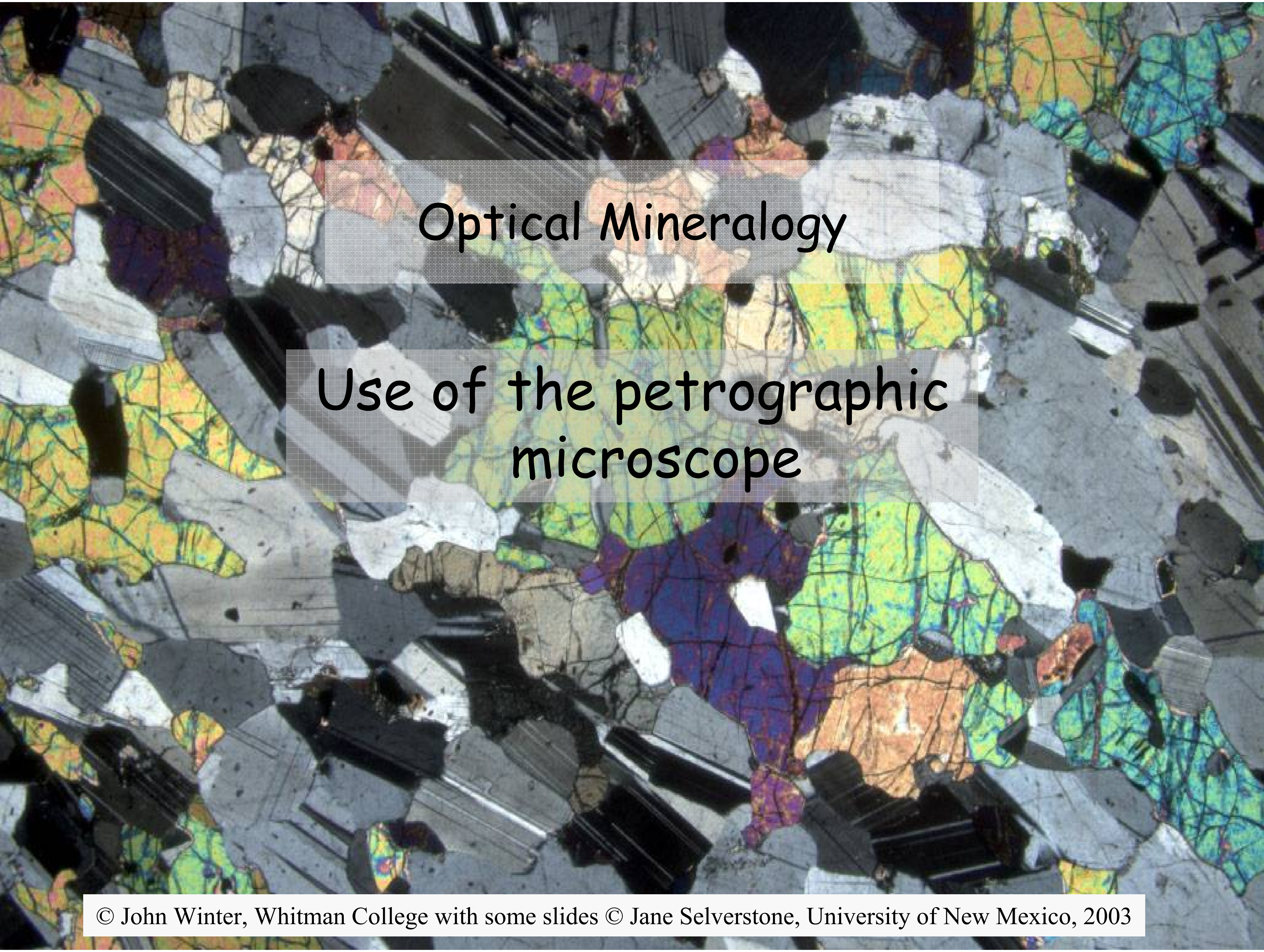
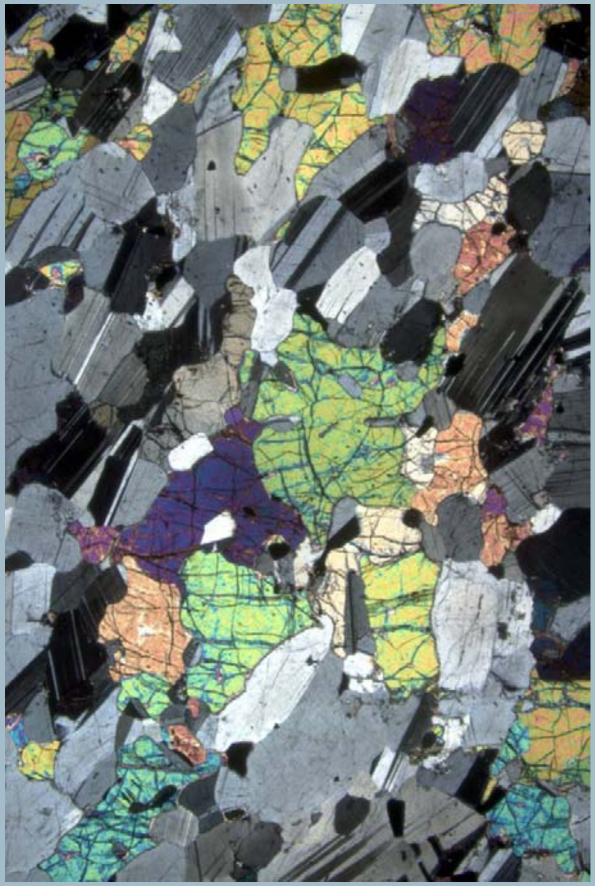


Optical Mineralogy

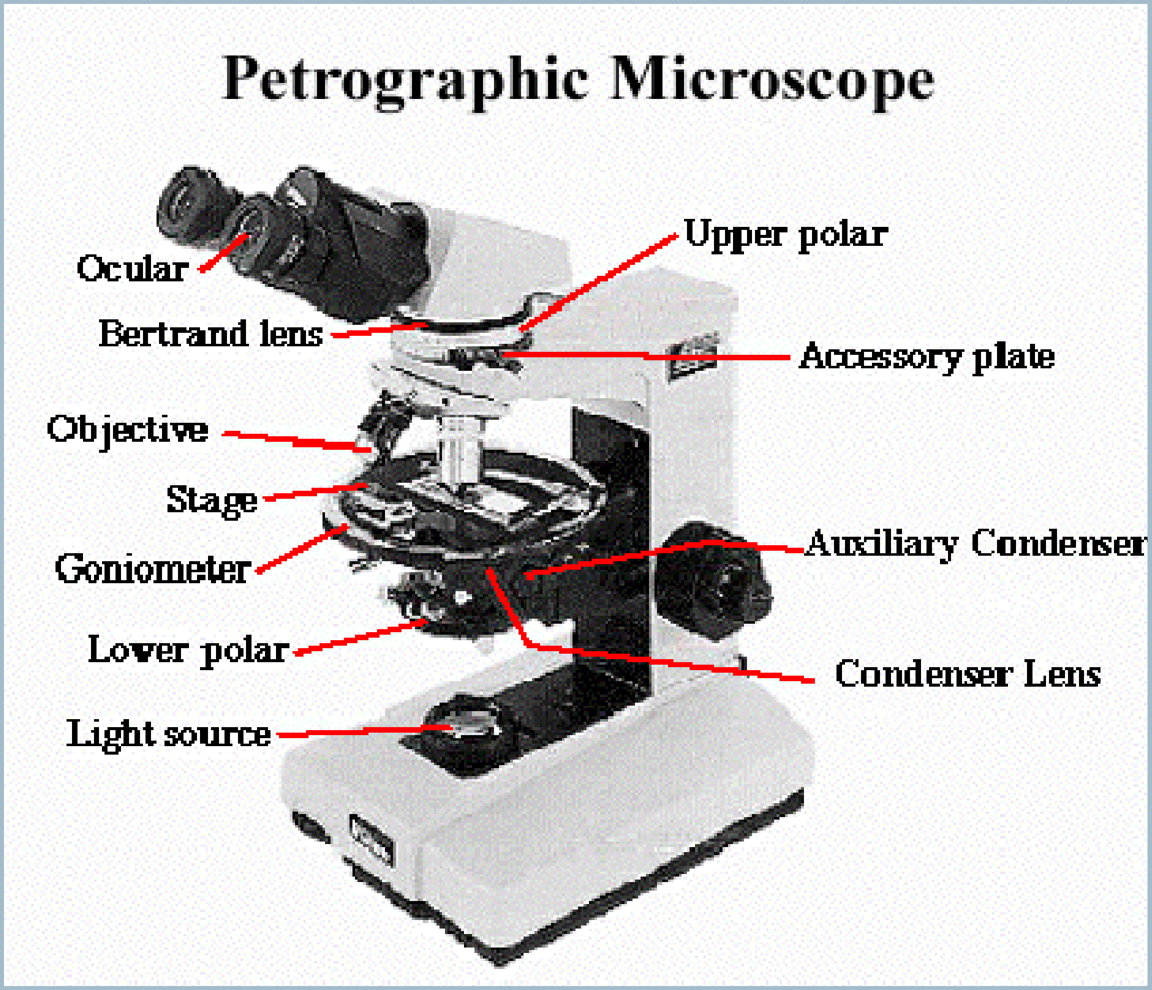
Use of the petrographic microscope

Why use the microscope??



- Identify minerals *(no guessing!)*
- Determine rock type
- Determine crystallization sequence
- Document deformation history
- Observe frozen-in reactions
- Constrain P-T history
- Note weathering/alteration

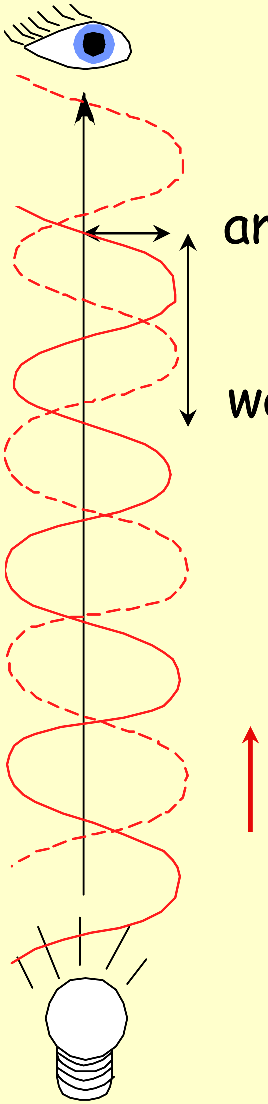
The petrographic microscope



Also called a polarizing microscope

In order to use the scope, we need to understand a little about the physics of light, and then learn some tools and tricks…

What happens as light moves through the scope?



your eye

amplitude, *A*

wavelength, λ

light ray

$I = f(A)$

waves travel from source to eye

light source

light travels as waves

Frequency = # of waves/sec to pass a given point (hz)

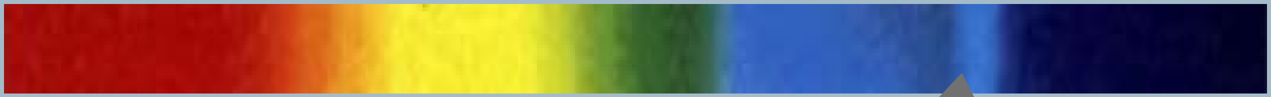
$f = v/\lambda$ v = velocity

(in physics v = c, but no longer)

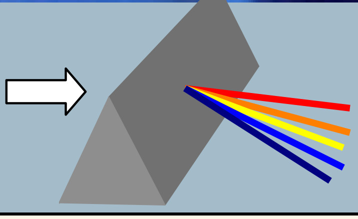
Electromagnetic spectrum & visible portion

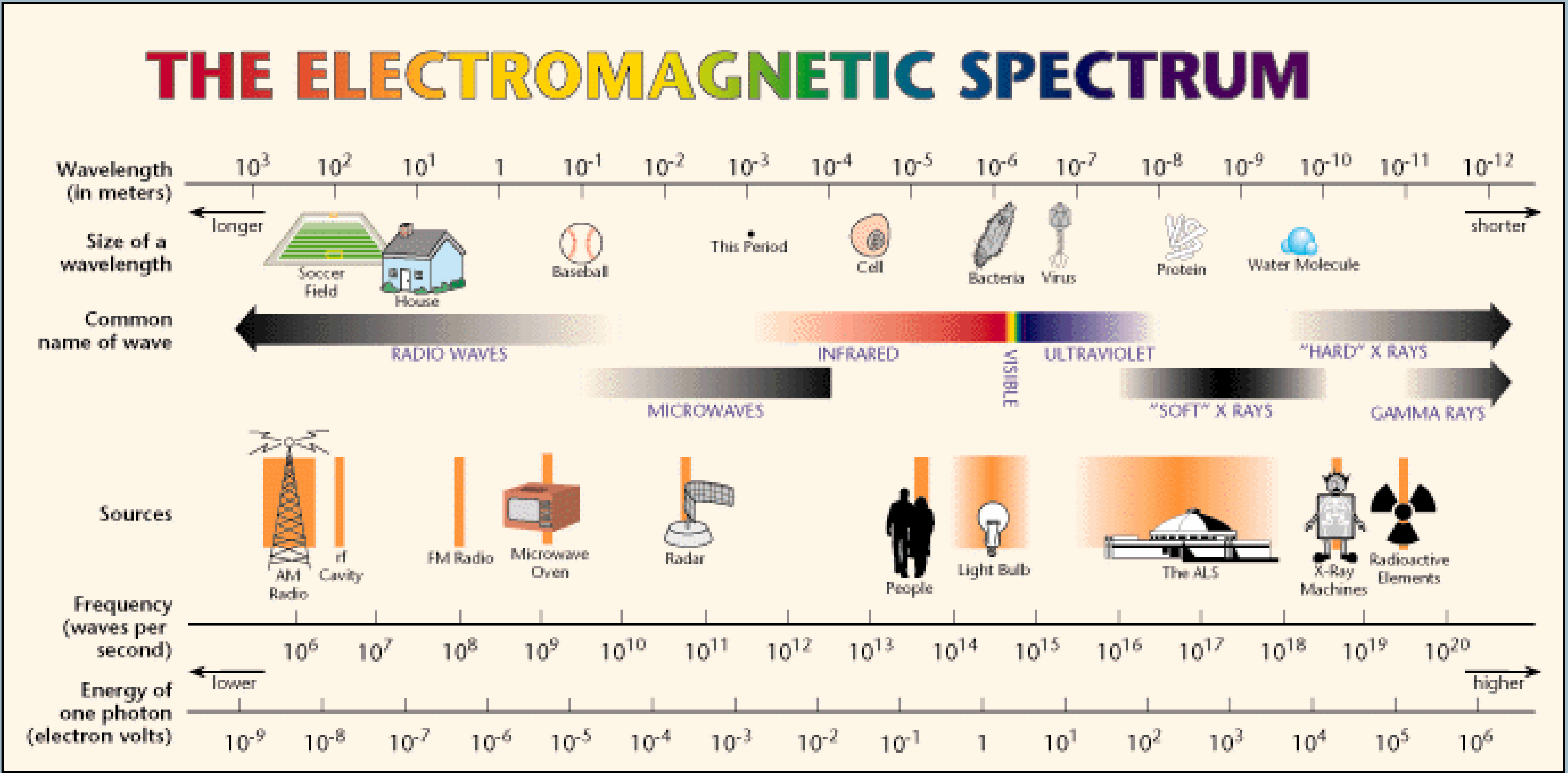
Violet (400 nm) → Red (700 nm)

White = ROYGBV



(can be separated by dispersion in a prism)





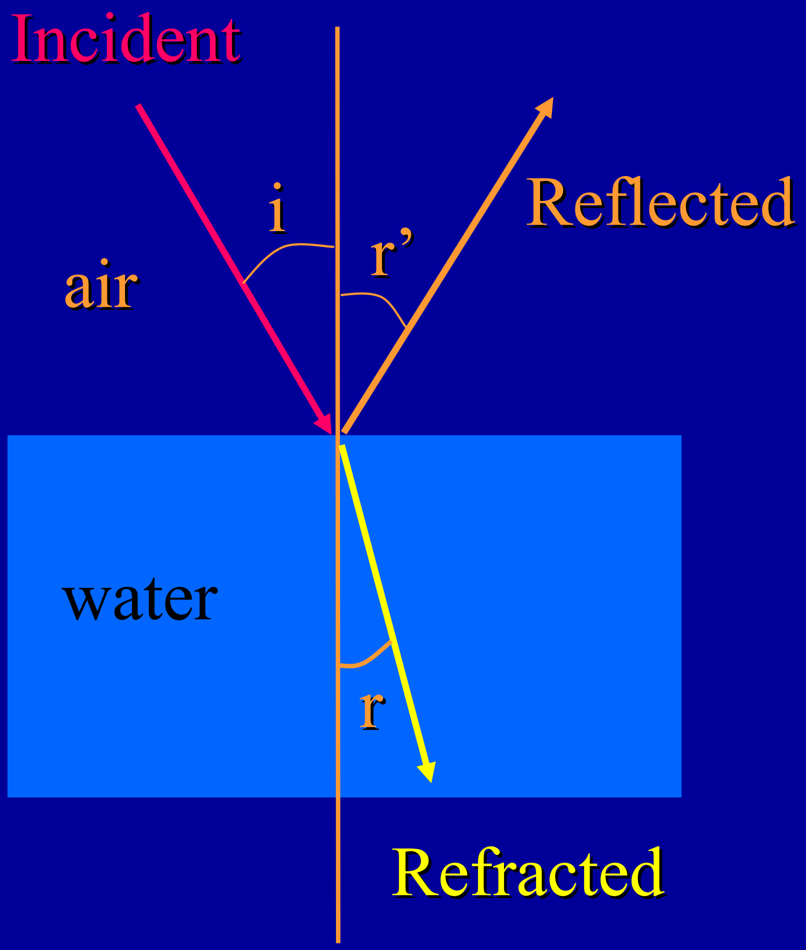
Refraction

Incident ray and reflected ray:

1) ∠ of incidence i = ∠ of reflection r'

2) coplanar "plane of incidence"

(⊥ plane of interface)



Refracted ray:

1) Slower in water (or glass)

2) ∠ r ≠ ∠ i

Depends on Δ velocity

Index of refraction

For a substance x:

$n_x = v_{air}/v_x$

n_{air} = ??

light is slower in water, glass, crystals

Is n_{water} greater or less than 1??

Larger n associated with slower V !!

Snells Law:

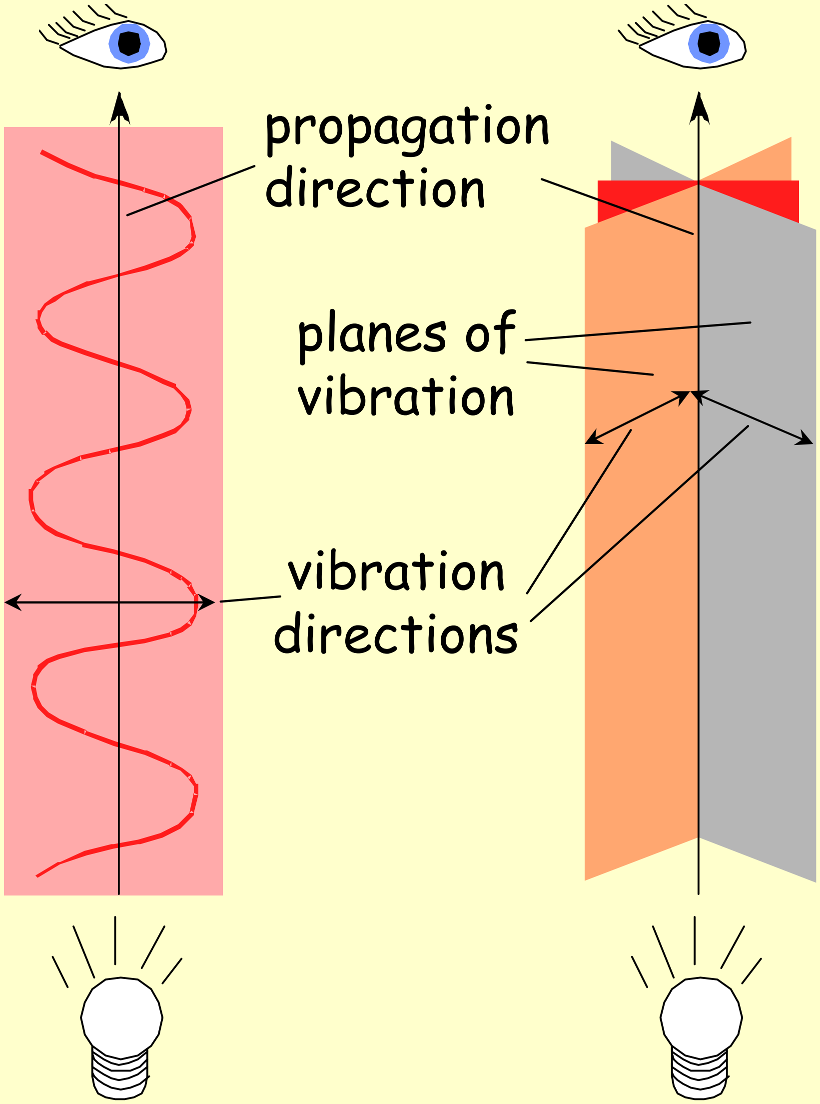
$$n_i \sin i = n_r \sin r$$

for 2 known media (air/water) $\sin i/\sin r = n_r / n_i = \text{const}$

So can predict angle change (or use ∠ to determine n_r)

What happens as light moves through the scope?

Each photon vibrates as a wave form in a single plane



Light beam = numerous photons, all vibrating in the same plane

propagation direction

planes of vibration

vibration directions

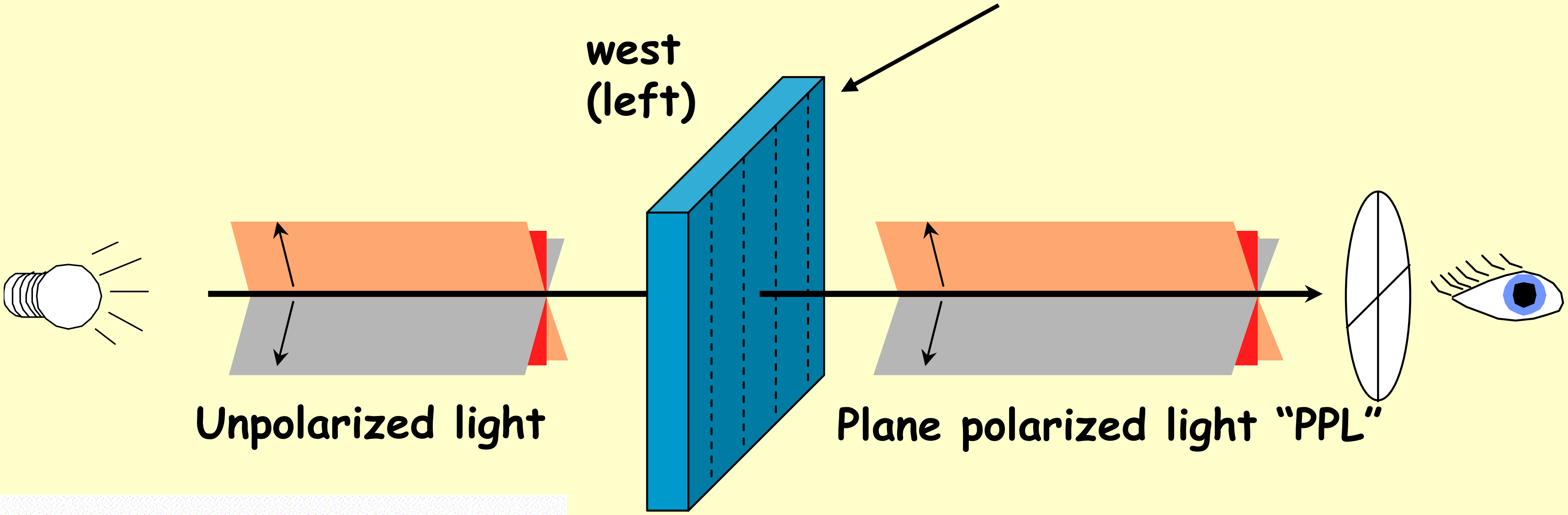
Light beam = numerous photons, each vibrating in a different plane

Vibration in all directions ~ perpendicular to propagation direction

Polarized Light

Unpolarized Light

1) Light passes through the **lower polarizer**

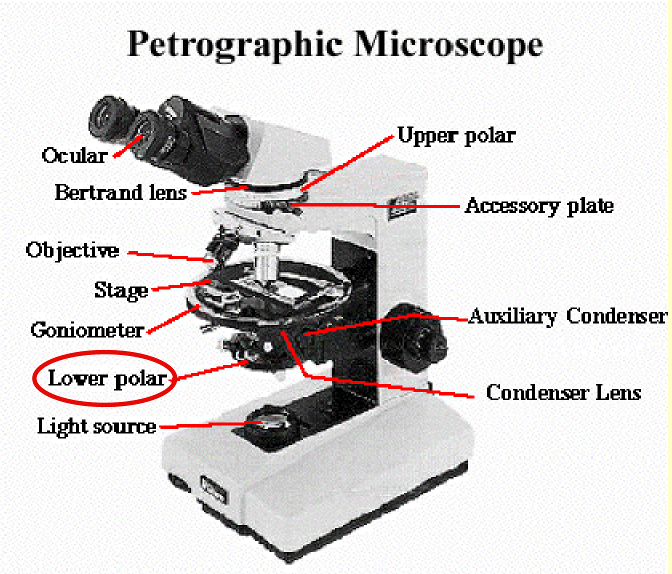


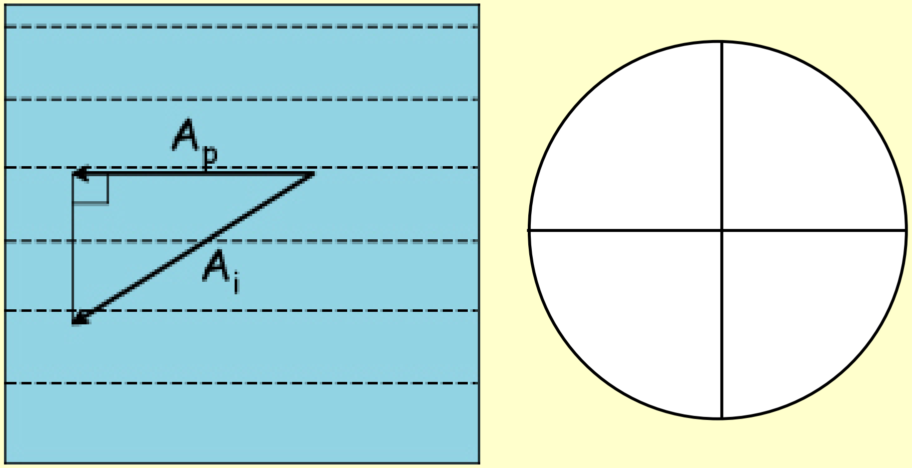
west (left)

Unpolarized light

Plane polarized light "PPL"

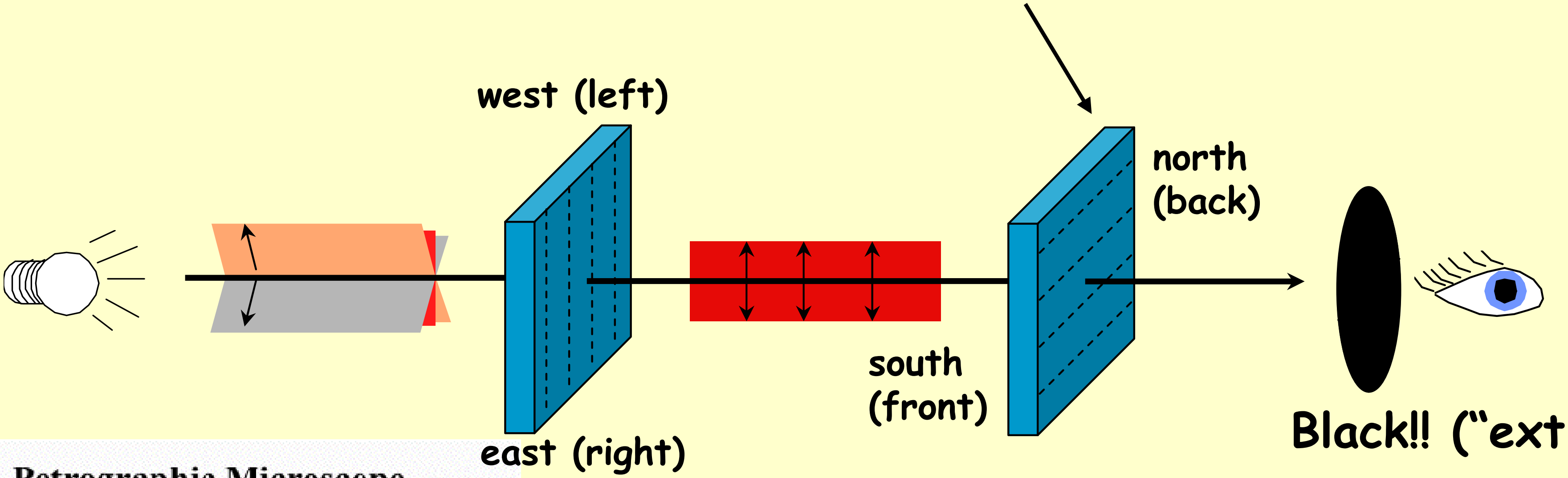
east (right)





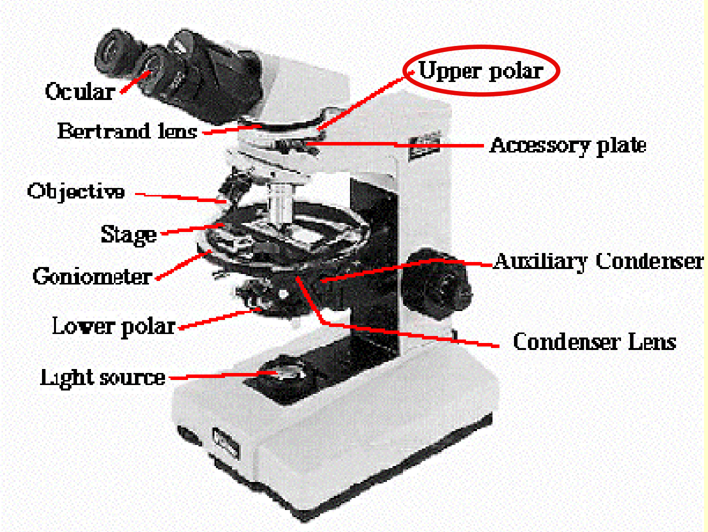
Only the component of light vibrating in E-W direction can pass through lower polarizer – light intensity decreases

2) Insert the **upper polarizer**



Black!! ("extinct")

Petrographic Microscope



XPL=crossed nicols
(crossed polars)

Now what happens?
What reaches your eye?

Why would anyone design a microscope that prevents light from reaching your eye???

The Optical Indicatrix

Shows how n_i varies with **vibration** direction.

Vectors radiating from center

Length of each proportional to n_i for light vibrating in the direction of the vector

Indicatrix = surface connecting tips of vectors

(a representational construct only!)

Isotropic media have all n_i the same (by definition)

What is the shape of an isotropic indicatrix?

Amorphous materials or isometric crystals are (optically) isotropic with a **spherical** indicatrix

The Isotropic Indicatrix

A section through the center of an indicatrix → all n for light propagating ⊥ the section

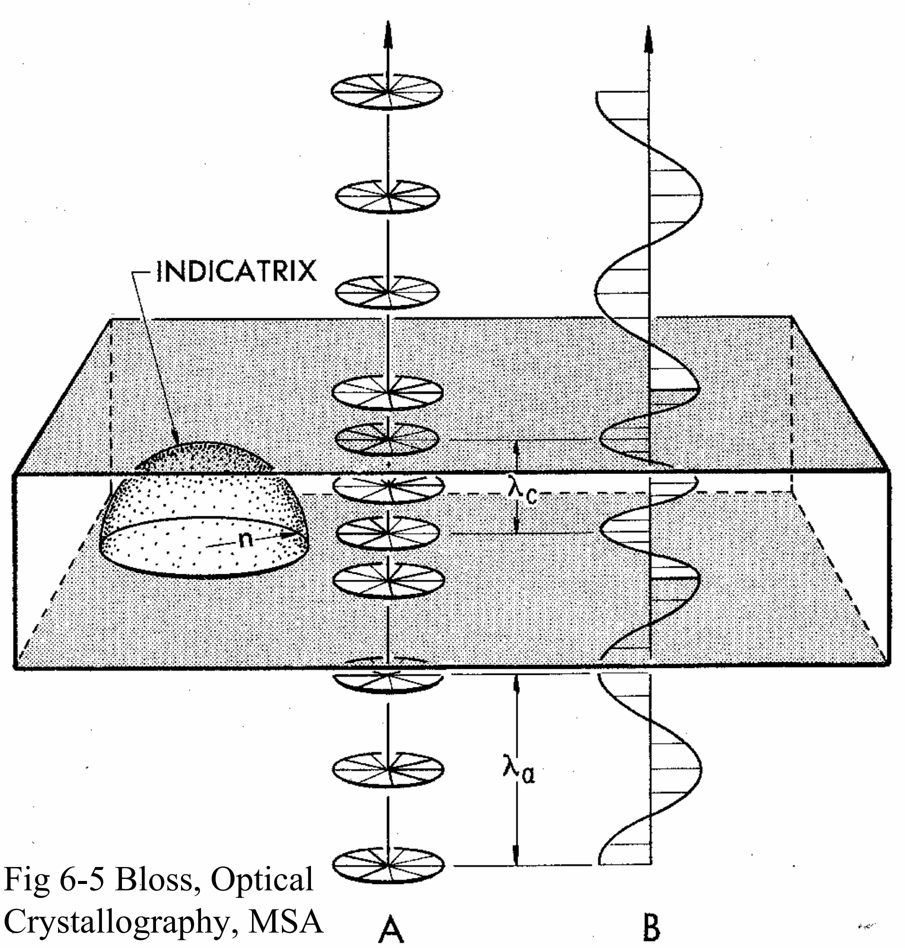


Fig 6-5 Bloss, Optical Crystallography, MSA

Conventions:

1) Indicatrix w/ center on interface surface

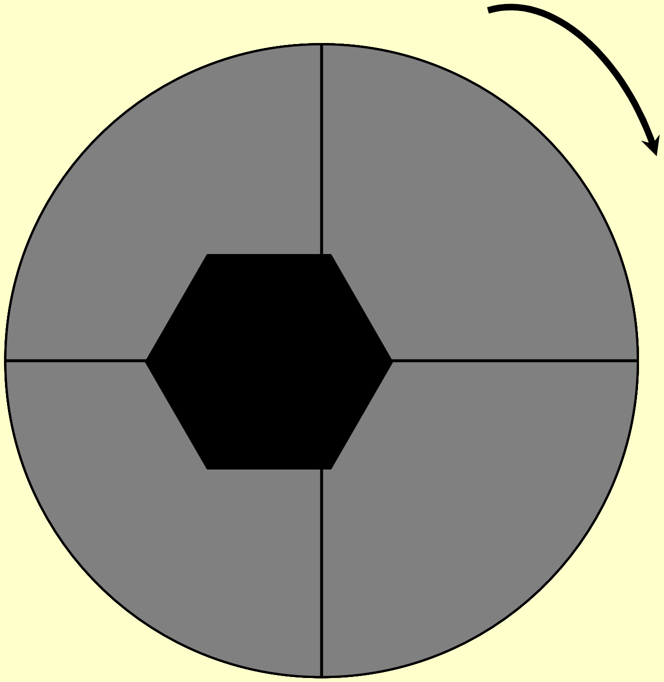
2) n (radial vectors of circular section in this case) same in all possible vibration directions

Incoming light can (and will) vibrate in the same direction(s) it did prior to entry

If unpolarized, it will remain so.

Only effect is slower velocity (rep. by closer symbol spacing)

Review: With any **isotropic** substance (spherical indicatrix), when the analyzer is inserted (= "crossed-nicols" or "**XPL**") no light passes → **extinct**, even when the stage is rotated



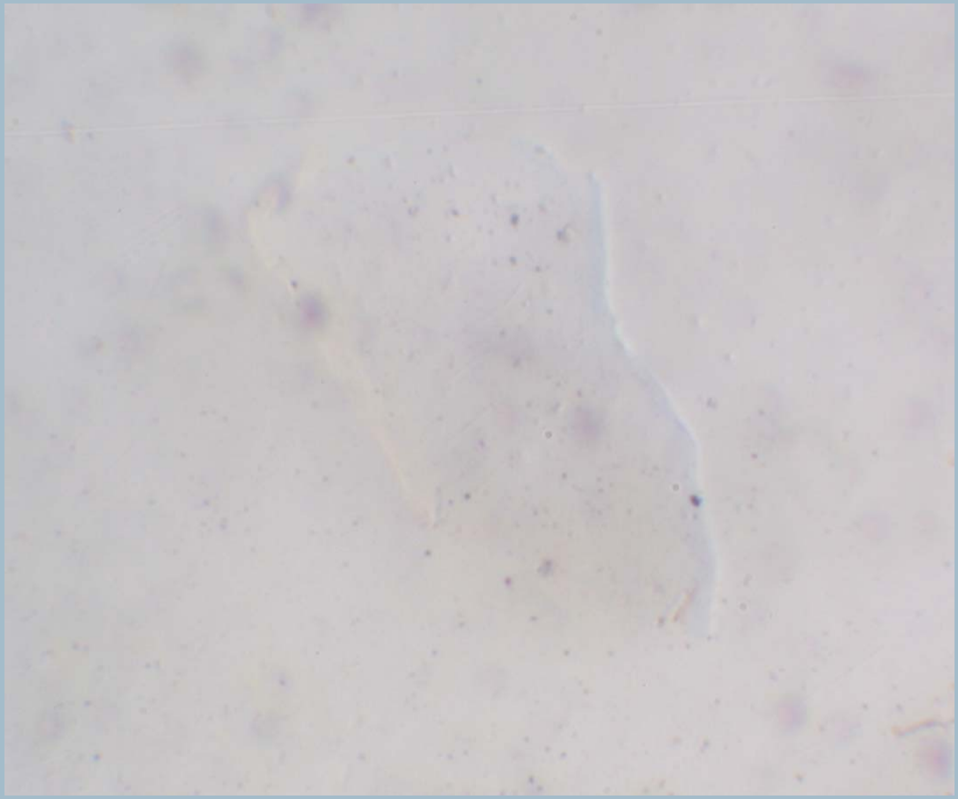
Note: the gray field should also be extinct (glass and epoxy of the thin section are also isotropic), but is left lighter for illustration

Liquids, gases, amorphous solids such as glass, and isotropic minerals (isometric crystal system) stay black in all orientations

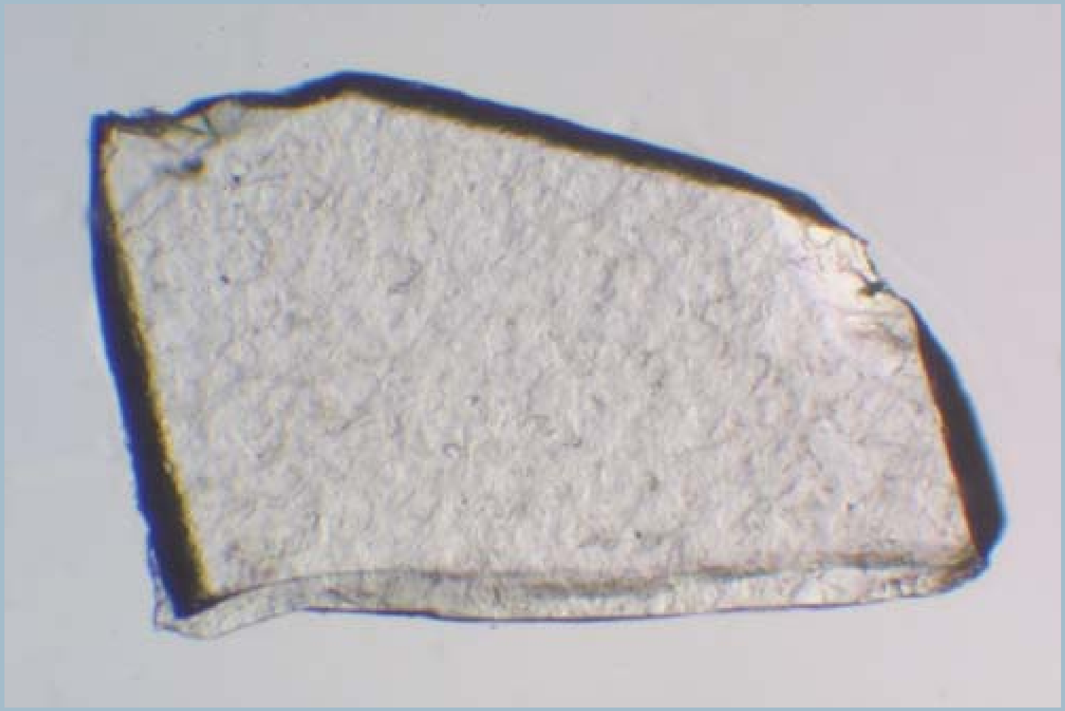
Mineral properties in PPL: **relief**

- Relief is a measure of the **relative** difference in **n** between a mineral grain and its surroundings
- Relief is determined visually, in PPL
- Relief is used to estimate n

garnet: n = 1.72-1.89
quartz: n = 1.54-1.55
epoxy: n = 1.54



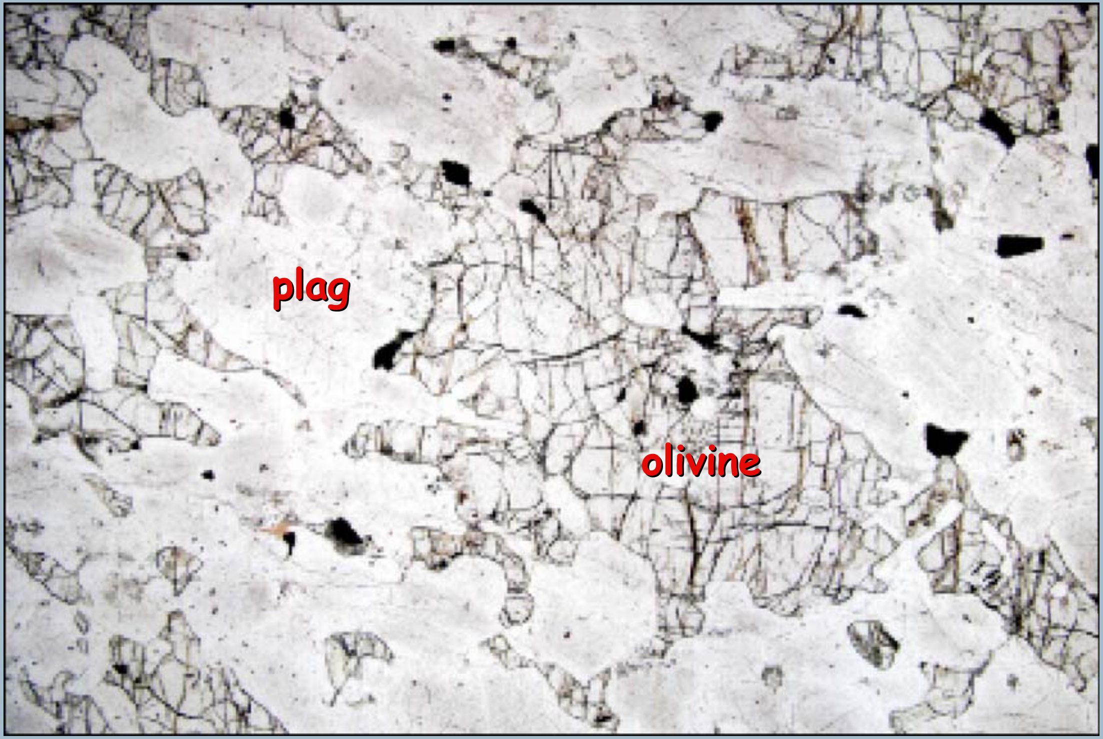
Quartz has low relief



Garnet has high relief

Mineral properties in PPL: **relief**

- Relief is a measure of the **relative** difference in **n** between a mineral grain and its surroundings
- Relief is determined visually, in PPL
- Relief is used to estimate n

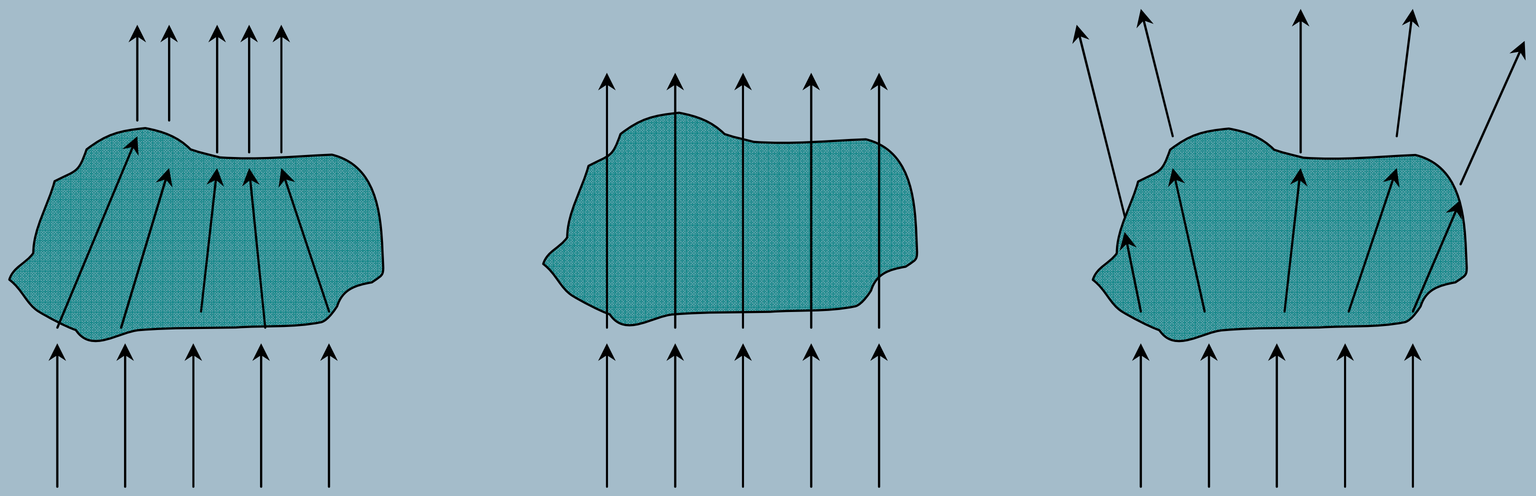


- Olivine has high relief
- Plagioclase has low relief

olivine:	n = 1.64-1.88
plag:	n = 1.53-1.57
epoxy:	n = 1.54

What causes relief?

Difference in speed of light (n) in different materials causes refraction of light rays, which can lead to focusing or defocusing of grain edges relative to their surroundings



Hi relief (+)

Lo relief (+)

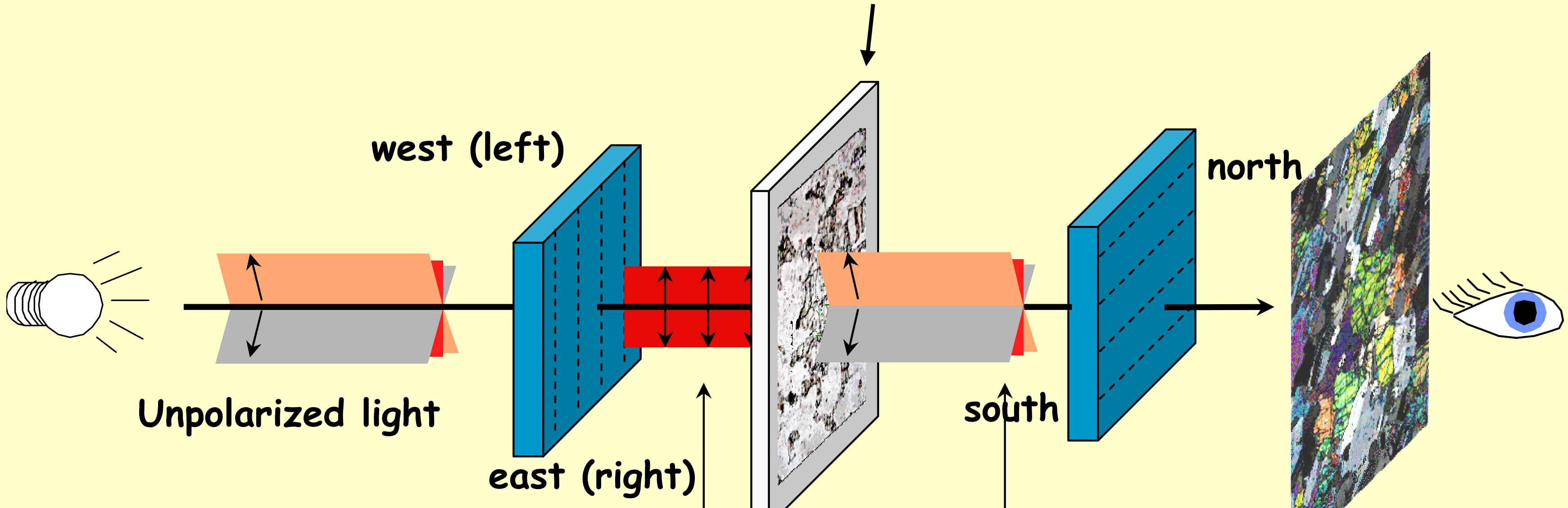
Hi relief (-)

$n_{xtl} > n_{epoxy}$

$n_{xtl} = n_{epoxy}$

$n_{xtl} < n_{epoxy}$

Now insert a **thin section** of a rock in XPL



west (left)

north

Unpolarized light

east (right)

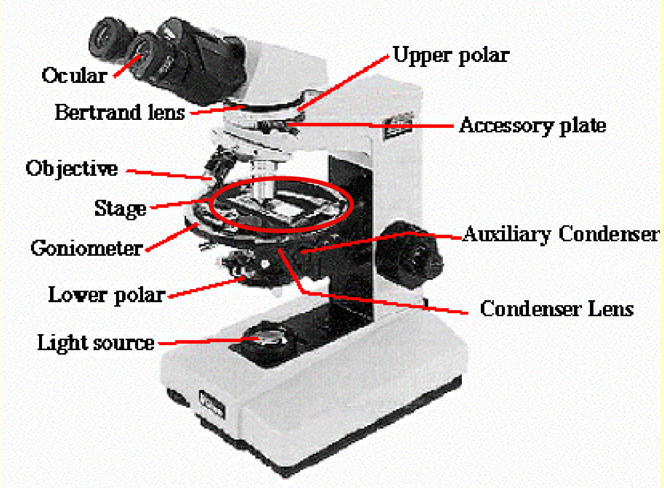
south

Light vibrating E-W

Light vibrating in
many planes and
with many
wavelengths

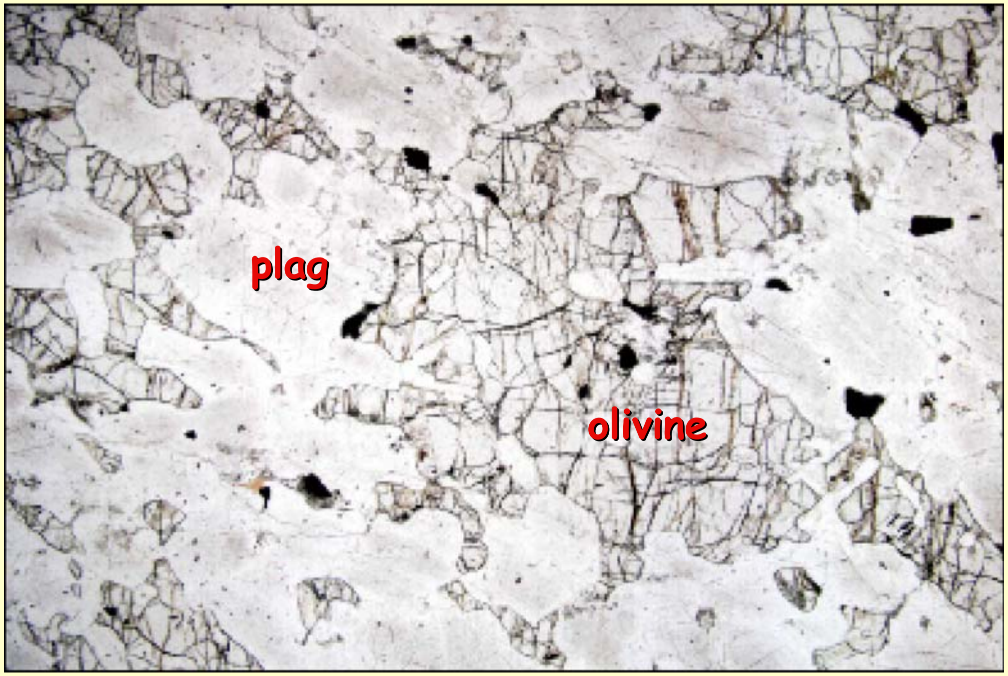
Light and colors
reach eye!

Petrographic Microscope

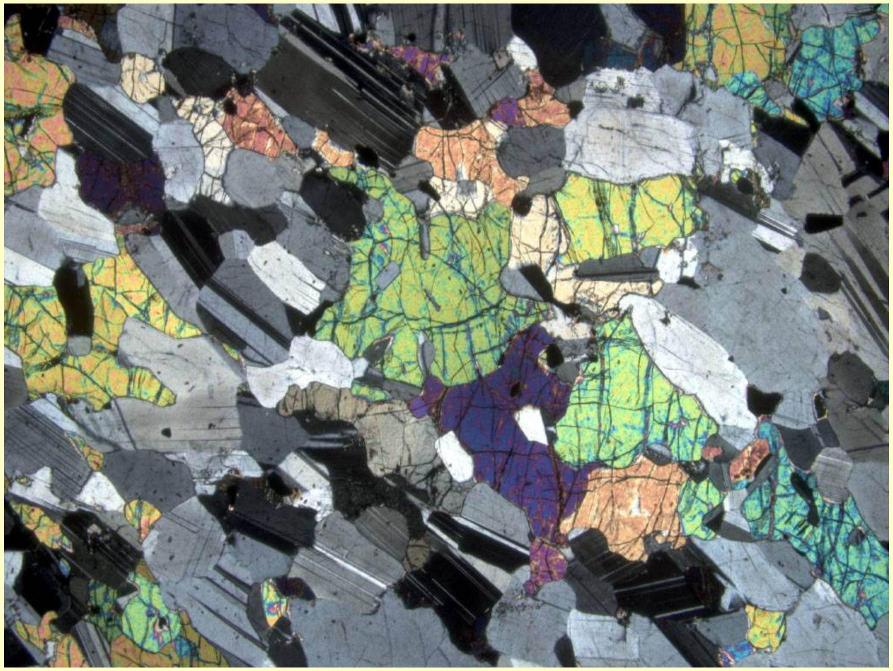


How does this work??

Conclusion has to be that minerals somehow **reorient** the planes in which light is vibrating; some light passes through the upper polarizer

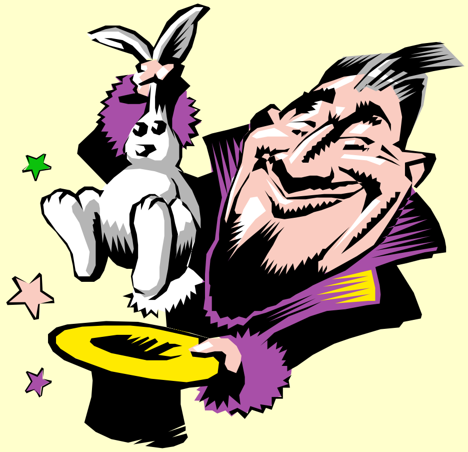


PPL



XPL

Minerals act as magicians!!



But, note that some minerals are better magicians than others (i.e., some grains stay dark and thus can't be reorienting light)

Anisotropic crystals

Calcite experiment and double refraction

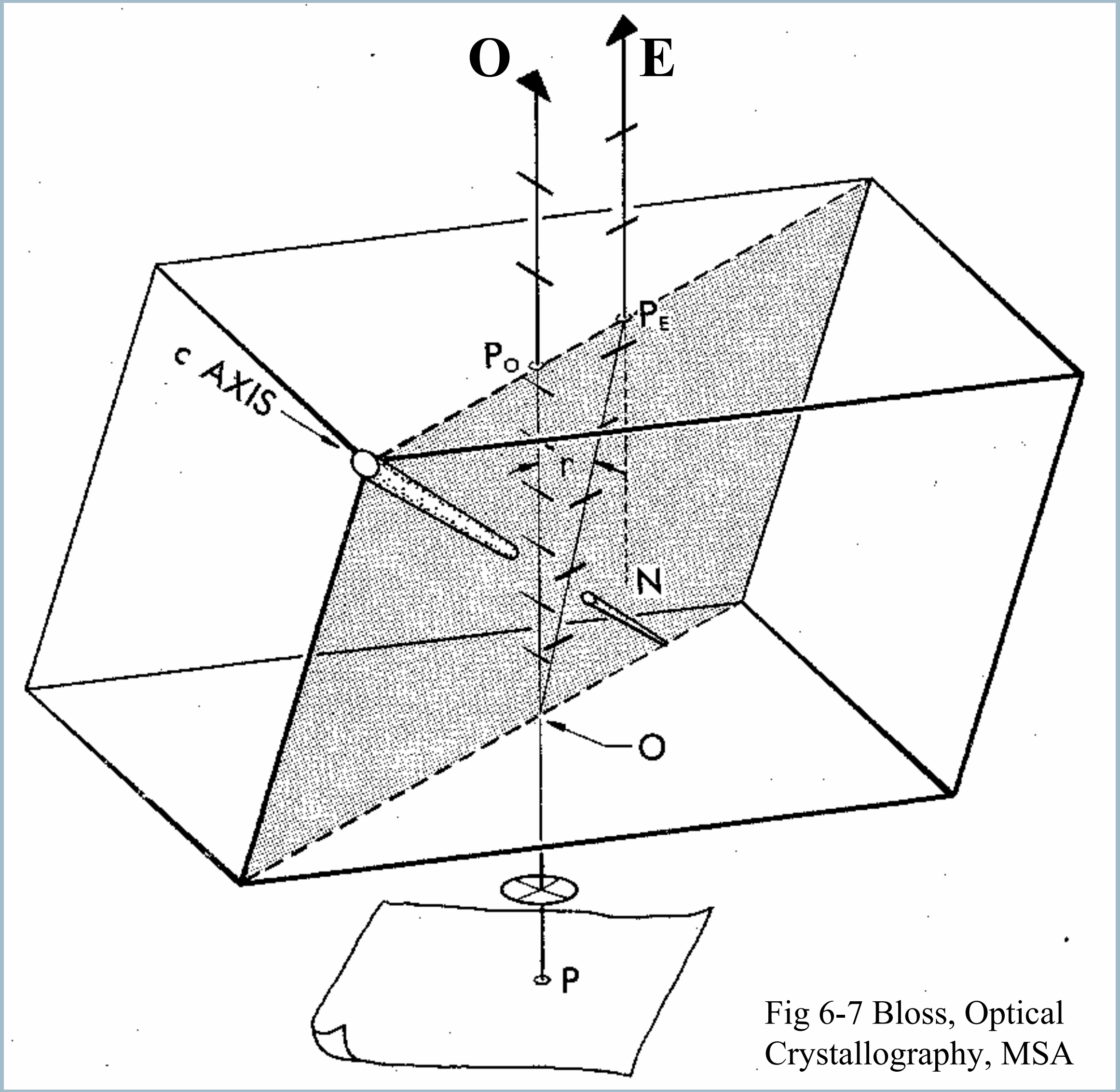


Fig 6-7 Bloss, Optical Crystallography, MSA

O-ray (Ordinary)

Obeys Snell's Law and goes straight

Vibrates ⊥ plane containing ray and c-axis ("optic axis")

E-ray (Extraordinary)

deflected

Vibrates in plane containing ray and c-axis

..also doesn't vibrate ⊥ propagation, but we'll ignore this as we said earlier

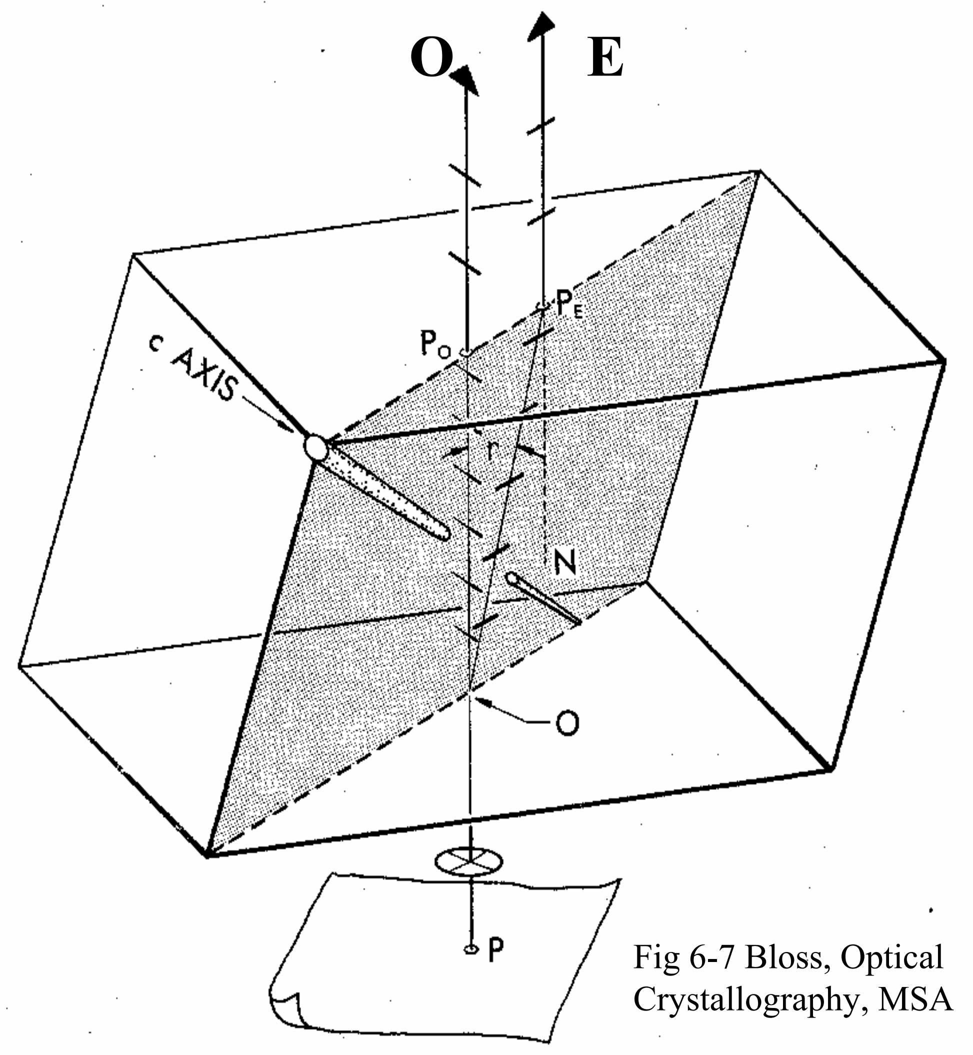


Fig 6-7 Bloss, Optical Crystallography, MSA

IMPORTANT: A given ray of incoming light is restricted to only 2 (mutually perpendicular) vibration directions once it enters an anisotropic crystal

Called privileged directions

Each ray has a different n

$\omega = n_o$

$\varepsilon = n_E$

in the case of calcite $\omega < \varepsilon$

…which makes the O-ray dot appear above E-ray dot

Some generalizations and vocabulary

- Amorphous materials and isometric minerals (e.g., *garnet*) are **isotropic** – they cannot reorient light. These minerals are always extinct in crossed polars (XPL).
- All other minerals are **anisotropic** – they are all capable of reorienting light (acting as magicians).
- All **anisotropic** minerals contain one or two special *propagation* directions that do **not** reorient light.
    - Minerals with **one** special direction are called **uniaxial**
    - Minerals with **two** special directions are called **biaxial**

$n > 1$ for ani

$n = f($v

Indicatrix r

Indicatrix =

Note: psoid.

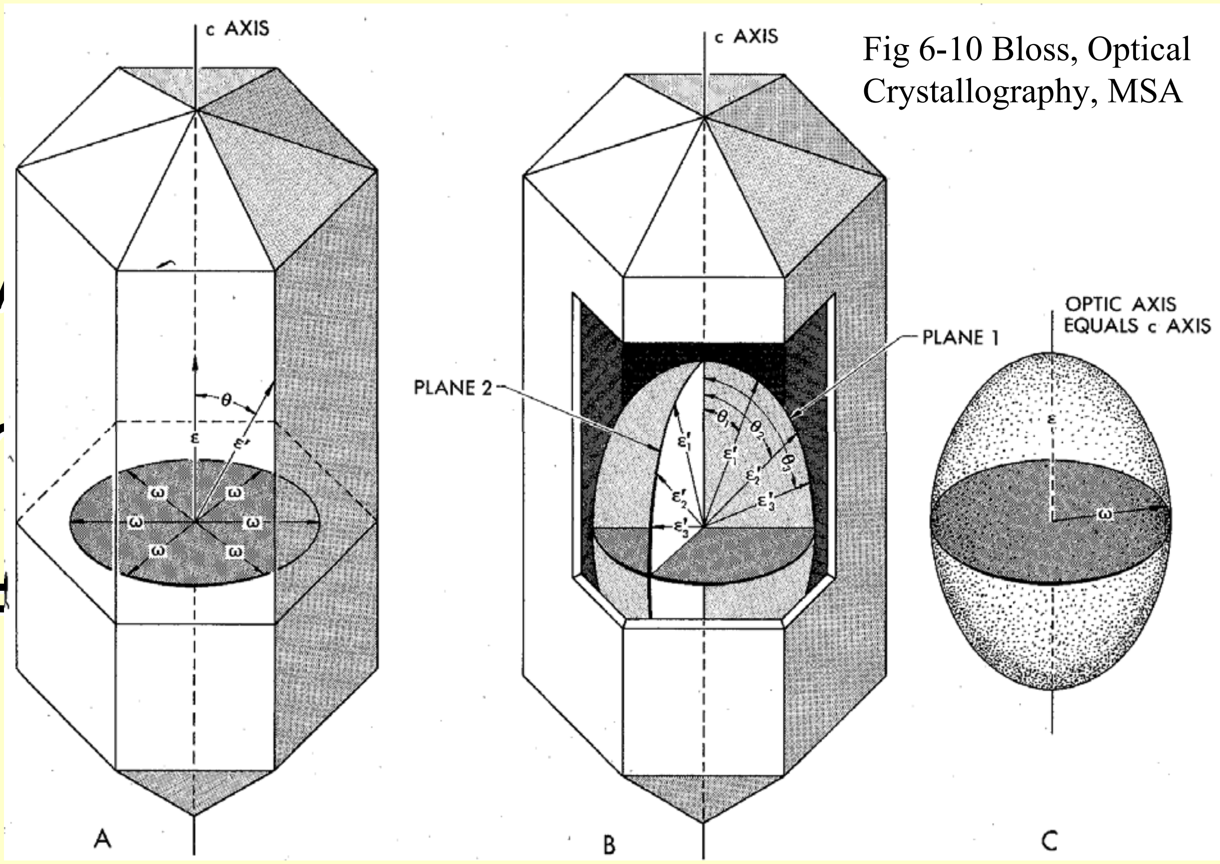


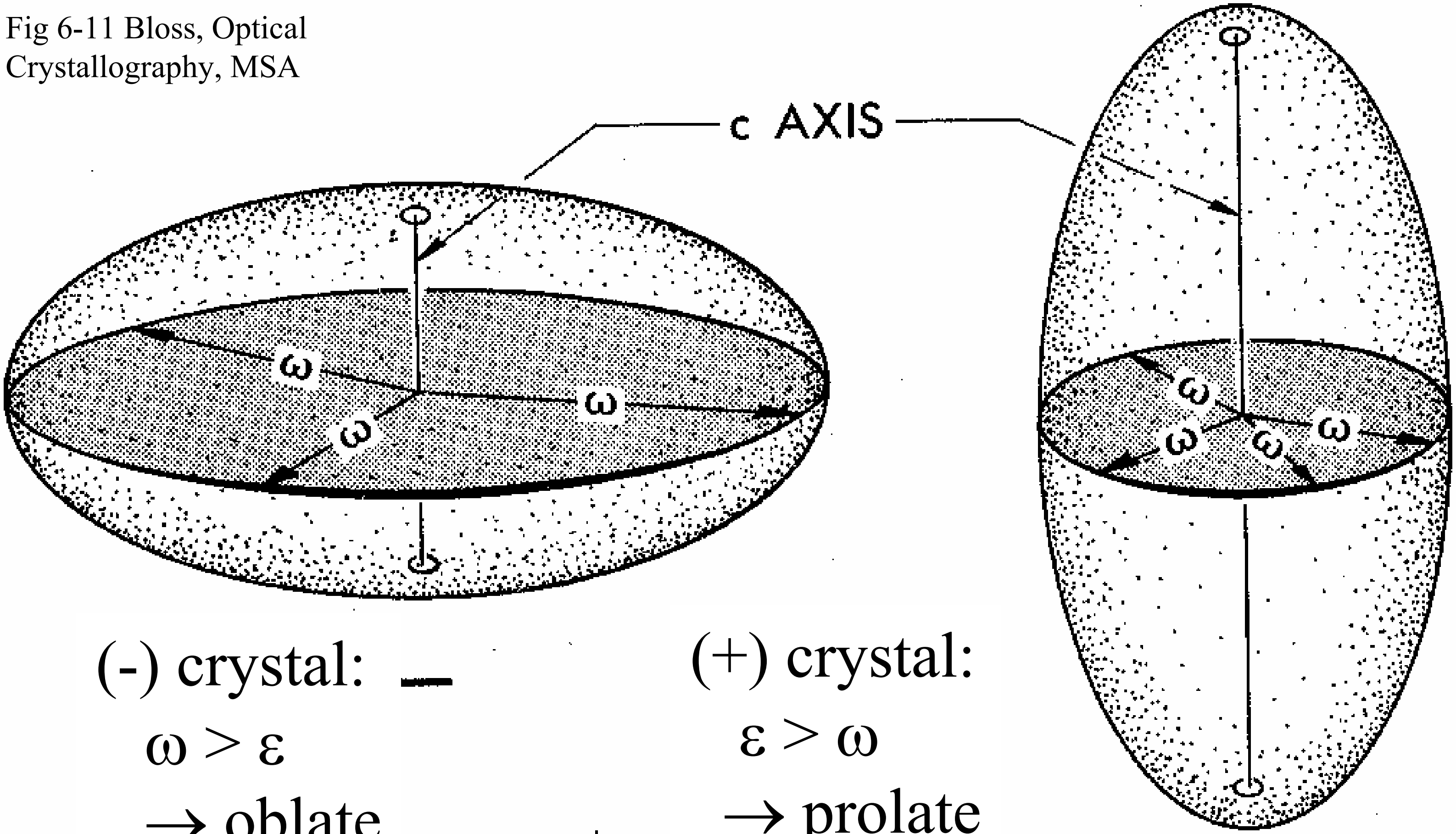
Fig 6-10 Bloss, Optical Crystallography, MSA

Hexagonal and tetragonal crystals have one unique crystallographic axis (c axis) ⊥ 2 identical ones

The optical properties reflect this as well: **ellipsoid of rotation about c** (optically **uniaxial**) and c = the **optic axis**

Uniaxial ellipsoid and conventions:

Fig 6-11 Bloss, Optical Crystallography, MSA



(-) crystal:

ω > ε

→ oblate

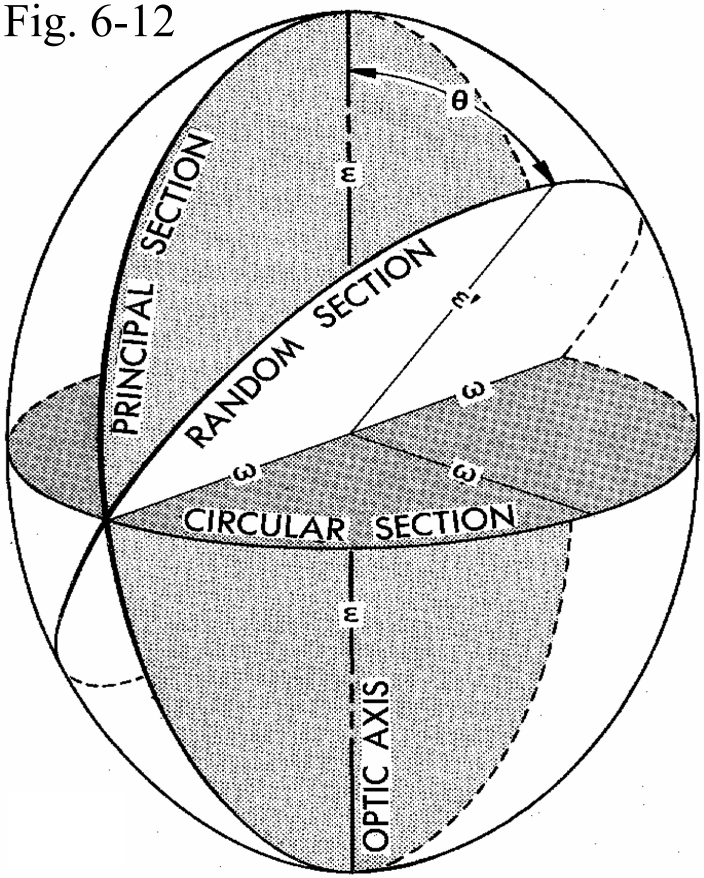
(+) crystal:

ε > ω

→ prolate

Depending on light propagation we can have:

Fig. 6-12



- Circular Section
  - $\perp$ optic axis: all ω's
- Principal Sections
  - have ω and true ε: max & min n's
- Random Sections (ε' and ω)
- All sections have ω!!

Any non-circular cut through the center of a uniaxial indicatrix will have ω as one *semiaxis and* ε' (or true ε) as the other

Calcite experiment and double refraction

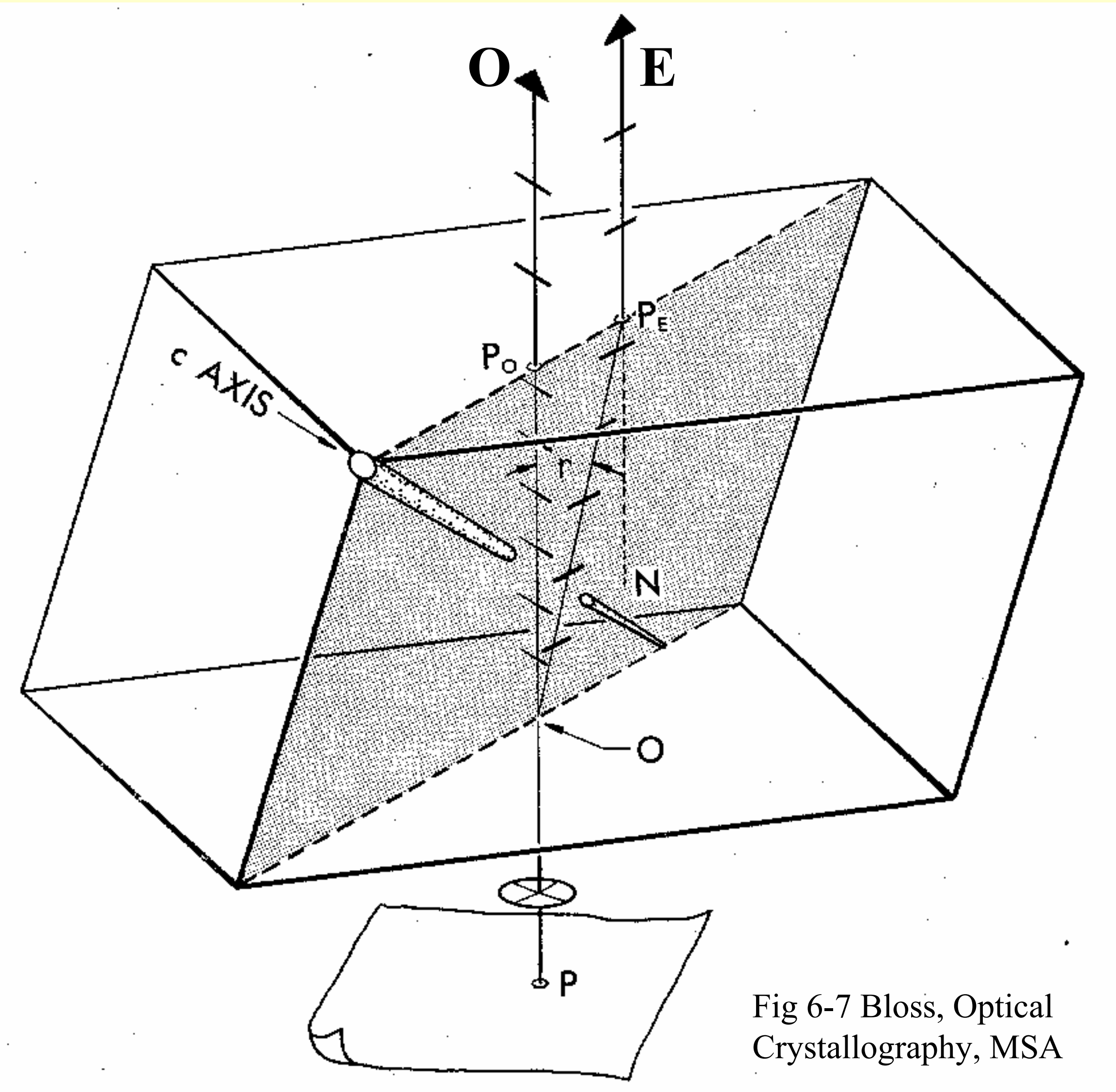


Fig 6-7 Bloss, Optical Crystallography, MSA

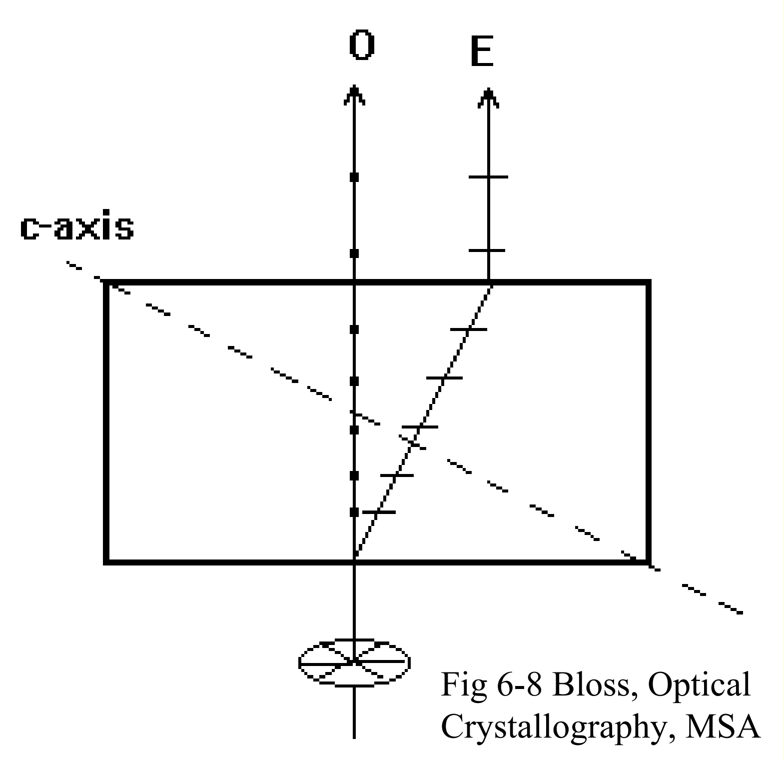


Fig 6-8 Bloss, Optical Crystallography, MSA

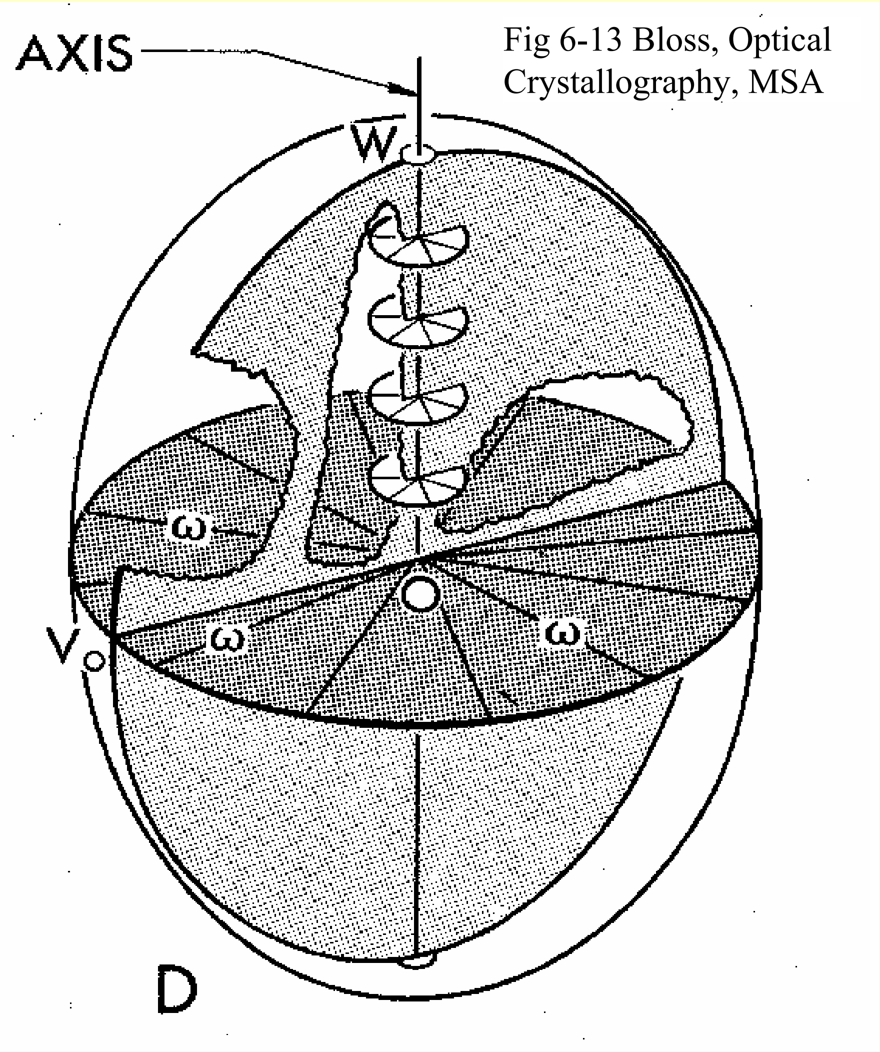


Fig 6-13 Bloss, Optical Crystallography, MSA

Circular Section: all rays are O-rays and vibrate parallel ω

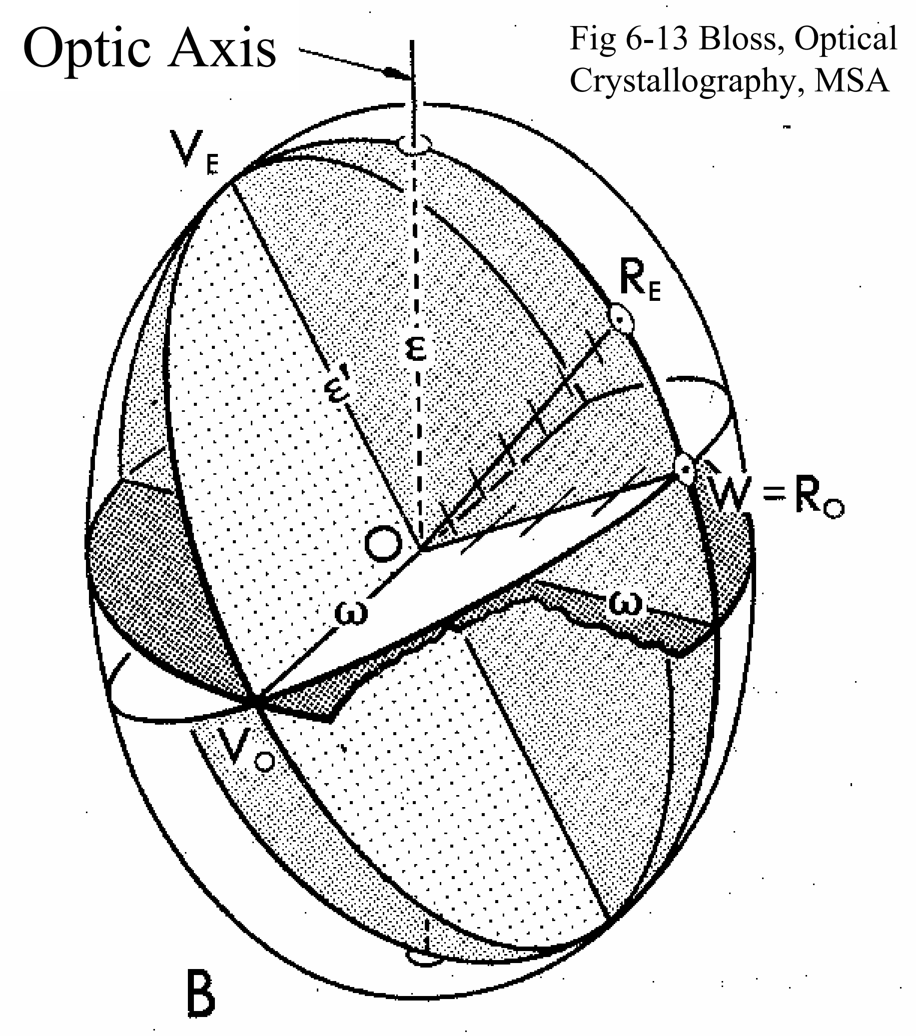
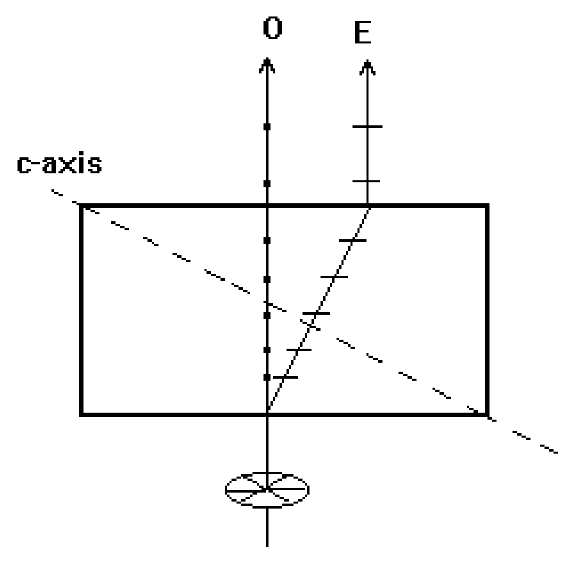


Fig 6-13 Bloss, Optical Crystallography, MSA



Random Section: O-ray vibrates parallel ω

E-ray vibrates parallel ε'

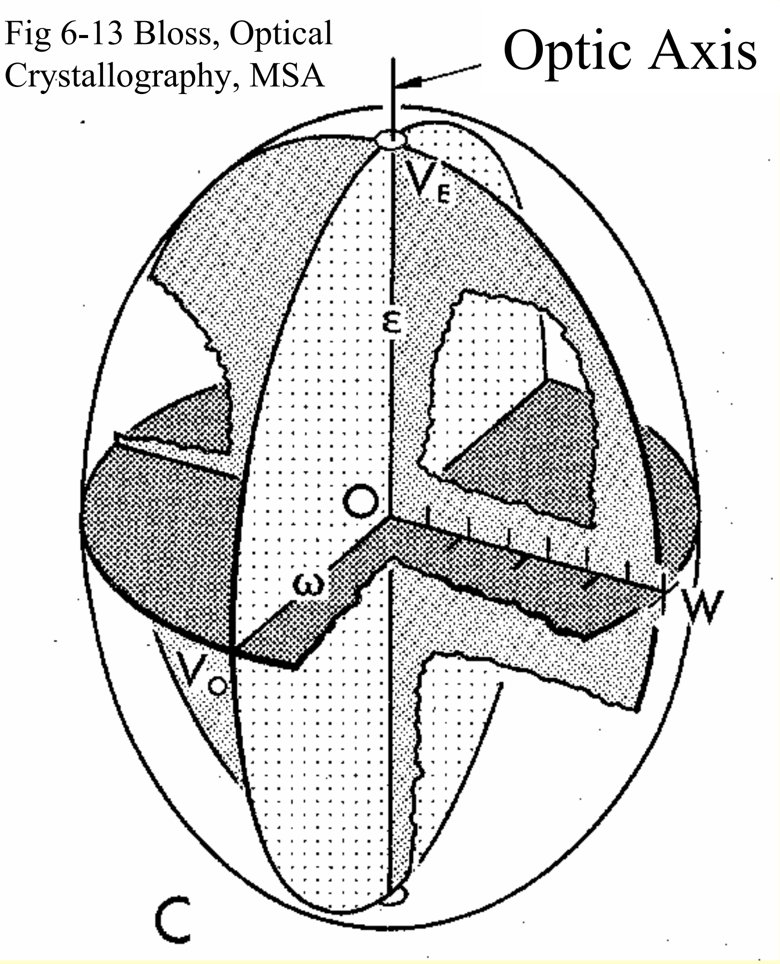


Fig 6-13 Bloss, Optical Crystallography, MSA

Principal section:

This is essentially the same as random, but here ε' is really true ε.

In this case both rays really do vibrate ⊥ propagation & follow same path (as we have simplified the random case)

We shall consider random and principal as alike, only the value of ε varies.

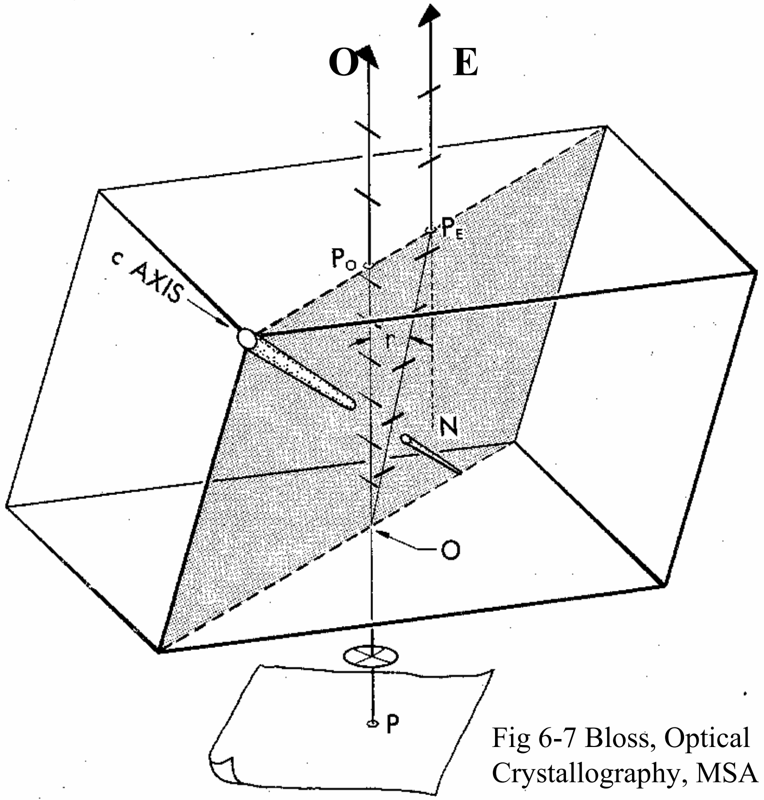


Fig 6-7 Bloss, Optical Crystallography, MSA

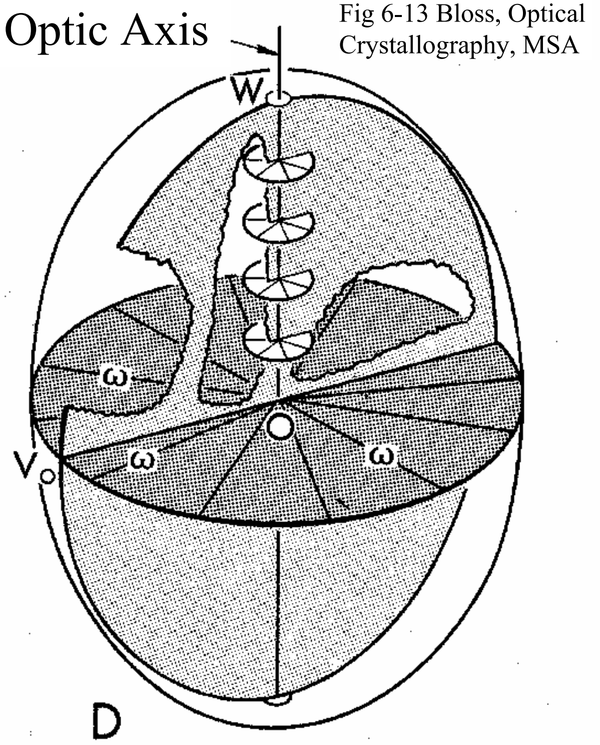
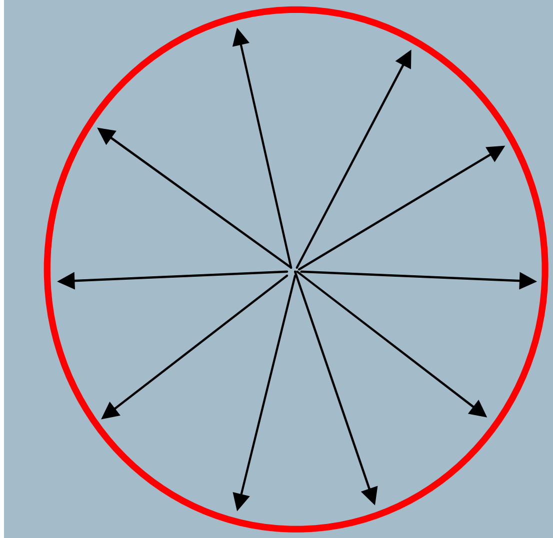


Fig 6-13 Bloss, Optical Crystallography, MSA

Essentially 2 possibilities (light coming toward you)



1. Circular section

- Light prop. || OA
- All vibration directions ⊥c are the same n

- Like isotropic

  (no unique plane containing ray and c-axis)
- Only one ray (O-ray) with n = ω (doesn't split to two rays)
- Extinct with analyzer in and stays that way as rotate stage (behaves as though isotropic)
- If incident light is unpolarized it will remain so

Essentially 2 possibilities (light coming toward you)

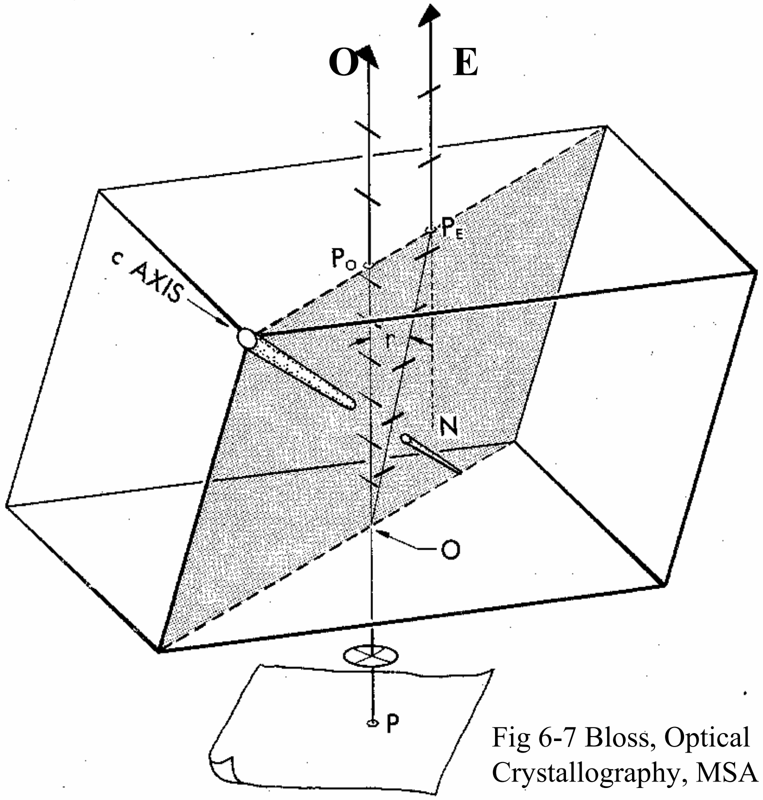
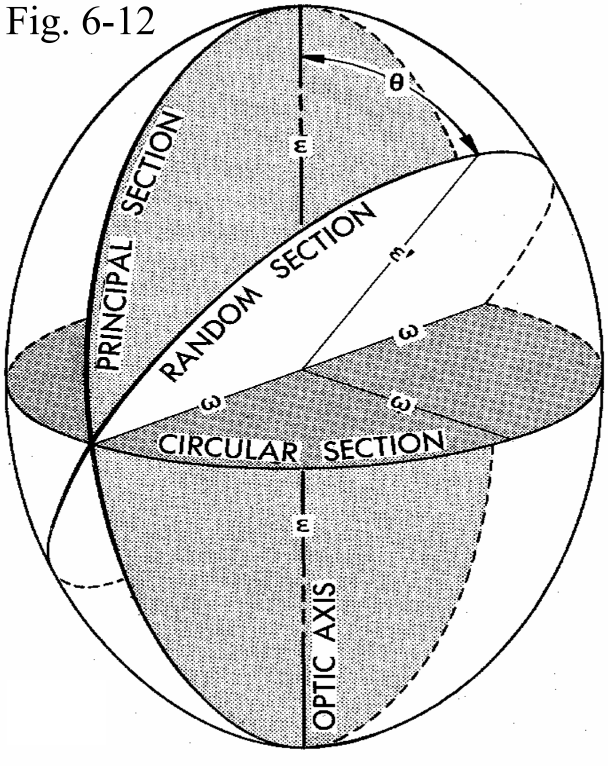
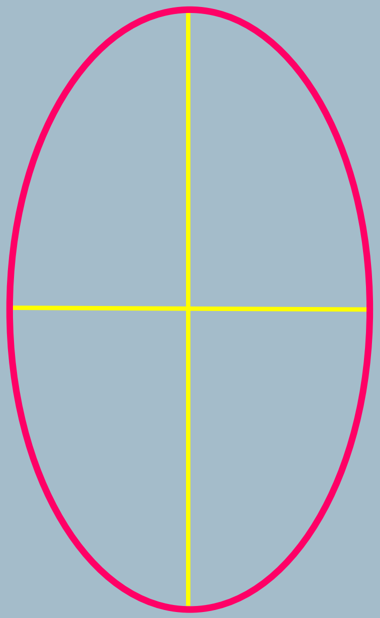


Fig 6-7 Bloss, Optical Crystallography, MSA

Fig. 6-12





2. Elliptical section

- Any orientation other than circular

- 2 rays
- Only 2 privileged vibration directions
- O-ray with n = ω
- E-ray with n = ε′ or ε (depending on section)
- Does not stay same as rotate (more later)

D: Polarized at random angle

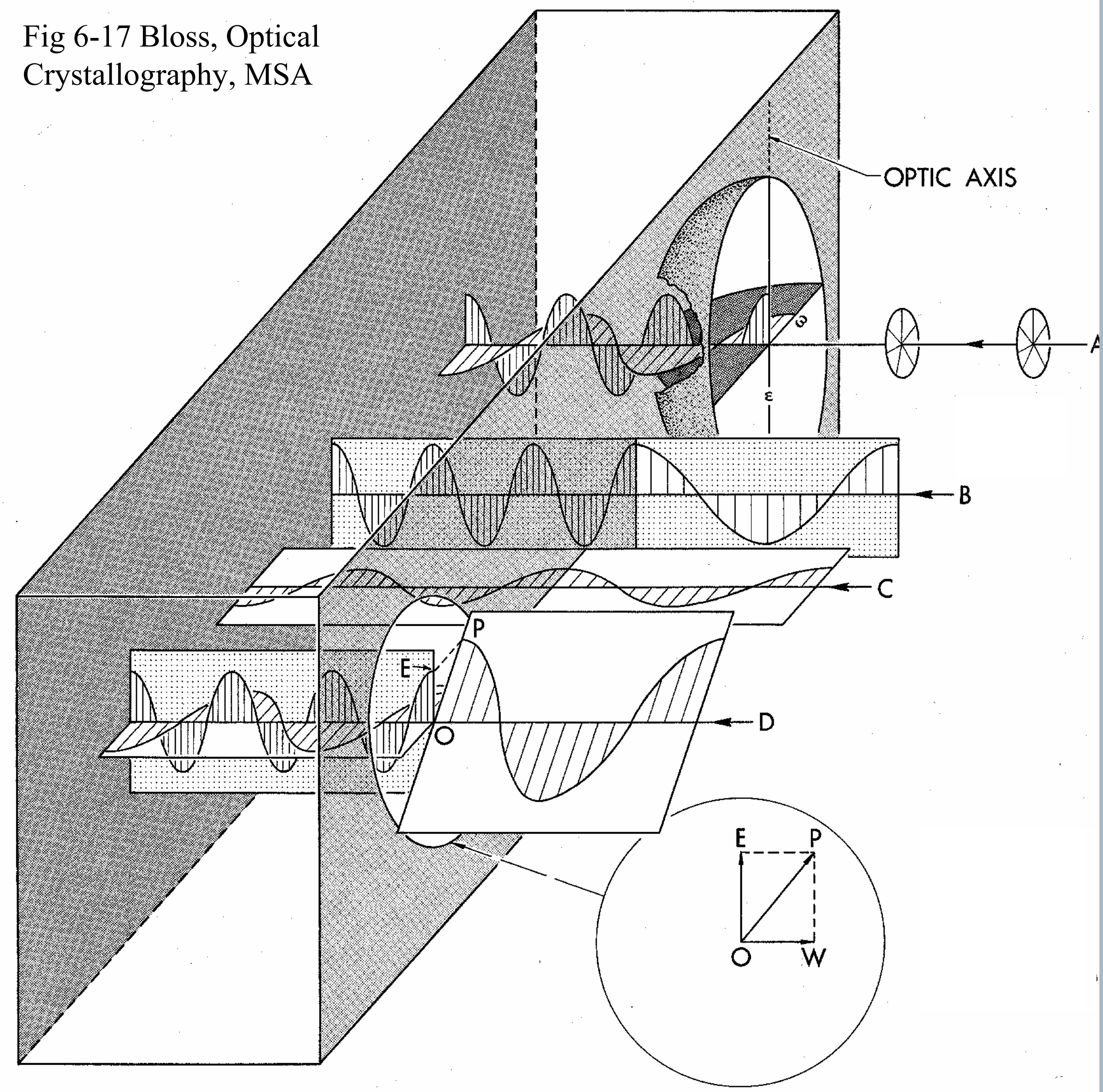


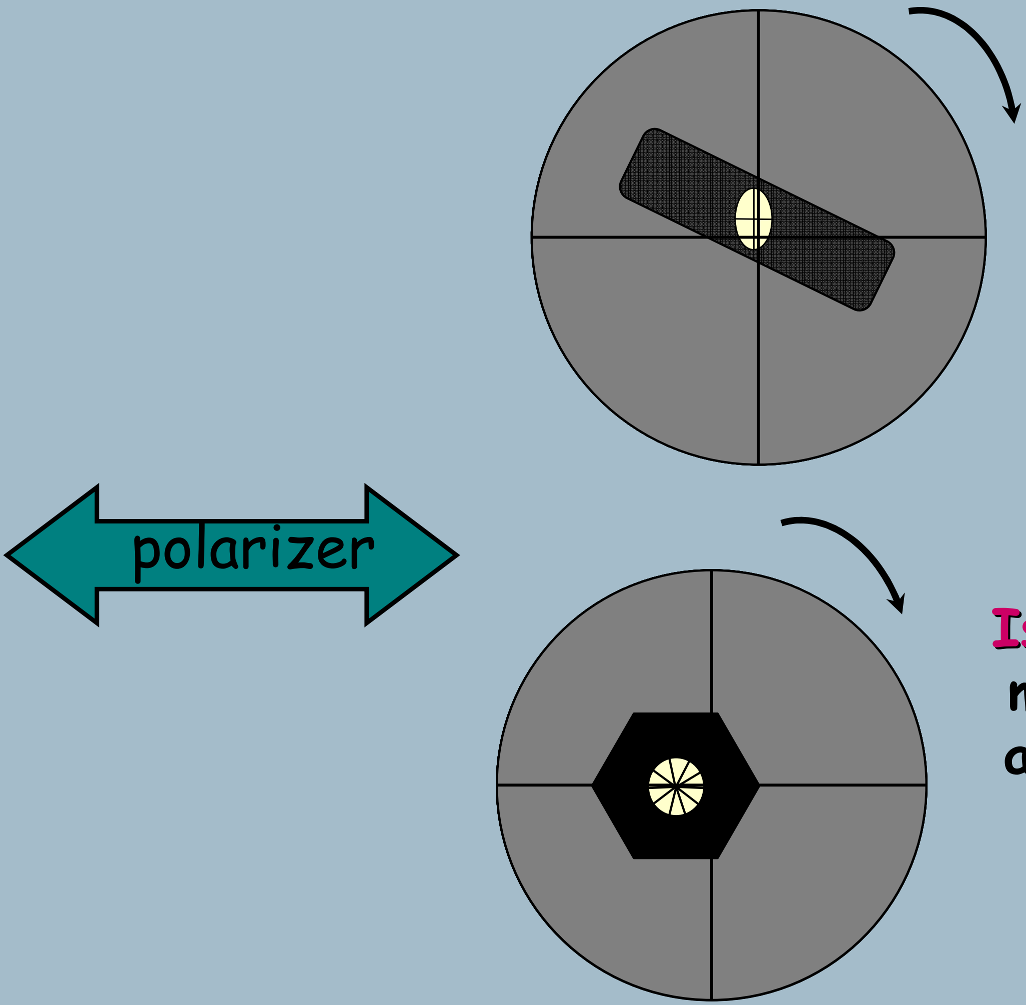
Fig 6-17 Bloss, Optical Crystallography, MSA

Resolves into components parallel ε and parallel ω

This figure rotates the light source
(we rotate the crystal)

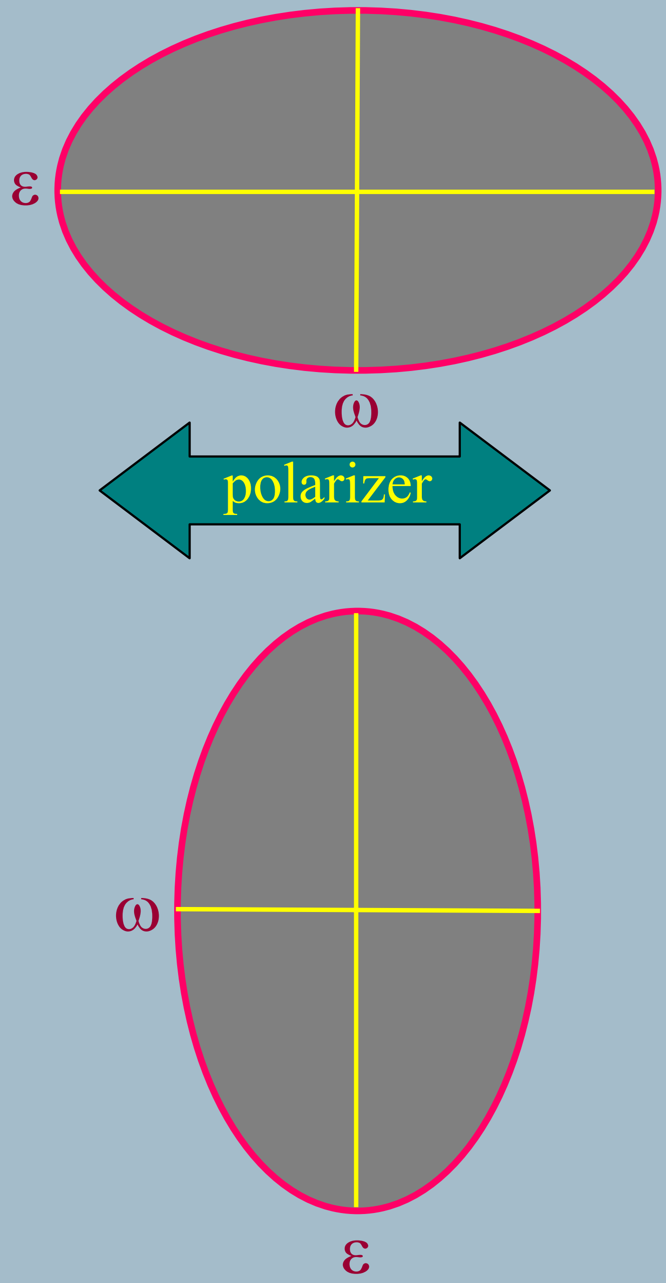
Rotating the stage

Anisotropic minerals **with an elliptical indicatrix section** change color as the stage is rotated; these grains go black 4 times in 360° rotation-**exactly every 90°**



Isotropic: glass or isometric minerals or look down optic axis of anisotropic minerals

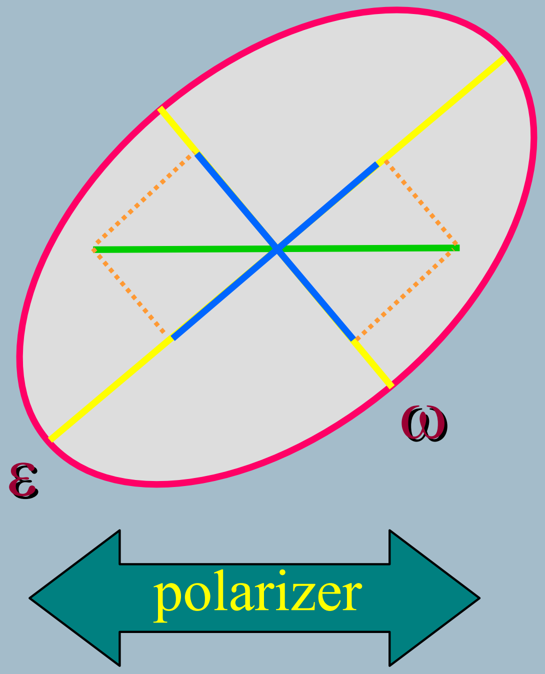
Consider rotating the crystal as you watch:



B = polarizer vibration direction parallel ε
→ only E-ray
Analyzer in → **extinct**

C = polarizer vibration direction || ω
→ only O-ray
also → **extinct** with analyzer

Consider rotating the crystal as you watch:



D

Polarized light has a component of each

Splits → two rays

one is O-ray with $n = \omega$

other is E-ray with $n = \varepsilon$

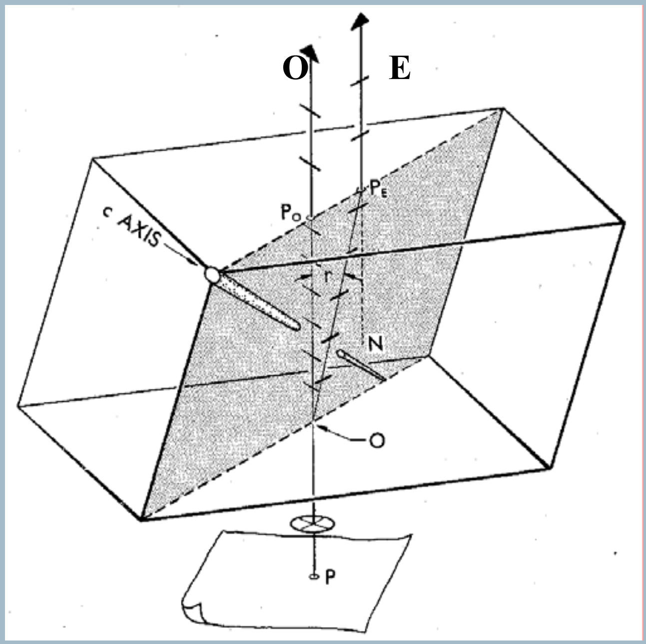
When the rays exit the crystal they

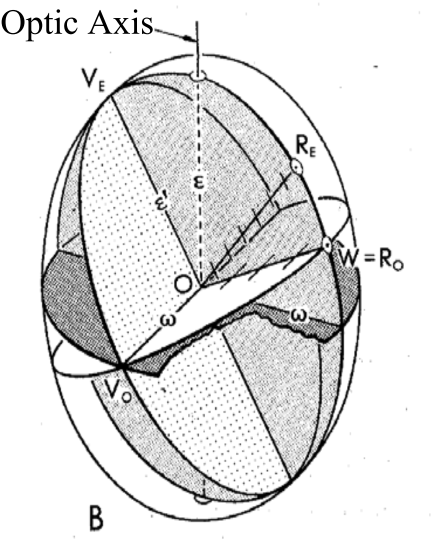
recombine

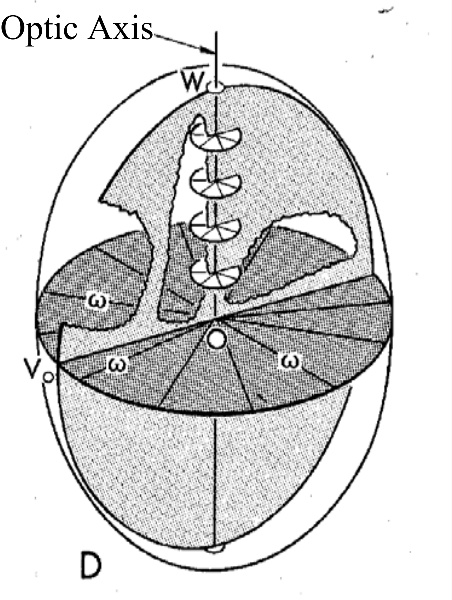
REVIEW

- Calcite: Fig 6-7
  - 2 rays, each polarized
  - vibrate ⊥ each other & in plane of incidence
- Indicatrix- uniaxial
  - Random Section
    - O-ray vibrates paralle
    - E-ray vibrates parallel
  - Principal section
  - Circular section

ε' and ω = "privileged vibration directions"







Interference

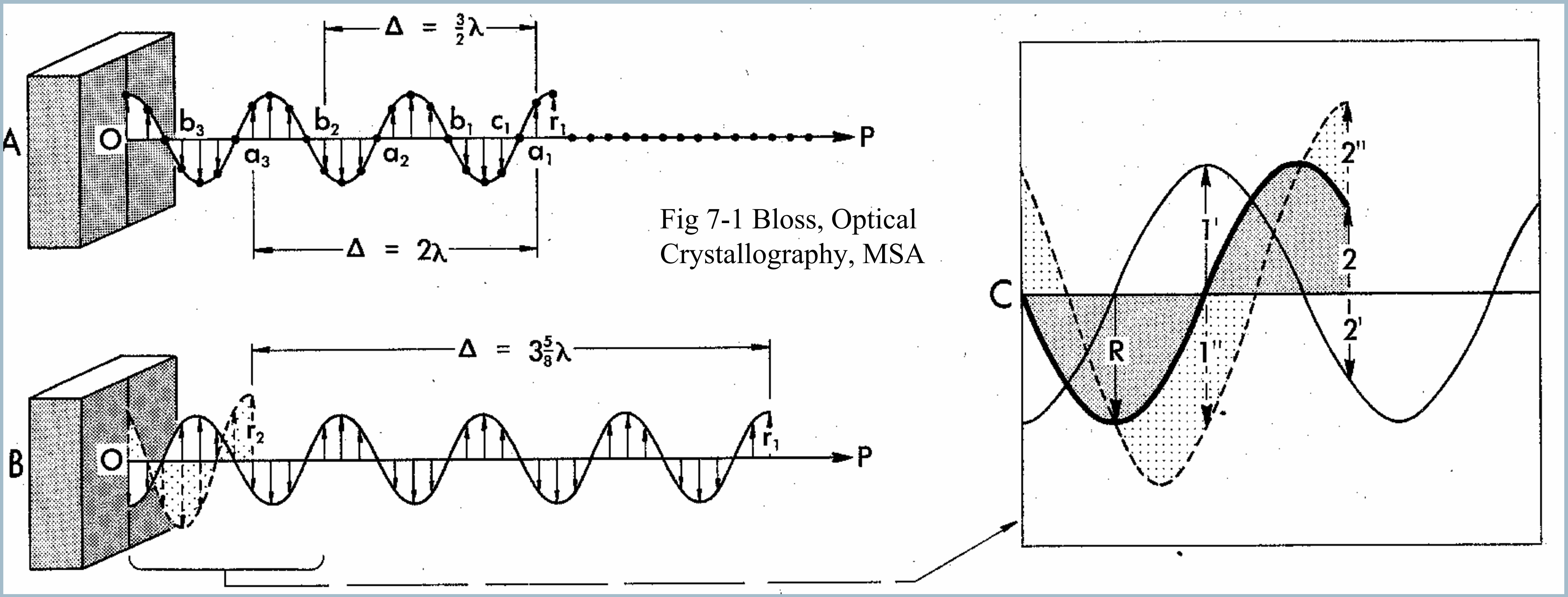


Fig 7-1 Bloss, Optical Crystallography, MSA

B: Instant later with a second ray entering

C: Shows algebraic sum → interference → **composite ray**

If both waves in phase → **constructive interference** with amplitude greater than either (intensity = A^2)

Interference

Fig 7-2 Bloss, Optical Crystallography, MSA

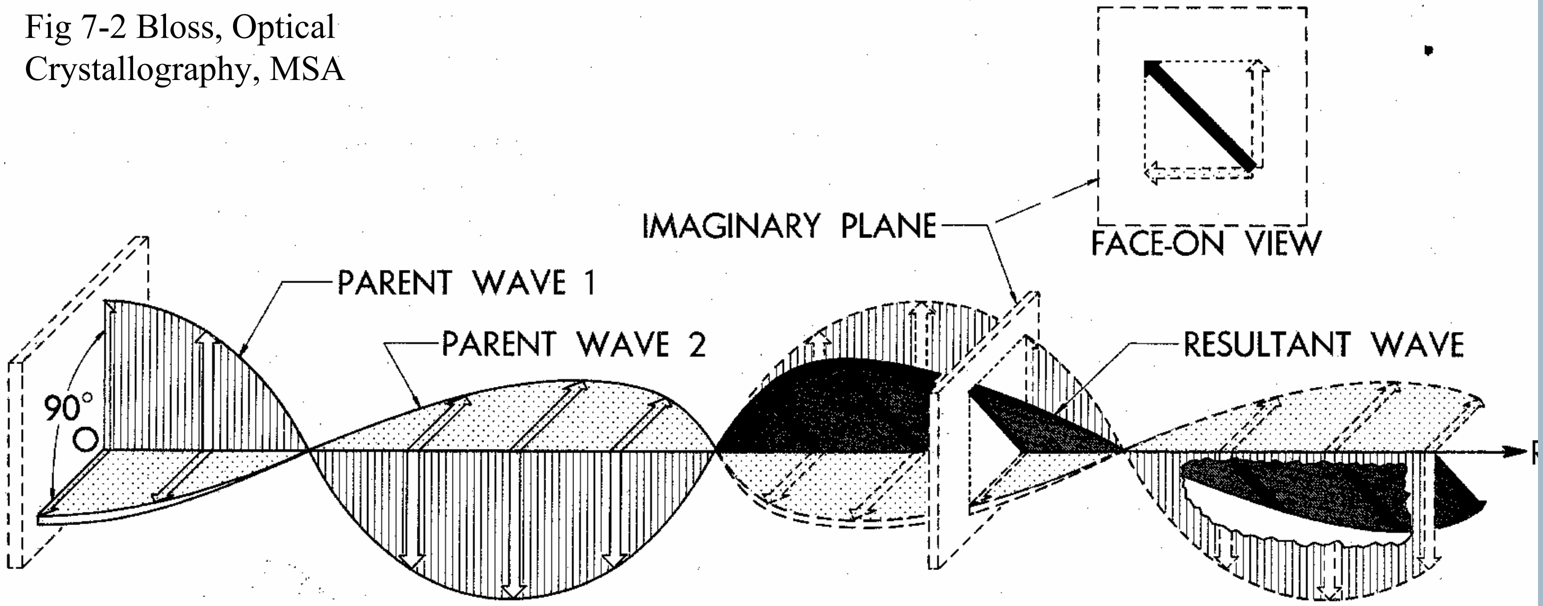


Fig. 7-2. Interference between two waves, polarized in mutually perpendicular planes, to produce a resultant wave motion (polarized in another plane). The imaginary plane indicates how, at any point along *OR*, the vibration vectors of the two parent motions (hollow arrows) may be added vectorially to produce the vibration vectors (solid arrows) of the resultant wave.

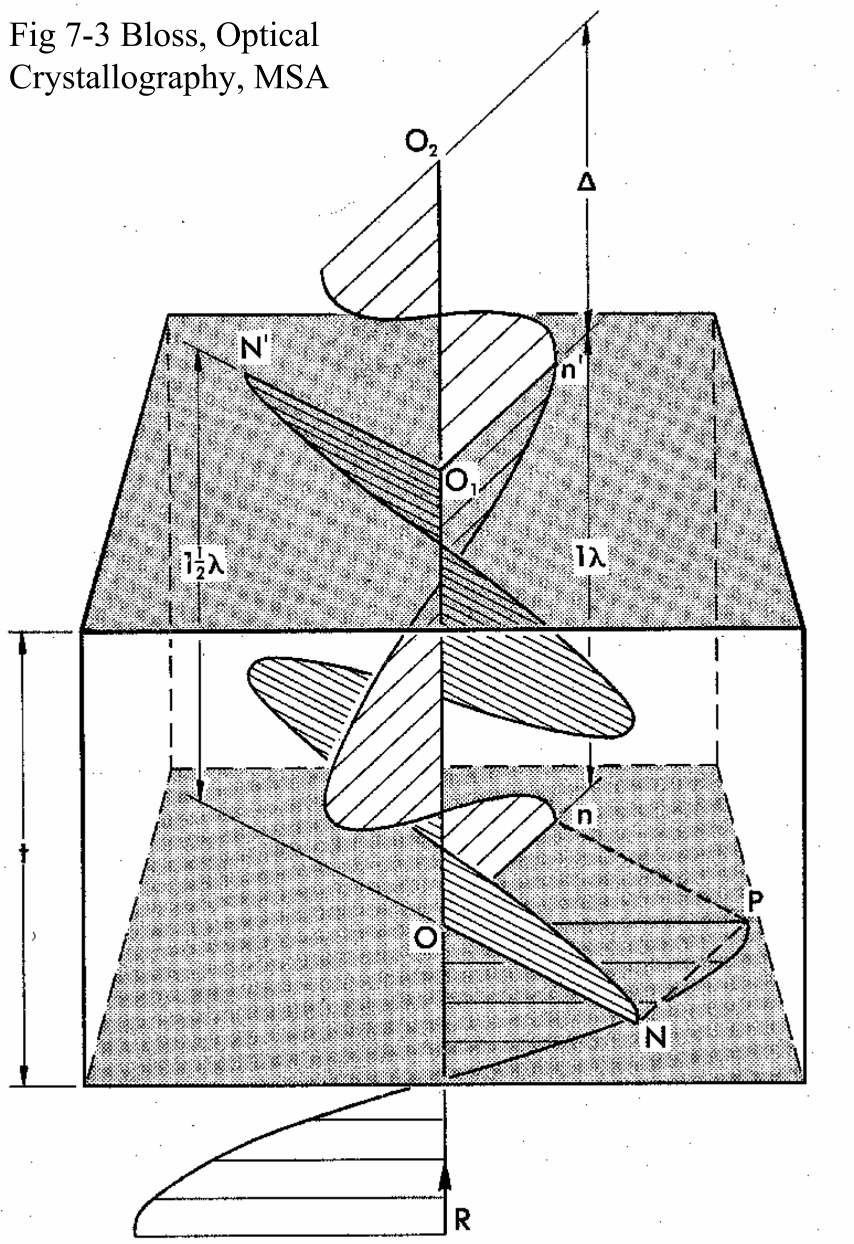
Interference of light polarized in perpendicular planes

- This works in air & isotropic media, but not in crystals where vibrate independently

Now we're ready for a big step

Interference

Fig 7-3 Bloss, Optical Crystallography, MSA



Plane polarized light enters xl. & resolved into 2 rays (if not || optic axis), which vibrate ⊥ each other & **travel at different velocities** (since have different n)

- Will thus **travel diff # of λ** (even if frequency same or similar)
- **So if in phase when enter, won't be when exit!!**
- The **path diff** (Δ) between O-ray and E-ray **= t (|ω-ε'|)** (t = thickness)
  - absolute value because the crystal can be (+) or (-)
- Δ then = t(N-n) and each mineral has a ~unique ω and ε, Δ is thus a function of the **thickness**, the **mineral** observed, and the **orientation**

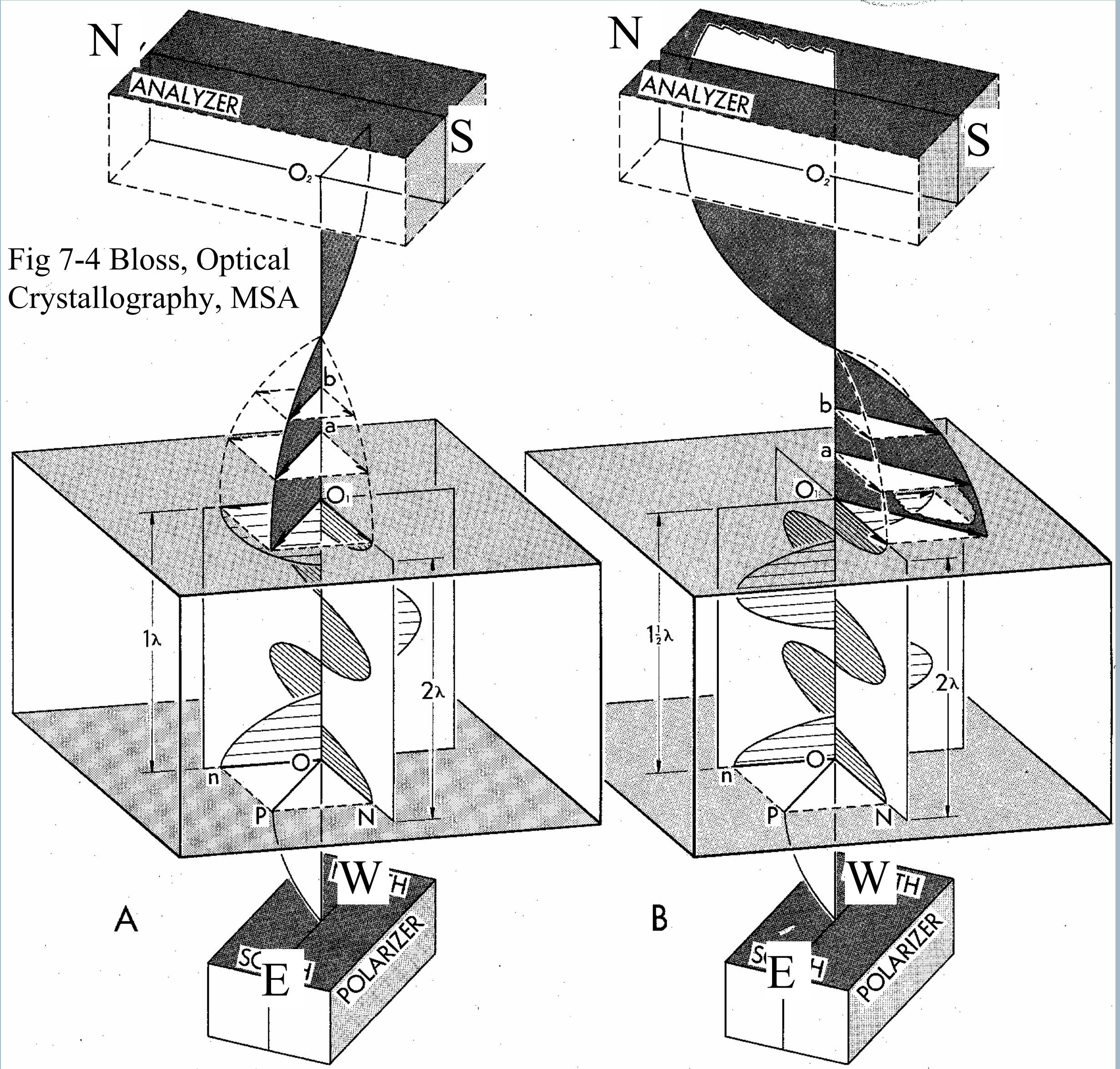


Fig 7-4 Bloss, Optical Crystallography, MSA

Fig. 7-4. The mutual interference, after their emergence from an anisotropic crystal at 45 degrees off extinction, of what were formerly the slow and fast waves within the crystal. In (A), passage through the crystal has produced a path difference of 1λ between these waves, and their resultant wave motion after exit at O_1 is polarized in the same plane as the light from the polarizer. For (B), where their path difference is $\frac{1}{2}\lambda$, the resultant wave motion after exit at O_1 is at 90 degrees to the plane of polarization of light from the polarizer. Between crossed nicols, therefore, the resultant light emergent from the crystal is for (A) completely extinguished by the analyzer but for (B) completely transmitted (reflectional and absorptional losses being neglected).

Interference

2 crystals of equal t, but different Δn_i

A: $n = {}^1/_2 N$

n=small ref index

N=large " "

- slow ray requires 2 periods & fast only one
- thus come out **polarized in same plane as entered**
- **→ no transmission by analyzer in XPL**

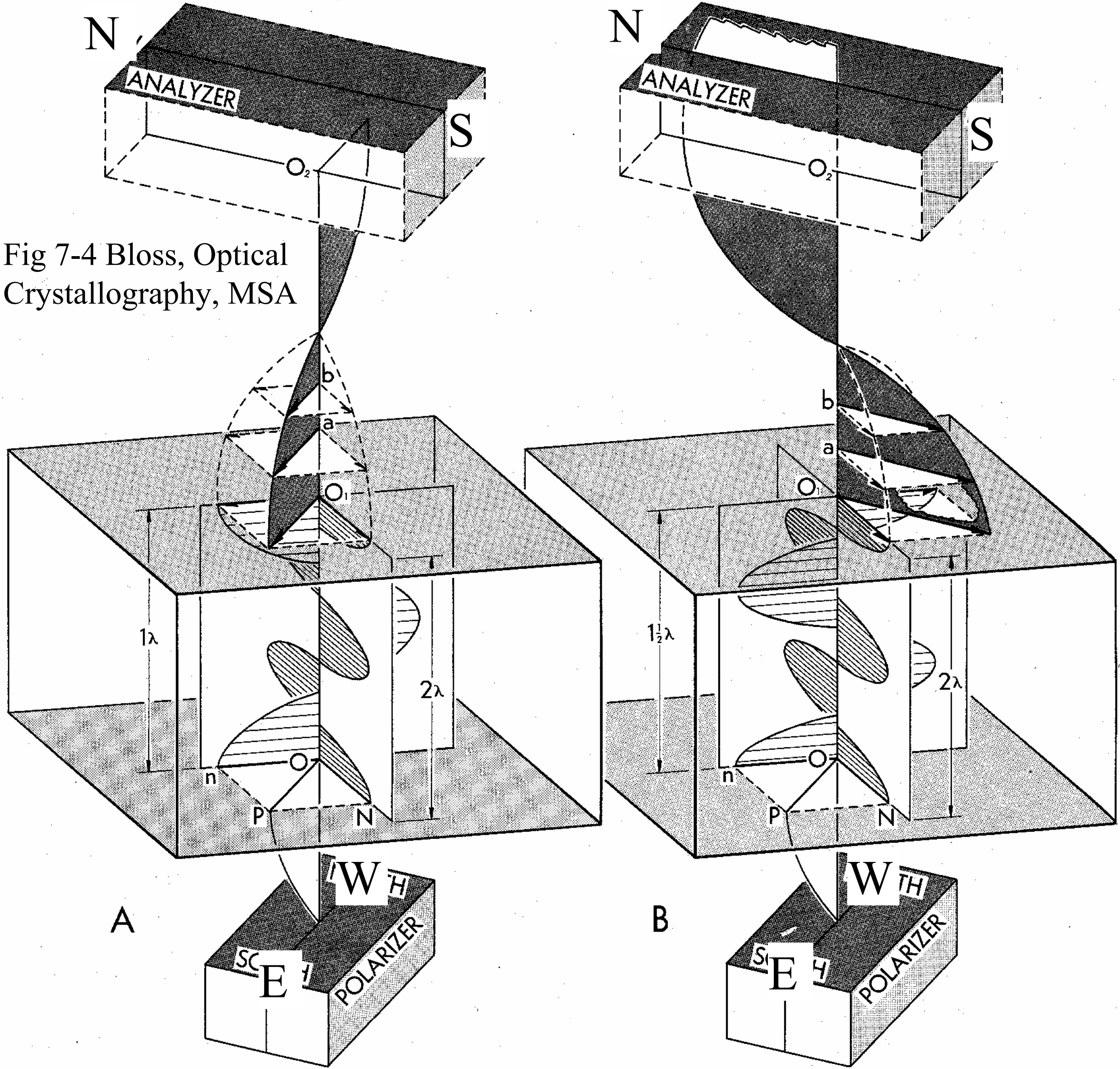


Fig 7-4 Bloss, Optical Crystallography, MSA

Fig. 7-4. The mutual interference, after their emergence from an anisotropic crystal at 45 degrees off extinction, of what were formerly the slow and fast waves within the crystal. In (A), passage through the crystal has produced a path difference of 1λ between these waves, and their resultant wave motion after exit at O_1 is polarized in the same plane as the light from the polarizer. For (B), where their path difference is $\frac{1}{2}\lambda$, the resultant wave motion after exit at O_1 is at 90 degrees to the plane of polarization of light from the polarizer. Between crossed nicols, therefore, the resultant light emergent from the crystal is for (A) completely extinguished by the analyzer but for (B) completely transmitted (reflectional and absorptional losses being neglected).

Interference

2 crystals of equal t, but different Δn_i

B: **$n = {}^{3}/_{4}\ N$**

- Slow ray requires 2 periods & fast 1.5
- → 100% transmission by analyzer in XPL

Transmission by the Analyzer

Determined by:

a) **Angle between analyzer and polarizer** (fixed at 90°)

b) **Angle between polarizer and closest privileged direction of xl**

- When polarizer || either privileged vibration direction → extinct, since only one ray & it's cancelled
- Every crystal goes extinct 4 times in 360° rotation (unless isotropic)

Transmission by the Analyzer

c) Δ = path difference = t (N-n)

Fig. 7-4 → t(N-n) = 1λ → 0% transmission

t(N-n) = 1.5λ → 100% transmission

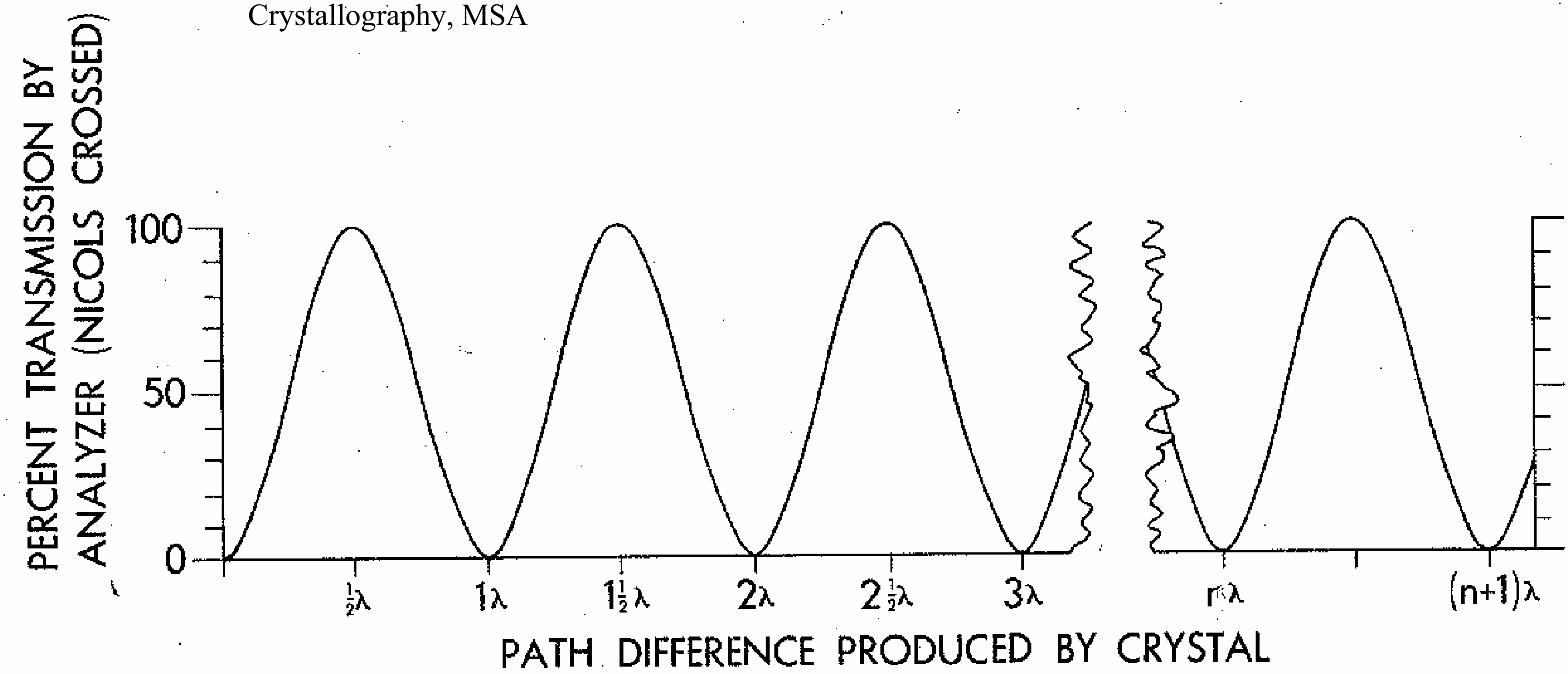


Fig 7-6 Bloss, Optical Crystallography, MSA

Transmission by the Analyzer

Determined by:

d) λ of light a new concept

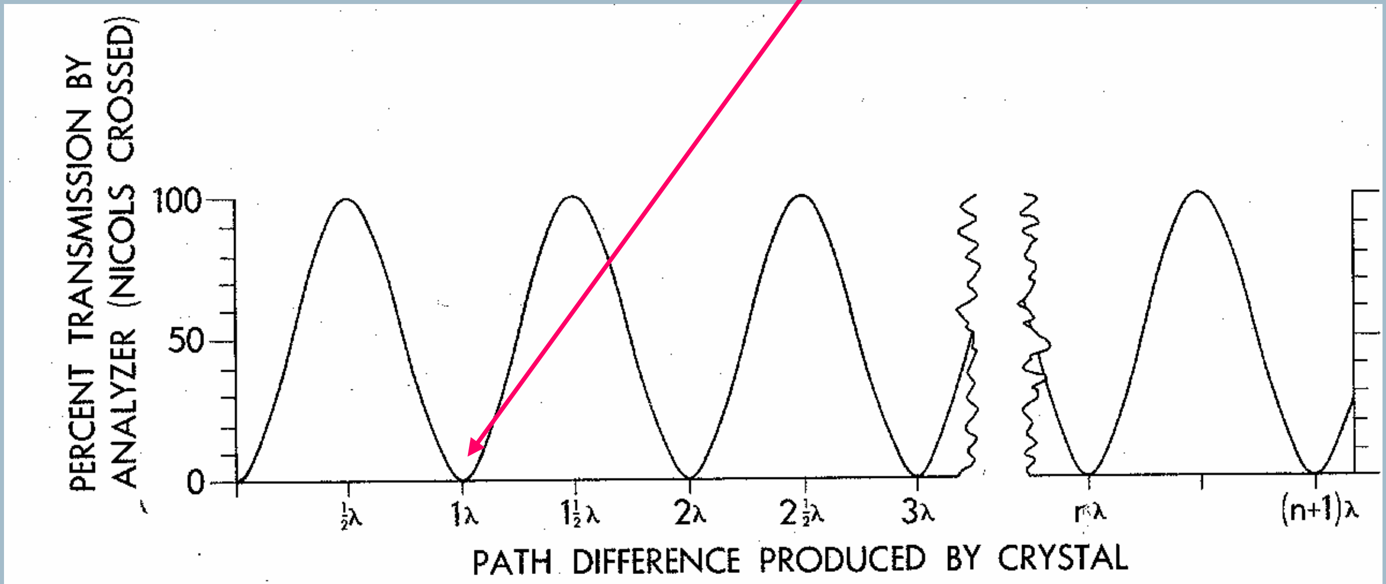
- in part (c) Δ has been expressed in terms of λ
- ...but it's really an absolute retardation, some finite # of nm (or A or miles...)
- If the transmitted light is white (mixed), each wavelength will be retarded t(N-n) by the same absolute distance, which will be a different x/λ

Transmission by the Analyzer

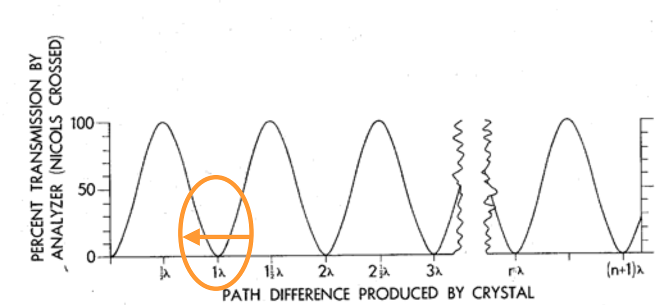
Example: assume xl has t(N-n) that will retard Δ = 550 μm & viewed 45^{o} off extinction (max intensity)

retardation →	550	550	550	550	550	550
selected light λ →	400	440	489	550	629	733
	$1^{3}/_{8}\,\lambda$	$1^{1}/_{4}\,\lambda$	$1^{1}/_{8}\,\lambda$	$1\,\lambda$	$^{7}/_{8}\,\lambda$	$^{3}/_{4}\,\lambda$

You can see 550 μm gets no transmission & others varying amount



retardation →	550	550	550	550	550	550
selected light λ	400	440	489	550	629	733
	$1^3/_8$ λ	$1^1/_4$ λ	$1^1/_8$ λ	1 λ	$^7/_8$ λ	$^3/_4$ λ



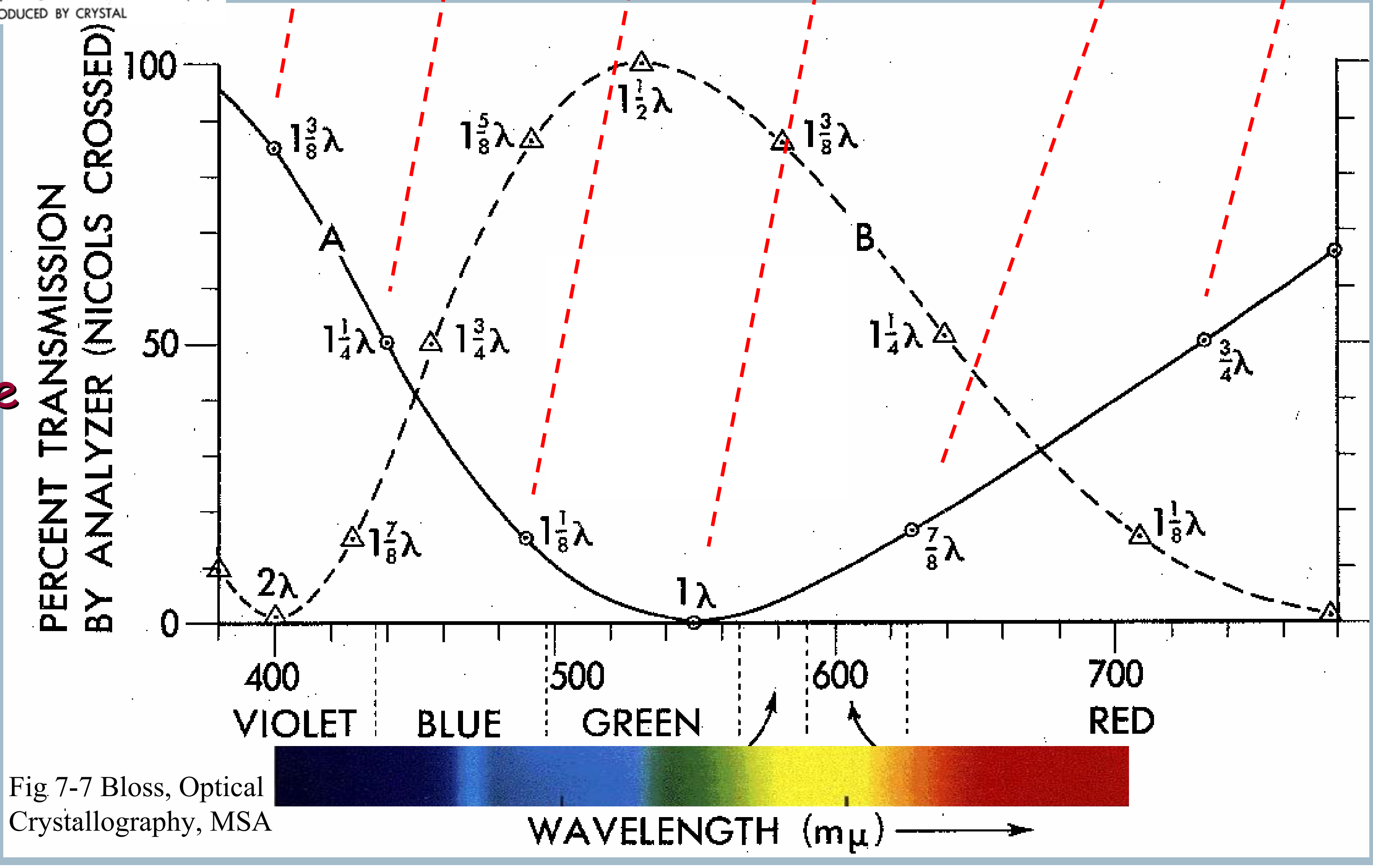
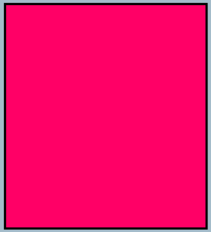
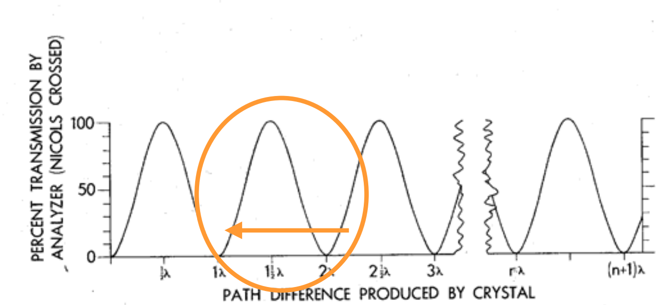


Fig 7-7 Bloss, Optical Crystallography, MSA

no green & more red-violet **interference color**



retardation →	800	800	800	800	800	800	800
selected light λ	400	426	457	550	581	711	800
	2 λ	$1^{7}/_{8}$ λ	$1^{3}/_{4}$ λ	$1^{1}/_{2}$ λ	$^{7}/_{8}$ λ	$1\ ^{1}/_{8}$ λ	1 λ



Dashed curve:

no red

or violet

& more

green

🟩

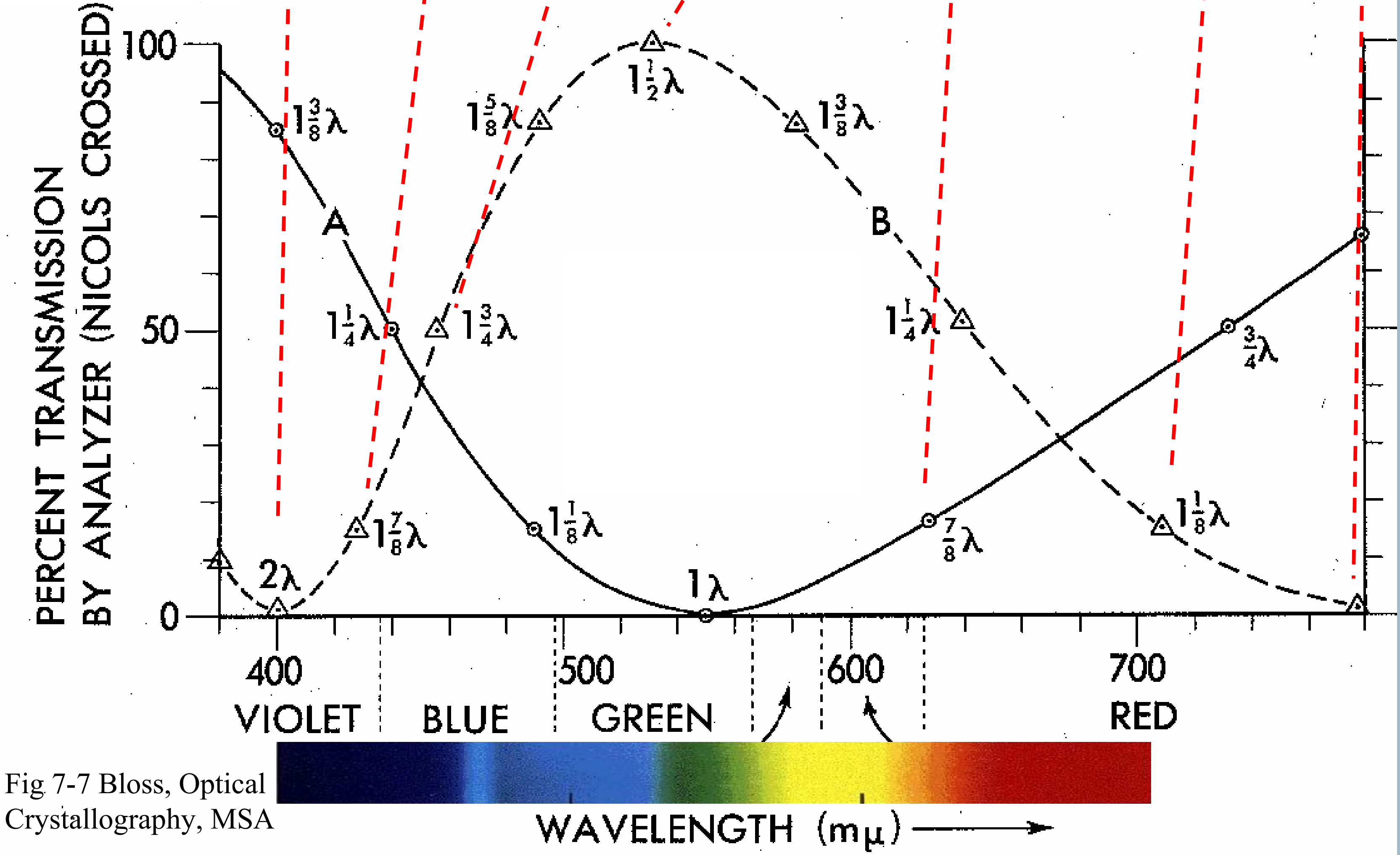
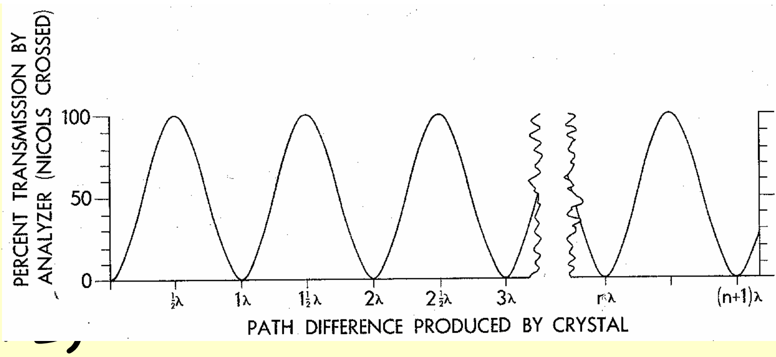


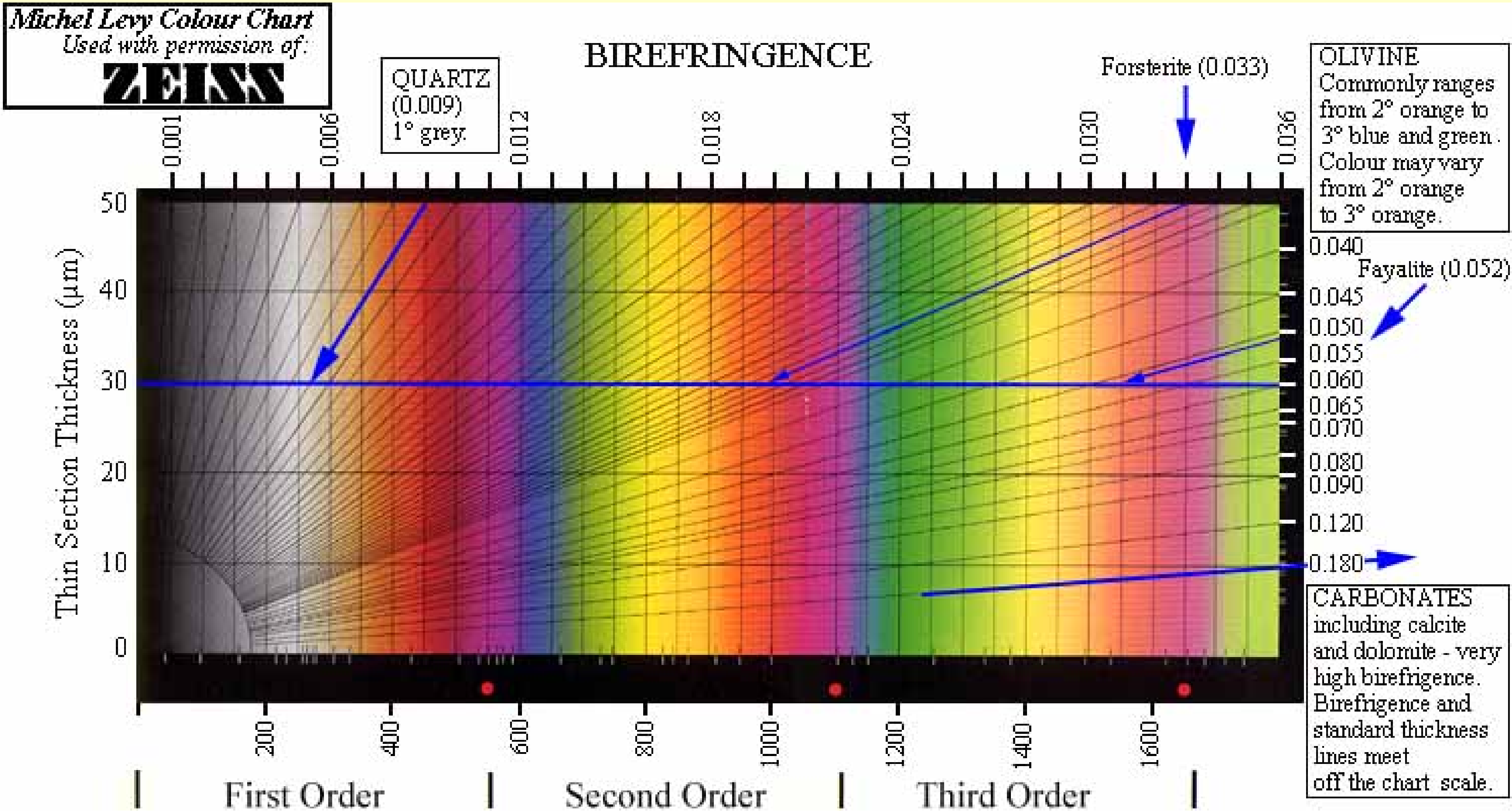
Fig 7-7 Bloss, Optical Crystallography, MSA

Color chart



Colors one observes when polars are crossed (X

Color can be quantified numerically: $\delta = n_{high} - n_{low}$



QUARTZ (0.009) 1° grey.

Forsterite (0.033)

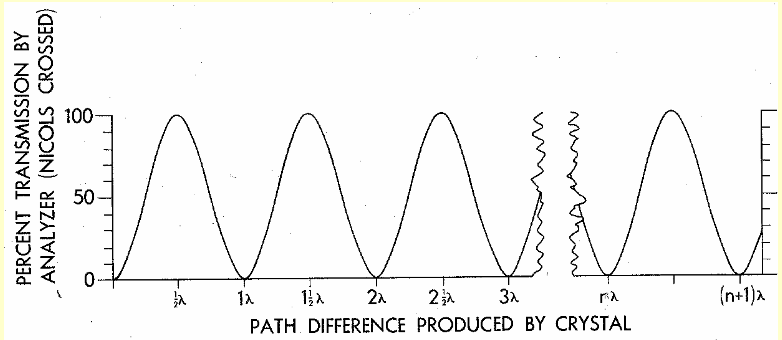
OLIVINE Commonly ranges from 2° orange to 3° blue and green. Colour may vary from 2° orange to 3° orange.

Fayalite (0.052)

CARBONATES including calcite and dolomite - very high birefrigence. Birefrigence and standard thickness lines meet off the chart scale.

Color chart

Shows the relationship between retardation, crystal thickness, and interference color



550 μm → red violet

800 μm → green

1100 μm → red-violet again (note repeat ↑)

0-550 μm = "1st order" 550-1100 μm = 2nd order 1100-1650 μm = 3rd order…

Higher orders are more pastel

Estimating birefringence

1) Find the crystal of interest showing the highest colors (Δ depends on orientation)

2) Go to color chart

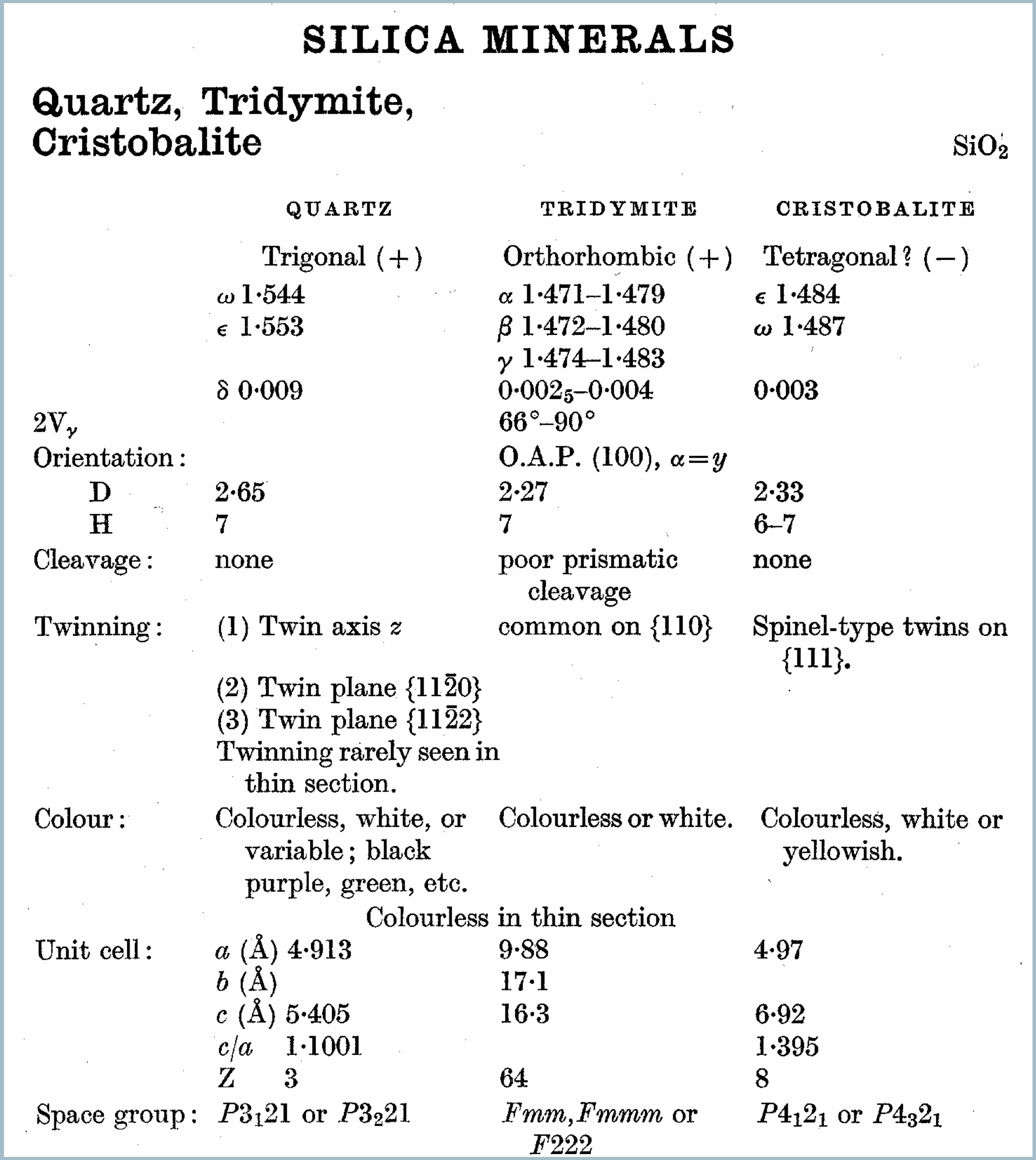
thickness = 30 microns

use 30 micron line + color, follow radial line through intersection to margin & read birefringence

Suppose you have a mineral with second-order green

What about third order yellow?

Example: Quartz ω = 1.544 ε = 1.553

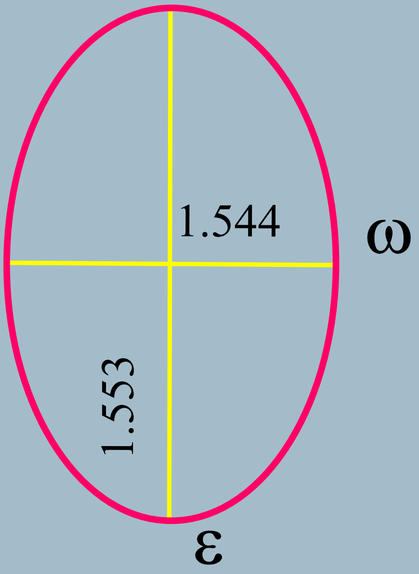


SILICA MINERALS

Quartz, Tridymite, Cristobalite

SiO$_2$

	QUARTZ	TRIDYMITE	CRISTOBALITE
	Trigonal (+)	Orthorhombic (+)	Tetragonal? (−)
	ω 1·544 ε 1·553	α 1·471–1·479 β 1·472–1·480 γ 1·474–1·483	ε 1·484 ω 1·487
	δ 0·009	0·002$_5$–0·004	0·003
2V$_\gamma$		66°–90°	
Orientation:		O.A.P. (100), α=*y*	
D	2·65	2·27	2·33
H	7	7	6–7
Cleavage:	none	poor prismatic cleavage	none
Twinning:	(1) Twin axis *z* (2) Twin plane {11$\bar{2}$0} (3) Twin plane {11$\bar{2}$2} Twinning rarely seen in thin section.	common on {110}	Spinel-type twins on {111}.
Colour:	Colourless, white, or variable; black purple, green, etc.	Colourless or white.	Colourless, white or yellowish.
	Colourless in thin section		
Unit cell:	*a* (Å) 4·913	9·88	4·97
	b (Å)	17·1	
	c (Å) 5·405	16·3	6·92
	c/*a* 1·1001		1·395
	Z 3	64	8
Space group:	$P3_121$ or $P3_221$	*Fmm*, *Fmmm* or *F*222	$P4_12_1$ or $P4_32_1$



Data from Deer et al
Rock Forming Minerals
John Wiley & Sons

Example: Quartz $\omega = 1.544$ $\varepsilon = 1.553$

Sign??

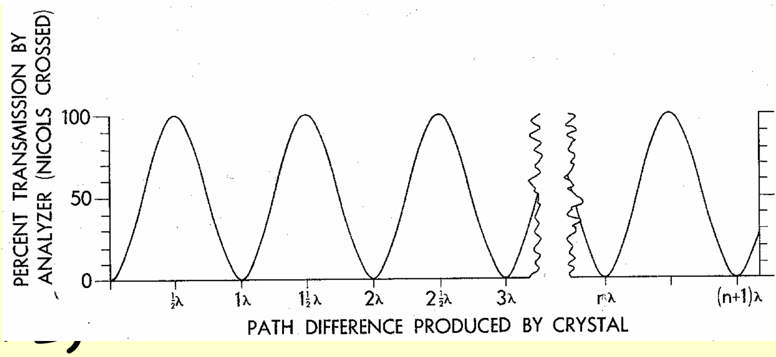
(+) because $\varepsilon > \omega$

$\varepsilon - \omega = 0.009$ called the **birefringence** (δ)

= **maximum** interference color (when seen?)

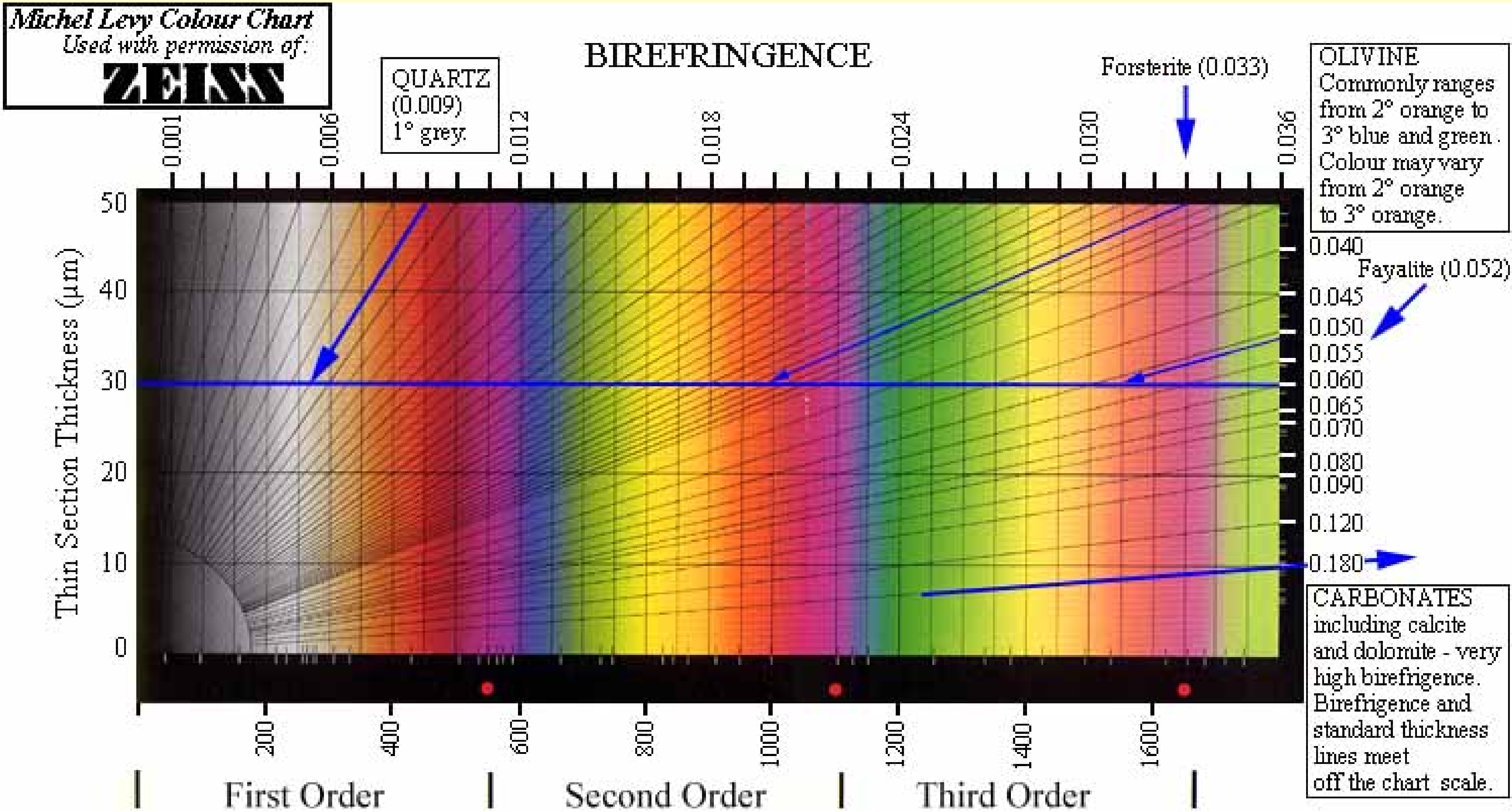
What color is this?? Use your chart.

Color chart



Colors one observes when polars are crossed (X

Color can be quantified numerically: $\delta = n_{high} - n_{low}$



Example: Quartz ω = 1.544 ε = 1.553

Sign??

(+) because $\varepsilon > \omega$

$\varepsilon - \omega$ = 0.009 called the **birefringence** (δ)

= **maximum** interference color (when see this?)

What color is this?? Use your chart.

For other orientations get $\varepsilon' - \omega$ → progressively lower color

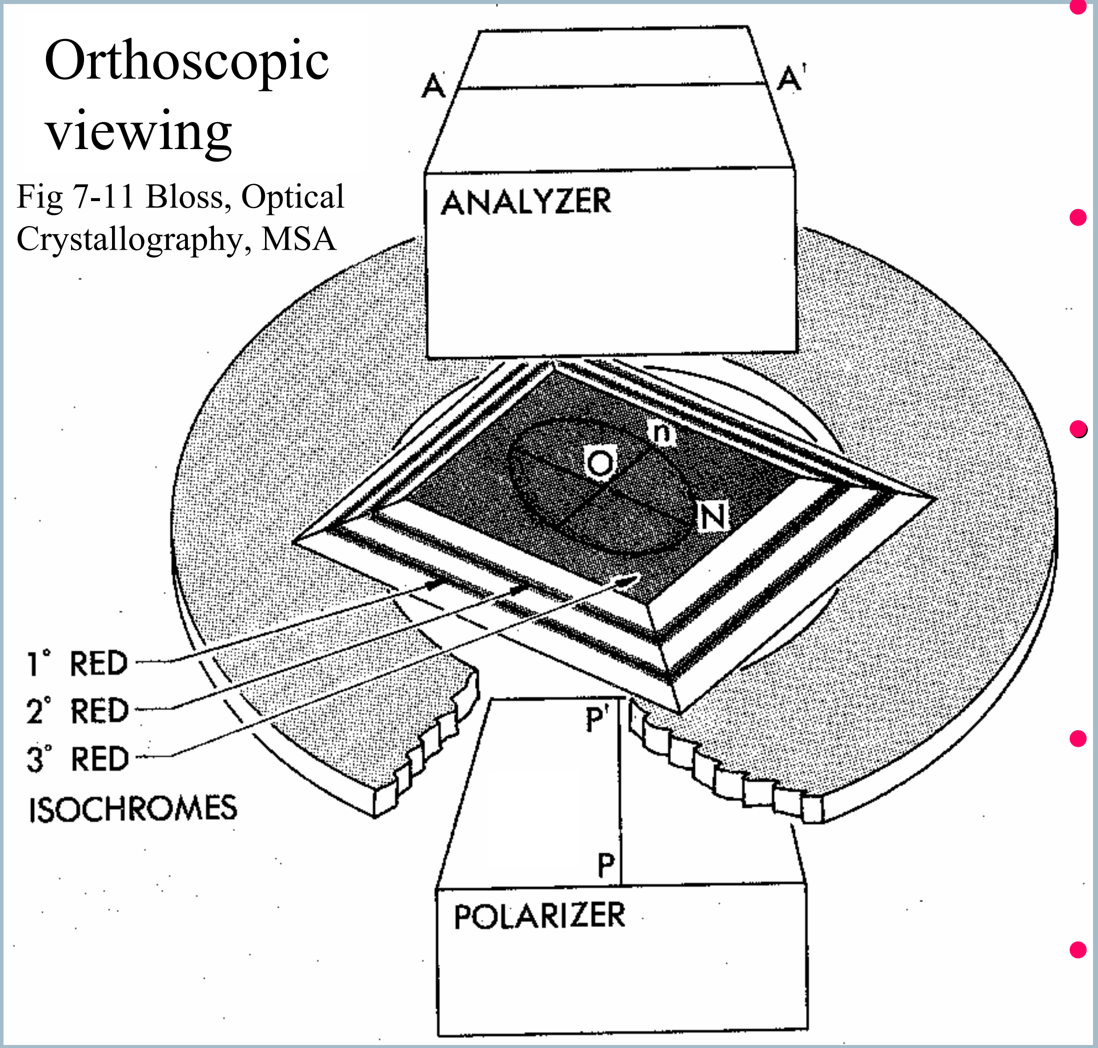
Rotation of the stage changes the intensity, but not the hue

Extinct when either privileged direction N-S (every 90°) and maximum interference color brightness at 45°

360° rotation → 4 extinction positions exactly 90° apart

So far, all of this has been orthoscopic (the normal way)

All light rays are ~ parallel and vertical as they pass through the crystal

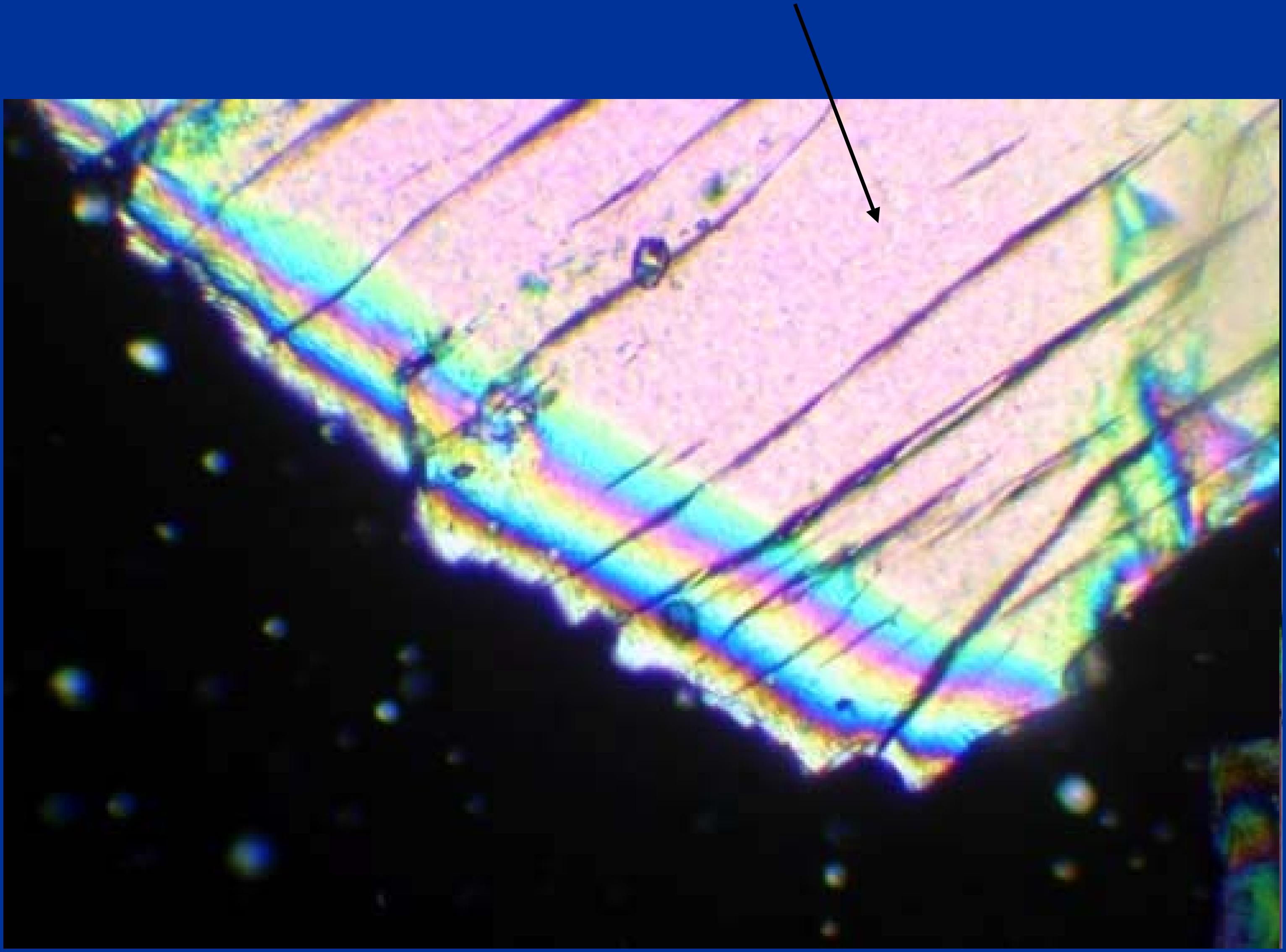


Orthoscopic viewing

Fig 7-11 Bloss, Optical Crystallography, MSA

- xl has particular interference color = f(biref, t, orientation)
- Points of equal thickness will have the same color
- **isochromes** = lines connecting points of equal interference color
- At thinner spots and toward edges will show a lower color
- Count isochromes (inward from thin edge) to determine order

What interference color is this?



If this were the maximum interference color seen, what is the birefringence of the mineral?

Conoscopic Viewing

A condensing lens below the stage and a Bertrand lens above it

Arrangement essentially folds planes of Fig 7-11 → cone

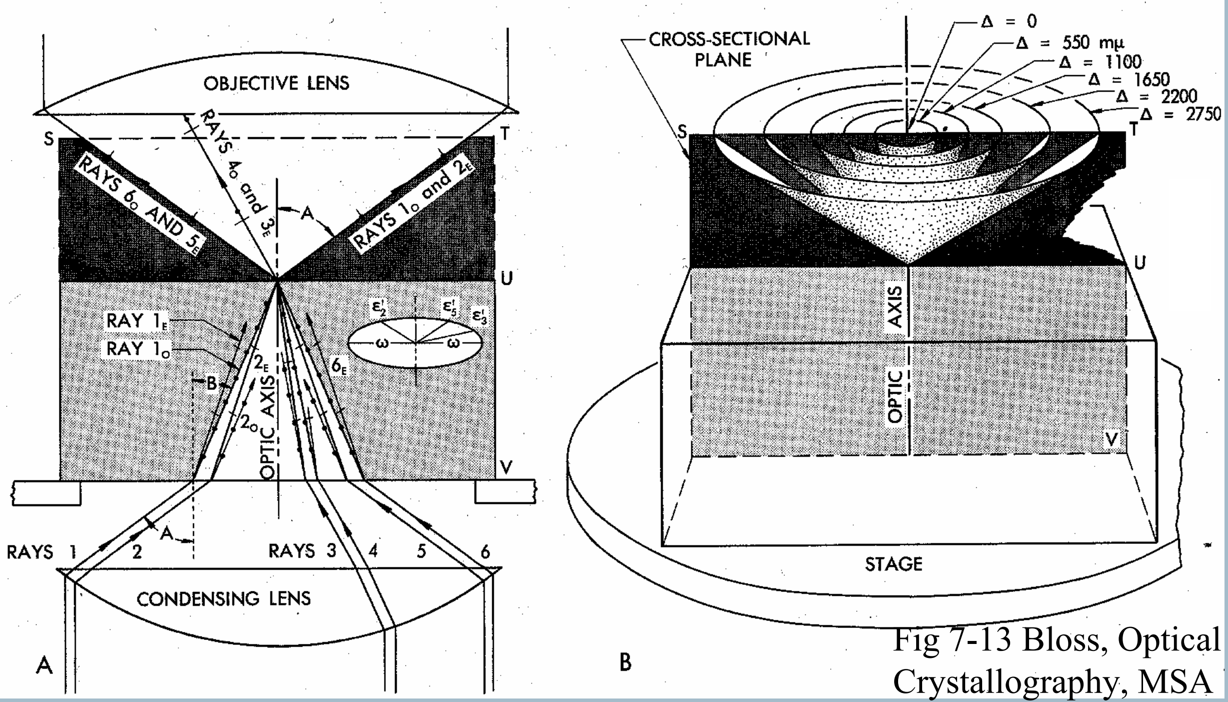


Fig 7-13 Bloss, Optical Crystallography, MSA

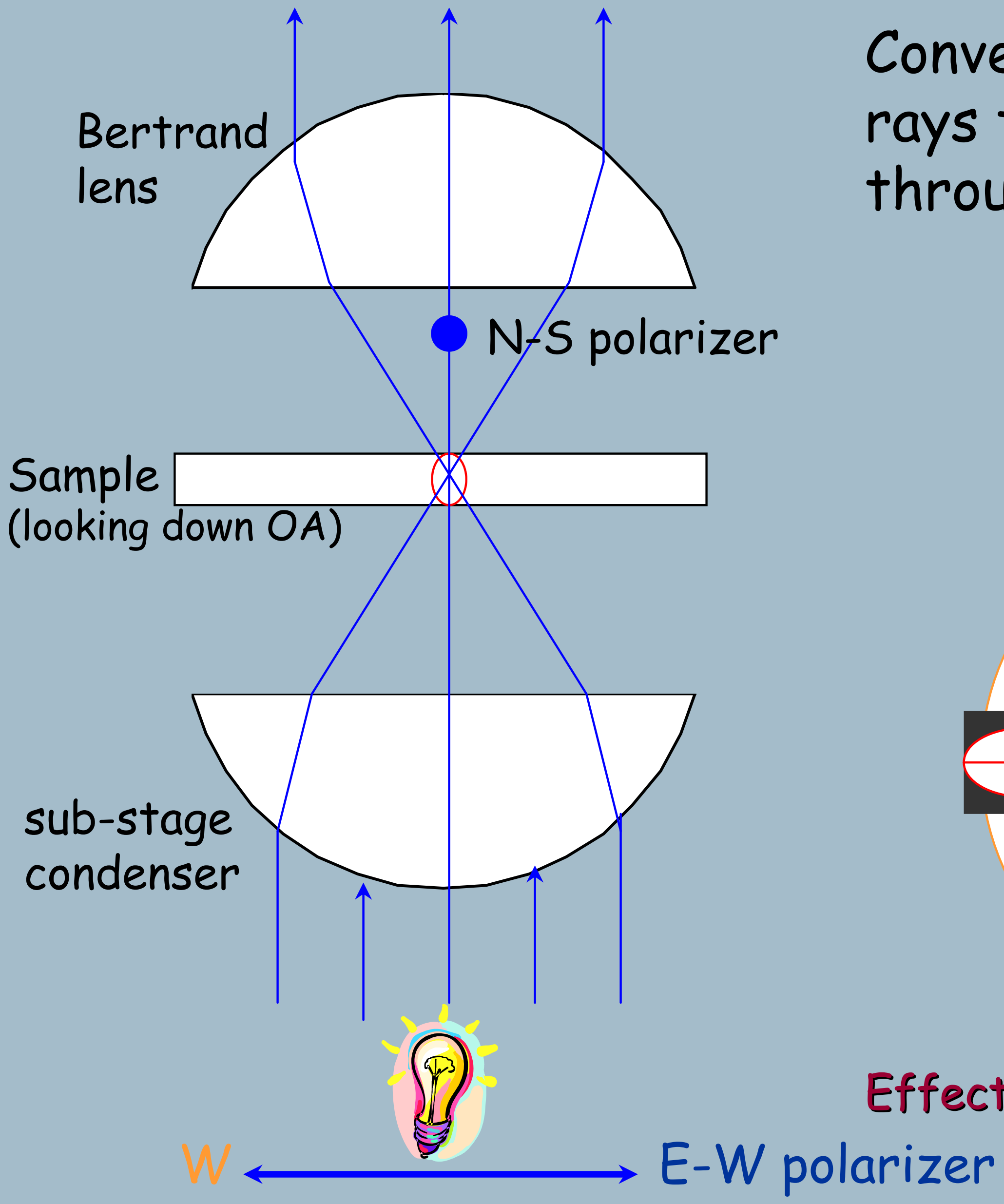
Light rays are refracted by condensing lens & pass through crystal in different directions

Thus different properties

Only light in the center of field of view is vertical & like ortho

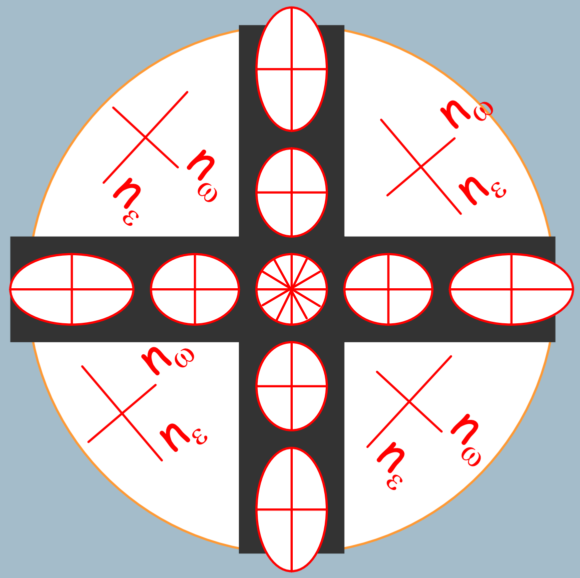
→ **Interference Figures** Very useful for determining optical properties of xl

How interference figures work (uniaxial example)



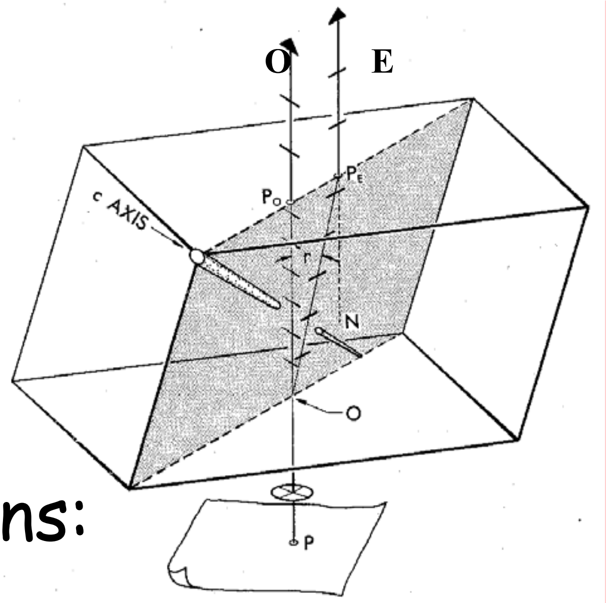
Converging lenses force light rays to follow different paths through the indicatrix

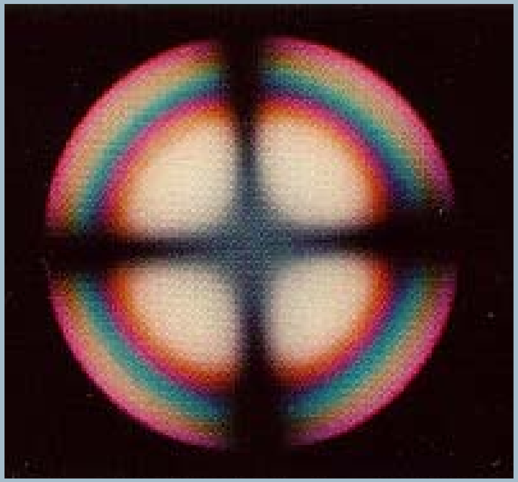
What do we see??



Effects of multiple cuts through indicatrix

Uniaxial Interference Figure





- Circles of isochromes
- Note vibration directions:
  - ω tangential
  - ε' radial & variable magnitude
- Black cross (isogyres) results from locus of extinction directions
- Center of cross (melatope) represents optic axis
- Approx 30° inclination of OA will put it at margin of field of view

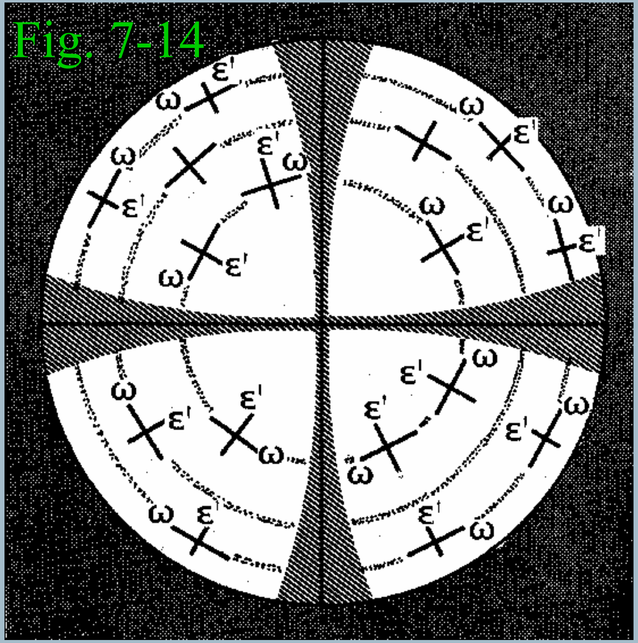
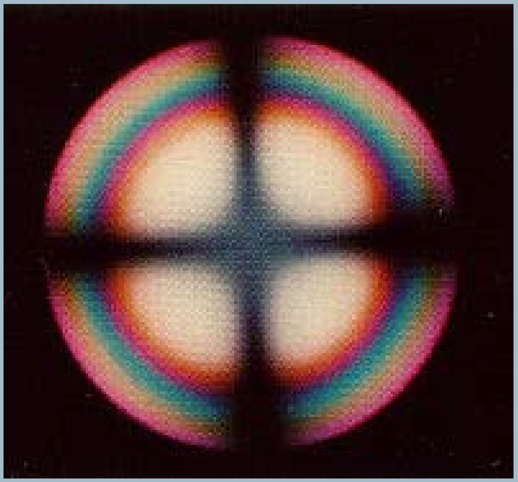


Fig. 7-14

Uniaxial Figure



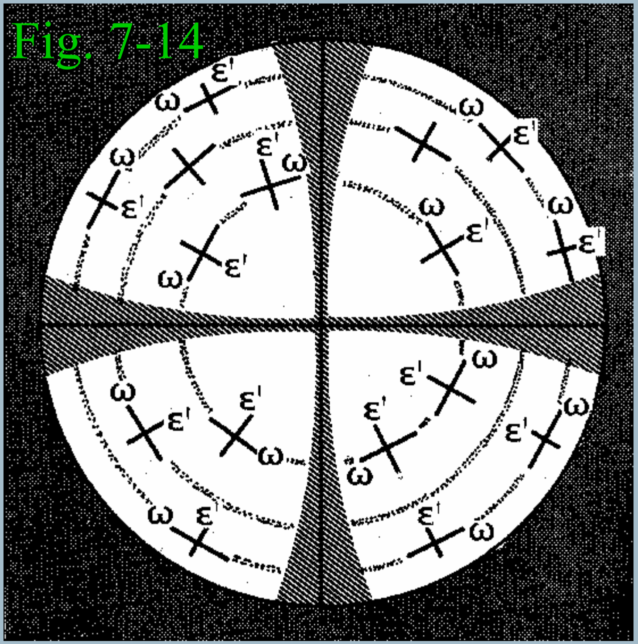
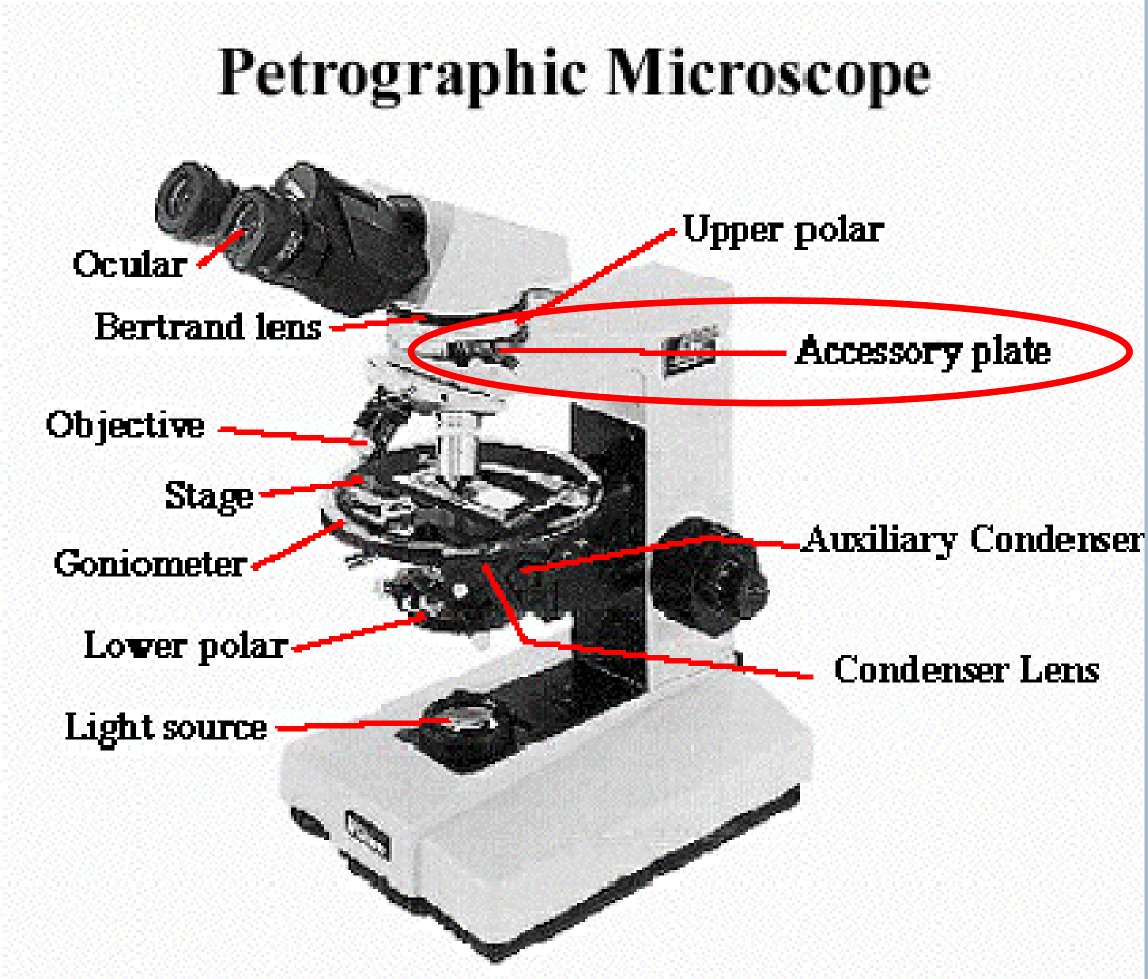


Fig. 7-14

- **Centered** axis figure as 7-14: when rotate stage cross does **not** rotate
- **Off center:** cross still E-W and N-S, but **melatope** rotates around center
- **Melatope outside field:** bars sweep through, but **always** N-S or E-W at center
- **Flash Figure:** OA in plane of stage Diffuse black fills field brief time as rotate

Accessory Plates

We use an insertable 1-order red (gypsum) plate



Accessory Plates

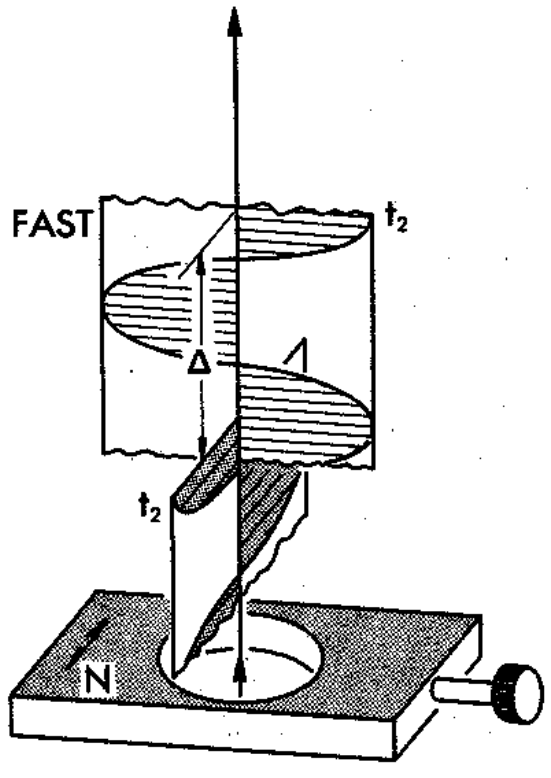


Fig 8-1 Bloss, Optical Crystallography, MSA

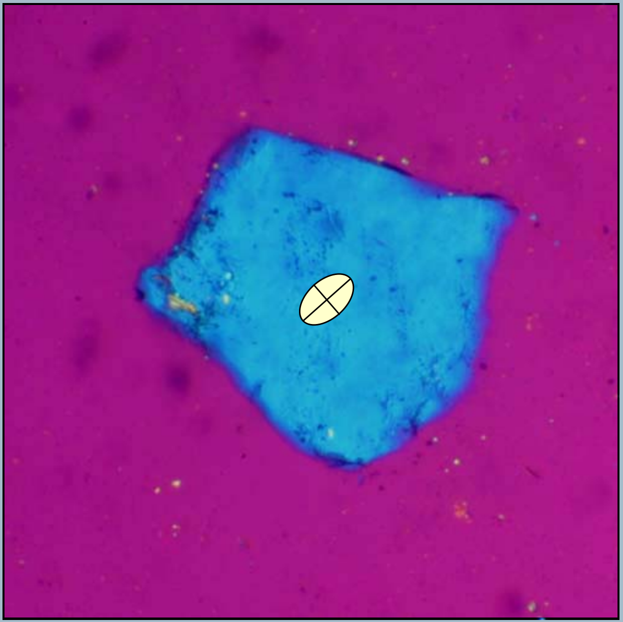
- We use an insertable 1-order red (gypsum) plate
- Slow direction is marked N↕ on plate
- Fast direction (n) || axis of plate
- The gypsum crystal is oriented and cut so that Δ = (N-n) → **550nm retardation**

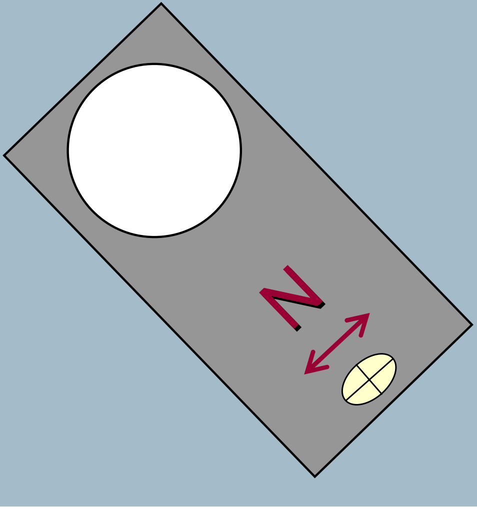
← it thus has the effect of retarding the N ray 550 nm behind the n ray

- If insert with no crystal on the stage → 1-order red in whole field of view

Accessory Plates

Suppose we view an anisotropic crystal with
Δ = 100 nm (1-order gray) at 45° from extinction



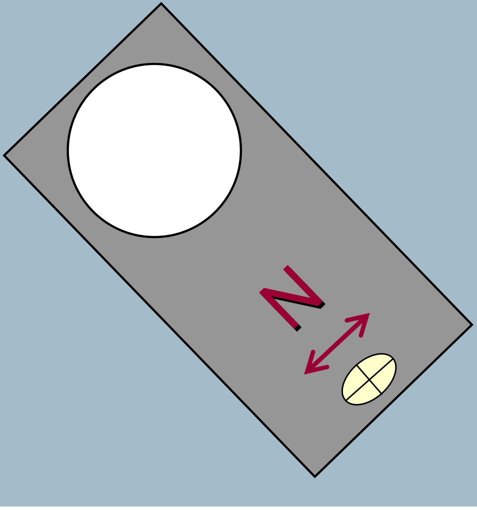


If $N_{gyp} \,||\, N_{xl} \rightarrow$ **Addition**

- Ray in crystal || N_{gyp} already behind by 100nm & it gets **further retarded** by 550nm in the gypsum plate
- 100 + 550 → 650nm
- What color (on your color chart) will result?
- Original 1° grey → **2° blue**

Accessory Plates

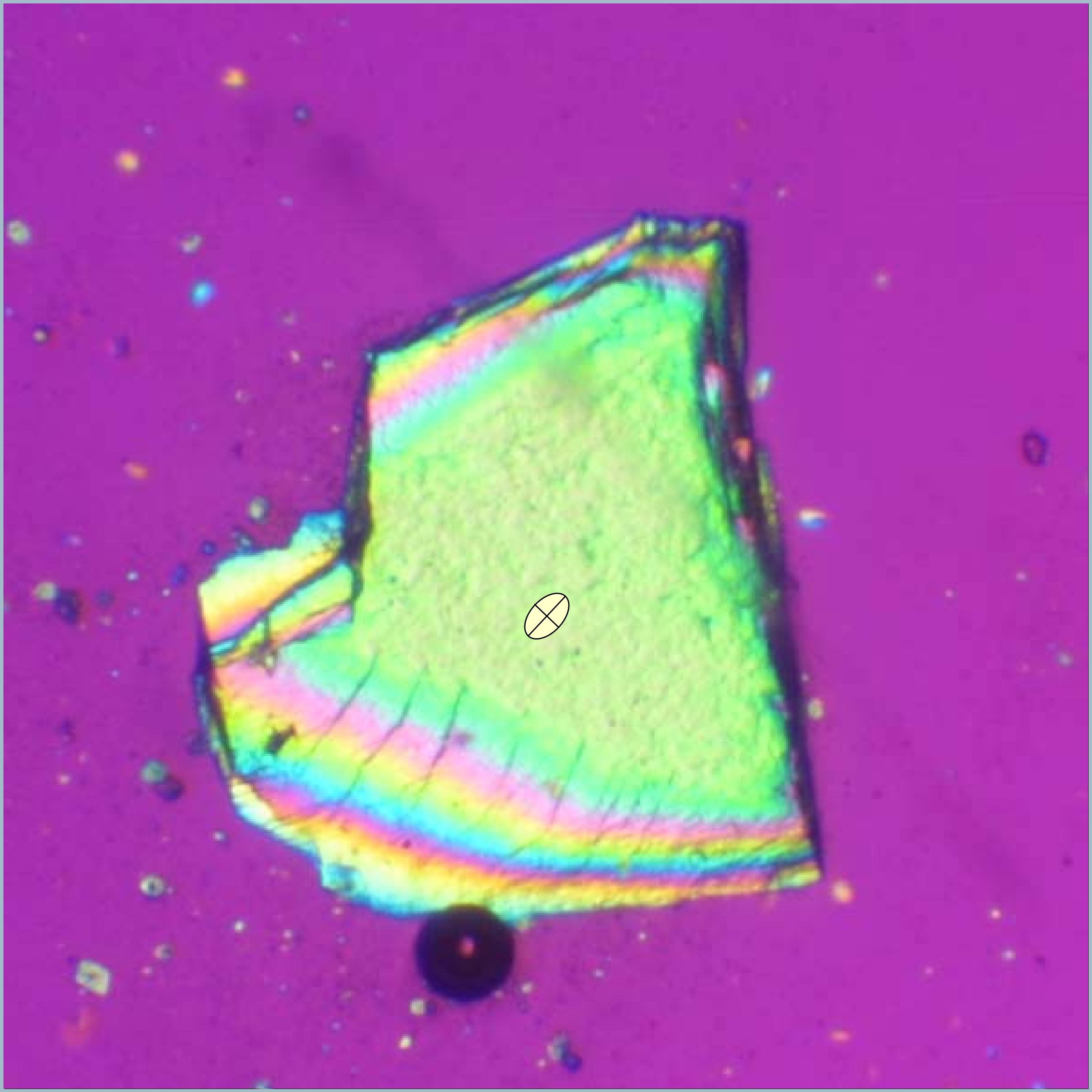
Now rotate the microscope stage and crystal 90° → $N_{gyp} \parallel n_{xl}$ (Δ still = 100 nm)

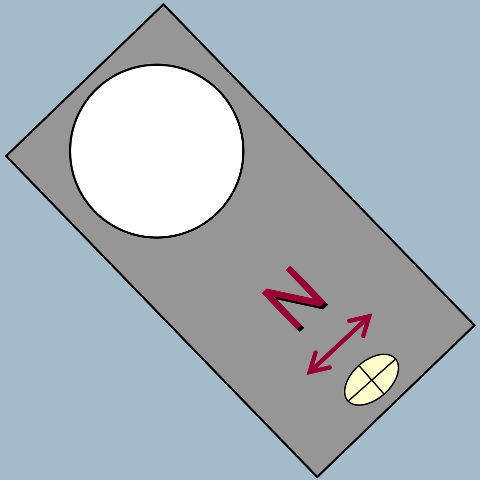


$N_{gyp} \parallel n_{xl}$ → **Subtraction**

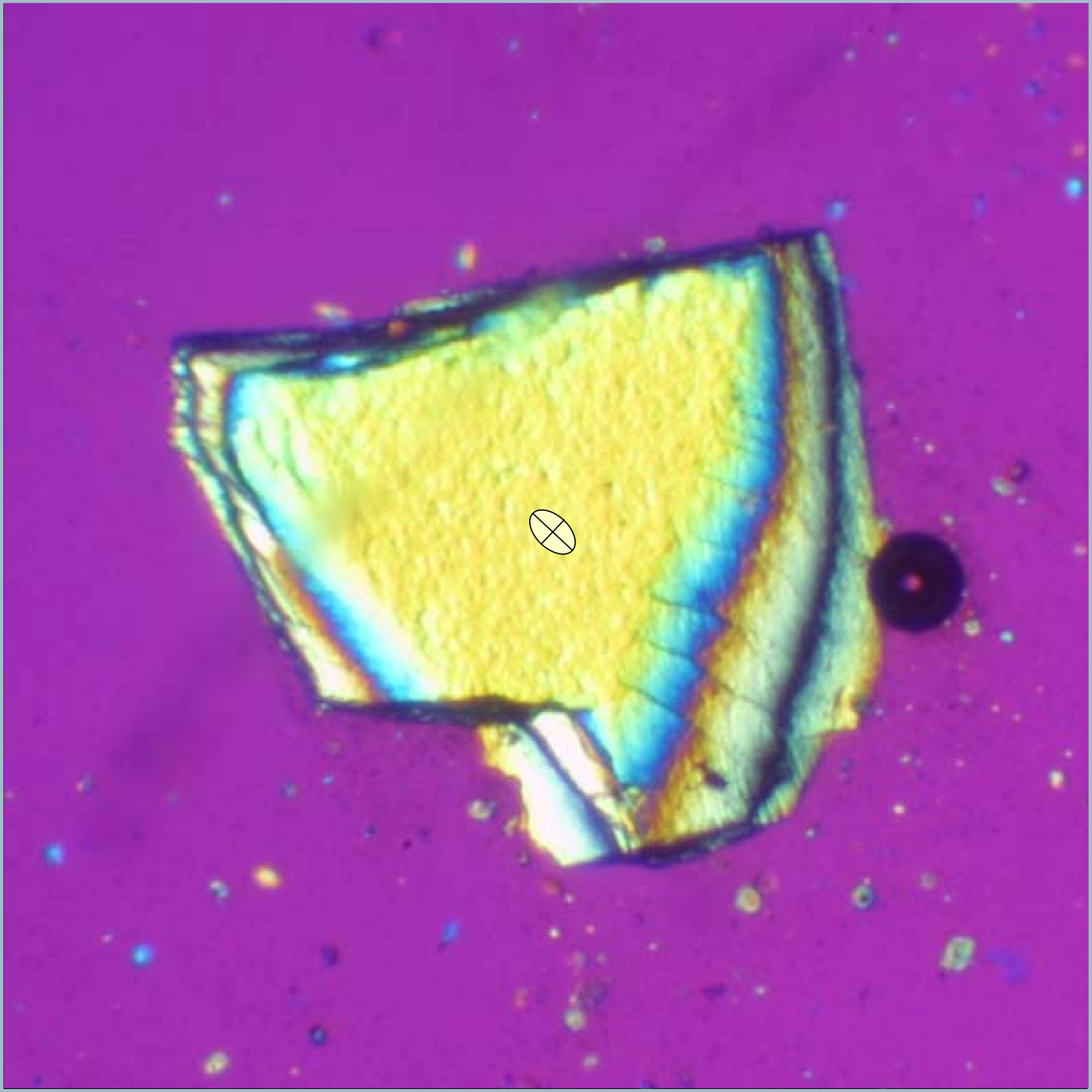
- Ray in the crystal that is parallel to N_{gyp} is **ahead** by 100nm
- 550μm retardation in gypsum plate → 450nm behind
- What color will result?
- 1° orange

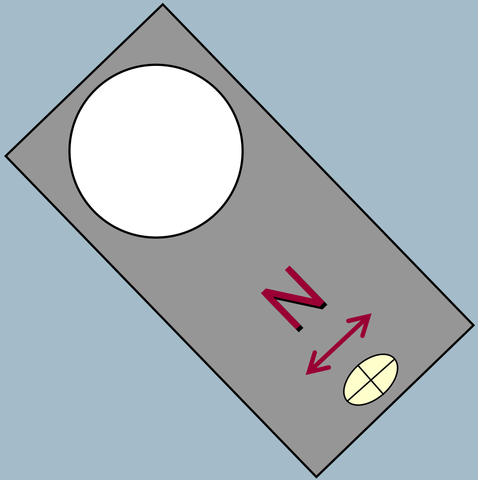
What will happen when you insert the gypsum plate?





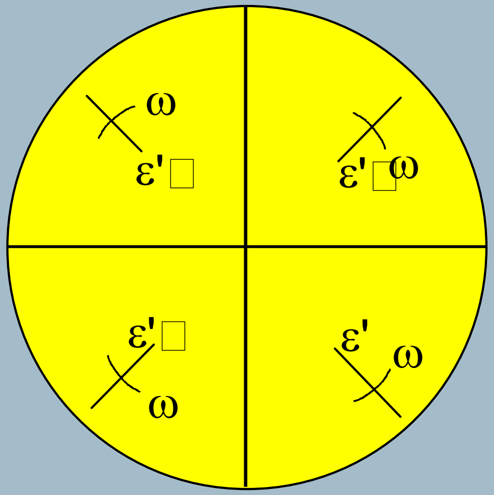
What will happen when you insert the gypsum plate?



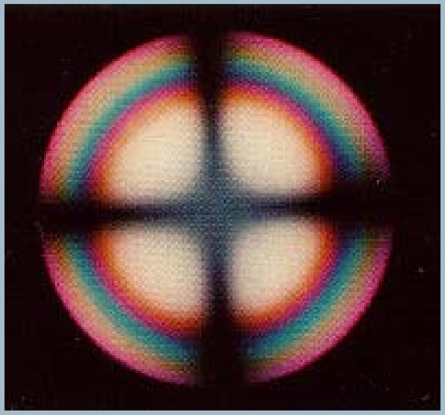


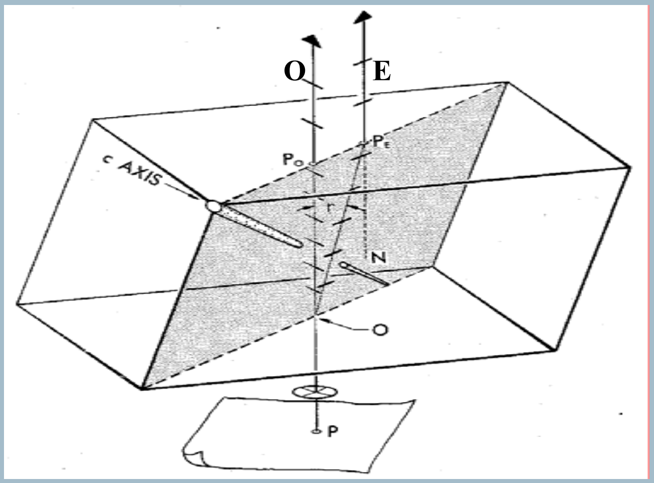
Optic Sign Determination

For all xls remember ε' vibrates in plane of ray and OA, ω vibrates normal to plane of ray and OA



(+) crystal:
ε’ > ω
so **ω faster**





1) Find a crystal in which the optic axis (OA) is vertical (normal to the stage). **How would you do that?**
2) Go to high power, insert condensing and Bertrand lenses to → optic axis interference figure

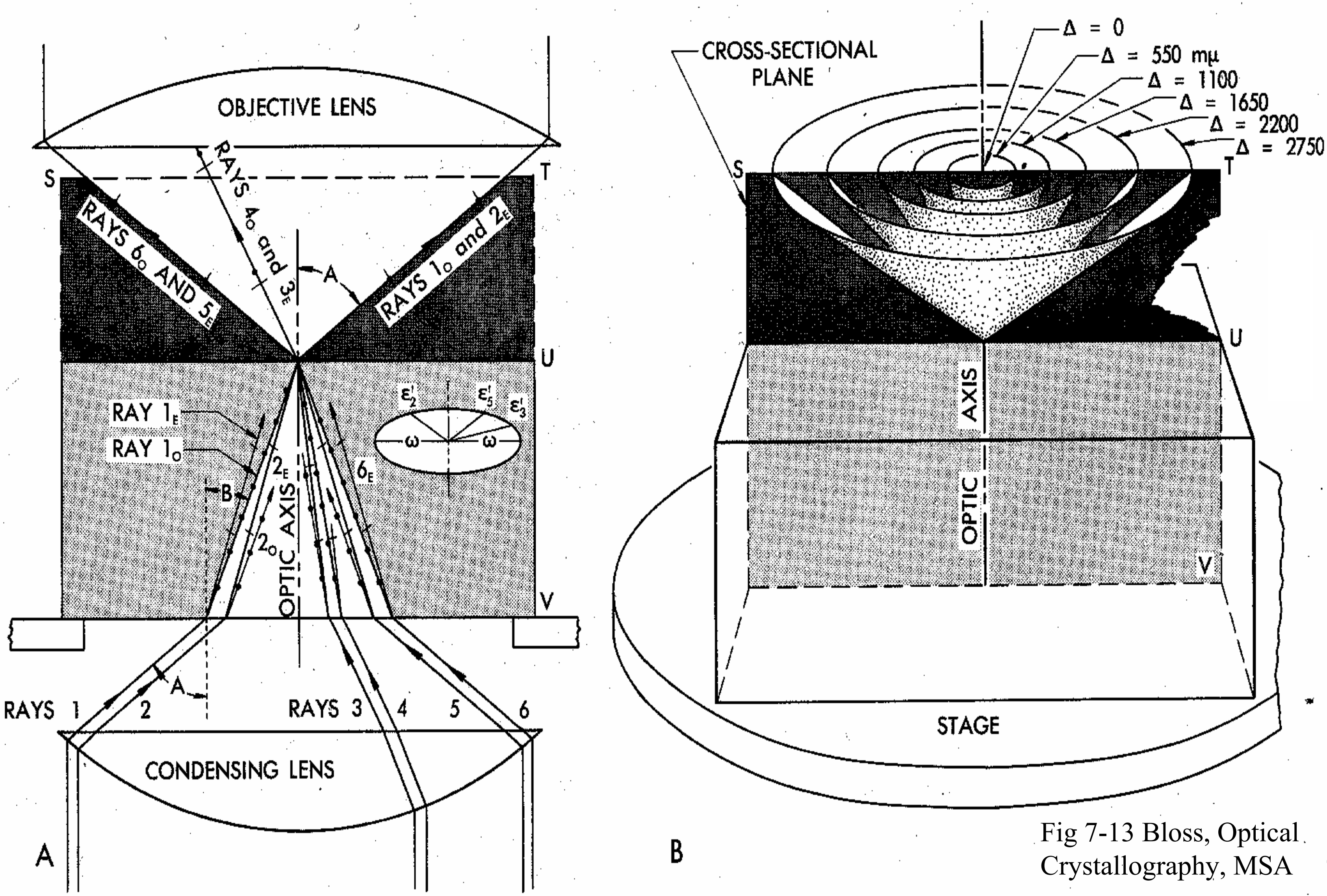
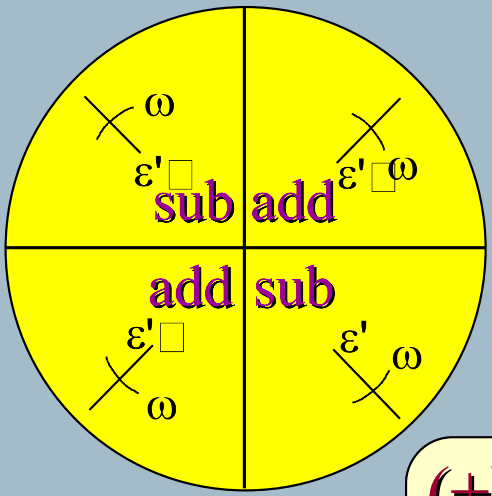
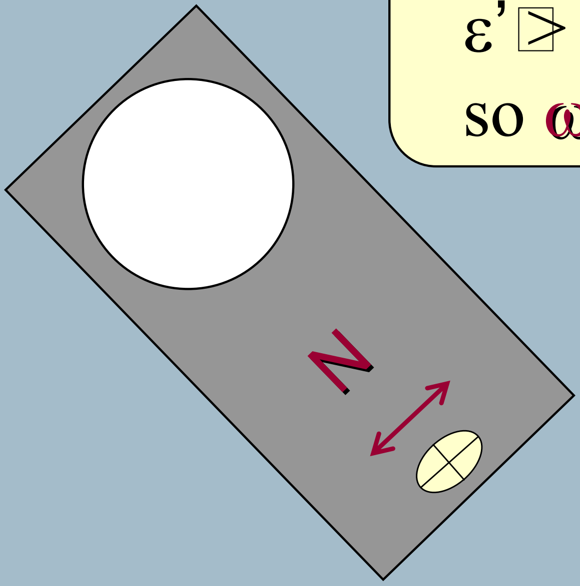


Fig 7-13 Bloss, Optical Crystallography, MSA

Optic Sign Determination



(+) crystal:
ε’ > ω
so **ω faster**



Inserting plate for a (+) crystal:

→ subtraction in NW & SE where n||N

→ addition in NE & SW where N||N

Whole NE (& SW) quads add 550nm

- isochromes shift up 1 order

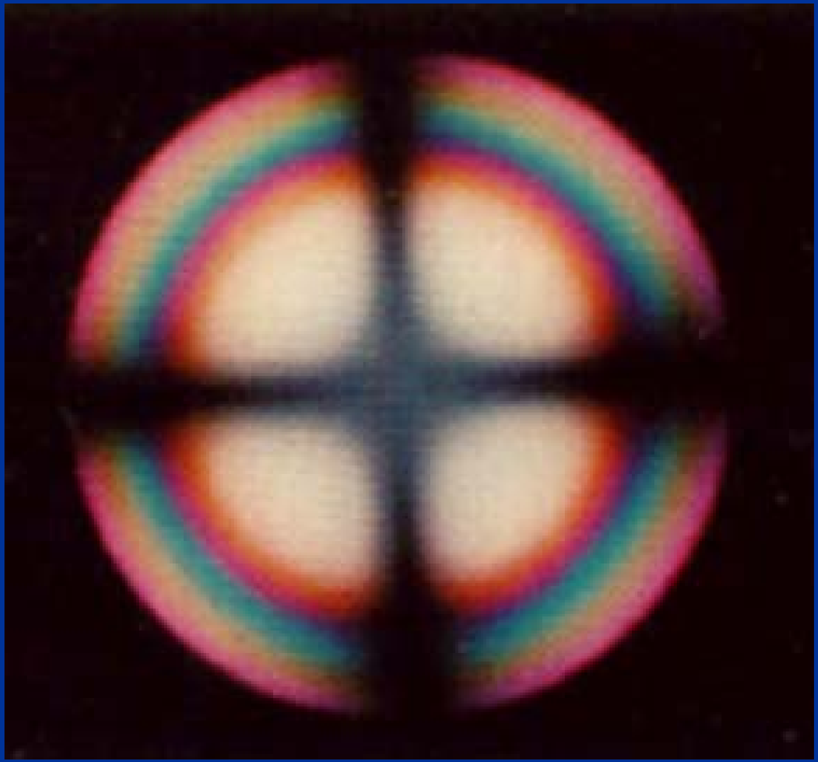
Isogyre adds → red

In NW & SE where subtract

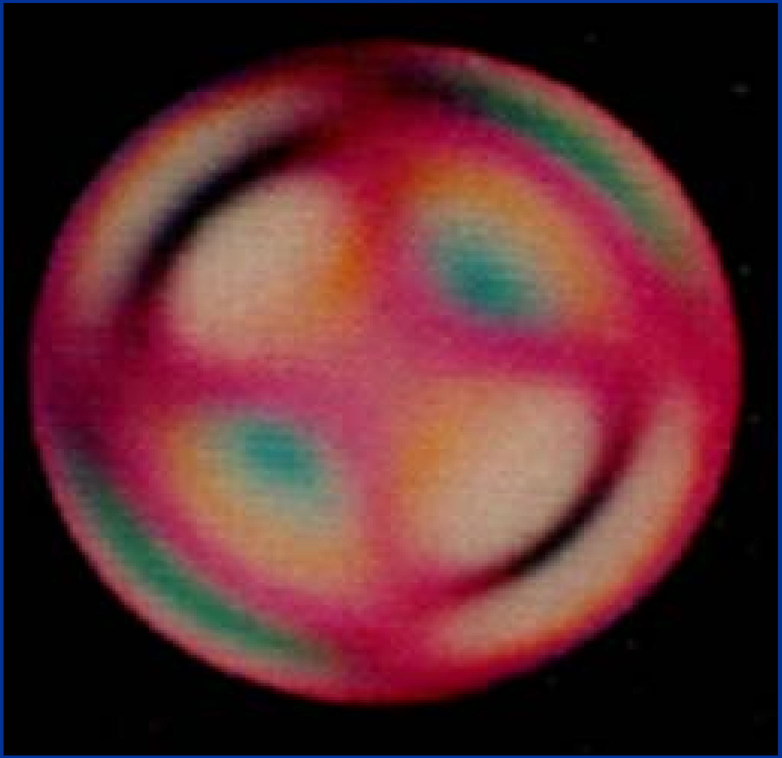
- Each isochrome loses an order

Near isogyre (~100nm)

- get 450 yellow in NW & SE (100-550)
- and 650 blue in NE & SW (100+550)

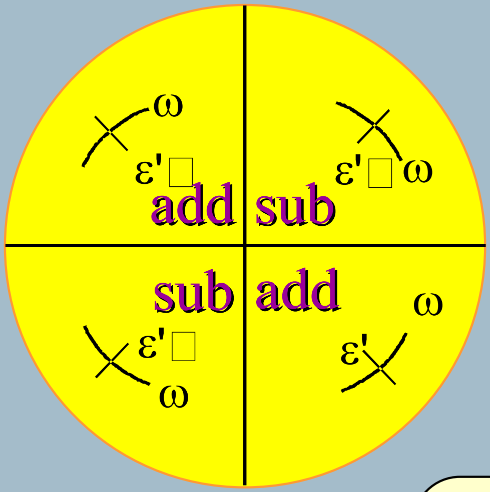


(+) OA Figure without plate



(+) OA Figure with plate
Yellow in NW is (+)

Optic Sign Determination



Inserting plate for a (-) crystal:

→ subtraction in NE & SW where n||N

→ addition in NW & SE where N||N

Whole NW (& SE) quads add 550nm

- isochromes shift up 1 order

Isogyre still adds → red

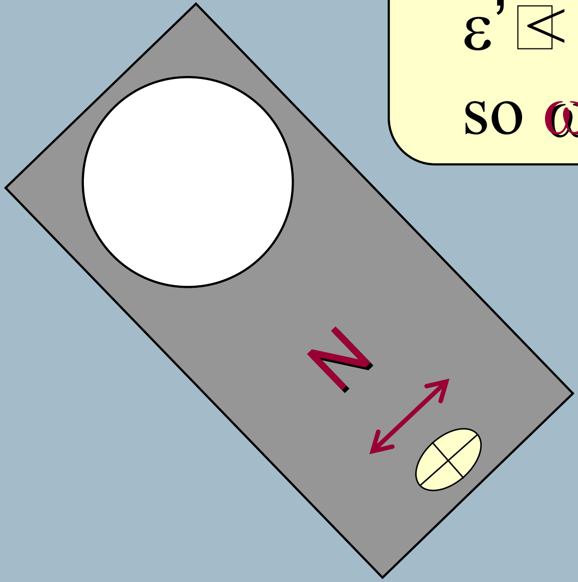
In NE & SW where subtract

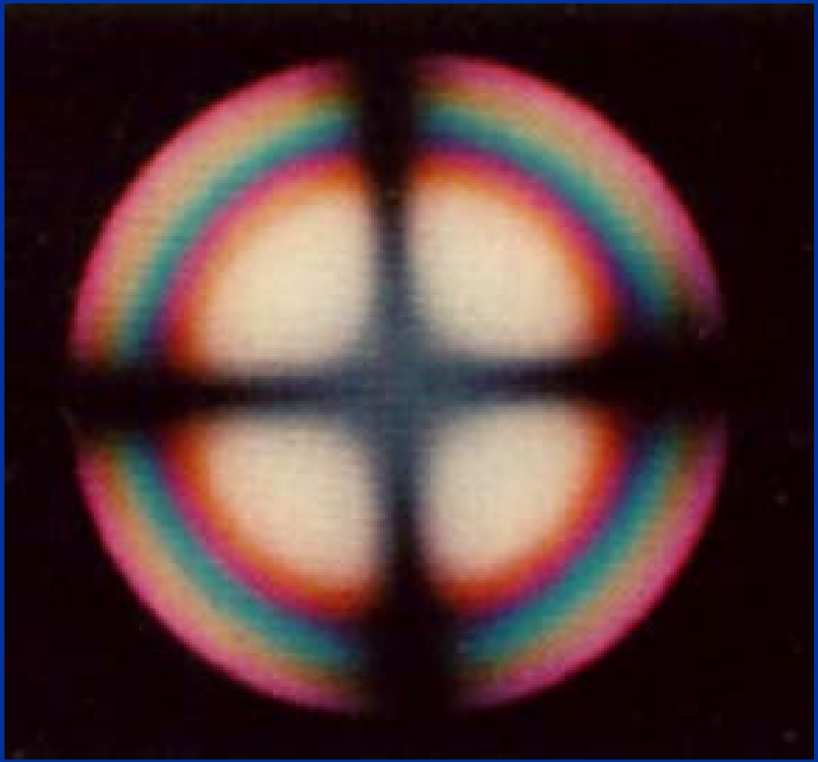
- Each isochrome loses an order

Near isogyre (~100nm)

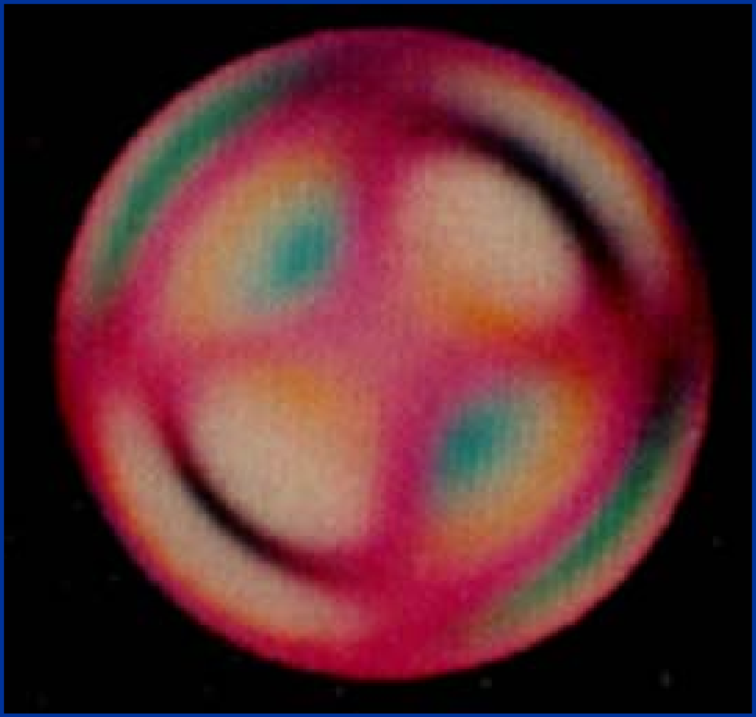
- get 650 blue in NW & SE
- and 450 yellow in NE & SW

(-) crystal:
$\varepsilon' < \omega$
so **ω slower**





(-) OA Figure without plate
(same as (+) figure)



(-) OA Figure with plate
Blue in NW is (-)

Orienting crystals to determine ω and ε

Can determine the refractive index of a mineral by crushing a bit up and immersing the grains in a series of oils of known refractive index.

When the crystal disappears perfectly $n_{mineral} = n_{oil}$

The trick is to isolate ω and true ε by getting each E-W (parallel to the polarized light)

Orienting crystals to determine ω and ε

To measure ω only (if all grains of a single mineral):

1) Find a grain with **low interference colors- ideally a grain that remains extinct as the stage is rotated**
2) (check for centered OA figure)
3) Determine optic sign while you're at it (for use later)
4) Back to orthoscopic : all rays are ω
5) Compare n_{xl} to n_{oil}

Orienting crystals to determine ω and ε

Now look at the other crystals of the same mineral:

If the crystals are randomly oriented in a slide or thin section you may see any interference color from gray-black (OA vertical) to the highest color possible for that mineral (OA in plane of stage and see ω and true ε).

Orienting crystals to determine ω and ε

To measure ε :

1) Find a grain with maximum interference colors
2) (Check for flash figure?)
3) Return → orthoscopic at lower power
4) Rotate 45° from extinction (either direction)

(+) xl $\varepsilon > \omega$ so ω faster

(-) xl $\omega > \varepsilon$ so ε faster

Thus whole grain will gain a color when $N_{xl} \parallel N_{gyp}$

i.e. slow direction is NE-SW

5) Figure out whether ε is NE-SW or NW-SE & rotate it to E-W extinction
6) Then only ε coming through!

Oils are then used → n

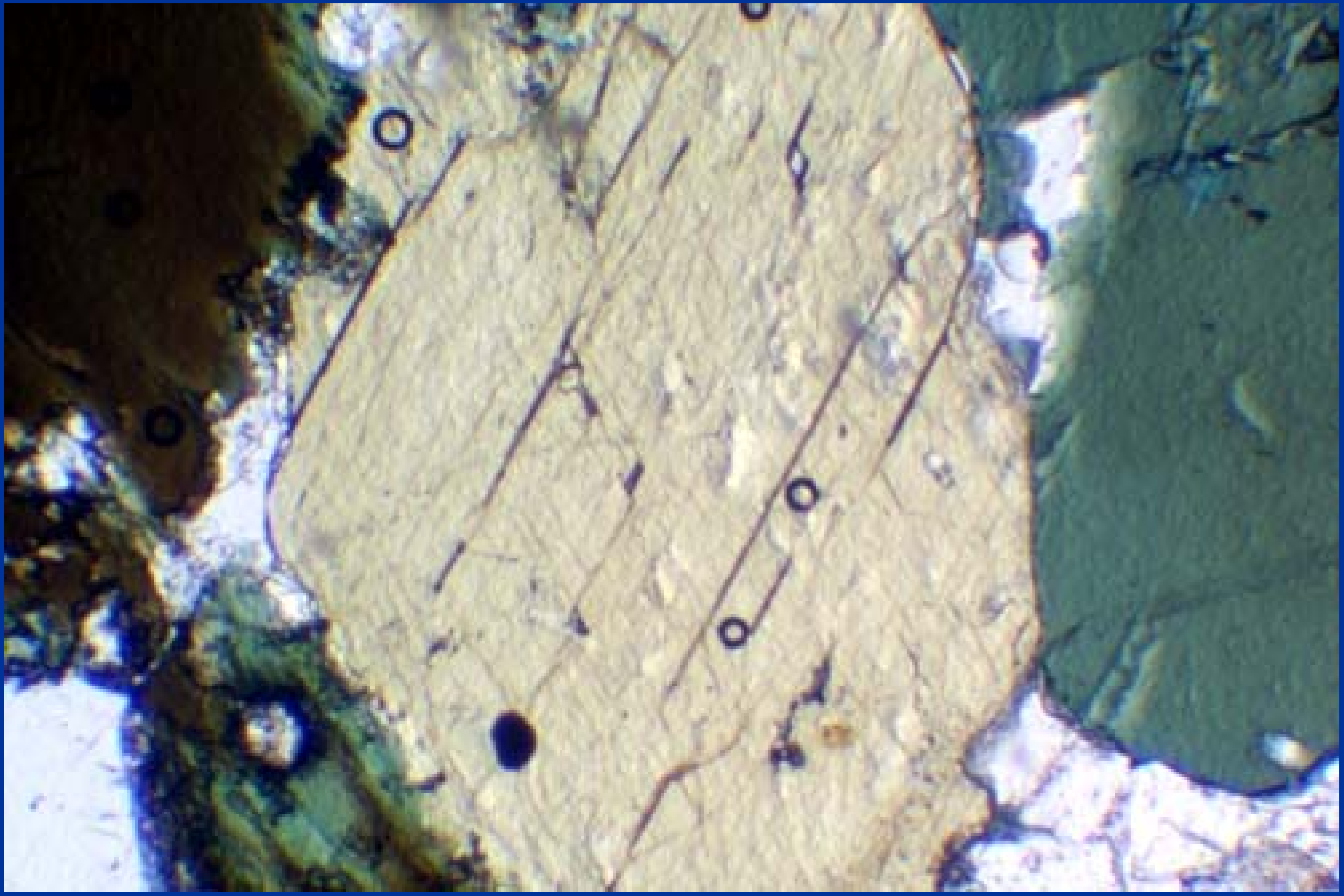
must redo with each new oil as get closer! Ugh!

Pleochroism

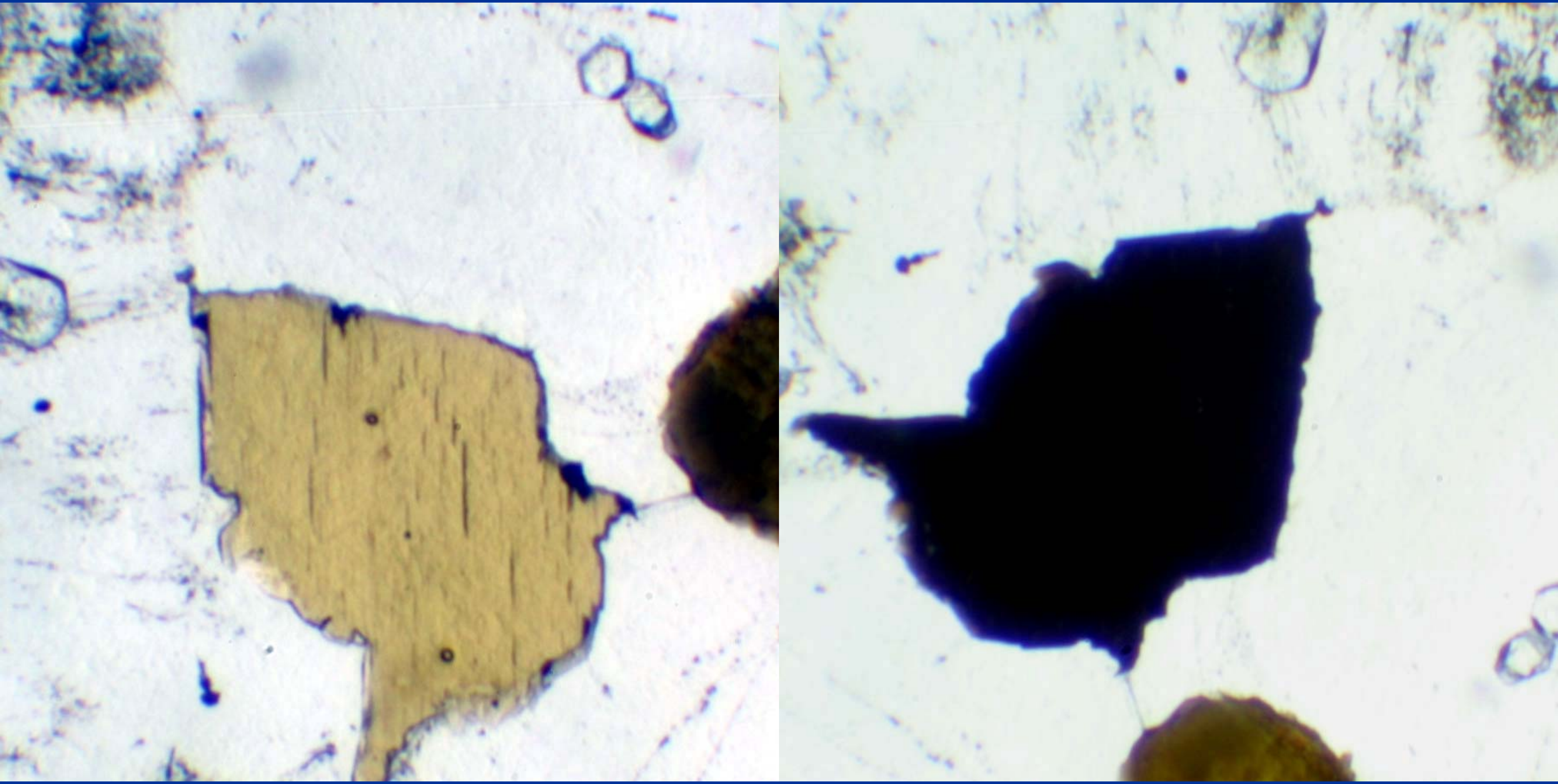
- Changes in **absorption color in PPL** as rotate stage (common in biotite, amphibole…)
- Pleochroic formula:
  - ☞ Example: Tourmaline:

    ε = dark green to bluish

    ω = colorless to tan
- Can determine this as just described by isolating first ω and then ε E-W and observing the color



Hornblende as stage is rotated



Biotite as stage is rotated

Biaxial Crystals

Orthorhombic, Monoclinic, and Triclinic crystals don't have 2 or more identical crystal axes

- The indicatrix is a general ellipsoid with three unequal, mutually perpendicular axes
- One is the smallest possible n and one the largest

Fig 10-1 Bloss, Optical Crystallography, MSA

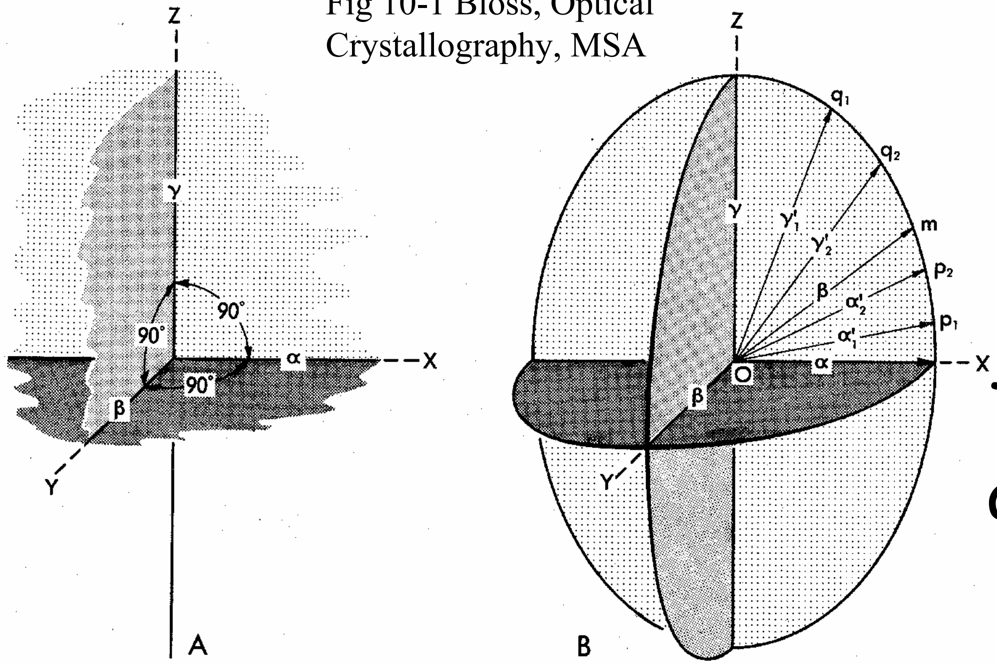


Fig. 9-1. (A) The three, mutually perpendicular, principal vibration axes, *X*, *Y*, and *Z*, and the common symbols for the indices of refraction of a biaxial mineral for light vibrating parallel to them. (B) Elliptical distribution of the index of refraction (as shown by the vector lengths) for light vibrating parallel to op_1, op_2, om, oq_2, oq_1 within the *ZX* plane.

α = smallest n (fastest)

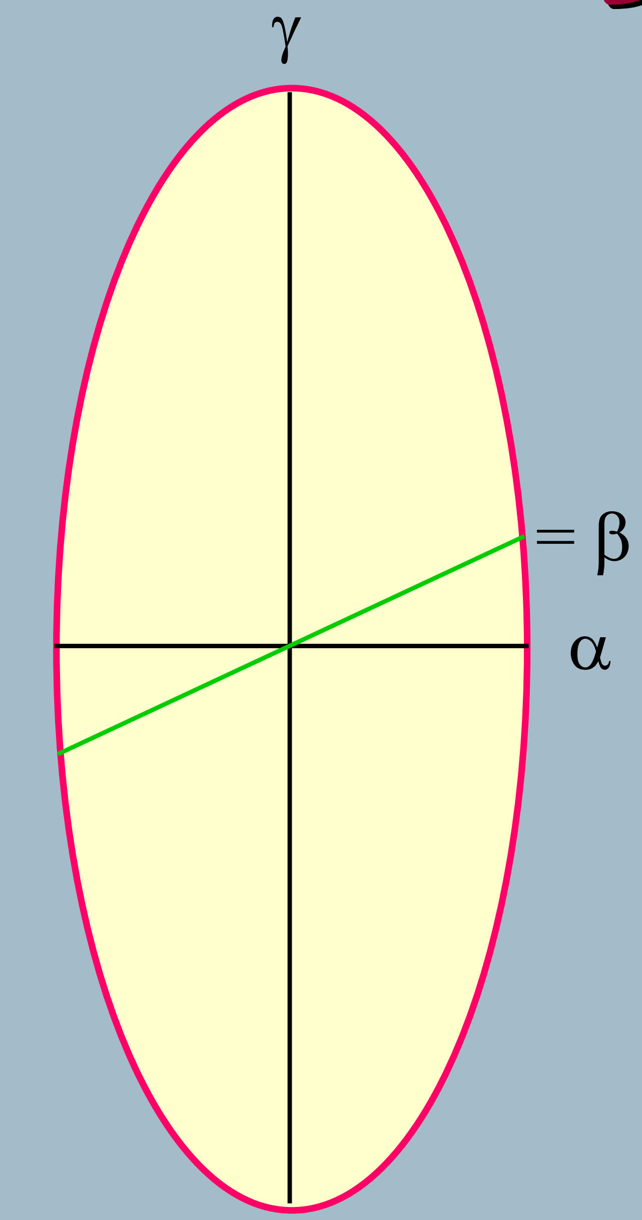
β = intermediate n

γ = largest n (slowest)

The principal vibration directions are x, y, and z ($x \parallel \alpha$, $y \parallel \beta$, $z \parallel \gamma$)

By definition $\alpha < \alpha' < \beta < \gamma' < \gamma$

Biaxial Crystals



Looking down true β

If α < β < γ then there must be some point between α & γ with n = β

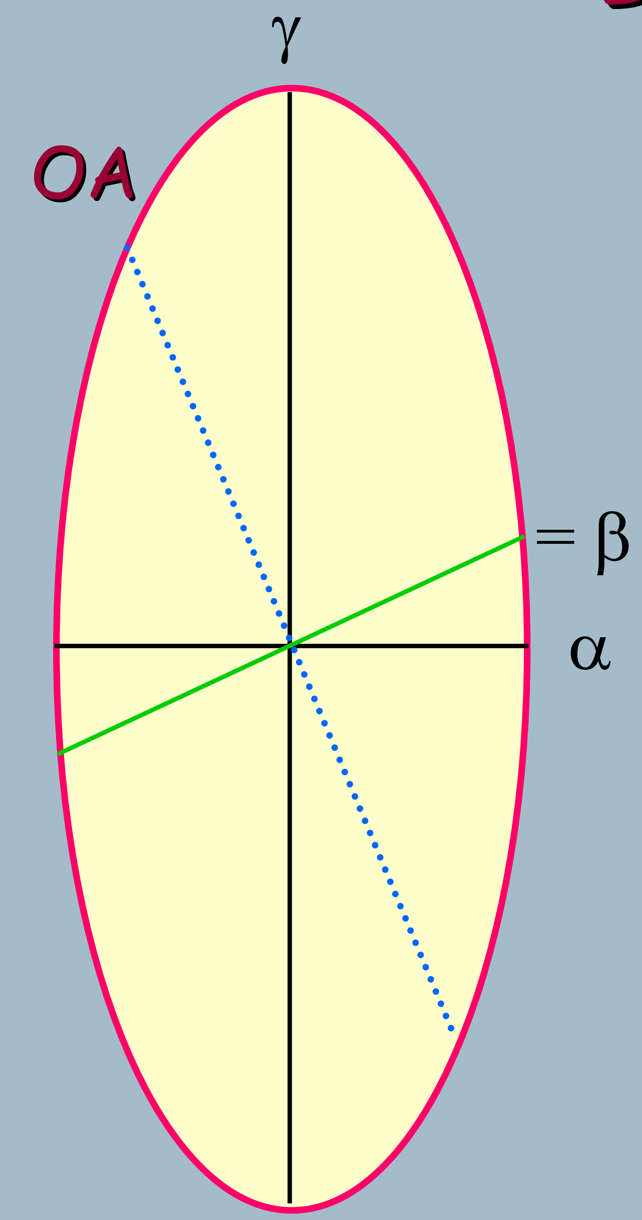
Because = β in plane, and true β is normal to plane, then the section containing both is a circular section

Has all of the properties of a circular section!

If look down it:

- all rays = β
- no preferred vibration direction
- polarized incoming light will remain so
- unpolarized " " " "
- thus appear isotropic as rotate stage

Biaxial Crystals

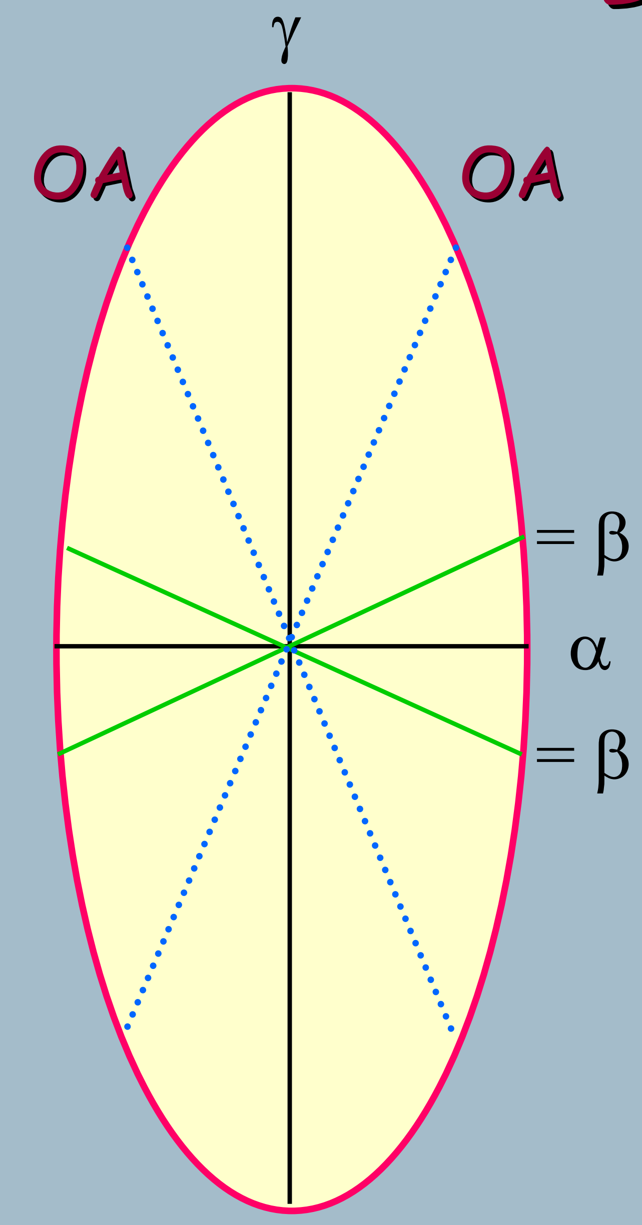


Looking down true β

If α < β < γ then there must be some point between α & γ with n = β

⊥ optic axis by definition

Biaxial Crystals



Looking down true β

If α < β < γ then there must be some point between α & γ with n = β

⊥ optic axis by definition

And there must be two! ⇒ **Biaxial**

Orthorhombic, Monoclinic, and Triclinic minerals are thus biaxial and Hexagonal and tetragonal minerals are uniaxial

Biaxial Crystals

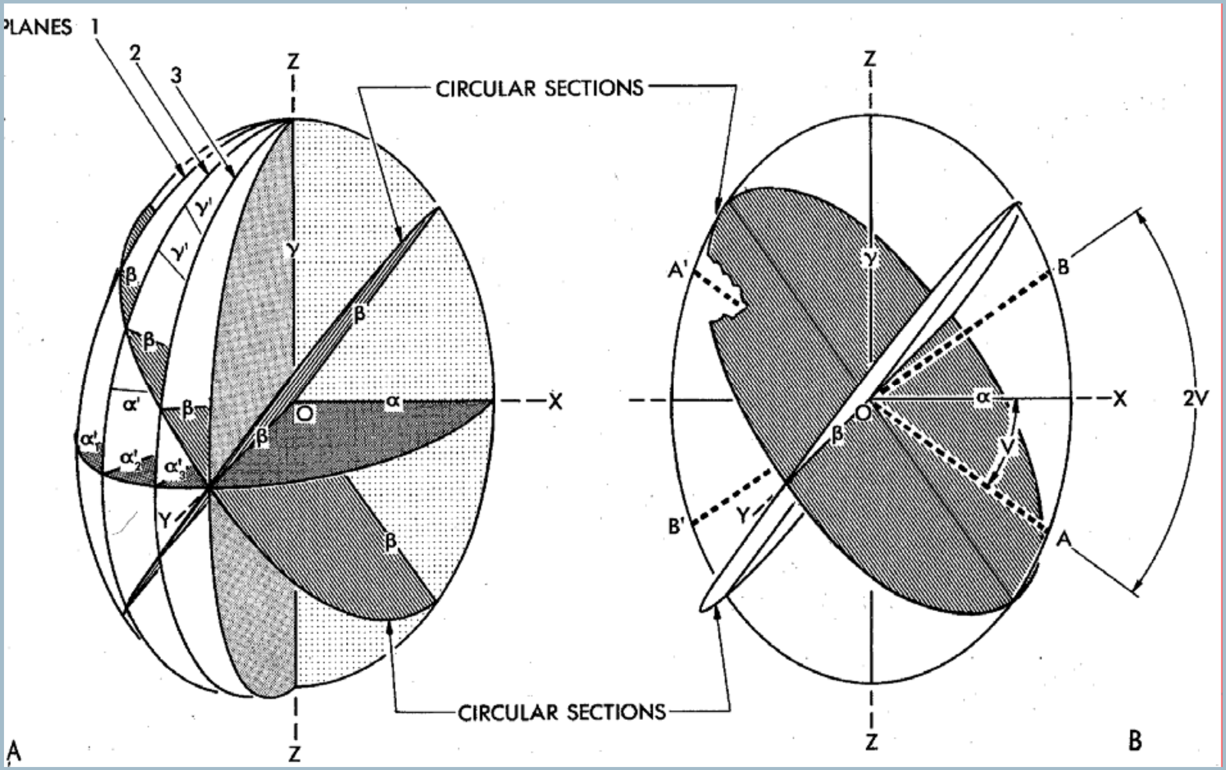


Fig 10-2 Bloss, Optical Crystallography, MSA

Nomenclature:

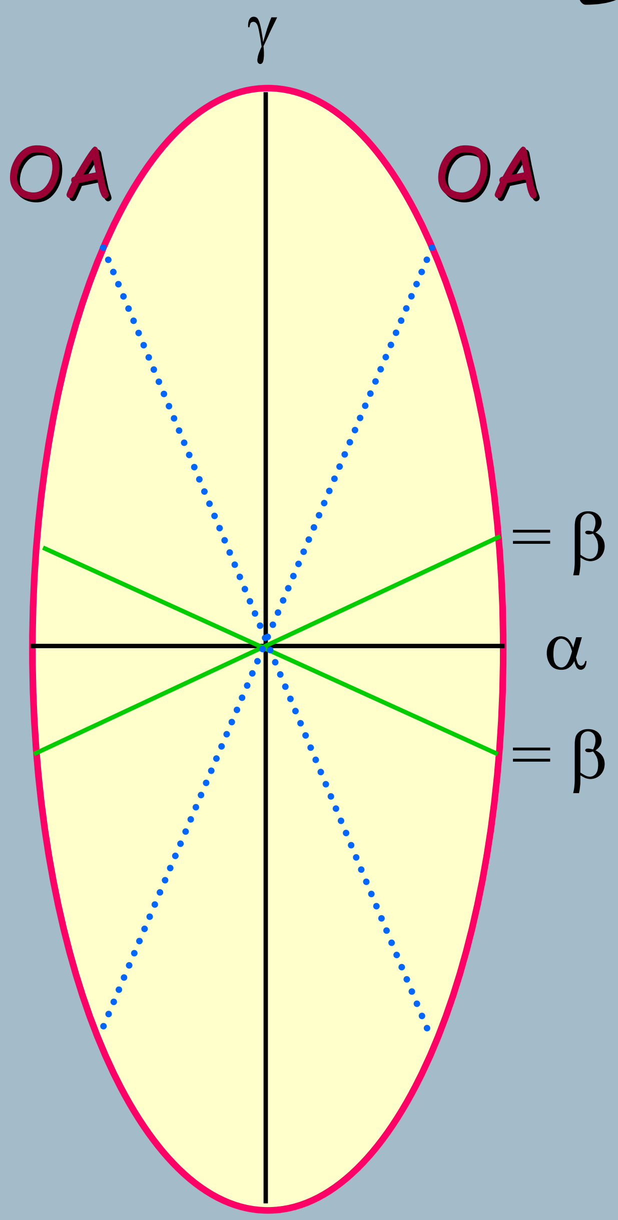
- 2 circular sections
  → 2 optic axes
  Must be in α-γ plane
  = **Optic Axial Plane (OAP)**
- Y || β direction ⊥
  OAP = **optic normal**

Acute angle between OA's = 2V

The axis that bisects acute angle = **acute bisectrix** = B_{xa}

The axis that bisects obtuse angle = **obtuse bisectrix** = B_{xo}

Biaxial Crystals

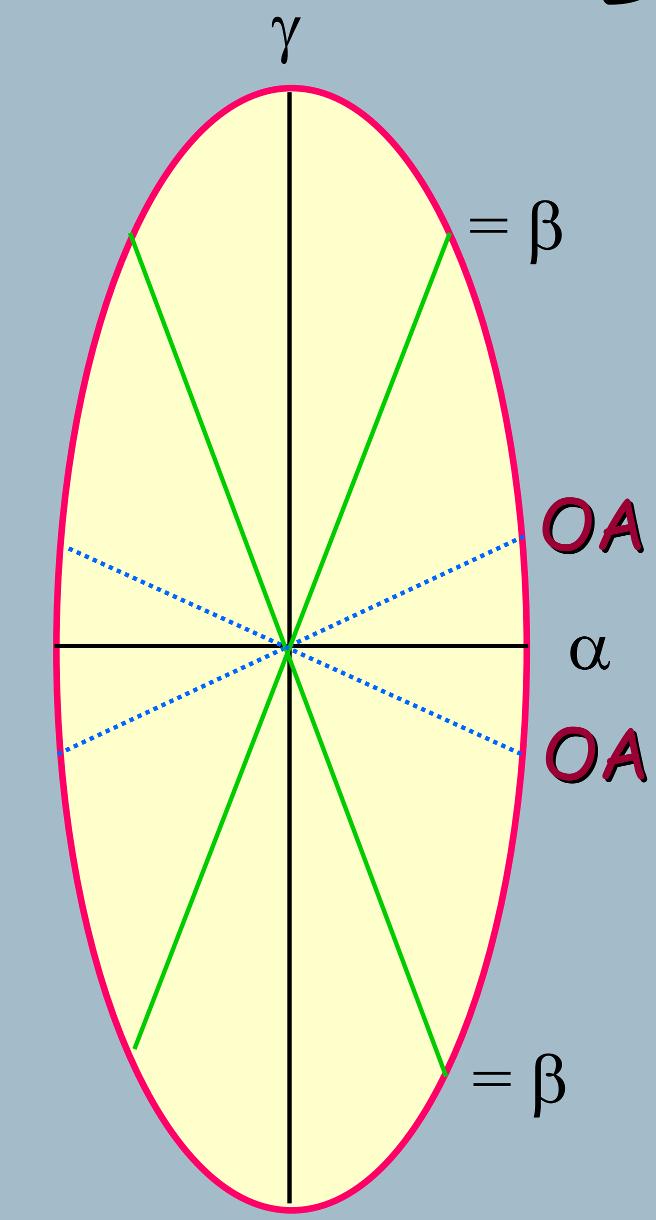


Looking down true β

B(+) defined as Z (γ) = B_{xa}

Thus β closer to α than to γ

Biaxial Crystals



Looking down true β

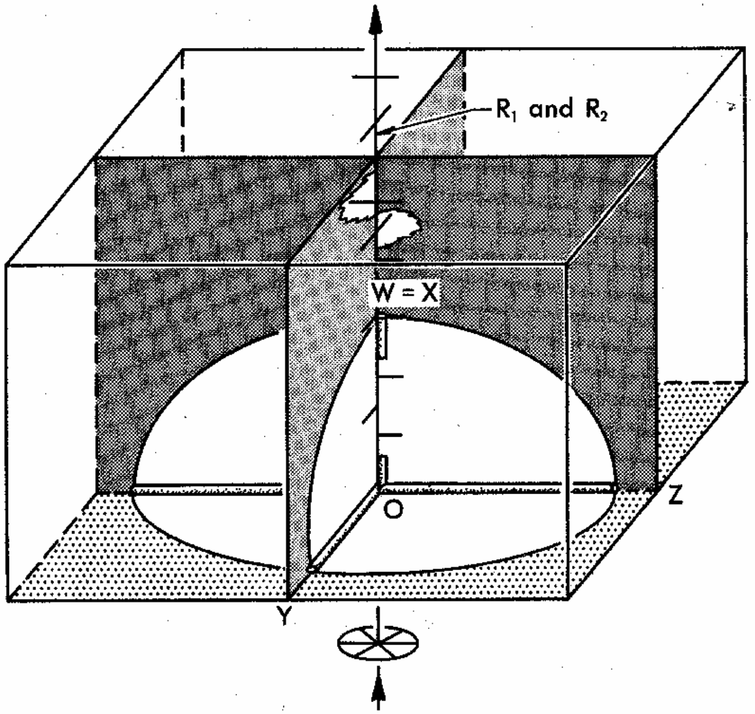
B(-) defined as X (α) = B_{xa}

Thus β closer to γ than to α

Let's see what happens to unpolarized light travelling in various directions through a biaxial crystal

Light will propagate with normal incidence to:

Fig 10-11C Bloss, Optical Crystallography, MSA



Coincidence of the rays OR_1 and OR_2 produced by normal incidence of an unpolarized ray on a principal plane YZ (stippled). Both ray-containing planes (light and dark shading) are now principal sections.

1) Principal Plane -

Includes 2 of the 3 true axes or principal vibration directions

Both = O-rays

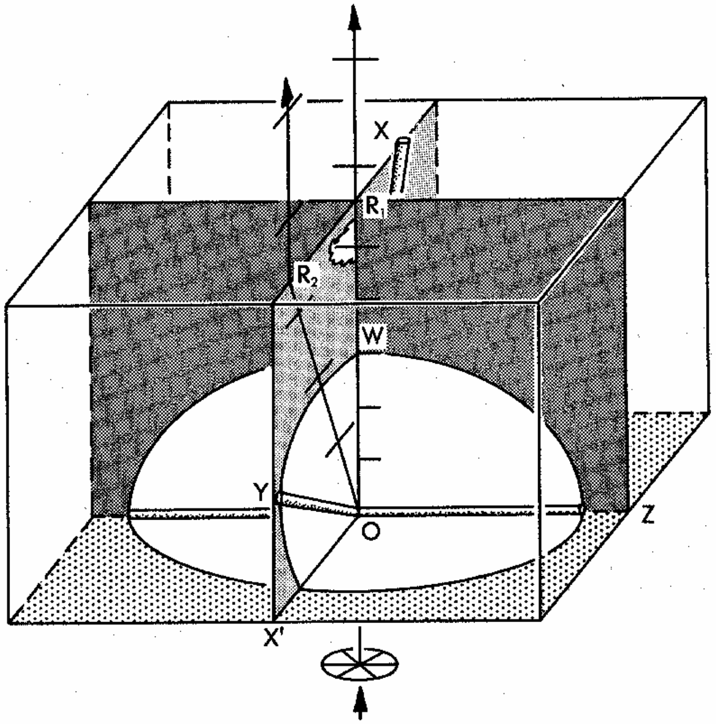
Both polarized, and vibrate ⊥ each other (as uniaxial)

One ray vibrates || Z and has n = γ and the other vibrates || Y and n = β

...or Z and X or Y and X

Let's see what happens to unpolarized light travelling in various directions through a biaxial crystal

Light will propagate with normal incidence to:



Rays resulting from the normal incidence of an unpolarized ray on a semirandom section $X'Z$. The ray-containing plane defined by wave normal OW and vibration OX' is a principal section.

Fig 10-11B Bloss, Optical Crystallography, MSA

2) Semi-random Plane

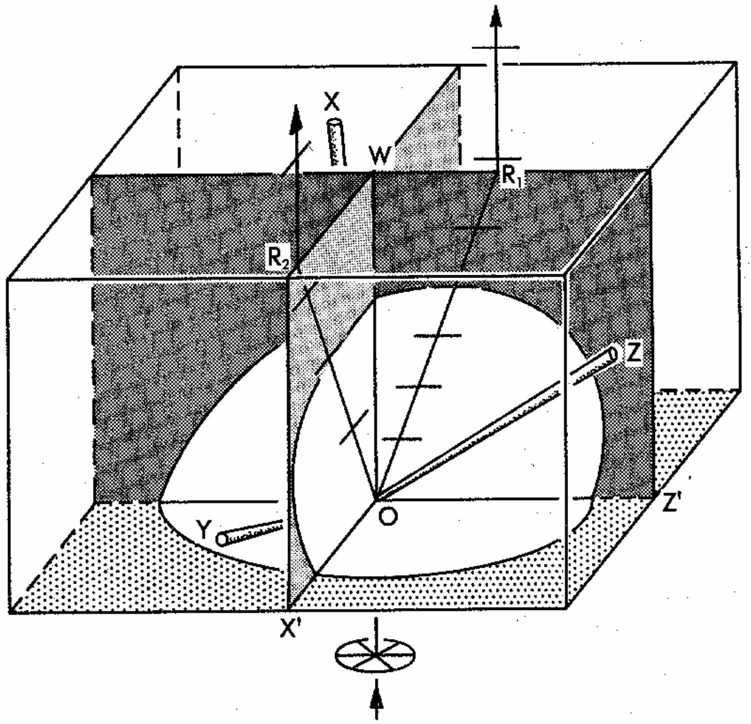
Includes one principal vibration direction

This is identical to uniaxial:

1 O-ray and 1 E-ray

γ and α' or β and γ'

… vibration in incident plane so indicatrix works!



The ray paths developed within a biaxial crystal as the result of normal incidence of an unpolarized ray upon a random section ($X'Z'$). The ray-containing planes defined by wave normal OW and vibrations OZ' or OX' are shaded dark and light, respectively, each being a random section. Deviations of the ray paths OR_1 and OR_2 from the wave normal OW have been exaggerated for illustrative purposes.

3) Random Plane

No principal vibration directions

→ 2 E-rays

One vibrates in the OWZ' plane

and || OZ' with n = γ'

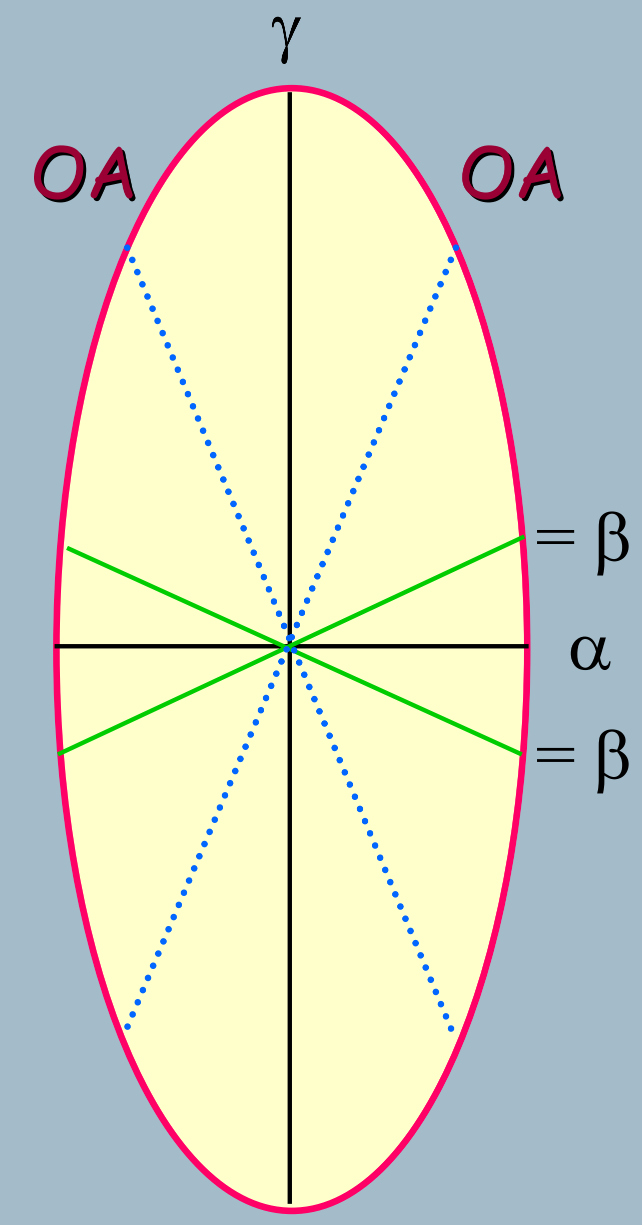
The other vibrates in the OWX'

plane and || OX' with n = α'

Fig 10-11A Bloss, Optical Crystallography, MSA

Vibration directions of 2 rays in all 3 cases are mutually perpendicular, and || to the longest and shortest axes of the indicatrix ellipse cut by the incident plane

This is the same as with uniaxial, only the names change



Looking down true β

4) Circular Section (either one)

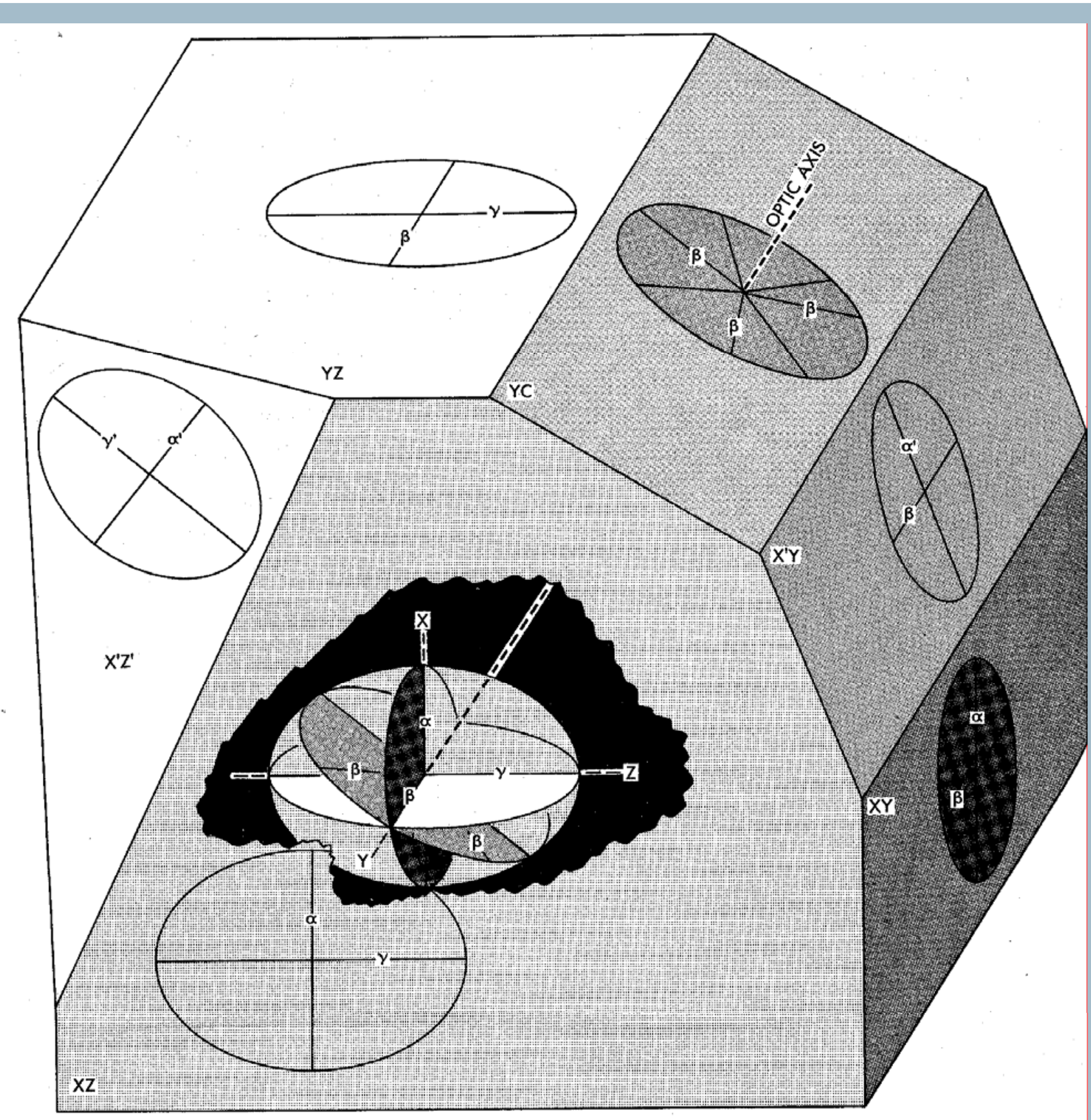
Acts as any circular section:

Unpolarized remains so

Polarized will pass through polarized in the same direction as entered with n = β

→ extinct in XPL and remains so as rotate stage

Review



The biaxial indicatrix in skeletal form is shown at the center of the crystal. Its intersection with different faces of the crystal, if it were moved translationally until its center fell on a crystal face, is shown for several faces. The major and minor axes of these ellipses of intersection represent the privileged directions of the crystal for normal incidence on that face. For face *YC*, since it intersects the indicatrix in a circle, innumerable privileged directions exist. The crystal's refractive indices for the privileged directions are also shown. See Table 9-2 for details of symbolism used for the faces.

Fig 10-10 Bloss, Optical Crystallography, MSA

Biaxial Interference Figures

B_{xa} figure (B_{xa} is vertical on stage)

As in uniaxial, condensing lens causes rays to emanate out from O

OX → OS → OA

results in decreasing retardation (color) as

$\gamma \rightarrow \beta$

OA → OT → OU

Increase again, but now because $\beta \rightarrow \alpha$

OX → OQ → OP

⇒ incr retardation (interference colors)

OR is random with α' and γ'

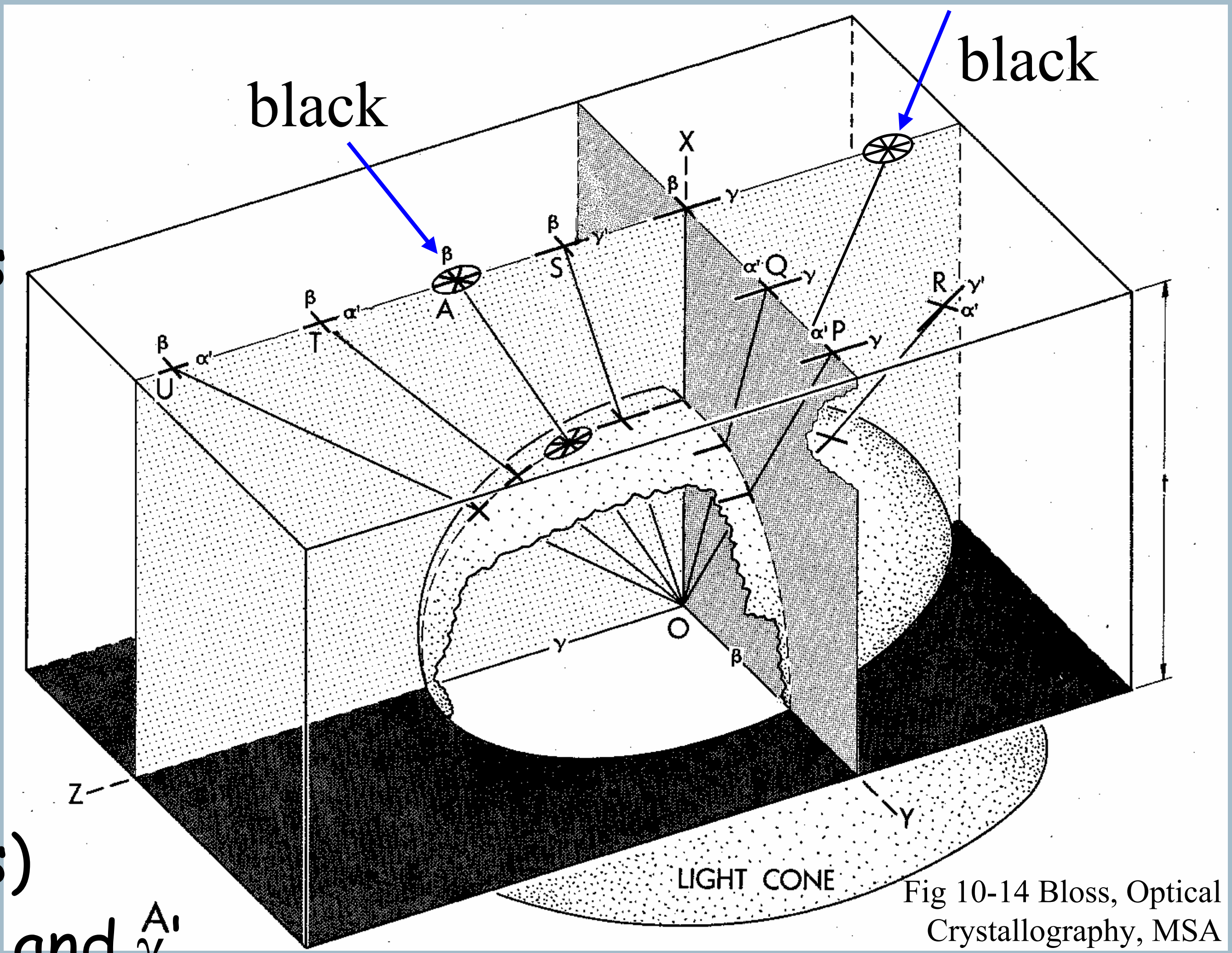


Fig 10-14 Bloss, Optical Crystallography, MSA

Biaxial Interference Figures

B_{xa} figure

Result is this pattern of isochromes for biaxial crystals

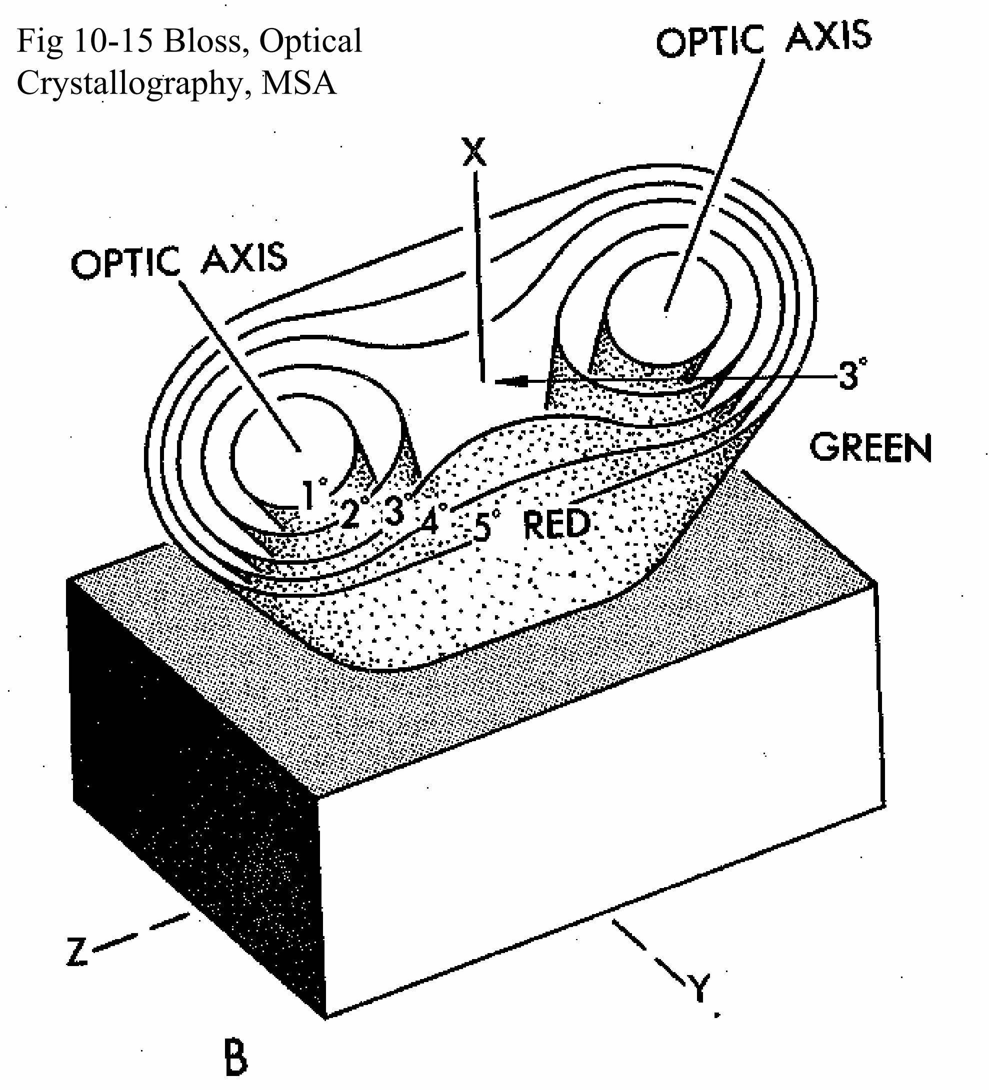


Fig 10-15 Bloss, Optical Crystallography, MSA

Biaxial Interference Figures

Biot-Fresnel Rule:
for determining privileged vibration directions of any light ray from path and optic axes

Calcite Expt: no longer a single plane containing ray and OA

Vibration directions bisect angle of planes as shown

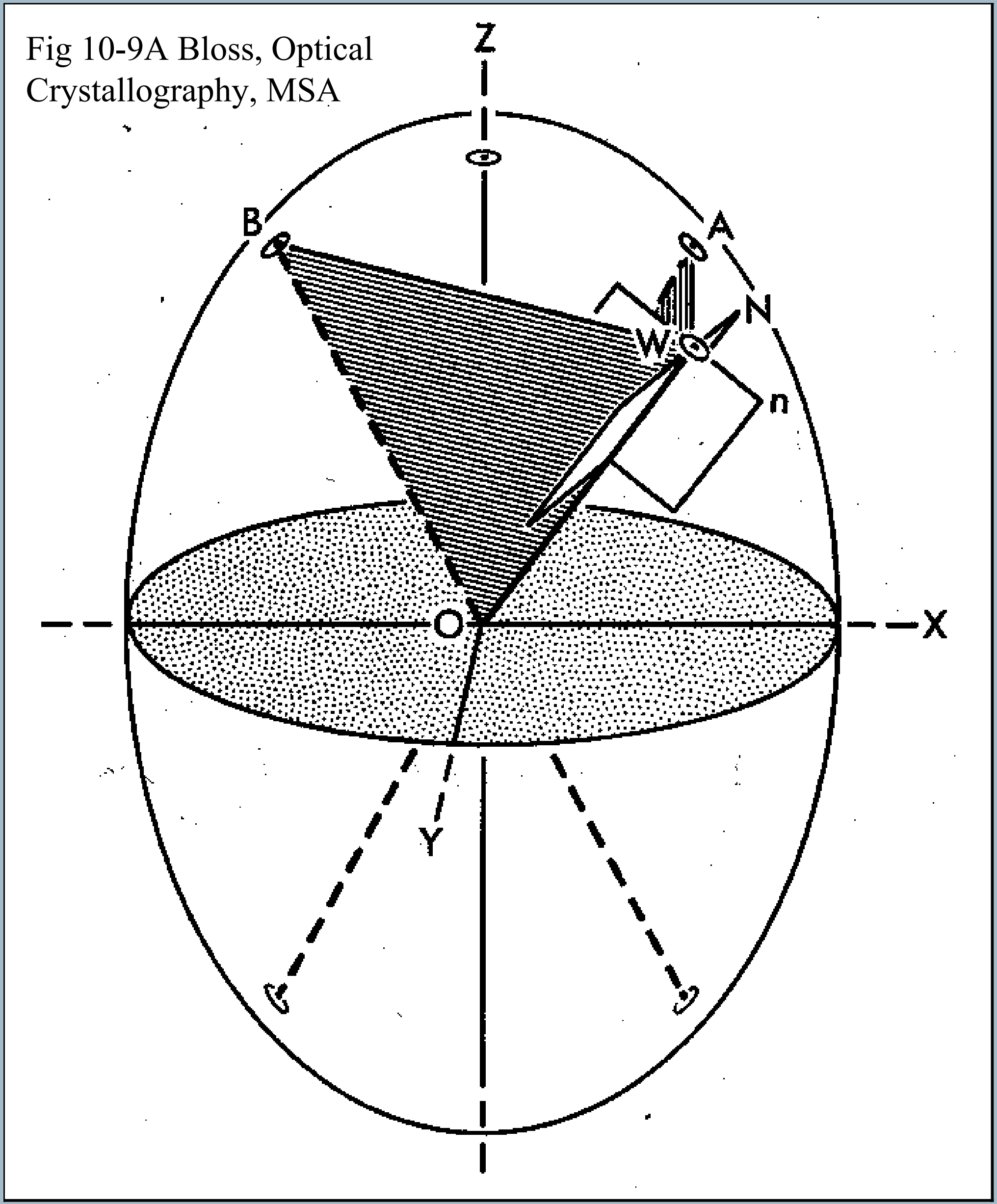


Fig 10-9A Bloss, Optical Crystallography, MSA

Biaxial Interference Figures

Application of B-F rule to conoscopic view B_{xa} figure

\+ = bisectrices of optic axis planes

Isogyres are locus of all N-S (& E-W) vibration directions

Since incoming light vibrates E-W, there will be no N-S component → extinct

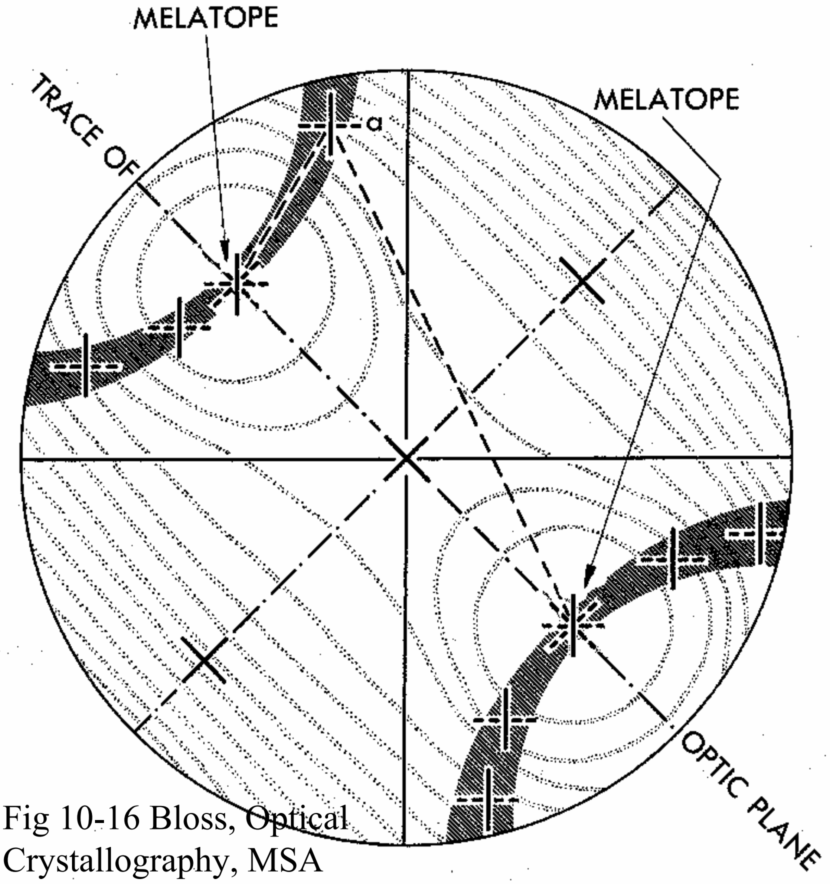
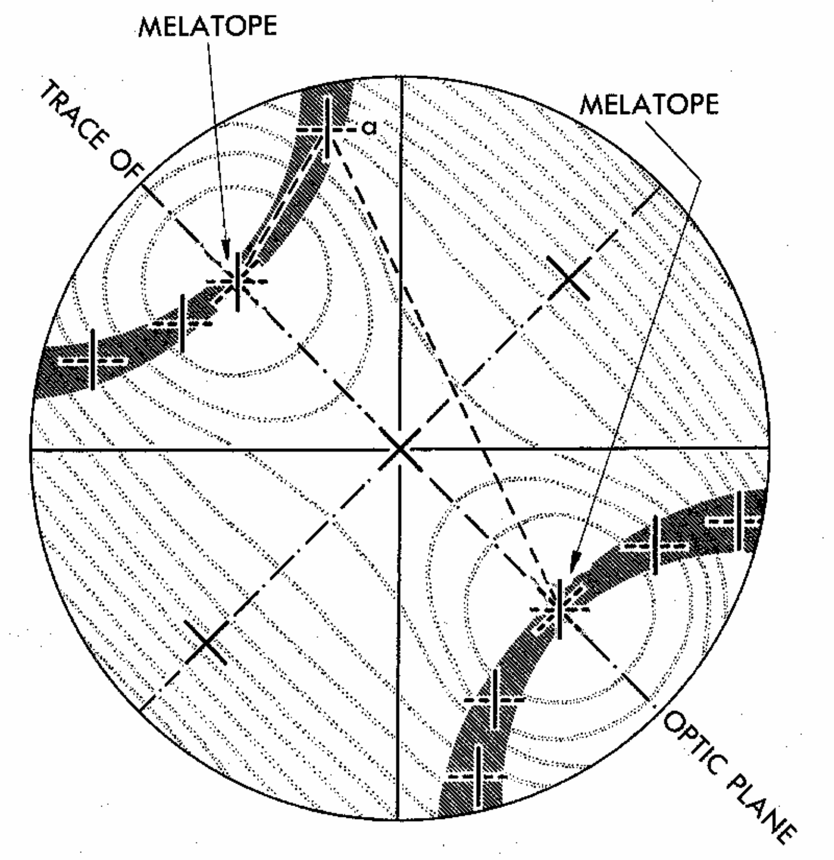


Fig 10-16 Bloss, Optical Crystallography, MSA

Centered, acute bisectrix figure at 45 degrees off extinction position. The two-dimensional analog of the Biot-Fresnel law is applied to point *a* to determine (approximately) the privileged directions for rays emerging there. At several points in the field of view the privileged directions for the rays emerging there are also shown.

Biaxial Interference Figures

Centered B_{xa} Figure



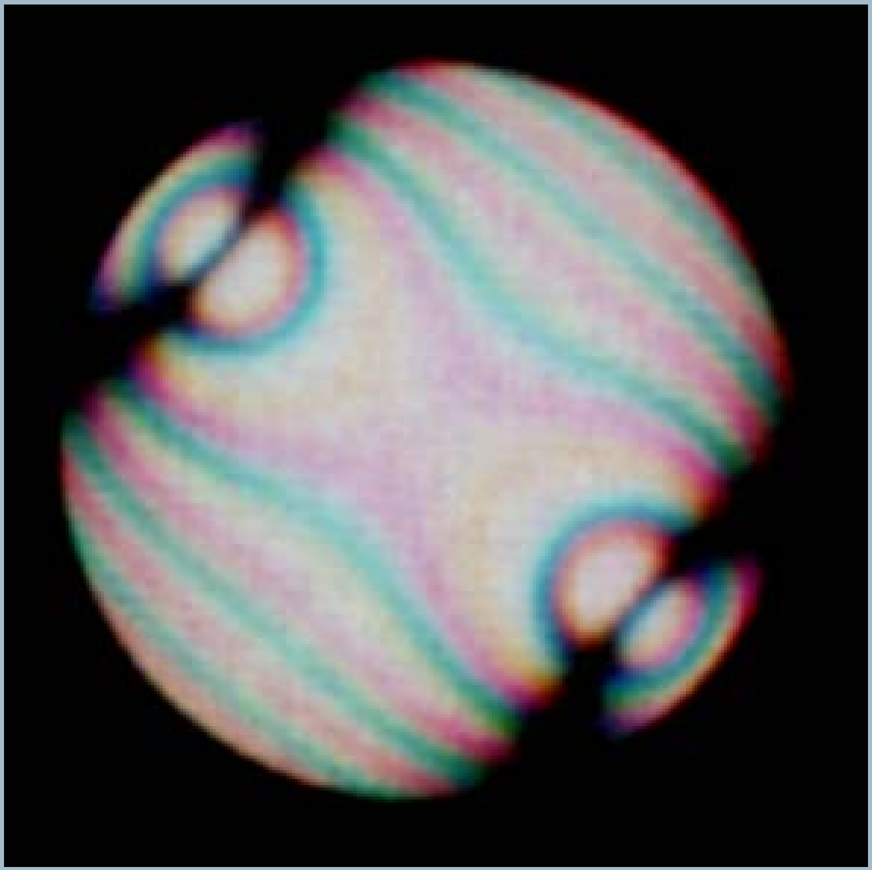


Fig 10-16 Bloss, Optical Crystallography, MSA

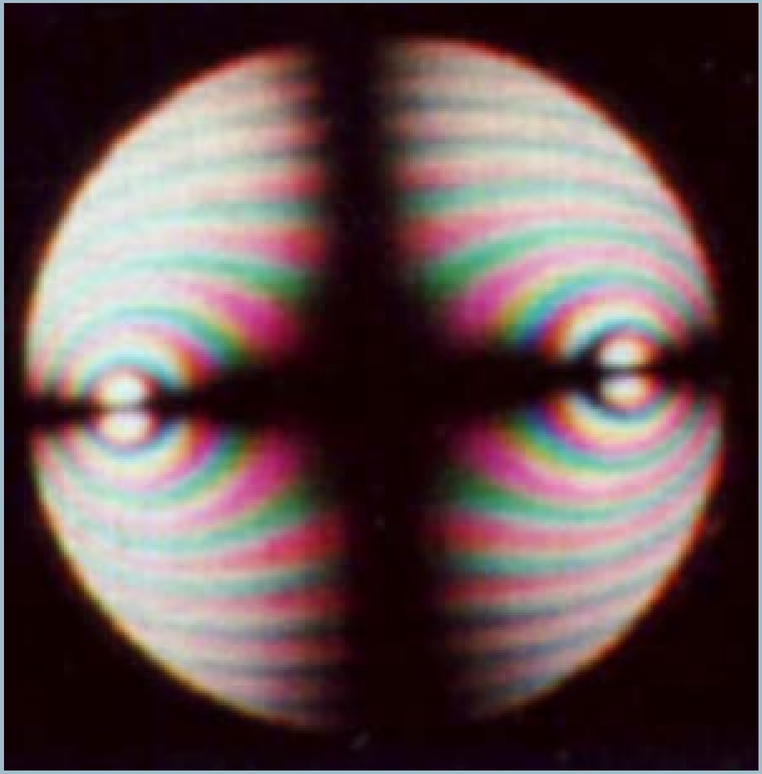
Biaxial Interference Figures

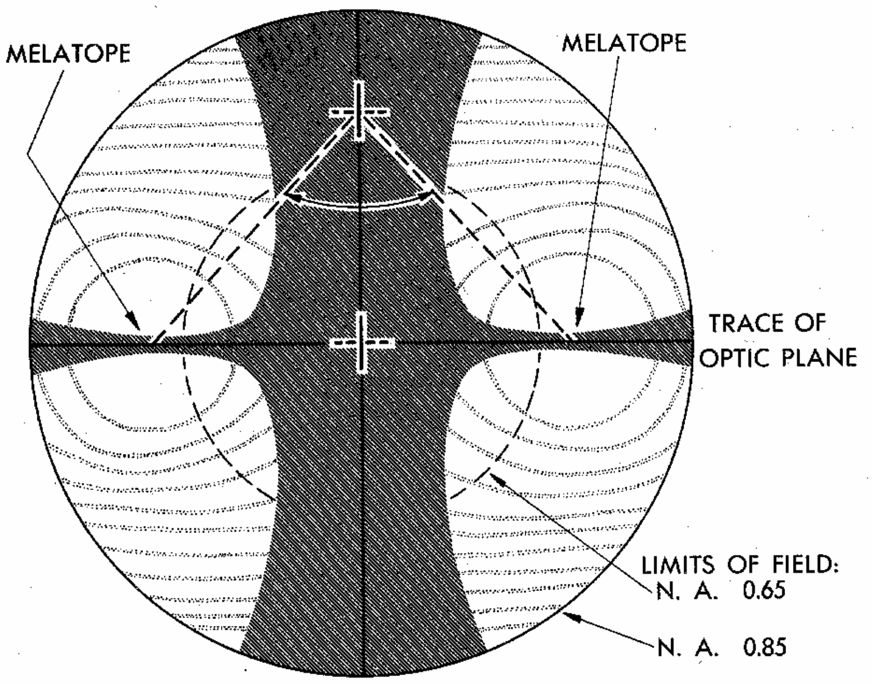
Same figure rotated 45°

Optic axes are now E-W

Clearly isogyres must swing

Demonstration



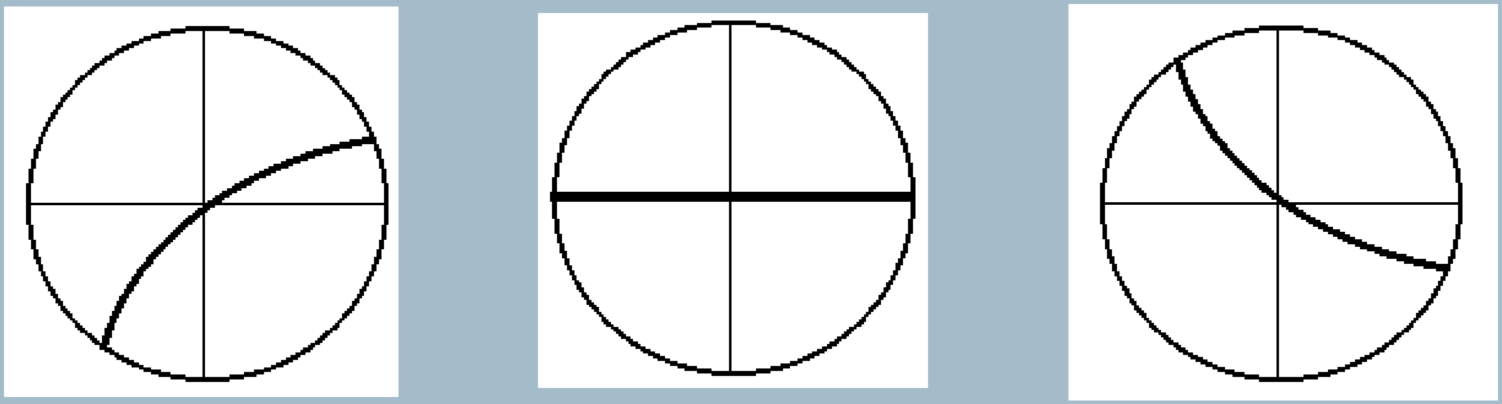


as seen if the microscope stage is rotated 45 degrees counterclockwise. Extinction occurs in the areas where rays emerge that vibrate parallel to the polarizer. The dashed circle marks the limits of the field of view if an objective of N. A. 0.65 is used instead of one of N. A. 0.85.

Fig 10-16B Bloss, Optical Crystallography, MSA

As rotate

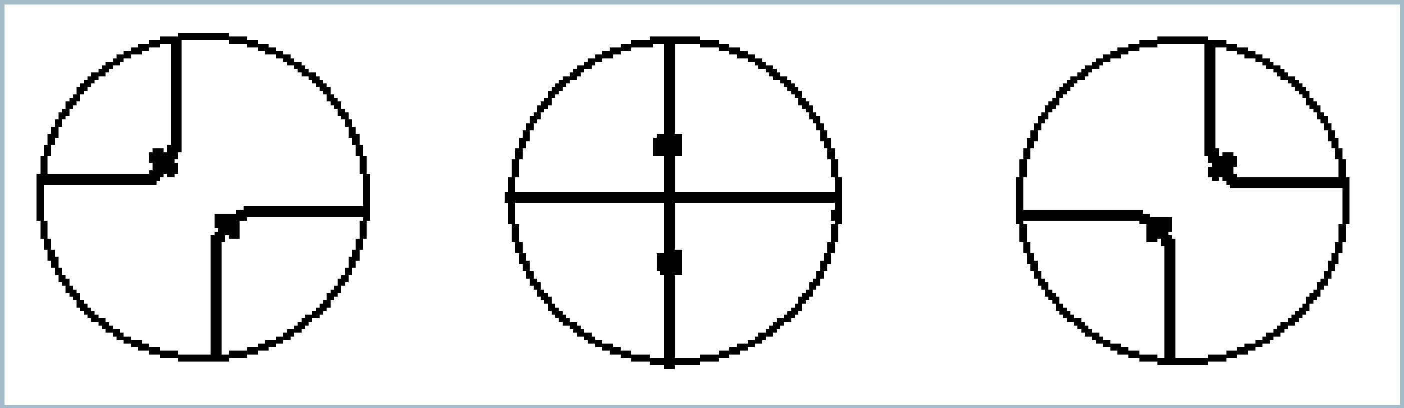
Centered Optic Axis Figure Large 2V:



Not much curvature

Makes use of B_{xa} awful

B_{xa} Figure with Small 2V:



Always use optic axis figures

  - ☞ Easiest to find anyway. Why?
- B_{xo} looks like B_{xa} with $2V > 90^o$
- Random Figures: Isogyre sweeps through field (not parallel x-hair at intersection, so can recognize from uniaxial even with this odd direction)
  - ☞ Useless if far from OA

Biaxial Optic Sign

B(-) $a = B_{xa}$ thus b closer to g

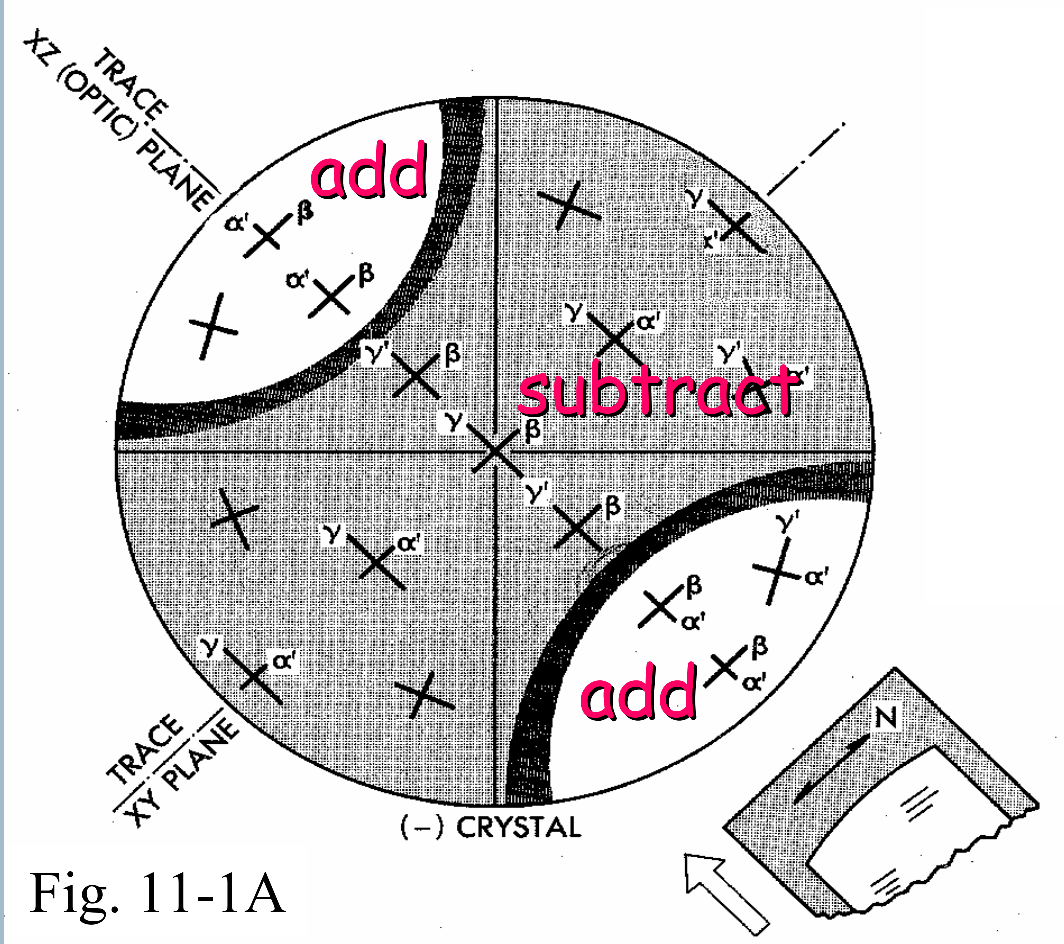
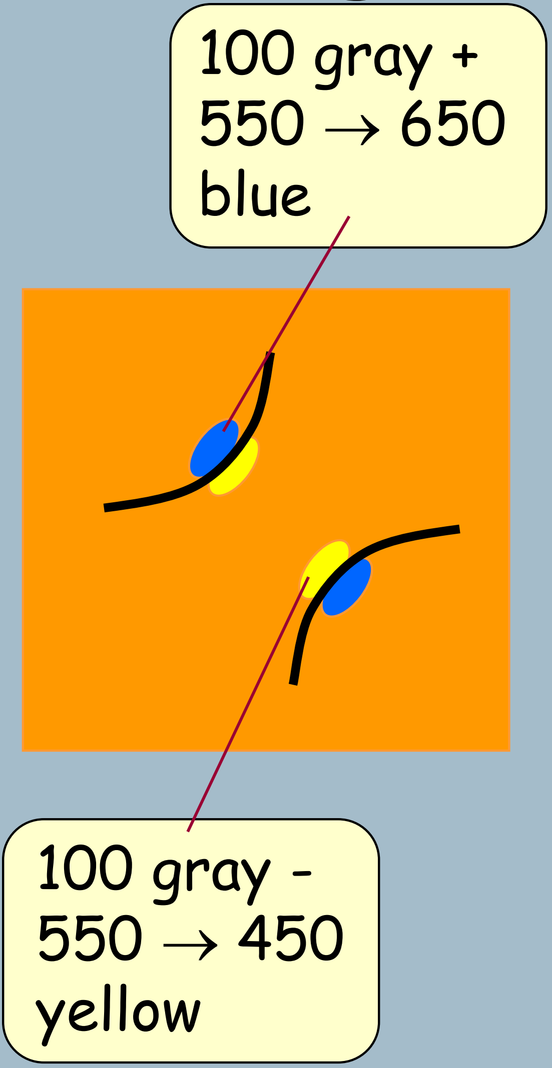


Fig. 11-1A

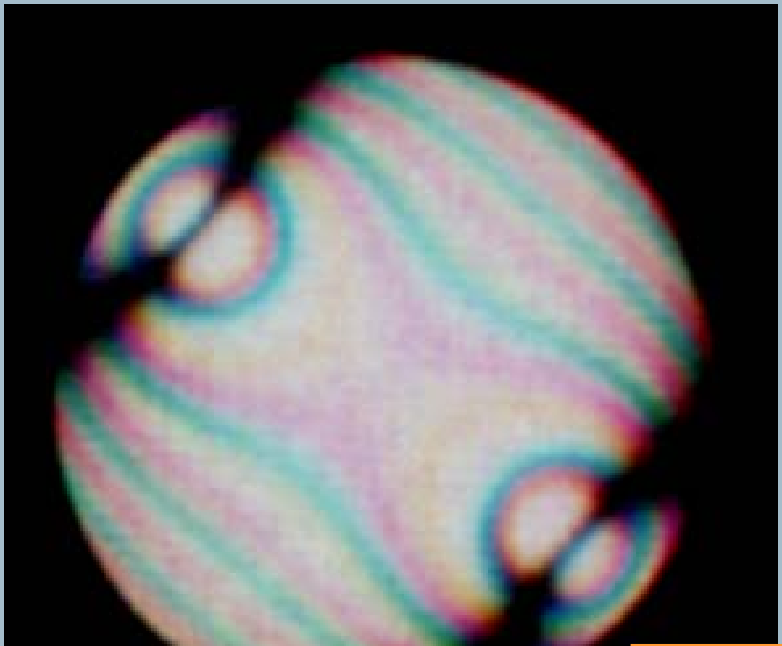


100 gray + 550 → 650 blue

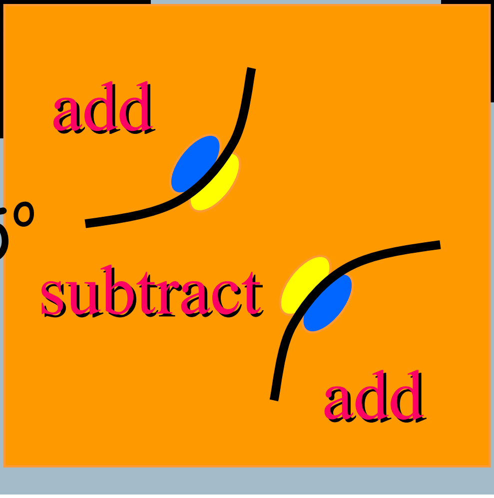
100 gray - 550 → 450 yellow

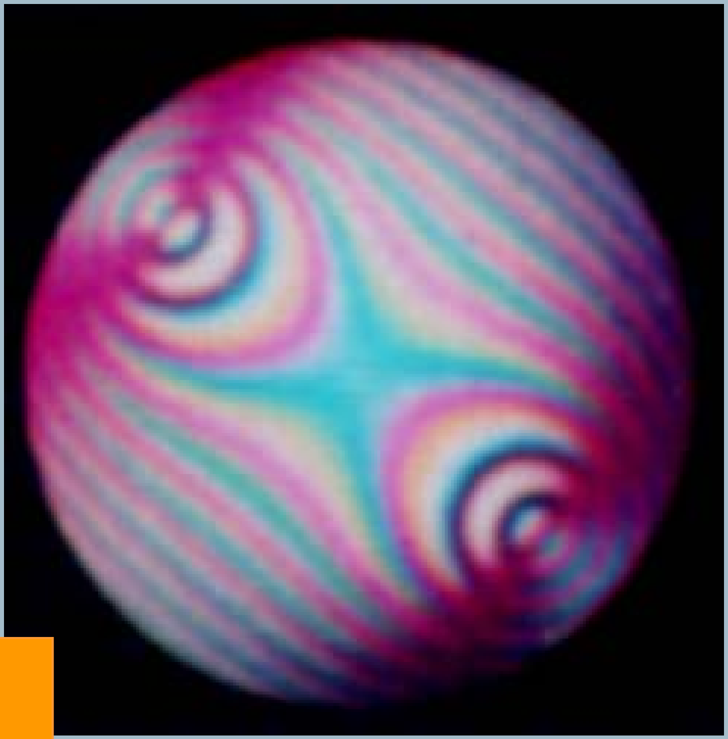
Biaxial Optic Sign

B(-) $\alpha = B_{xa}$ thus β closer to γ (in stage)



Centered B_{xa} 2V = 35°





Centered B_{xa} 2V = 35°
With accessory plate

Biaxial Optic Sign

B(+) $\gamma = B_{xa}$ thus β closer to α (in stage)

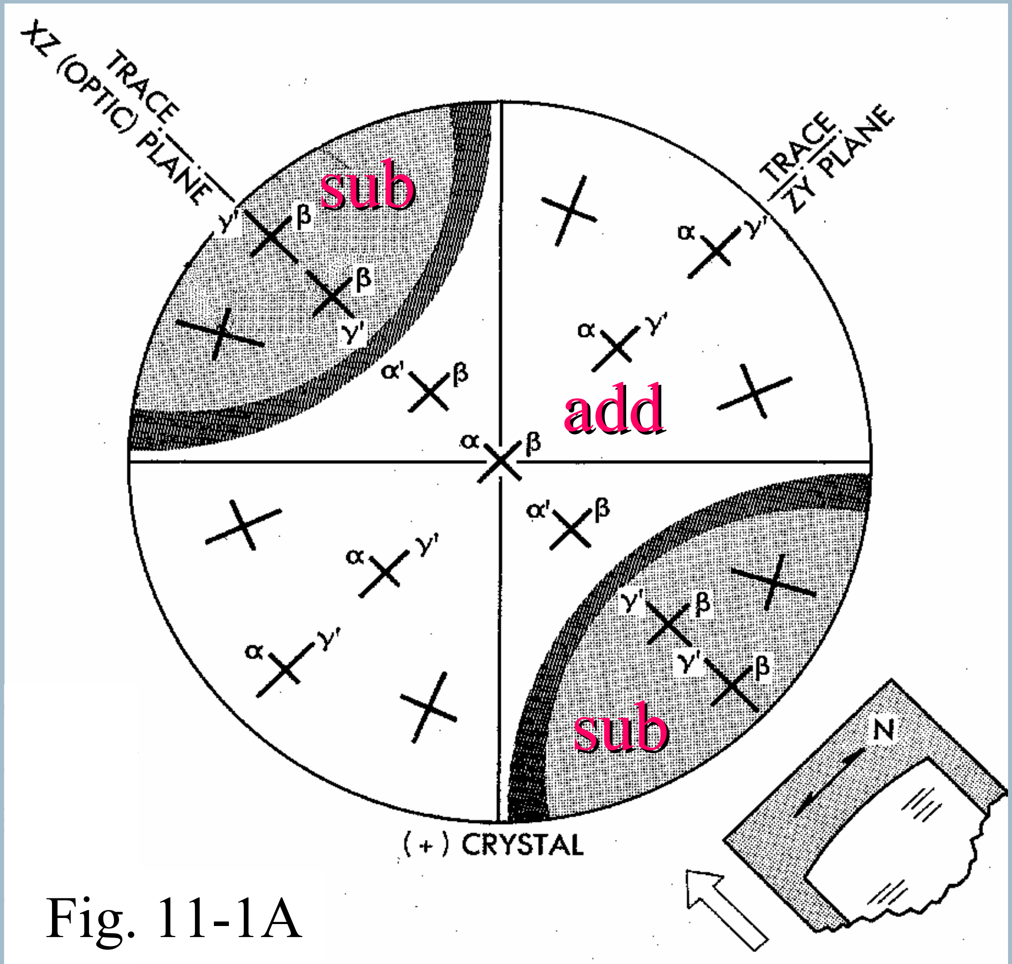
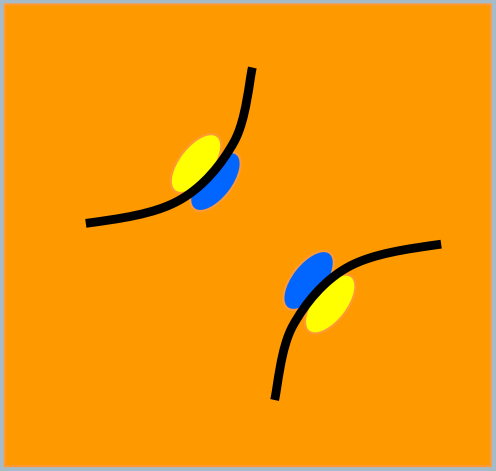


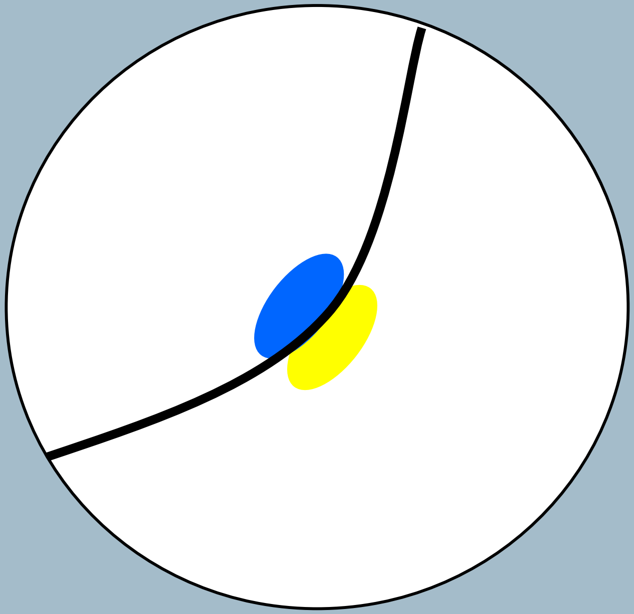
Fig. 11-1A



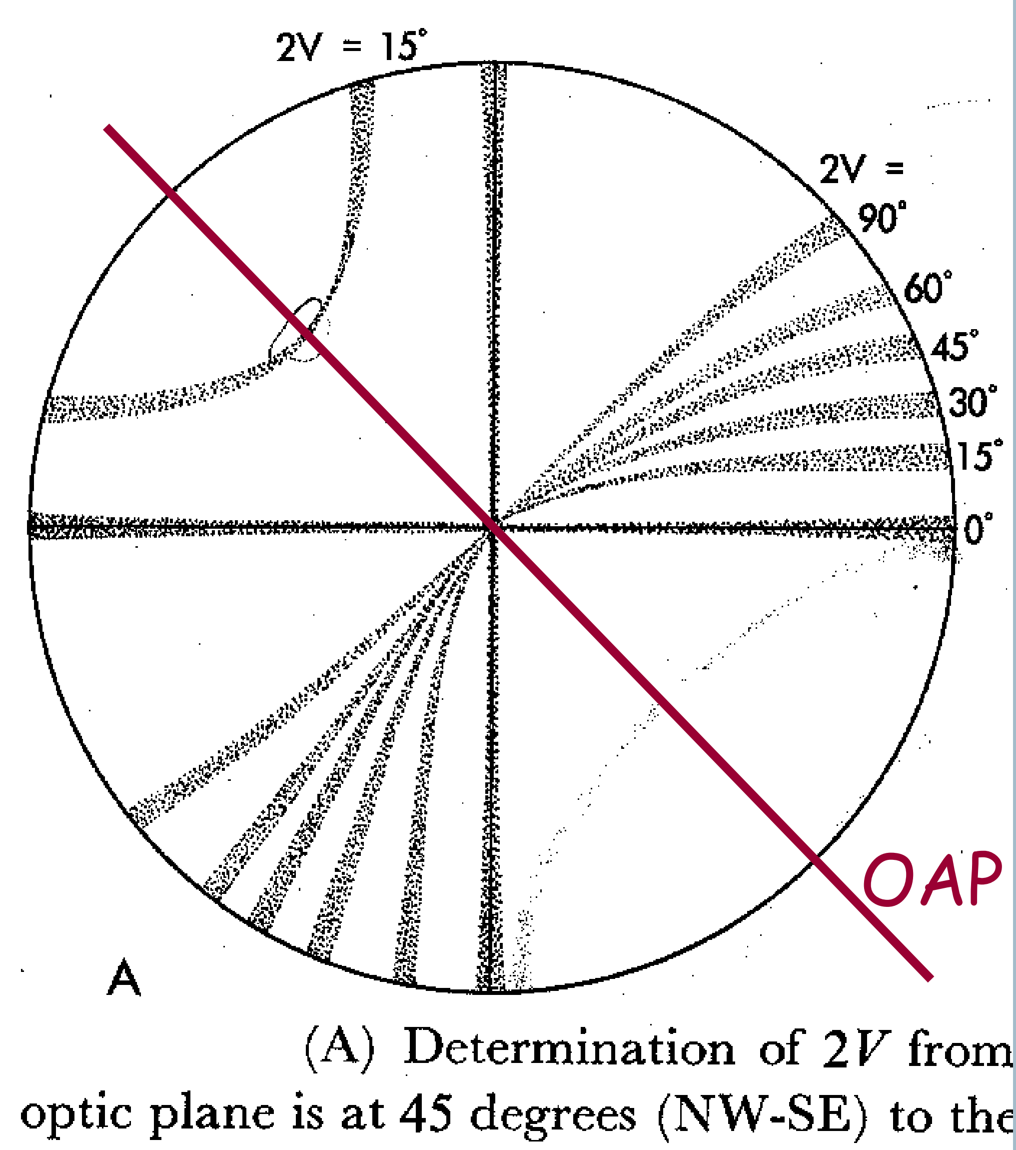
Always use Optic Axis Figure & curvature of isogyre to determine optic sign

How find a crystal for this?

Blue in NW is (-) still works



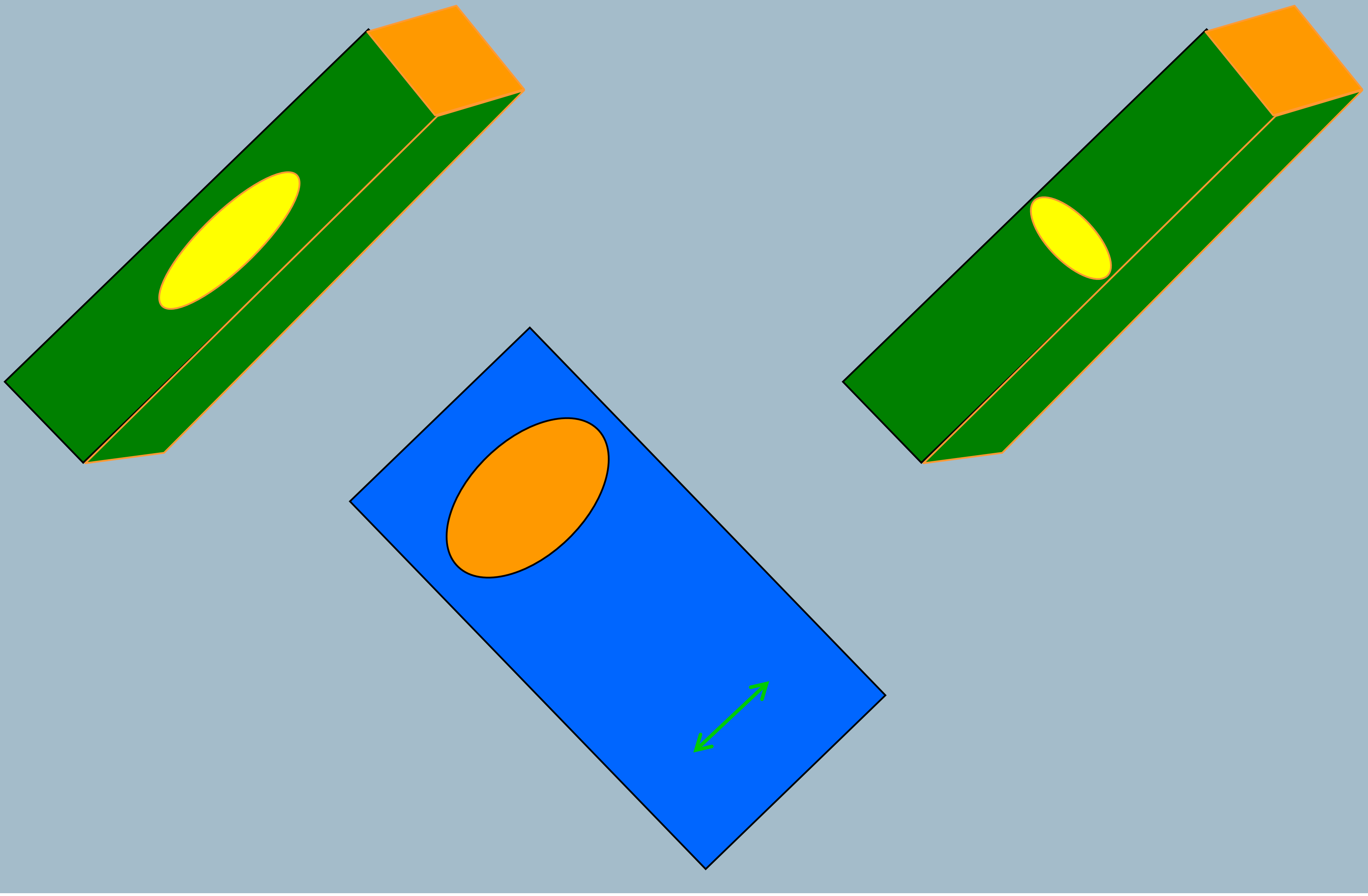
Estimating 2V



(A) Determination of 2V from
optic plane is at 45 degrees (NW-SE) to the

Fig 11-5A Bloss, Optical Crystallography, MSA

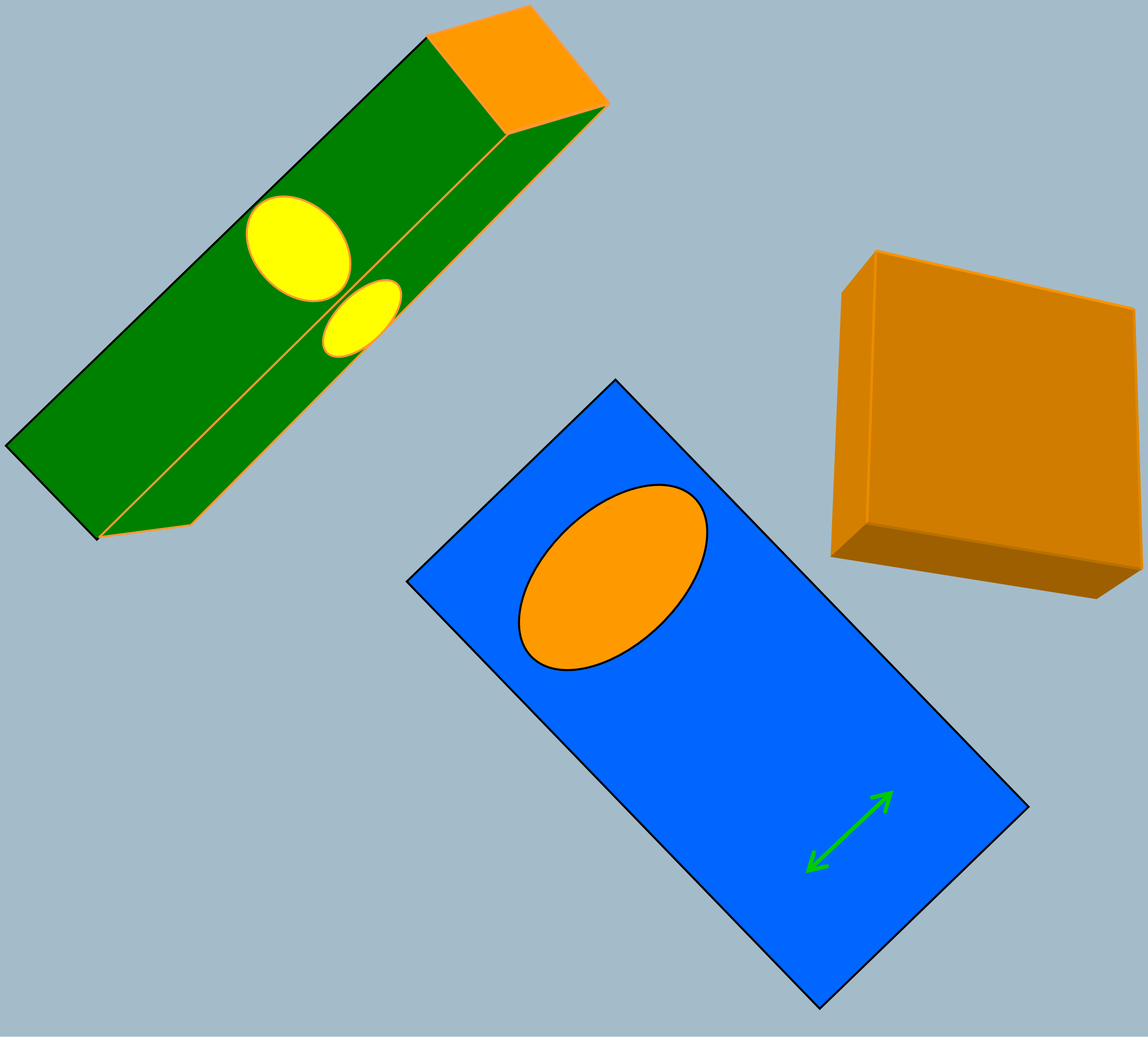
Sign of Elongation



If γ || elongation

If α || elongation

Sign of Elongation



Platy minerals may appear elongated too

Can still use sign of elongation on edges