The Molecular Basis of Color and Form: Chemistry in Art
A guided tour

- Basics
  - Light, Color and Matter (inorganic & organic)

- Applications of Chemistry in Art
  - Metals
  - Glass and Ceramics
  - Polymers
  - Paint media
  - Pigments
  - Dyes
  - Photography
What Is Light?

Light is a complex phenomenon that is classically explained with a simple model based on rays and wavefronts

http://micro.magnet.fsu.edu/primer/lightandcolor/index.html

http://www.physicsclassroom.com/Class/light/
Ancient Light Obsession

Ancient Sun God Tributes

Egyptian Sun God Aton

Aztec Sun God Tonatiuh

Figure 1

Inca Sun God Mask
Modern Light Obsession
Our own obsession
Where does light come from?

- **Luminous Objects** — emit light from within
- **Illuminated Objects** — reflect externally supplied light

The sun

The stars

The moon
Which are luminous objects?

A. Electric lights
B. The planets
C. Visible objects in light
D. Fires and flames
Spectroscopes analyze light...

- Qualitatively and Quantitatively measures light.
Observation of Light Sources

- Sunlight
- Incandescent Solids
  - * burning fuels
  - * heated wires (incandescent lights)

Continuous Spectrum
Light and Temperature

- As temperature goes up more “white light” is emitted
Observation of Light Sources

- Excited Gases, Atoms and Molecules produce a discrete or line spectrum.

Discrete or Line Spectrum

Line spectrum of Helium gas (He)
What is Light?

- **Electromagnetic Radiation (ER)**
  - a *form of energy* with an electrical and a magnetic component that vibrate perpendicular to each other

Vibrates in multitude of directions
Unpolarized Light

- Oscillates in all directions

Polarized light
- Oscillates in only one direction

Vertically polarized
Horizontally polarized
Creating Polarized Light

Using Polarizing Filters

Crossed Polarizing Filters
Crossed Polarizers

Light Passing Through Crossed Polarizers

Polarizer 1 (Vertical)  Polarizer 2 (Horizontal)

Incident Beam (Unpolarized)  Vertically Polarized Light Wave
Other ways to polarize light

- By reflection…
- By scattering…
- By refraction…

- Provides evidence for
  - Wave Theory of Light
Models or Theories of Light

- The **Wave Theory** — C. Huygens 1678
  Explains many common properties of light.
- The **Particle Theory** — Planck, Einstein early 1900’s
  Explains more light behaviors.
Light as a wave

- Characterized by
  - Speed (velocity)
  - Wavelength
  - Amplitude
  - Frequency
  - Energy
Speed, Wavelength & Amplitude

\( \lambda = \text{wavelength (nm)} \)

\( c = \text{speed} \)
\( 3.00 \times 10^{10} \text{cm/sec} \)

\( A = \text{amplitude (intensity)} \)
Speed of Light Varies

Speed of Light
Distance Traveled in 1 Second
Vacuum 186,000 Miles

Water 140,000 Miles

Glass 124,000 Miles

Figure 2

Diamond 77,500 Miles
Frequency ($\nu$ or nu)

- Number of waves passing a given point in a certain time or the number of oscillations per second (Hz)

![Diagram showing low and high frequency waves](image)
Relations between $\lambda$, $\nu$ and $E$

Long wavelength — low frequency — low energy

Short wavelength — high frequency — high energy

$\lambda = \text{wavelength}$
Electromagnetic Spectrum
Visible Light

Violet
4,000 Å
400 nm

Indigo
4,250 Å
425 nm

Blue
4,700 Å
470 nm

Aqua
4,900 Å
490 nm

Green
5,500 Å
550 nm

Yellow
6,000 Å
600 nm

Orange
6,300 Å
630 nm

Red
6,650 Å
665 nm

Dark Red
7,000 Å
700 nm
# Visible Light

<table>
<thead>
<tr>
<th>Color</th>
<th>Symbol</th>
<th>Wavelength</th>
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<tbody>
<tr>
<td>Red</td>
<td>R</td>
<td>700 nm</td>
</tr>
<tr>
<td>Orange</td>
<td>O</td>
<td>650 nm</td>
</tr>
<tr>
<td>Yellow</td>
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<td>Blue</td>
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<td>500 nm</td>
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<tr>
<td>Indigo</td>
<td>I</td>
<td>450 nm</td>
</tr>
<tr>
<td>Violet</td>
<td>V</td>
<td>400 nm</td>
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</tbody>
</table>
Electromagnetic Spectrum
Theories and Light’s Behavior

- Transmission
- Reflection and Scattering
- Refraction
- Polarization
- Interference
- Diffraction
- Emission
- Absorption

Wave Theory (1678)

Particle Theory (1900s)
Comparing Three Pictures

transparent  translucent  opaque

How would you describe this material?
Transmission of Light

- Light encounters different types of matter

- Light travels at its top speed in a vacuum.
- Light slows down when it enters more dense matter.
Reflection of light

Bending or change in direction of a light beam that occurs at the surface of a substance or object.
Reflection of Light

- off a smooth surface (ie. mirror)
  ![Specular Reflection](image)

- off a rough surface (ie. white paper)
  ![Diffuse Reflection](image)
Polarization by Reflection

- Reflection off a non-metallic surface
  - Polarizes light parallel to surface
  - Asphalt road, water, snow

Polaroid® Sunglasses
Gem Cutting & Reflection

The Ideal Cut

Refraction and total internal reflection

Loss of light if angles are incorrect.

Too deep

Too shallow
Spearfishing & Refraction
Refraction

- Bending or change in direction of light as it passes from a medium of one density into another medium of different density.

The normal or perpendicular to the surface
Refractive Index of Matter

- Quantitative measure of bending of light
  \[ RI = \frac{\text{velocity of light in air}}{\text{velocity of light in matter}} > 1 \]

Diamond RI = 2.47
Flint glass RI = 1.6

- The higher the RI the more the light is bent by the matter.
- Higher frequency light (short wavelengths) is bent more than lower frequency light.
Dispersion of light

- Produces a rainbow spectrum

- Blue light bent more than red light
Double Refraction

- Iceland Spar
  - Calcite Crystal — CaCO₃
Iceland Spar Double Refraction
Using Polarized Light

- Identification of crystalline chemicals
  - Cholesterol acetate
  - Acetylcholine
  - DDT Insecticide

- Identification of fibers
  - Nylon
  - Polyester
Finding Defects in Materials

- Blister packs used in medicinals, pharmaceuticals, and cosmetics
Diffraction and Interference

Young's Double Slit Experiment

Light Propagation Direction

Coherent Laser Light

Destructive Interference

Barrier with Double Slits

Constructive Interference

Screen

Intensity Distribution of Fringes
Bending of light as it passes through a narrow opening or past a sharp edge of an object.

Short wavelength light is bent more than long wavelength light.
Diffraction Demonstration

- Each produces a unique pattern of diffraction
- Openings between dots on slide mimic spacing between atoms
Diffraction patterns
Diffraction Gratings

- Contain grid of narrow grooved lines
- Used to **disperse** white light in spectrophotometers and spectrosopes
- C-Spectra®
Measuring Wavelength

- \( n\lambda = d \frac{X}{L} \)  
  \textit{Grating Equation}

- \( d = \text{distance between lines in diffraction grating} \)
  - \( d = 1\text{mm/lines} = 1\text{mm/500lines} = 0.002\text{mm} \)

\[ L^2 = X^2 + Y^2 \]
\[ L = \sqrt{X^2 + Y^2} \]
Interference Colors in Nature

Figure 3

Interference Structures in Butterfly Wings

Morpho Butterfly

Magnified View of Wing Scales

Scale Ridges

Wing Scale Base Lamella

Ridge Plates

Air Spaces

Attachment to Lamella

Peacock Feather

Abalone Shell

Iridescent Opal
Interference Phenomenon

Reflected Light Pathways Through Soap Bubbles

Constructive Interference (Wave Fronts in Step)

Reflected Light Path

Incident Light Path

Thin Part of Bubble

Figure 2

Destructive Interference (Wave Fronts Out of Step)

Incident Light Path

Outer Surface of Bubble

Reflecting Light Path

Inherent Surface of Bubble

Thick Part of Bubble
Interference filter

[Diagram of interference filter action showing incident light waves, reflected light wave, metallic layer, dielectric layer, and transmitted light waves.]

Figure 7
Constructive Interference

Two in-phase waves add together to produce a brighter light.
Destructive Interference

Two out-of-phase waves cancel each other out to produce a dark area
Aurora borealis

The Earth is mostly shielded by its magnetic field from penetration of the hostile solar wind plasma.
Why is the foam white?

1. Reflection and scattering of light
2. Refraction of light
3. Polarization of light
4. Diffraction of light
5. Interference of light
Why is the straw “broken”?

1. Reflection and scattering of light
2. Refraction of light
3. Polarization of light
4. Diffraction of light
5. Interference of light
Why does soap bubble have colored patterns on it?

1. Reflection and scattering of light
2. Refraction of light
3. Polarization of light
4. Diffraction of light
5. Interference of light
What accounts for this?

1. Reflection and scattering of light
2. Refraction of light
3. Polarization of light
4. Diffraction of light
5. Interference of light

Figure 1
Why is the sky blue?

Visible Light Spectrum

- **ROYGBIV**
  - long wavelength
    - low frequency
    - Least readily scattered part of spectrum.
  - short wavelength
    - high frequency
    - Most readily scattered part of spectrum.

![Diagram of sunlight scattering](image_url)

- **short wavelengths**
- **long wavelengths**
Why is the sun yellow and orange?

The yellow appearance of the noon-day sun is due to the scattering of the higher frequencies of sunlight.

Rays from Sun (during mid-day)

Rays from Sun (during sunset)