Unpolarized vs. Polarized Light

Electric field

Magnetic field

Electric filed

unpolarized light

polarized light

end view

side view
How to Make Polarized Light

unpolarized

polarized
Light After Two Polarizers

polarization aligned with filter → all light gets through
polarization angled to filter → some light gets through
polarization 90° to filter → no light gets through
Details of Light After Two Polarizers

- Polarization was changed (angle)
- The intensity was reduced ($I = I_0 \cos \theta$)
Unpolarized Light After Isotropic Crystal

Isotropic regardless of orientation

No change in polarization
Polarized Light After Isotropic Crystal

Isotropic regardless of orientation

No change in polarization
Unpolarized Light After Uniaxial Crystal: Orientation Dependence

- **Isotropic**
  - No polarizer
  - Light is isotropic, unaffected by crystal orientation.

- **Anisotropic**
  - Two polarizers
  - Light polarization depends on crystal orientation.

- **Two polarizers**
  - Ordinary light $I_{\text{ordinary}}$
  - Extraordinary light $I'_{\text{extraordinary}}$
Polarized Light After Uniaxial Crystal: Orientation Dependence

- **no polarizer**: No change
- **one polarizer**:
  - Ordinary light
  - Extraordinary light

Isotropic vs. Anisotropic
Demo: Images after Calcite (Uniaxial Crystal) and Polarizer

Nicol Polarizing Prism

Figure 3

Ordinary Ray

Extraordinary Ray

Unpolarized White Light

© TheDigitalPicture.com
Pleochroism: Change in Contrast and Colors of Crystal Particles under Polarized Light

Medium $n = 1.662$
Pleochroism: Change in Colors of Crystal Particles
Change in Contrast of Crystal Particles

Birefringent Calcite Crystal Electric Vector Orientations

Figure 3

(a) (b) (c)
Pleochroism: Change in Contrast

Pleochroic Fiber

N || Light blue/purple

15 μm

N ⊥ Dark purple

ppl
s- and p-Polarized Lights

s: oscillating parallel to the reflection surface
p: oscillating perpendicular to the reflection surface
Reflection of Polarized Light

- More s-polarized light is reflected (30 degree)
- More p-polarized light is refracted
- 100 % s-polarized is reflected at Brewster angle ($\theta_B$)
- glass ($\sim 56^\circ$), water ($\sim 55^\circ$),
Polarizer in Daily Life

Figure 2

Light Waves Vibrating Perpendicular to the Highway

Light Waves Vibrating Parallel to the Highway
Direct and Reflected Light

- Unpolarized light is reflected and can cause glare.
- Glasses transmit vertically polarized light, reducing glare.
- Light partially polarized in the horizontal plane by reflection.
Images after Polarizer

LCD and Polarizer

Figure 3
More about LCD: Color and Contrast

- a pixel consisting of the red, green and blue color

Black, White, and Gray: Nothing, All, or Some

Red, Green and Blue: Pure Colors

Cyan, Purple, and Yellow: Combinations of Two Colors

Mixtures of Three Colors

Interference of Light

- Same directions
- Constant phase relationship (coherent)
Thin Film Interference of Light: Reflection Angle Dependence
If wave B travels extra 360 nm, then red is gone, you can see _________ color.
Complementary Color

CIE xy Chromaticity Diagram

- Complementary Color

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- Complementary Color
Red ($\lambda$) = 720 nm

If wave B and D travels extra 360 nm ($\frac{1}{2}\lambda$) and 1080 nm ($\frac{3}{2}\lambda$), then red is gone, you can see same cyan color.
Polarized Light Microscope Configuration

Figure 1
What’s More in Polarized Light Microscope

- Specialized Stage - a 360-degree circular rotating specimen stage
- Eyepieces with a cross wire reticle (or graticule) to mark the center of the field of view.
- Strain Free Objectives - P, PO, or Pol on the barrel.
- Centerable Revolving Nosepiece
- Strain Free Condenser
- Bertrand Lens
- Compensator and Retardation Plates
• Strain (or stress): a source of distorted images
• Use homogenous (isotropic) glasses, crystals and other materials used to make the lenses
• Avoid multiple lenses which are cemented together and mounted in close proximity with tightly fitting frames.
Circular Stage

Circular Stage with Optional Mechanical Translation Attachment

- Specimen Clip
- 360° Graduated Perimeter
- X-Translation Knob
- Graduated Locator Markings
- Slide Clip
- Y-Translation Knob
- Stage Rotation Lock
- Centering Knob
- Mechanical Stage Mounting Holes
- Centering Knob

Figure 6
1. Put a recognizable speck of something exactly under the crosshair intersection.
2. Rotate the stage until the speck is as far from the intersection as possible.
3. Turn the stage (or objective) centering screws to move the speck half way back to the crosshair intersection
4. Move the thin section to bring the speck back to the crosshair intersection.
Microscopic Images with Different Polarizer Setup

- Plane-polarized light
- Crossed polarizers
- Crossed polarizers and a full-wave retardation plate
How Polarized Light Microscope Works

Unpolarized light

Light vibrating E-W

Light vibrating in many planes and with many wavelengths

Light and colors reach eye

white light
Views With and Without Analyzer
Origin of Colors

- Polarizer
- Polarized light > minerals (uniaxial or biaxial)
- Splits two components with different speeds
- Retardation (R)
- Analyzer > combine
- Destructive interference
- You can see complementary color
Retardation

Crests and troughs cancel

Uniaxial crystal
Retardation (R)

- Thickness of crystal (T)
- \( \Delta n (n_1 - n_2) \)
- Birefringence (B): \( \Delta n = n_1 - n_2 \)
- B: Highest – lowest refractive index in a material
- Retardation \( \propto T \cdot \Delta n \)

\[
B = \frac{R(\text{nm})}{[T(\mu\text{m}) \cdot 1000]}
\]

<table>
<thead>
<tr>
<th>Substance</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotropic (n)</td>
<td>0</td>
</tr>
<tr>
<td>Uniaxial (2n)</td>
<td>(</td>
</tr>
<tr>
<td>Biaxial (3n)</td>
<td>( \gamma - \alpha )</td>
</tr>
<tr>
<td>Fibers</td>
<td>(</td>
</tr>
</tbody>
</table>
Rock Thin Section: Retardation Depends on Birefringence
Why Repeating Colors
Orders of Colors

- Most consistently repeating color is red ~560 nm
- 0 – 550 nm: 1\textsuperscript{st}
- 550 – 1100 nm: 2\textsuperscript{nd}
- 1100 – 1650 nm: 3\textsuperscript{rd}

<table>
<thead>
<tr>
<th>Retardation</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 nm (isotropic)</td>
<td>Black (~gray)</td>
</tr>
<tr>
<td>1\textsuperscript{st} – 3\textsuperscript{rd}</td>
<td>Vibrant colors of variety of colors</td>
</tr>
<tr>
<td>4\textsuperscript{th} – 8\textsuperscript{th}</td>
<td>Pale repeating (pink &amp; green)</td>
</tr>
<tr>
<td>Above 8\textsuperscript{th}</td>
<td>White (washed out)</td>
</tr>
</tbody>
</table>
Orders of Colors: Fibers

Cord Around Victim's Neck

Undrawn Nylon Cord Tied to Concrete Blocks

Drawn

IC 4 Orders

15μm

IC 1 Order
<table>
<thead>
<tr>
<th>Qualitative Term</th>
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</thead>
<tbody>
<tr>
<td>Isotropic</td>
<td>0</td>
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<tr>
<td>Low</td>
<td>$B &lt; 0.01$</td>
</tr>
<tr>
<td>Moderate</td>
<td>$0.01 &lt; B &lt; 0.05$</td>
</tr>
<tr>
<td>High</td>
<td>$0.05 &lt; B$</td>
</tr>
</tbody>
</table>
Michel Lévy Color Chart

Measure thickness > color > birefringence
How to Calculate Birefringence

\[ B = \frac{R(\text{nm})}{T(\mu\text{m}) \cdot 1000} \]

\[ = \frac{640 \text{ nm}}{72 \mu\text{m} \cdot 1000} \]

\[ = 0.009 \]

From ML Chart
How to Calculate Birefringence
Extinction: Special Orientation

Optical axis is parallel (or perpendicular) to the polarization

Uniaxial crystal
Types of Extinction

parallel

30°

Oblique (inclined)

Symmetrical (distorted)

Symmetrical (distorted)
Symmetrical Extinction

Refractive Index Ellipsoid

Optical Axis

Ordinary Wavefront

Polarizer Azimuth

Extraordinary Wavefront

Figure 5

(a)  
(b)  
(c)  
(d)
Basic Vector Operation

\[ \vec{A} + \vec{B} = \vec{C} \]

\(\vec{V}\) has two components, \(\vec{V}_x\) and \(\vec{V}_y\)
Symmetrical Extinction: Vector Analysis

What you can see is the magnitude of $R$ (Analyzer Component)

\[ R_a = 0 \quad R_b < R_c \]
Parallel Extinction: Fibers and Hairs

Cant’ see hairs (or fibers) if they are aligned parallel (or perpendicular) to polarization
Exercise

• Decide isotropic and anisotropic of five of your samples

• Check the extinction

• Measure the size of any of anisotropic mineral sample

• Calculate birefringence of your anisotropic mineral sample