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GEOLOGY 585: OPTICAL MINERALOGY & PETROLOGY

Symmetry and Mineral Optics

- Optical properties obey and reflect the symmetry of the crystal structure

Minerals are Grouped into Six Crystal Systems based on Symmetry

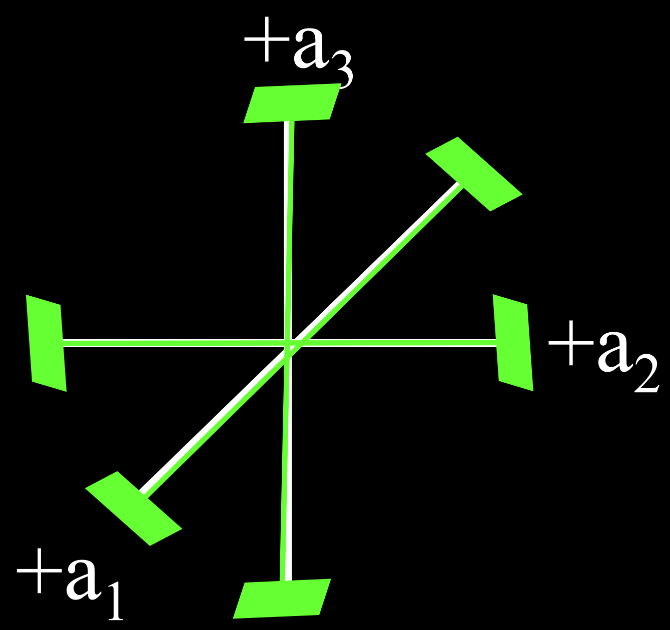
System	Characteristic Symmetry
• Isometric (Cubic) System	four 3 or $\bar{3}$
• Hexagonal System	one 6, $\bar{6}$, 3 or $\bar{3}$
• Tetragonal System	one 4 or $\bar{4}$
• Orthorhombic System	three 2 and/or m
• Monoclinic System	one 2 and/or m
• Triclinic System	1 or $\bar{1}$

Crystallographic Axes

- Reference axes
- Conventional ways to hold and refer to faces on crystals
- Different convention for each system

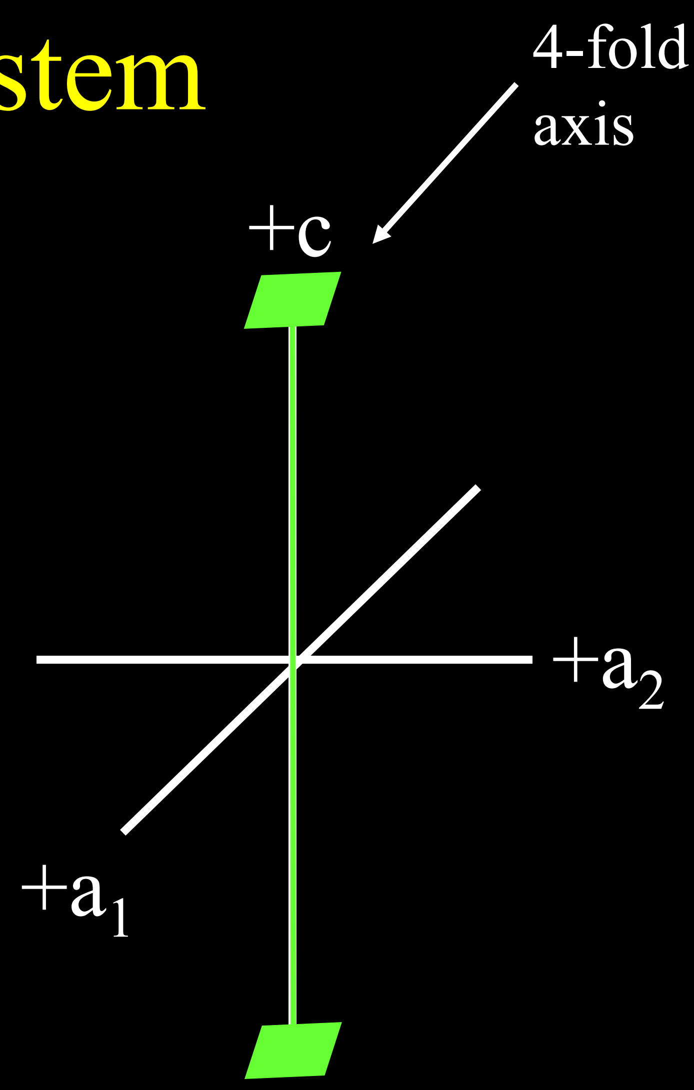
Crystallographic Axes: Isometric System

- Three perpendicular axes
- Coincide with three 4-fold or 2-fold axes
- All equal length
- Called a_1, a_2, a_3
- Garnet, halite, pyrite and fluorite are isometric



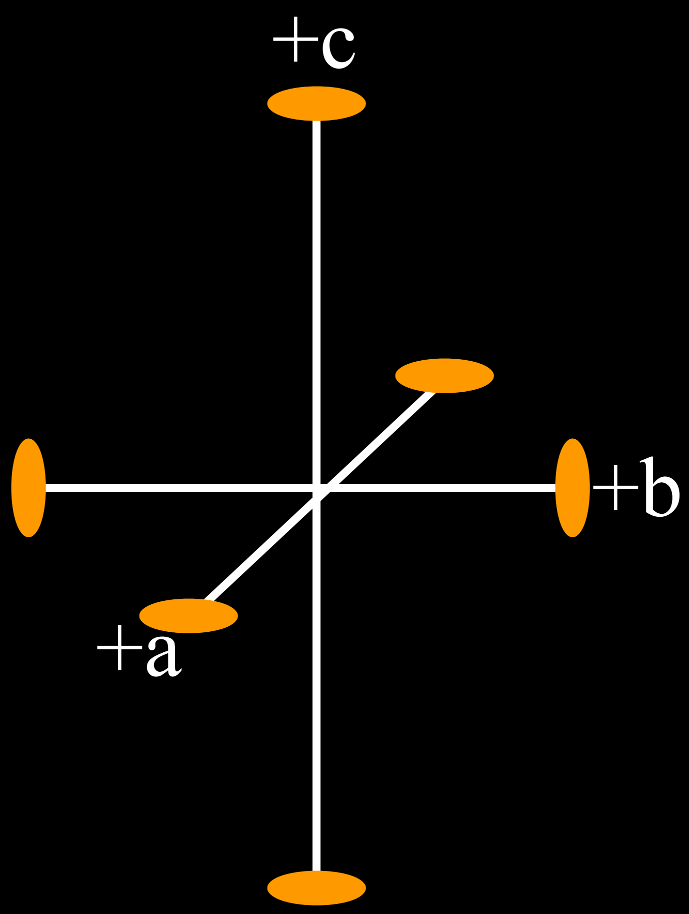
Crystallographic Axes: Tetragonal System

- Must have one 4 or 4-bar axis
- Three perpendicular axes
- Vertical axis, c, coincides with 4 or 4-bar axis
- One axis, c, is longer or shorter than other two, a_1 and a_2, which are equal



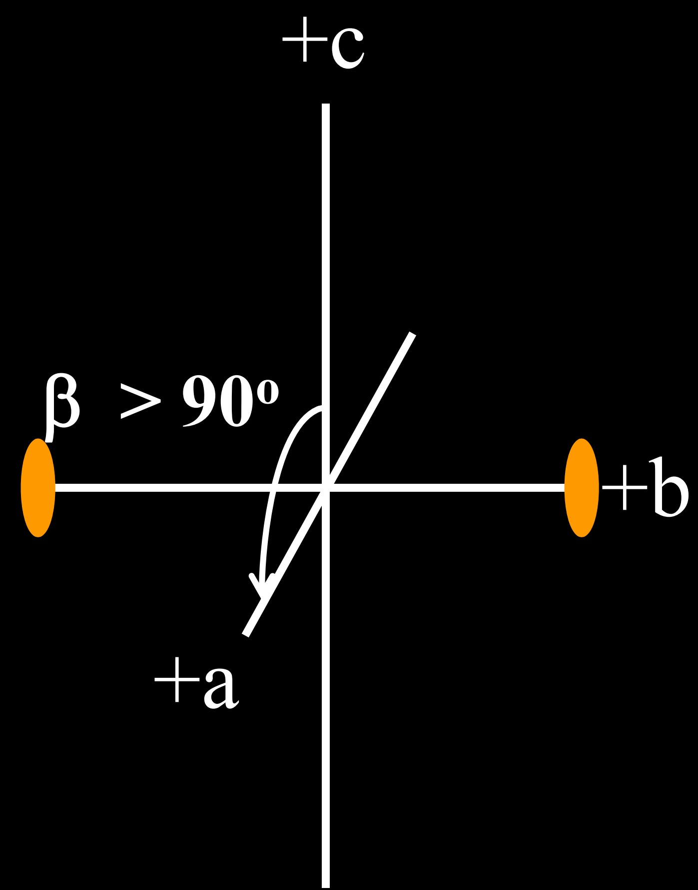
Crystallographic Axes: Orthorhombic System

- Has three 2-fold axes and/or one mirror plane
- Three perpendicular axes - coincide with 2-fold axes or are perpendicular to mirror planes
- All different lengths
- called a, b, c



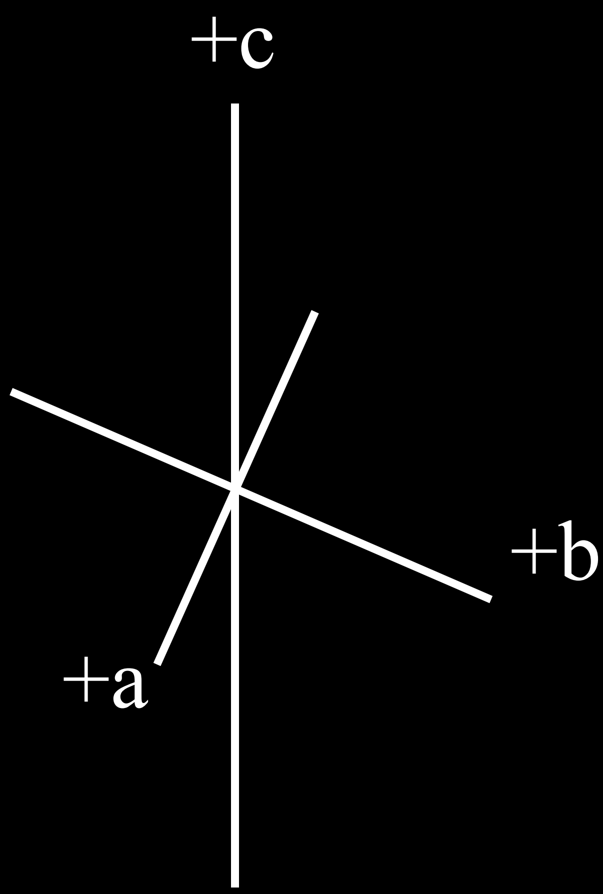
Crystallographic Axes: Monoclinic System

- Has one 2-fold axis or mirror
- All axes different lengths
- Called a, b, c
- **b** axis coincides with 2-fold axis or is $\perp$ mirror plane
- **c** is parallel to long edges
- **a** slants down to the front
- a $\perp$ b, b $\perp$ c, angle between a and c>90^o



Crystallographic Axes: Triclinic System

- No perpendicular axes
- All different lengths
- Called a, b, c



There are 32 ways in which symmetry operations can be combined

- 32 point groups or crystal classes
- Hermann-Mauguin (H-M) Symbols are a simple numeric way to represent the symmetry of each class
- Three-place symbols
- Different content for each system
  - isometric ______ ______ ______
  - hexagonal ______ ______ ______
  - tetragonal ______ ______ ______
  - orthorhombic ______ ______ ______
  - monoclinic ______
  - triclinic ______

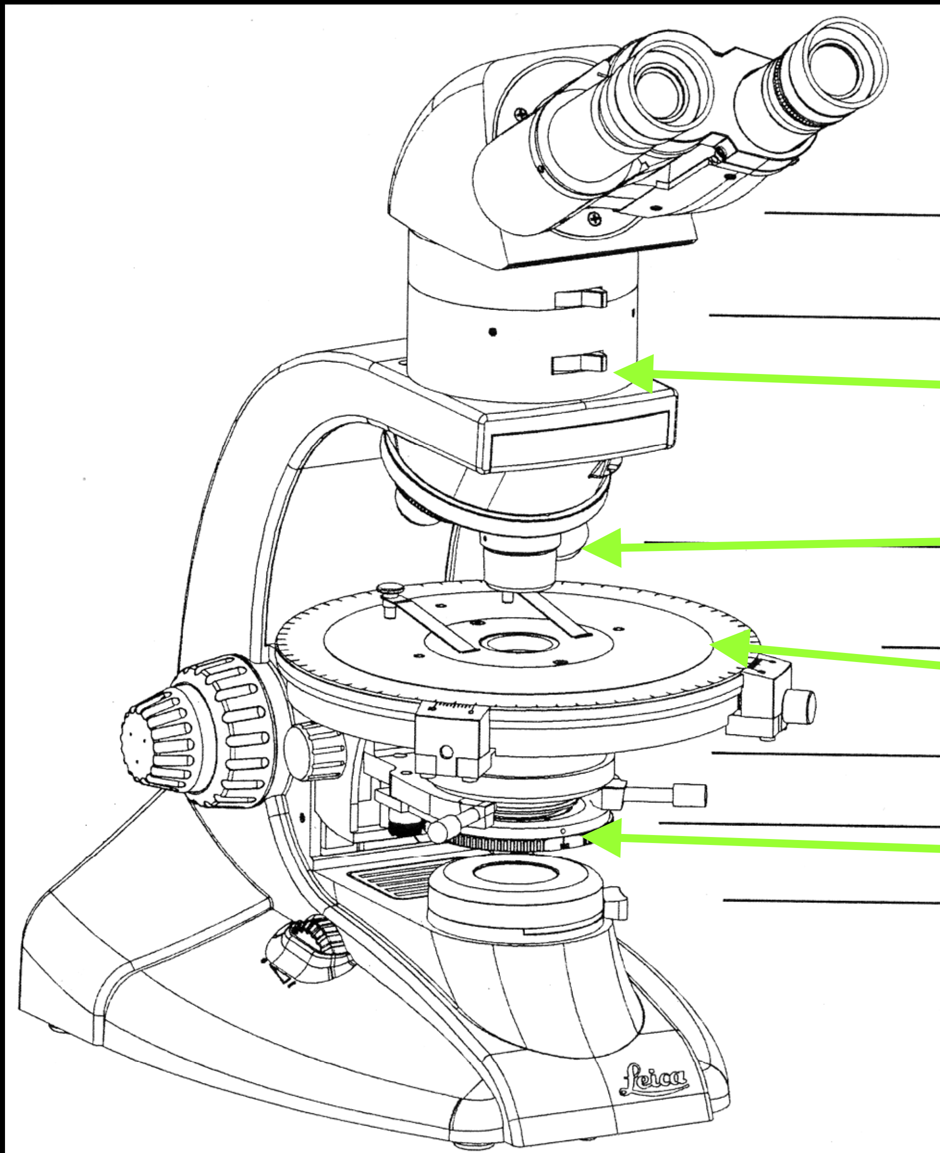
Summary of the Crystal Systems

CRYSTAL SYSTEM	CHARACTERISTIC SYMMETRY	AXIAL RELATIONSHIPS	PLACES IN THE H-M SYMBOL	CRYSTAL CLASSES	OPTICAL CLASSIFICATION
Isometric	four 3 or $\bar{3}$	$a_1=a_2=a_3$ $\alpha^*=\beta=\gamma=90^o$	1–symmetry of **a** axes 2–3 or $\bar{3}$ (diagonal) 3–other (edge to edge)	$\mathbf{4/m\,\bar{3}\,2/m}$**, $\bar{4}3m$, 432, $2/m\,\bar{3}$, 23	Isotropic
Hexagonal	one 6, $\bar{6}$, 3 or $\bar{3}$	$a_1=a_2=a_3\neq c$ $a\wedge c=90^o$ $a_1\wedge a_2=120^o$ $a_2\wedge a_3=120^o$	1–symmetry of **c** axis 2–symmetry of **a** axes 3–other (between **a** axes)	$\mathbf{6/m\,2/m\,2/m}$, $\bar{6}2m$, 6mm, 622, $6/m$, $\bar{6}$, 6, $\bar{3}$ $2/m$, 3m, 32, $\bar{3}$, 3	Uniaxial
Tetragonal	one 4 or $\bar{4}$	$a_1=a_2\neq c$ $\alpha=\beta=\gamma=90^o$	1–symmetry of **c** axis 2–symmetry of **a** axes 3–other (between **a** axes)	$\mathbf{4/m\,2/m\,2/m}$, $\bar{4}2m$, 4mm, 422, $4/m$, $\bar{4}$, 4	Uniaxial
Orthorhombic	three 2 and/or m	$a\neq b\neq c$, $c>b>a$ $\alpha=\beta=\gamma=90^o$	1–symmetry of **a** axis 2–symmetry of **b** axes 3–other (between **c** axes)	$\mathbf{2/m\,2/m\,2/m}$, 222, mm2	Biaxial
Monoclinic	one 2 and/or one m	$a\neq b\neq c$, $\alpha=\gamma=90^o$ $\beta>90^o$	1–symmetry of **b** axis	$\mathbf{2/m}$, 2, m	Biaxial
Triclinic	1 or $\bar{1}$	$a\neq b\neq c$, $\alpha=\beta>90^o$ γ > or < 90^o	1–1 or $\bar{1}$	$\mathbf{\bar{1}}$, 1	Biaxial
*	$\alpha = b\wedge c$, $\beta = a\wedge c$, $\gamma = a\wedge b$				
**	The holohedral or highest symmetry class in each system is shown in bold letters				

The Petrographic Microscope

- Plane-polarized light from below (polarizer)
  - EW or NS? biotite is darkest parallel to polarizer
- Removable “analyzer” above sample
- Rotatable stage
- Various microscopes

The Petrographic (polarizing) Microscope



New Leica Microscopes

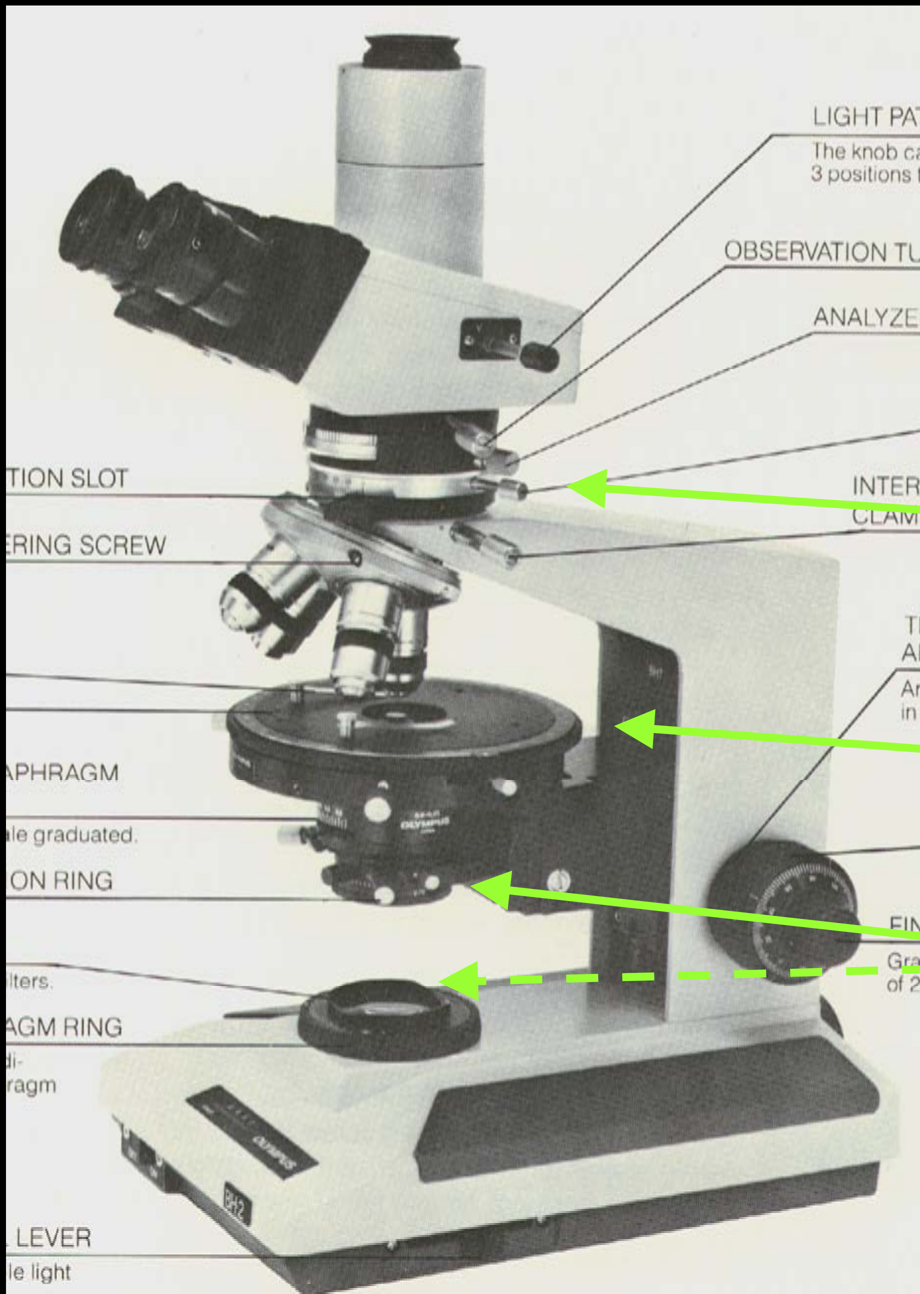
Analyzer (NS)

Objectives

Rotating Stage

Polarizer (EW, perpendicular to Analyzer)

The Petrographic (polarizing) Microscope



Older Olympus Microscopes

Analyzer (NS or EW)

Rotating Stage

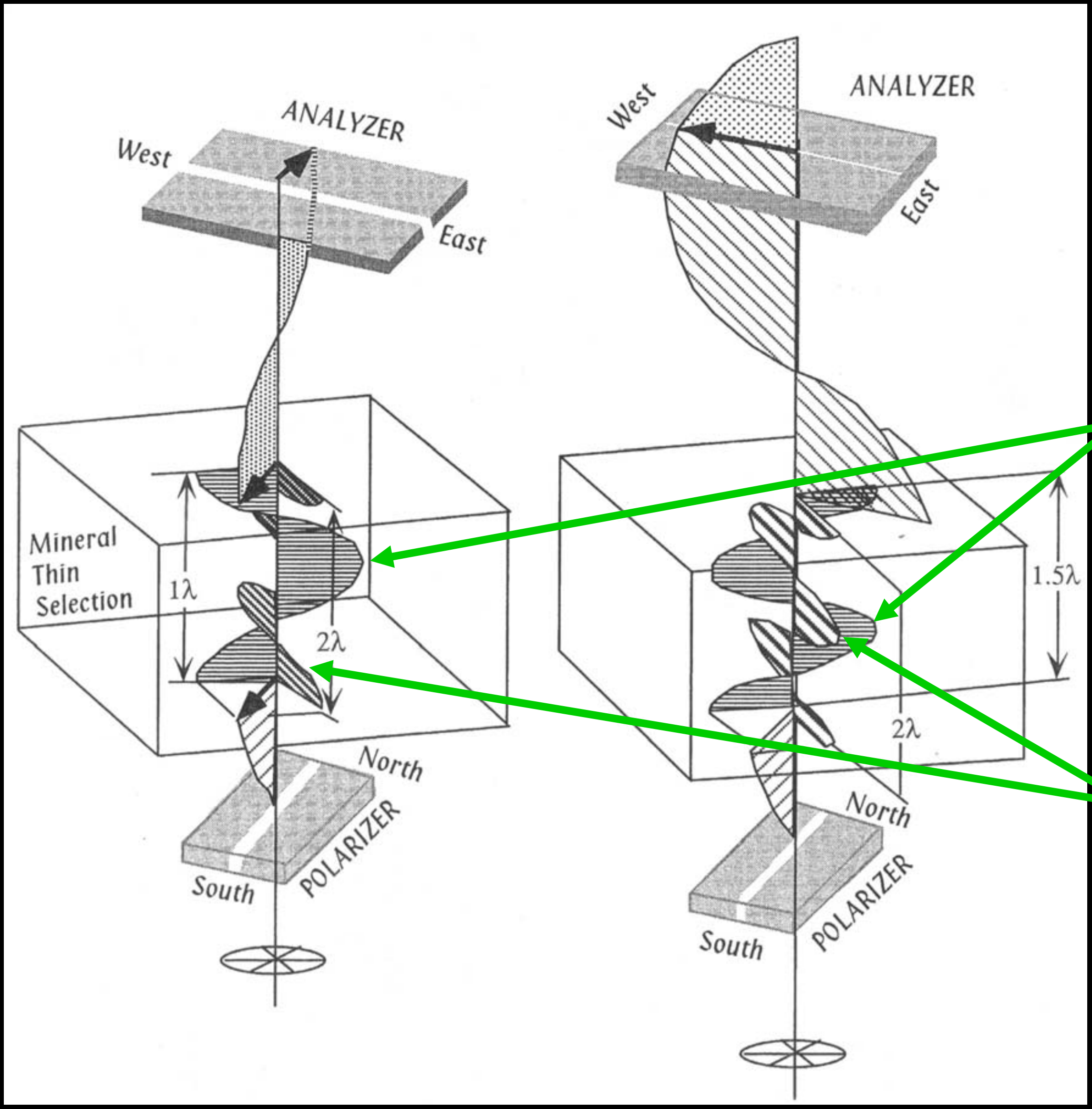
Polarizer (EW or NS, perpendicular to Analyzer)

Interaction of light with minerals

- Polarized light travels right through isotropic minerals, and travels at the same speed in all directions
- In anisotropic minerals, polarized light is split into two rays vibrating at 90° to each other in two special “allowed vibration directions,” the two rays travel at different speeds

Light passing thru an anisotropic mineral

If recombined wave is per-pendicular to Analyzer, no light passes, mineral is dark



If recombined wave is parallel to the Analyzer, all light passes, mineral appears brightest

"fast" ray, long λ

"slow" ray short λ

Lagging of the “slow” ray behind the “fast” ray is called Retardation

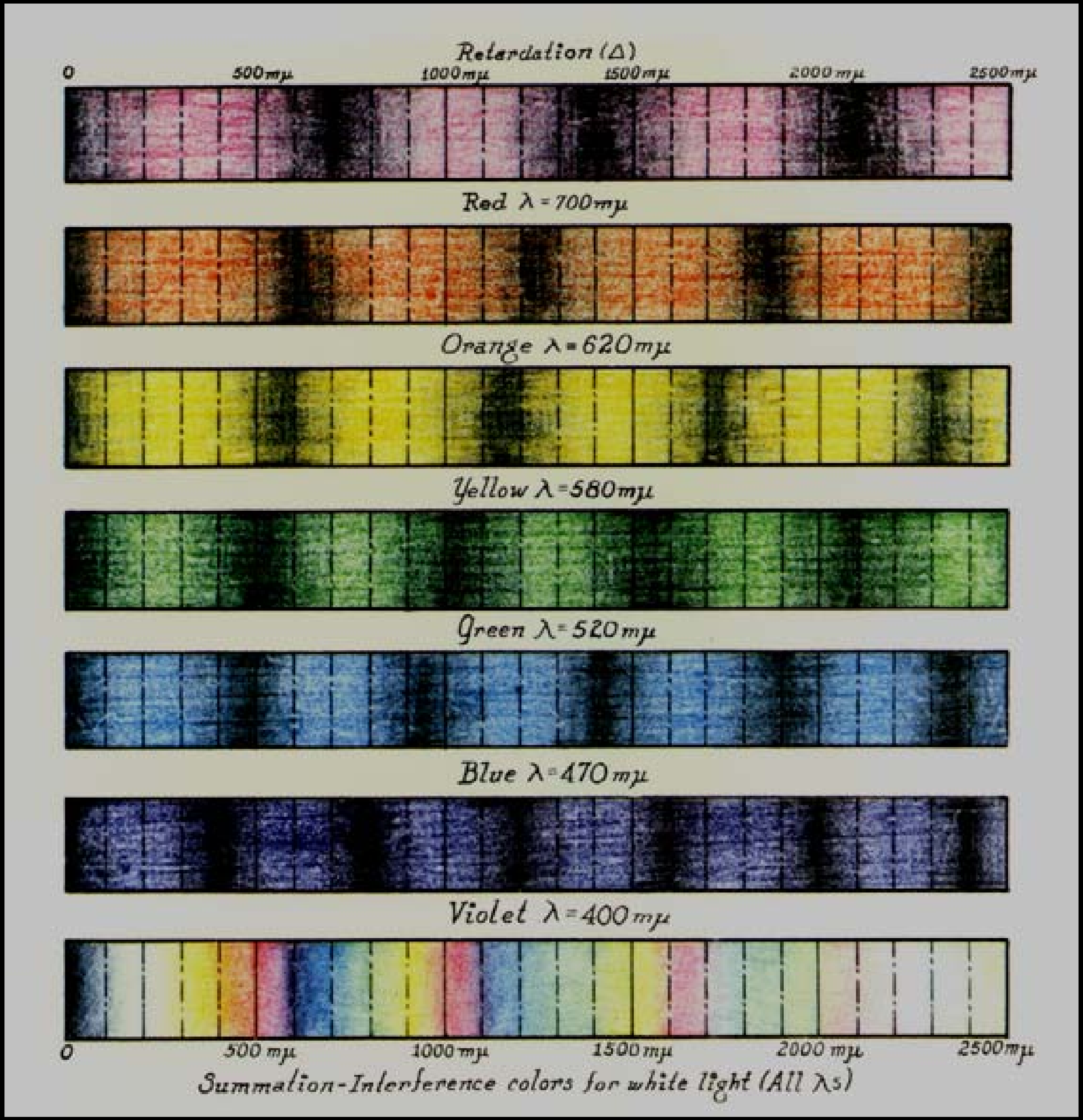
- When the two rays recombine at the Analyzer, they interfere (constructively or destructively) with each other and there is generally a component of light parallel to the Analyzer
- Different colors of light experience different amounts of Retardation

Retardation and Interference

Quartz Wedge between Crossed Polaroid Films in Monochromatic (Na_D; λ=590nm) Light

Note constructive and destructive interference

Interference Colors



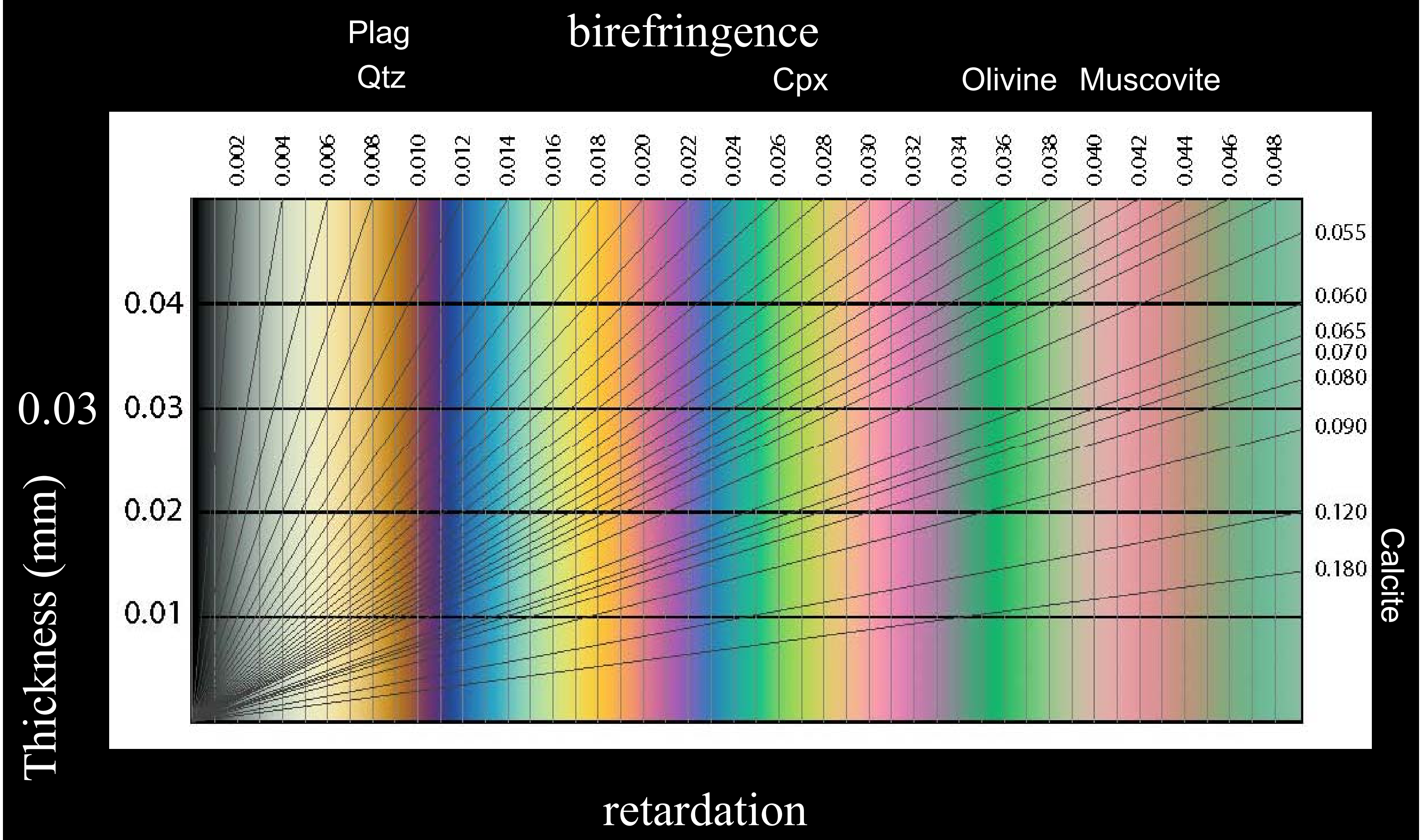
Constructive (bright) and Destructive Interference (black) for different colors sums to the interference colors (at the bottom) for white light

(Phillips, 1971)

Interference Colors depend on:

- The amount of retardation caused by the mineral in a certain direction
  - How anisotropic is the mineral?
  - δ, maximum difference in refractive index
- And the thickness of the mineral (typically a 30 μm thin section)

Interference Colors



Properties viewed in Plane-polarized light (PPL)

- Relief (relative)
  - Becke lines – bright line moves toward medium with higher refractive index (distance increased)
- Color
  - Pleochroism
- Grain shape
- Cleavages
- Alteration
- Others?

Properties in Cross-polarized light (XPL)

- Birefringence
  - None, zero → isotropic
  - Interference colors → anisotropic
  - How high? low, medium, high, extremely high
- Extinction
  - parallel extinction?
  - extinction angle?
- Others?

Optical Groupings

- Isotropic
  - Same properties in all directions
  - Light travels at the same speed in all directions
  - Isometric symmetry
- Uniaxial
  - One unique axis, one direction in which the mineral appears isotropic = optic axis = c axis
  - Tetragonal or Hexagonal symmetry
- Biaxial
  - Three principal refractive indices, two directions in which the mineral appears isotropic = optic axes – angle between them is 2V
  - Orthorhombic, Monoclinic or Triclinic symmetry

Uniaxial and Biaxial Optics

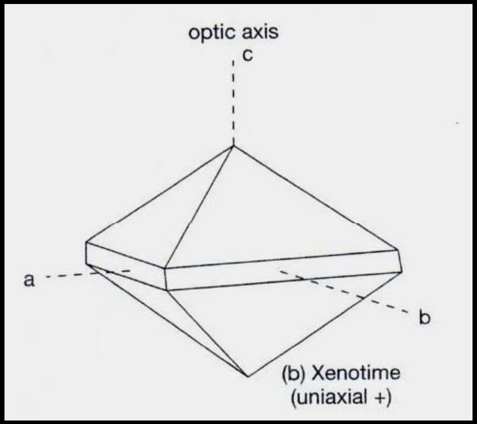
- David Hirsch – Uniaxial Indicatrix Movie
- http://almandine.geol.wwu.edu/~dave/courses/407resources/UniPosIndicatrix.mov
- David Hirsch – Biaxial Indicatrix Movie
- http://almandine.geol.wwu.edu/~dave/courses/407resources/BiaxialNegativeIndicatrix.mov
- A really good Optical Mineralogy course
- Dr. Greg Finn, Brock University, Canada
- http://www.brocku.ca/earthsciences/people/gfinn/optical/222lect.htm

Uniaxial Minerals

The optic axis (direction along which mineral appears isotropic) is always parallel to c

ω, the ordinary ray, vibrates perpendicular to the c axis

ε, the extraordinary ray, vibrates parallel to the c axis



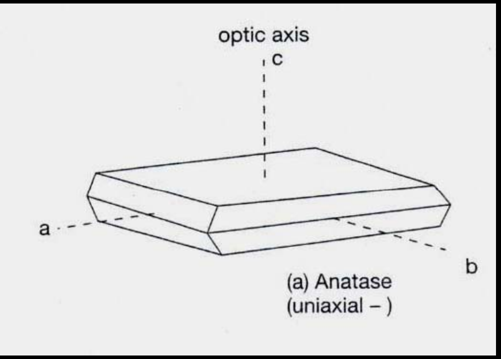
<u>Positive</u>

$\varepsilon > \omega$

$V_\varepsilon < V_\omega$

ω is fast ray

Quartz
Leucite
Zircon
Rutile



<u>Negative</u>

$\varepsilon < \omega$

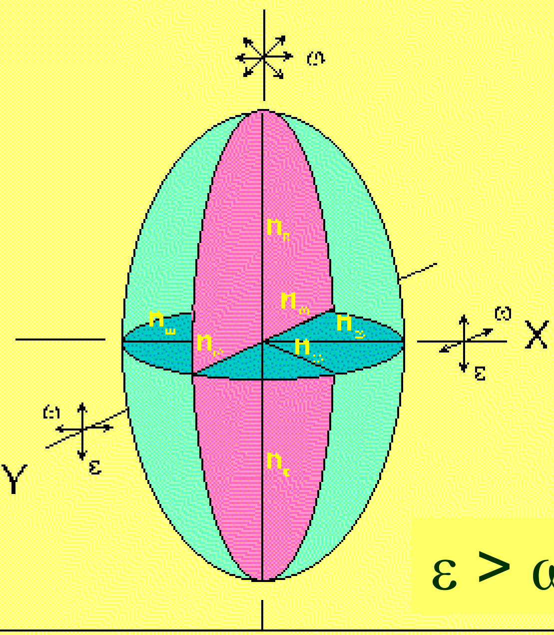
$V_\varepsilon > V_\omega$

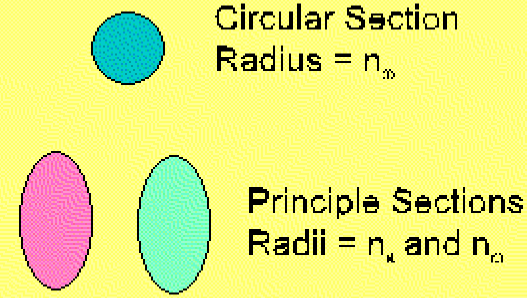
ω is slow ray

Beryl
Tourmaline
Apatite
Calcite, Dolo
Corundum

Uniaxial Indicatrix

Z = optic axis = c-axis





Unlaxial Positive Indicatrix
Elongated along the optic axis
c-axis = optic axis
c-axis = Z Indicatrix axis

$\varepsilon > \omega$

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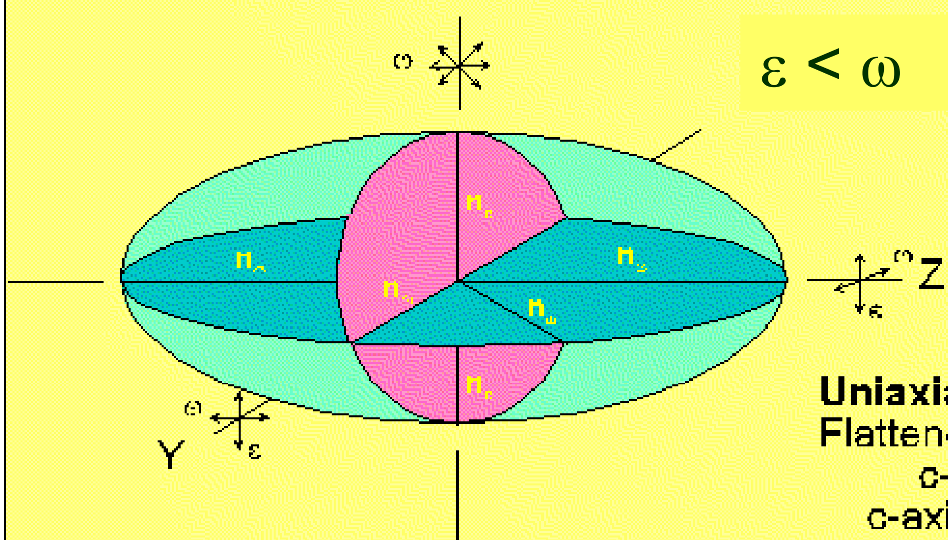
X = optic axis = c-axis

$\varepsilon < \omega$



Uniaxial Negative Indicatrix
Flattened along the optic axis
c-axis = optic axis
c-axis = X indicatrix axis

Determining the Optic Sign

- Obtaining an interference figure
  - Conoscopic Light – microscope setup
- Uniaxial Minerals
  - Centered Optic Axis figure
  - Looking down the c-axis
- Biaxial Minerals
  - Several options, Bxa, Bxo or Optic Axis (OA)
  - I suggest Optic Axis figure, easiest to find likely grains

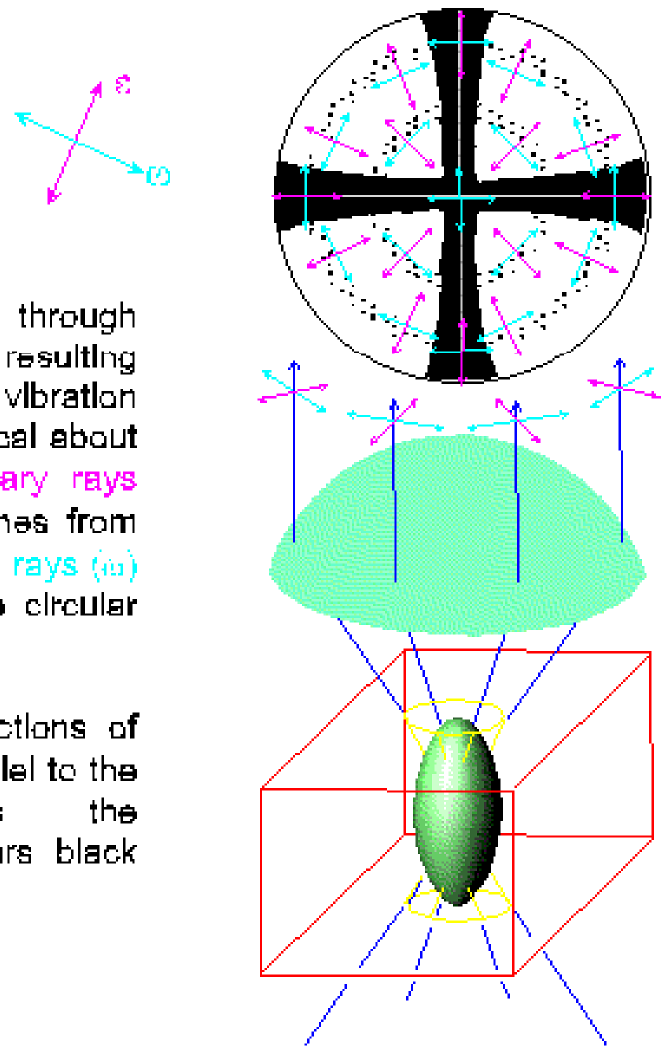
Uniaxial Figure & Optic Sign

- if $\varepsilon > \omega$, ω is the “fast ray” and the optic sign is negative
- if $\omega > \varepsilon$, ε is the slow ray and the optic sign is positive

Uniaxial Mineral – Conoscopic Light

Convergent light passes through the mineral, with the resulting indicatrix, and exits with a vibration pattern which is symmetrical about the melatope. Extraordinary rays (ε) vibrate along radial lines from the melatope and ordinary rays (ω) vibrate tangentially to the circular isochromes.

Where the vibration directions of the ω and ε rays are parallel to the polarization directions the interference figure appears black and forms the isogyres.



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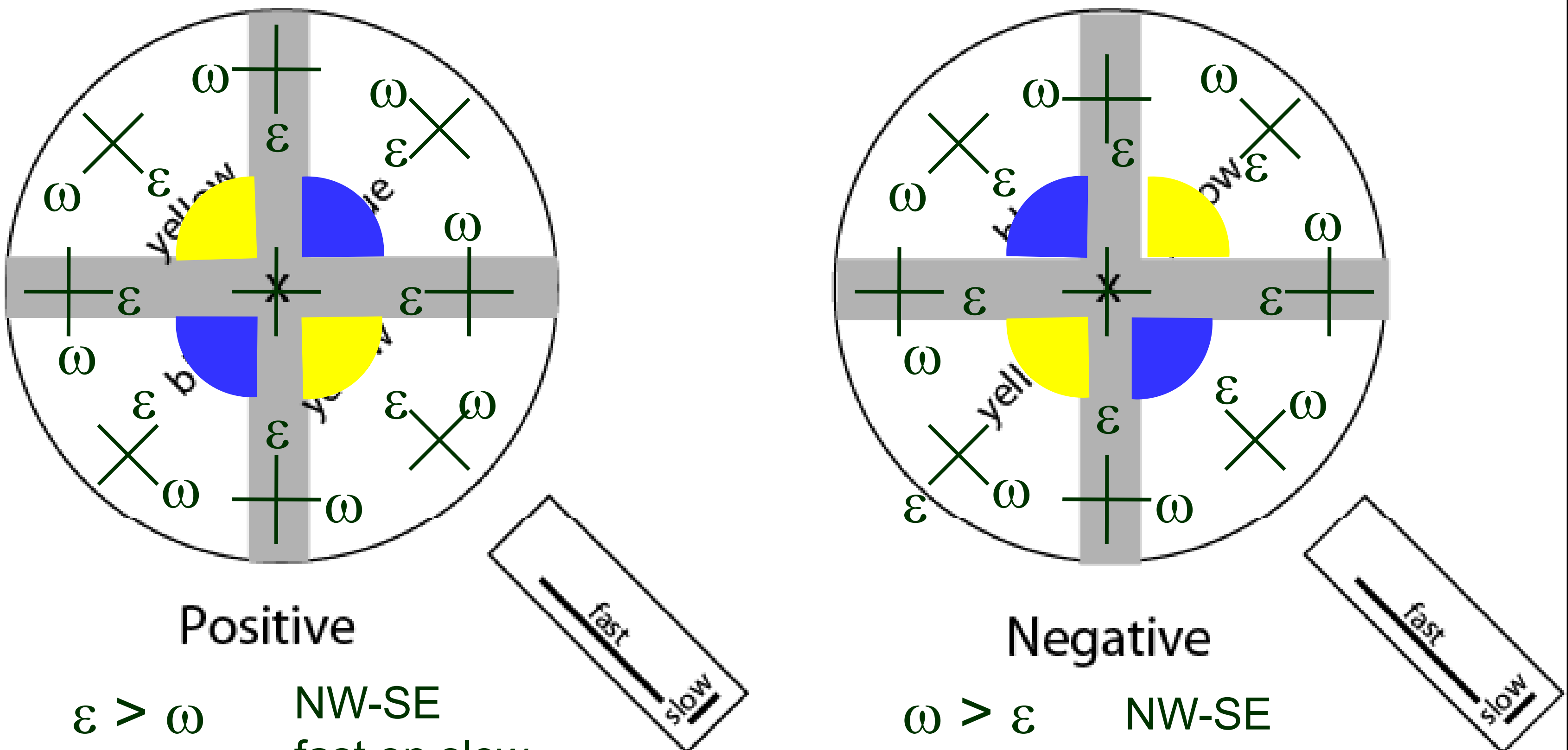
Uniaxial sign and interference figure

Uniaxial Interference Figure (centered)



$\varepsilon > \omega$
$V_\omega > V_\varepsilon$
ω fast

NW-SE
fast on slow
subtraction
yellow

$\omega > \varepsilon$
$V_\varepsilon > V_\omega$
ω slow

NW-SE
slow on slow
addition
blue

Biaxial Minerals

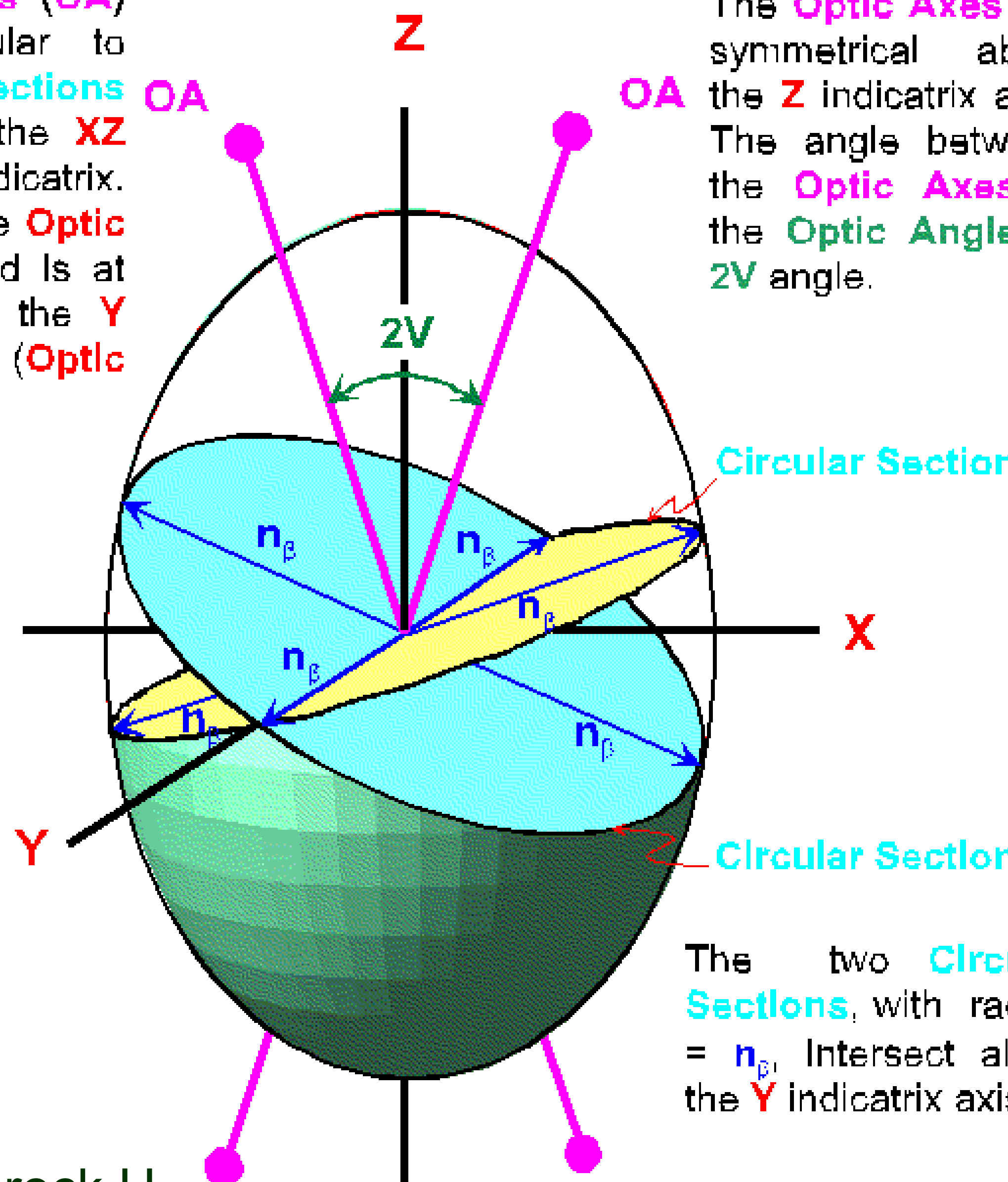
- X – vibration direction of fastest ray
- α – refractive index of light vibrating in X direction
- α – lowest refractive index
- Y – vibration direction of light traveling along OA
- β – refractive index of light vibrating $\perp$ to Optic Axis
- β – intermediate refractive index
- Z – vibration direction of slowest ray
- γ – refractive index of light vibrating in Z direction
- γ – highest refractive index

$\alpha < \beta < \gamma$ (always)   birefringence = $\delta = \gamma - \alpha$ (always)

Biaxial Indicatrix

The Optic Axes (OA) are perpendicular to the Circular Sections and lie within the XZ plane of the indicatrix. This plane is the Optic Axial Plane and is at right angles to the Y indicatrix axis (Optic Normal).

The Optic Axes are symmetrical about the Z indicatrix axis. The angle between the Optic Axes is the Optic Angle or 2V angle.



The two Circular Sections, with radius = n_β, intersect along the Y indicatrix axis.

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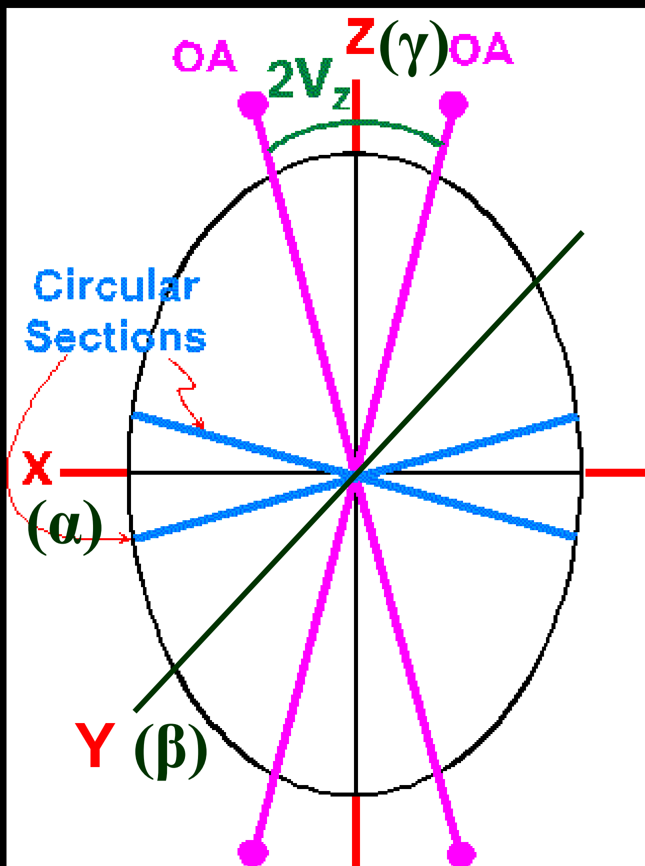
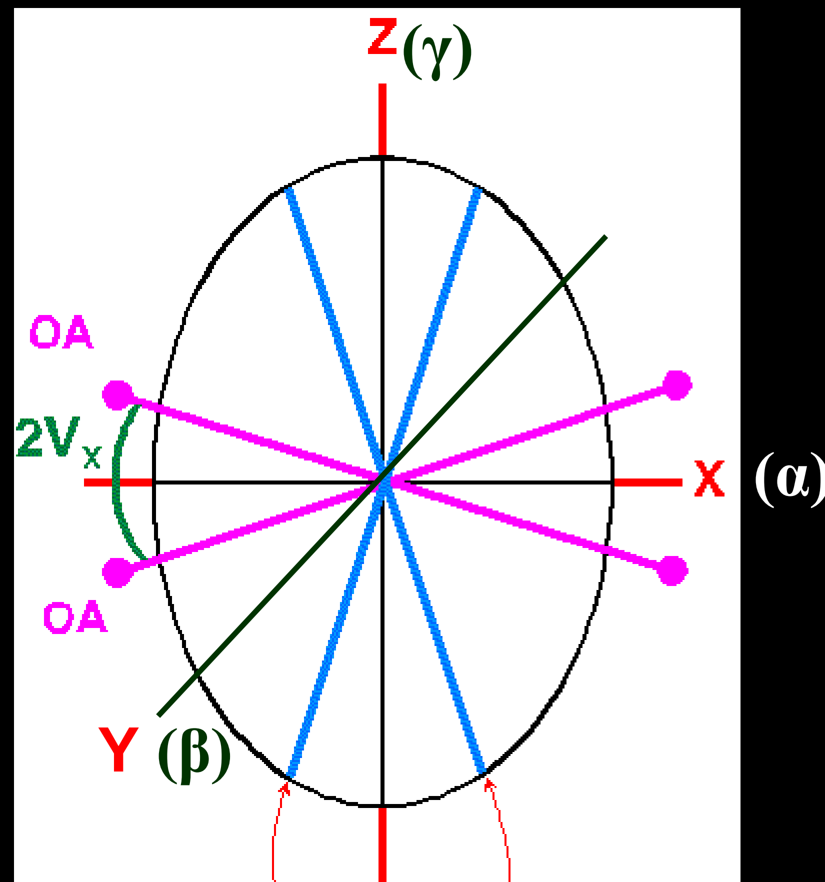
Biaxial Relationships



Biaxial Positive (+)
β closer to α
Z is Bxa



Biaxial Negative (-)
β closer to γ
X is Bxa

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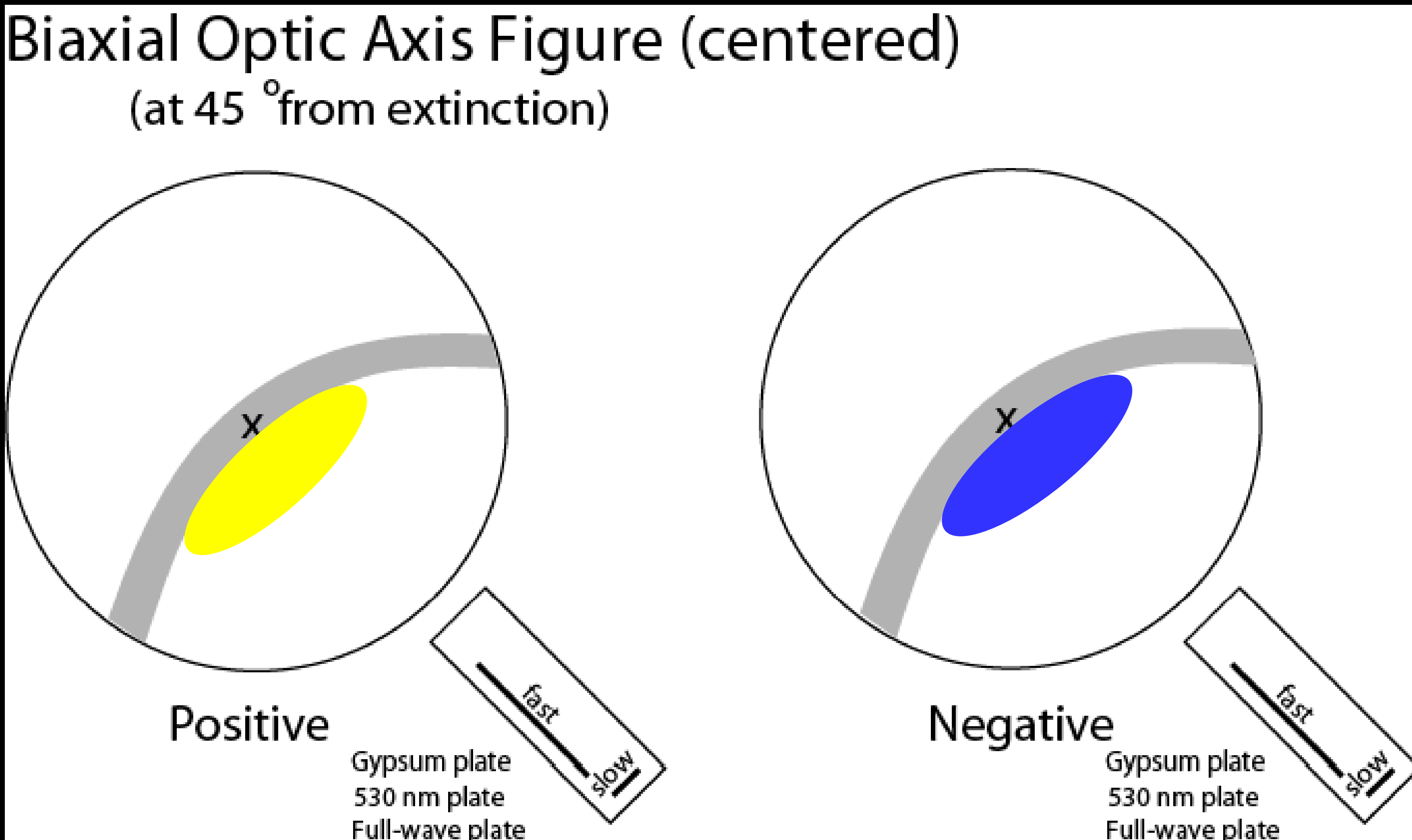
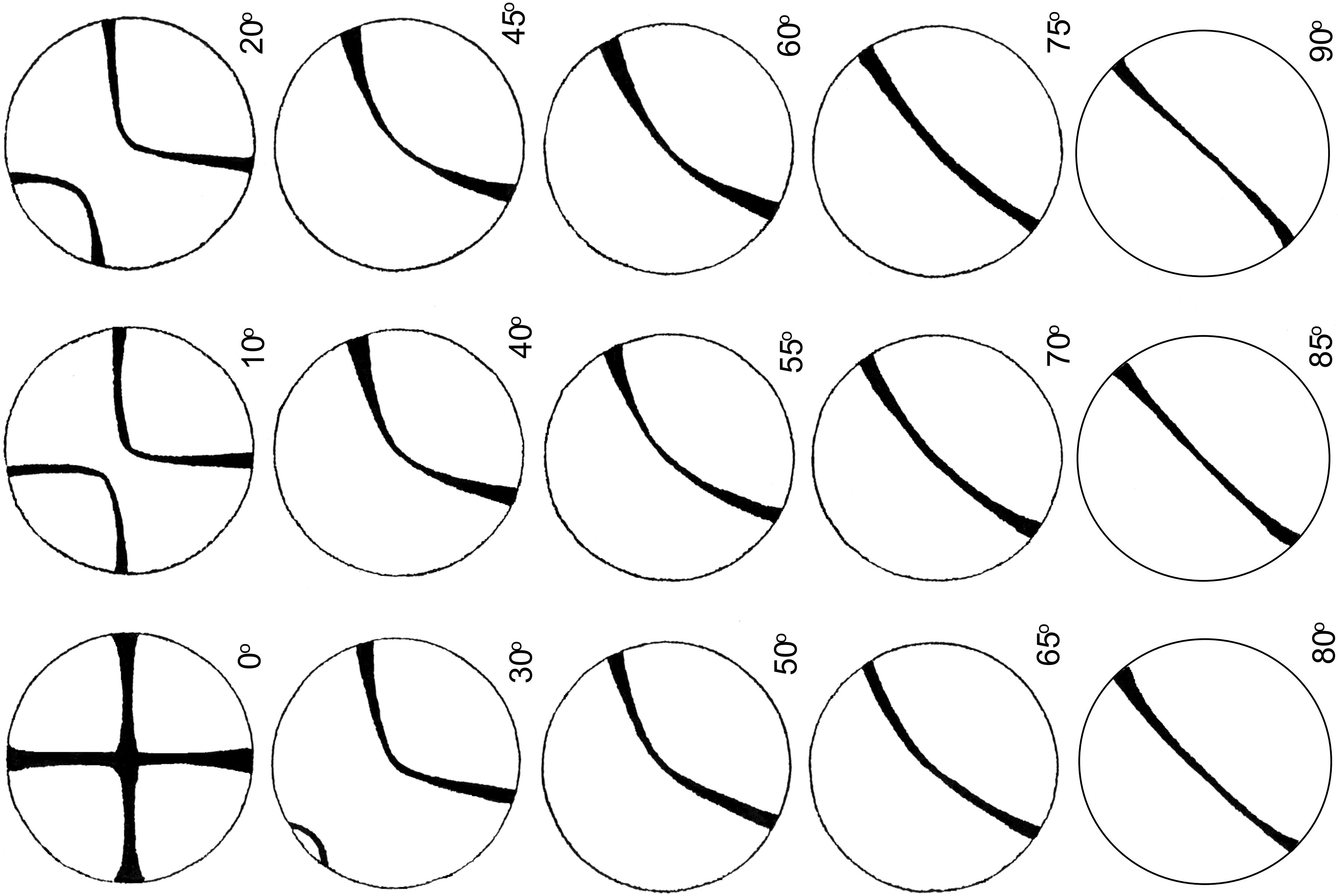
Determining Optic sign and 2V

- Conoscopic light
- Several possibilities, Bxa, Bxo and OA
- Optic Axis figure easiest to use
- OA, easiest to pick likely grains
  - looking down Optic Axis, grain appears isotropic
  - pick lowest birefringence grain you can find
  - rotate stage, you want one that stays black/gray
- Melatope stays in center, isogyre spins around

Biaxial Optic Axis Figure



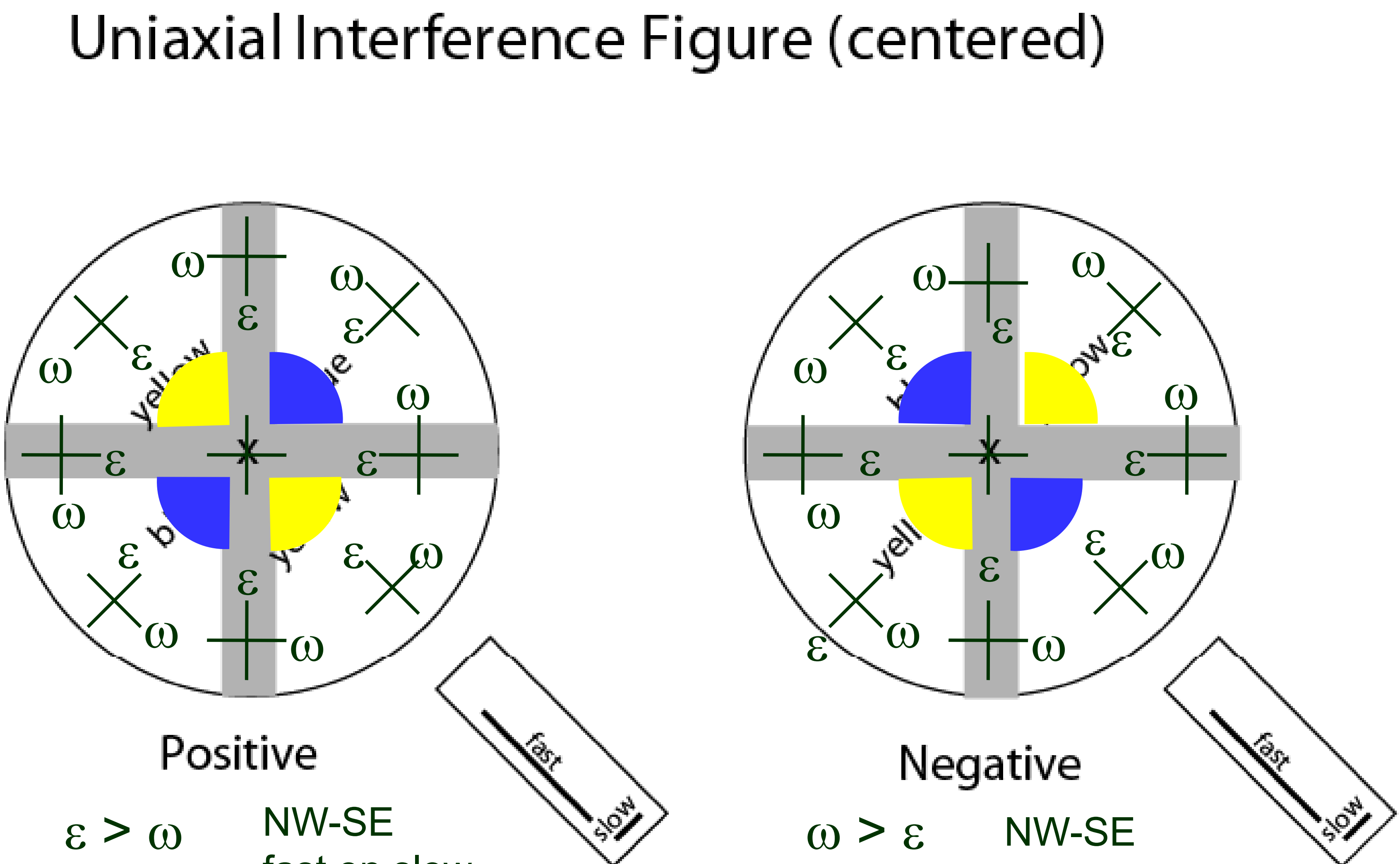
OPTIC AXIS FIGURE – CURVATURE OF ISOGYRES AS A FUNCTION OF 2V



Summary of the Crystal Systems

CRYSTAL SYSTEM	CHARACTERISTIC SYMMETRY	AXIAL RELATIONSHIPS	PLACES IN THE H-M SYMBOL	CRYSTAL CLASSES	OPTICAL CLASSIFICATION
Isometric	four 3 or $\bar{3}$	$a_1=a_2=a_3$ α*$=\beta=\gamma=90^o$	1–symmetry of **a** axes 2–3 or $\bar{3}$ (diagonal) 3–other (edge to edge)	$\boldsymbol{{}^{4}/_{m}\,\bar{3}\,{}^{2}/_{m}}$**, $\bar{4}3m$, 432, ${}^{2}/_{m}\,\bar{3}$, 23	Isotropic
Hexagonal	one 6, $\bar{6}$, 3 or $\bar{3}$	$a_1=a_2=a_3\neq c$ $a\wedge c=90^o$ $a_1\wedge a_2=120^o$ $a_2\wedge a_3=120^o$	1–symmetry of **c** axis 2–symmetry of **a** axes 3–other (between **a** axes)	$\boldsymbol{{}^{6}/_{m}\,{}^{2}/_{m}\,{}^{2}/_{m}}$, $\bar{6}2m$, 6mm, 622, ${}^{6}/_{m}$, $\bar{6}$, 6, $\bar{3}$ ${}^{2}/_{m}$, 3m, 32, $\bar{3}$, 3	Uniaxial
Tetragonal	one 4 or $\bar{4}$	$a_1=a_2\neq c$ $\alpha=\beta=\gamma=90^o$	1–symmetry of **c** axis 2–symmetry of **a** axes 3–other (between **a** axes)	$\boldsymbol{{}^{4}/_{m}\,{}^{2}/_{m}\,{}^{2}/_{m}}$, $\bar{4}2m$, 4mm, 422, ${}^{4}/_{m}$, $\bar{4}$, 4	Uniaxial
Orthorhombic	three 2 and/or m	$a\neq b\neq c$, $c>b>a$ $\alpha=\beta=\gamma=90^o$	1–symmetry of **a** axis 2–symmetry of **b** axes 3–other (between **c** axes)	$\boldsymbol{{}^{2}/_{m}\,{}^{2}/_{m}\,{}^{2}/_{m}}$, 222, mm2	Biaxial
Monoclinic	one 2 and/or one m	$a\neq b\neq c$, $\alpha=\gamma=90^o$ $\beta>90^o$	1–symmetry of **b** axis	$\boldsymbol{{}^{2}/_{m}}$, 2, m	Biaxial
Triclinic	1 or $\bar{1}$	$a\neq b\neq c$, $\alpha=\beta>90^o$ γ > or < 90^o	1–1 or $\bar{1}$	$\boldsymbol{\bar{1}}$, 1	Biaxial
*	$\alpha = b\wedge c$, $\beta = a\wedge c$, $\gamma = a\wedge b$				
**	The holohedral or highest symmetry class in each system is shown in bold letters				

Uniaxial sign and interference figure



Positive

$\varepsilon > \omega$

$V_{\omega} > V_{\varepsilon}$

ω fast

NW-SE
fast on slow
subtraction
yellow

Negative

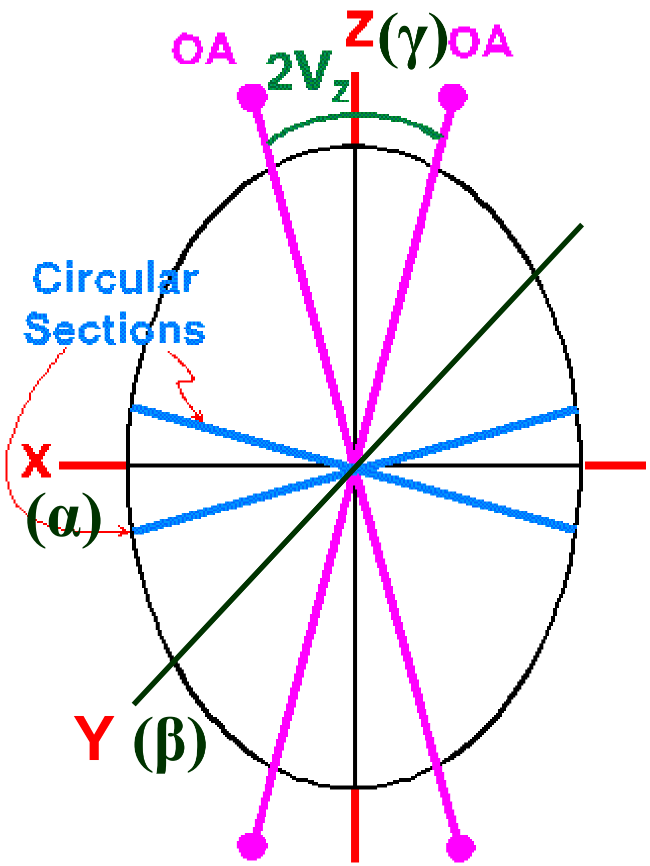
$\omega > \varepsilon$

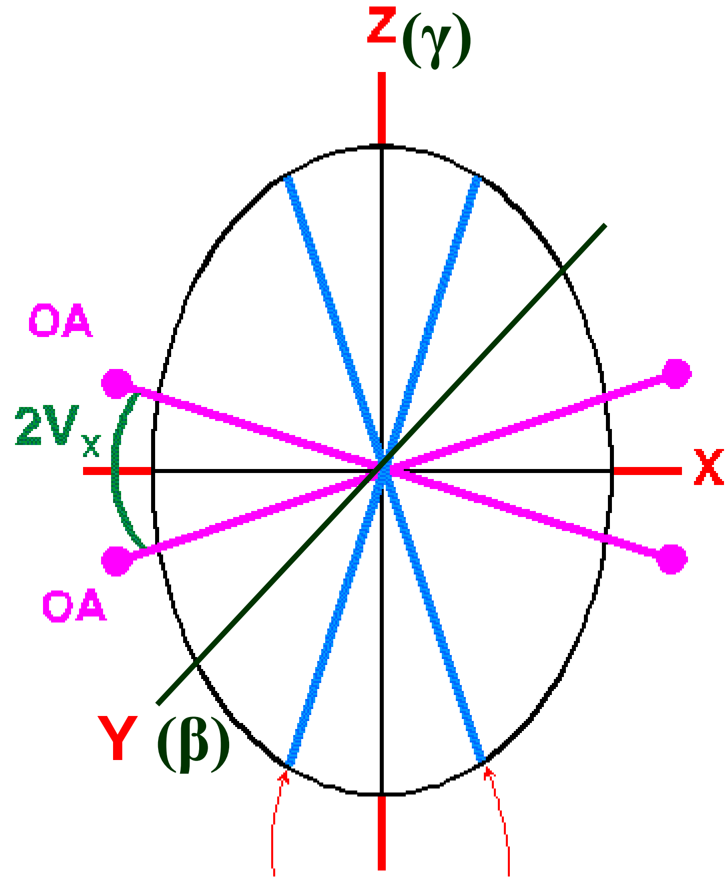
$V_{\varepsilon} > V_{\omega}$

ω slow

NW-SE
slow on slow
addition
blue

Biaxial Relationships





Biaxial Positive (+)
β closer to α
Z is Bxa

Biaxial Negative (-)
β closer to γ
X is Bxa

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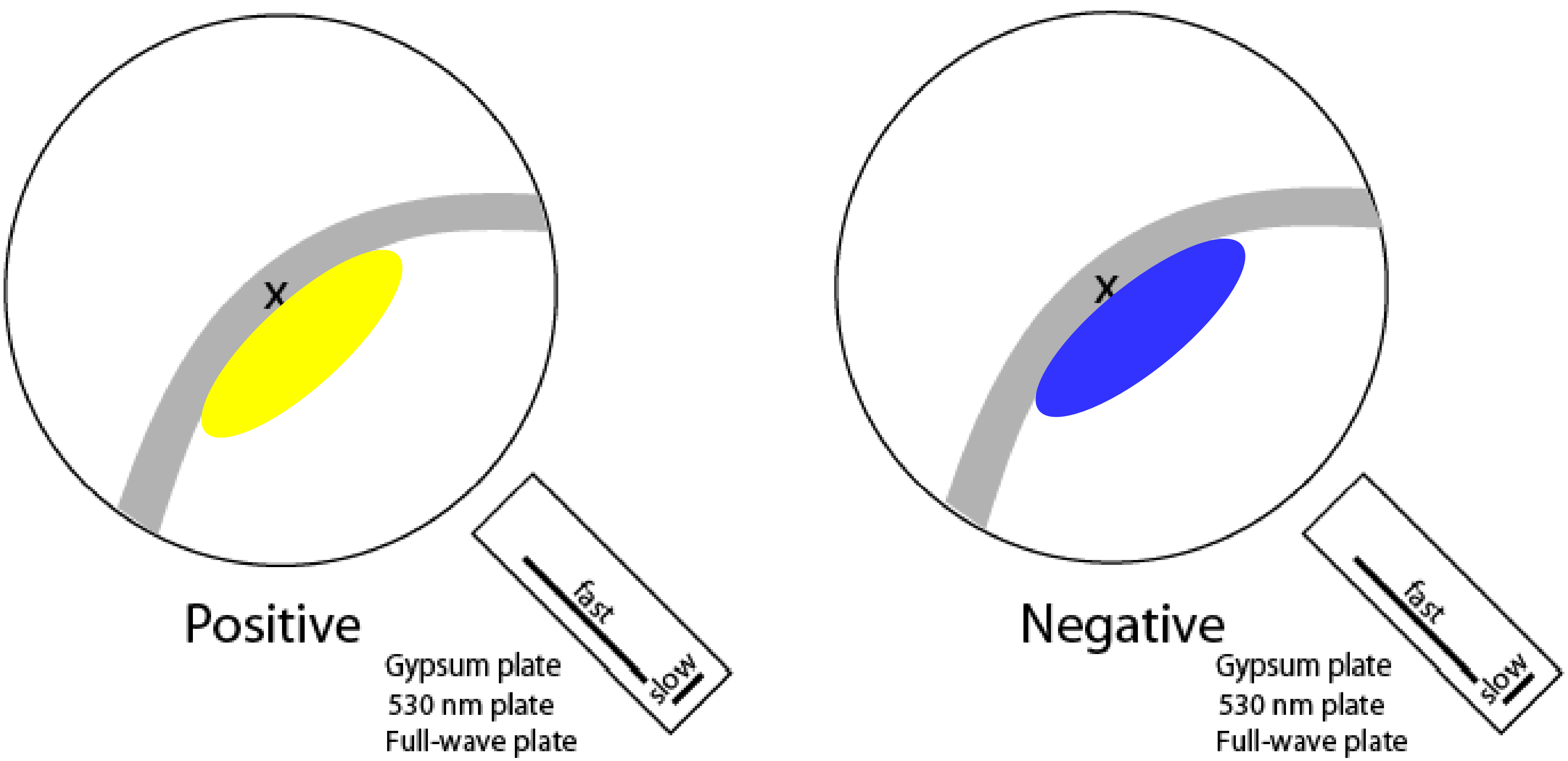
Biaxial Optic Axis Figure

Biaxial Optic Axis Figure (centered)

(at 45 °from extinction)



OPTIC AXIS FIGURE – CURVATURE OF ISOGYRES AS A FUNCTION OF 2V