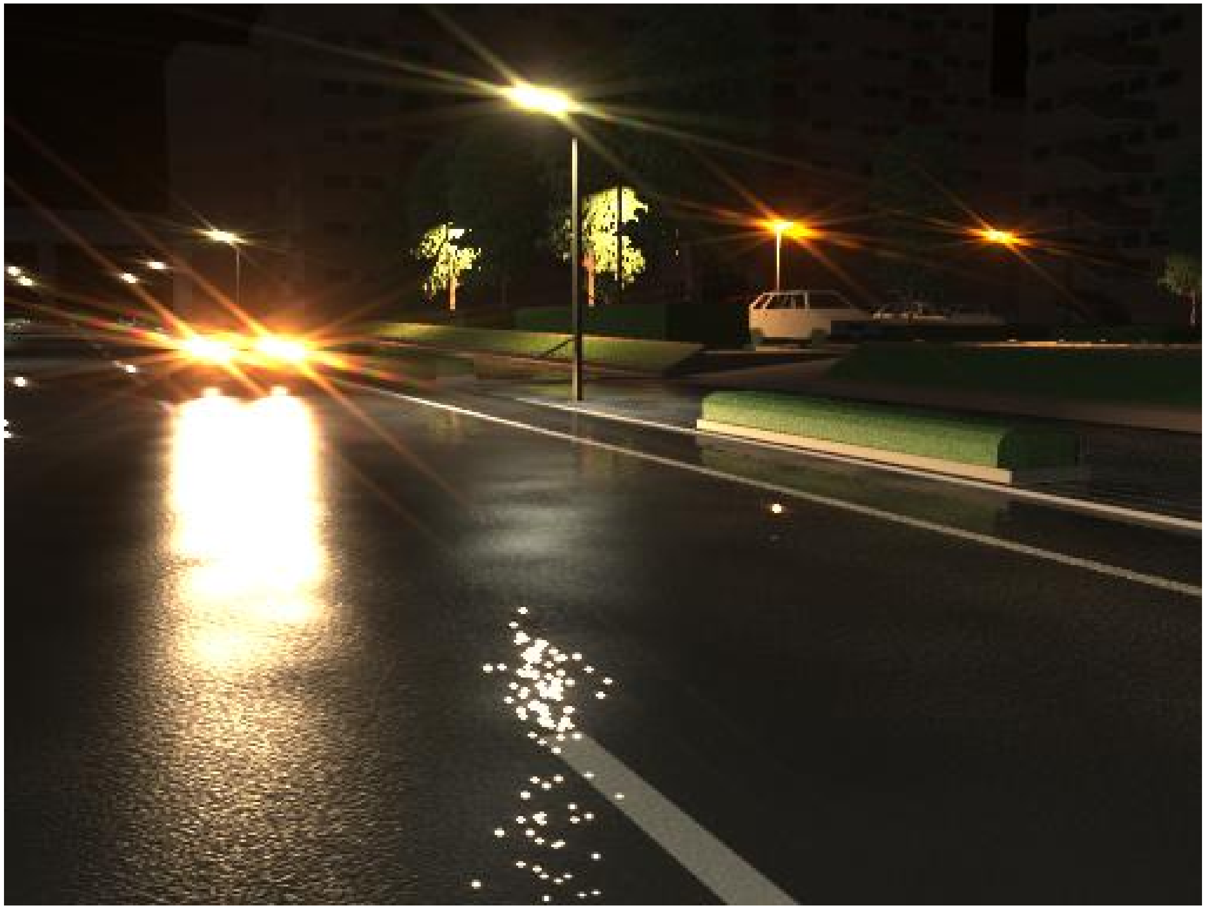
- Rendering results





Diffraction

Simpler form used in Nakamae et al, "*A Lighting Model Aiming at Drive Simulators", SIGGRAPH 1990*



- Image from http://www.eml.hiroshima-u.ac.jp/gallery/ - diffraction from eyelashes and pupils(1990)

Huygens and the Fresnel-Kirchhoff formula

- Stam introduced wave optics approach.
- Wave optics formula relating incoming to outgoing wave is precise mathematical form called Fresnel-Kirchhoff formula

$$U_p = \frac{-ikU_0 e^{-(i\omega t)}}{4\pi} \iint \frac{e^{ik(r+r')}}{rr'} \left[\cos(n,r) - \cos(n,r')\right] dA$$

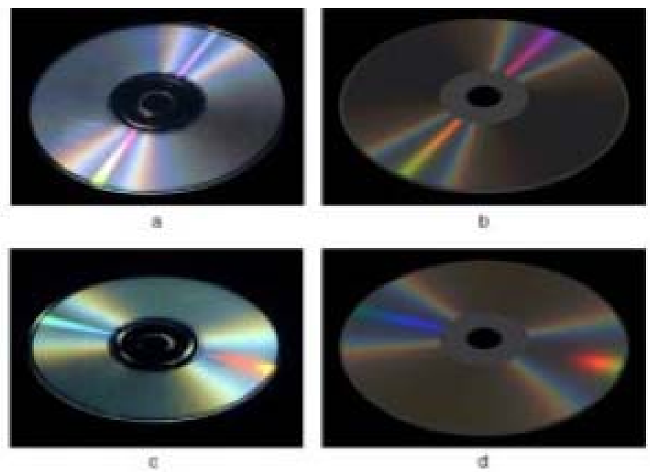
- Solving the Kirchoff Formula, Stam arrived at the following wavelength-dependent BRDF

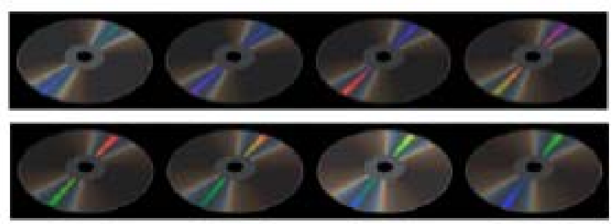
$$\mathrm{BRDF} = \frac{F^2 G}{w^2} \left(\frac{k^2}{4\pi^2} S_p(ku, kv) + |\langle p \rangle|^2 \delta(u, v) \right), \qquad (9)$$

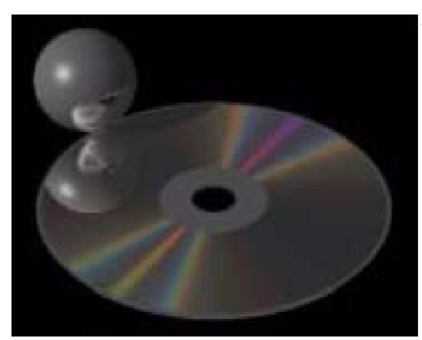
Stam's Result

Diffraction

- Yinlong Sun *et al*: Alternate technique, modelled CD ROM tracks, composite spectral model

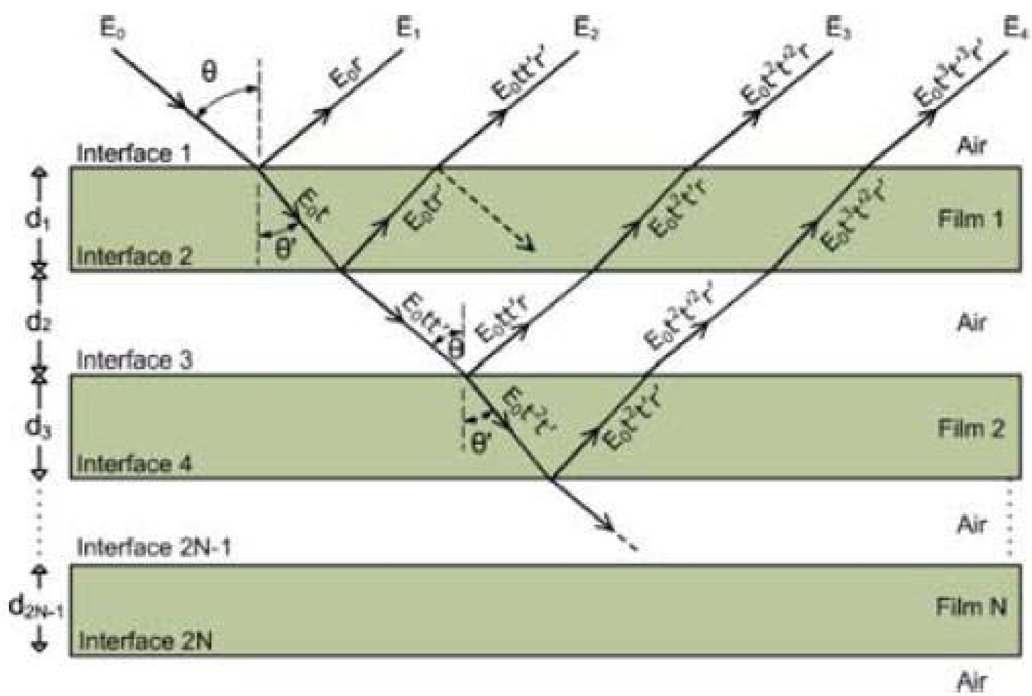






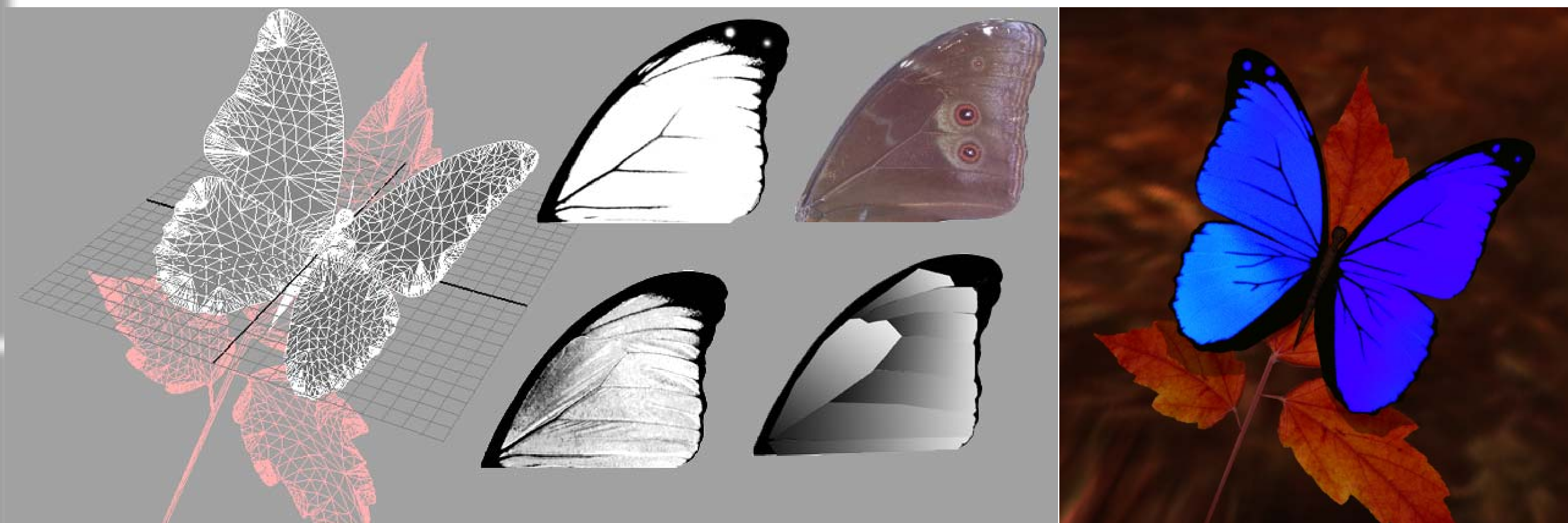
Structural Colors

- Iridescent colors caused by some animal skins
  - Morpho butterfly
  - Hummingbird wings
  - Snakes
  - Beetles
- Usually model as multi-layer thin film interference



Morpho Butterfly

- Iman Sadeghi, UCSD 2007 rendering contest
- Implemented 2006 paper by Yinlong Sun

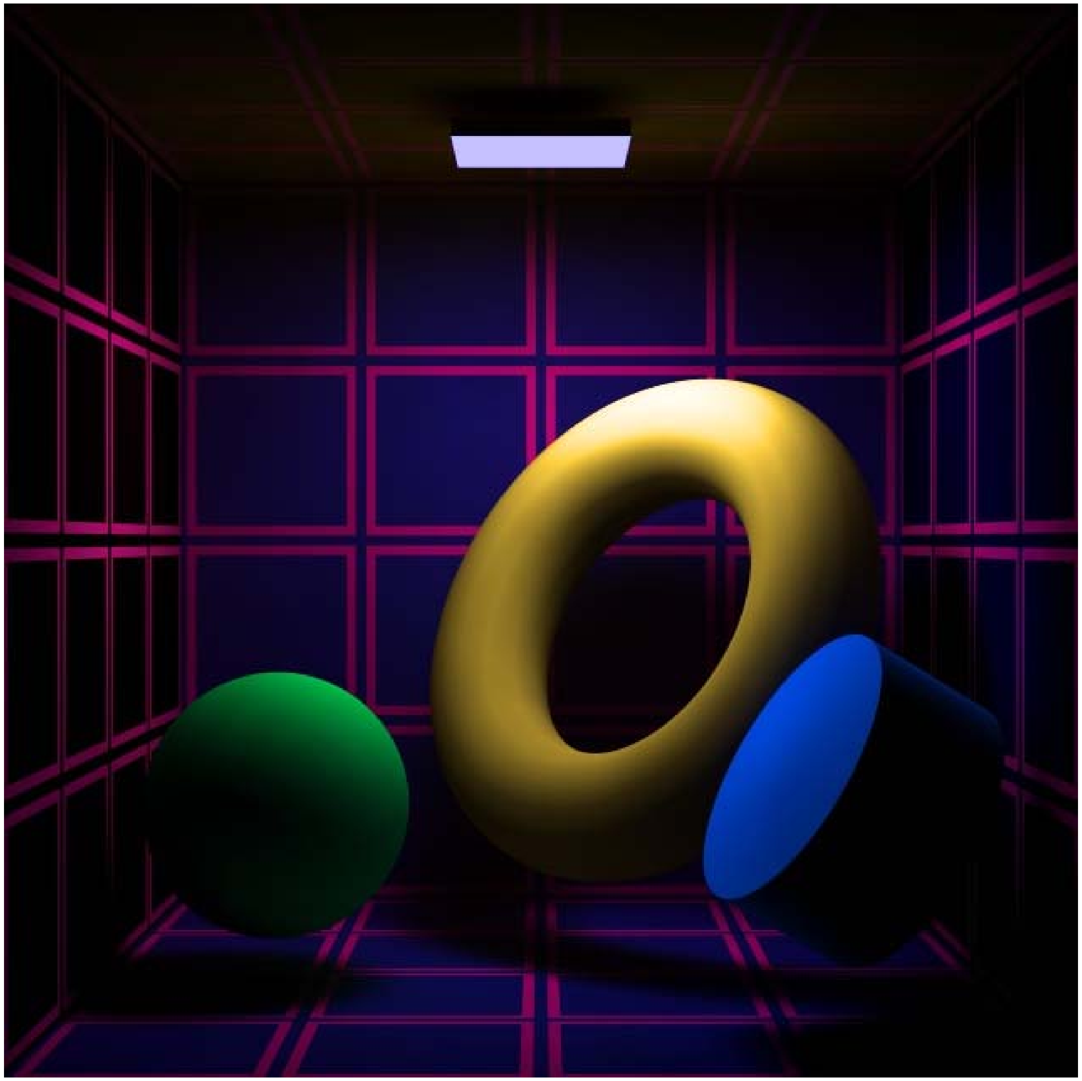


Phosphorescence & Flourescence

- **Phosphorescence**
  - Light absorbed
  - Re-emitted diffusely at later **time** (>10^{-8} secs)
  - Glassner: define delay function, scaling function for incident light
- **Flourescence**
  - Absorb light at one wavelength
  - Re-emit light immediately (>10^{-8} secs) at another wavelength
  - Glassner: Declare scaling function from input wavelength to output wavelength

Flourescence Example

- Wilkie et al, EGRW, 2001
- UV backlight, Walls and object painted with flourescent pigment



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