Uniaxial Optics I

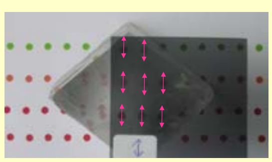
Covered in Chapter 6 of Nesse

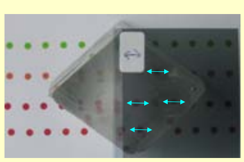
Uniaxial Minerals

- Have only one ______ axis and belong to the hexagonal and tetragonal systems
- Common minerals
  - Quartz - SiO_2
  - Nepheline - $NaAlSiO_4$
  - Calcite - $CaCO_3$
  - Dolomite – $(Ca,Mg)CO_3$
  - Apatite - $Ca_5(PO_4)_3(F,Cl,OH)$
  - Zircon – $ZrSiO_4$
  - Tourmaline – a borosilicate
    - $Na(Mg,Fe,Li,Al)_3Al_6\mathbf{(Si_6O_{18})(BO_3)_3}(OH,F)_4$

Double Refraction

Calcite - What happens?

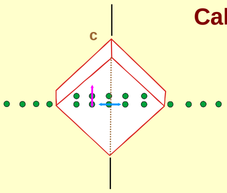




Each row of dots corresponds to one ray, each with its own **Vibration Direction** and **RI**.
The **Vibration Direction** can be determined using a polarizing filter
The **RI** can be determined using a microscope and immersion oils.

Double Refraction

Calcite – Why it happens?



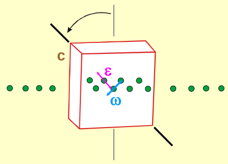
Two images are produced by laying the calcite on a single row of dots.

The vibration directions of the light rays that produce the two images are mutually perpendicular. One vibrates parallel to the c-axis, one vibrates perpendicular to the c-axis (Lab 3)

When the calcite is rotated one row of dots stays stationary and one row of dots rotates with the calcite

The stationary image corresponds to the **ordinary ray** (ω) which vibrates perpendicular to the c-axis

The rotating image corresponds to the **extraordinary ray** (ε) which vibrates parallel to the c-axis.



Double Refraction

Calcite – Why it happens?

- The ray corresponding to the image which _______ is called the **Extraordinary Ray – ε** (epsilon)
- The ray corresponding to the _________ image, which behaves a though it were travelling through an _________ mineral, is called the **Ordinary Ray – ω** (omega)
- The vibration direction of the **ordinary ray** lies in the {0001} plane of the calcite and is at 90° to the c-axis.
- The **extraordinary ray** vibrates __________ to the **ordinary ray**, _________ to the c-axis

Double Refraction

Calcite – Why it happens?

- Using a slab of calcite that had been cut in a random orientation and placed on the dots, two images would still appear
- If the random cuts had been at 90° to the c-axis, only one image would be produced

Calcite Refractive Indices

- In Uniaxial minerals the c-axis coincides with the _____ axis (the direction through the mineral along which light propagates without being split into two rays)
- For calcite, the RI for the
  - **ordinary ray** is _________, n_ω = 1.658, regardless of the direction through the grain that the light follows.
  - **extraordinary ray**, n_ε, is ________ ranging from 1.486 to 1.658. The RI is dependant on the direction that the light travels through the mineral.
    - If light travels _____________ to c-axis, n_ε = 1.486.
    - If the light travels __________ the the c-axis, n_ε = 1.658.
    - For intermediate directions through the grain n_ε will fall between the two extremes.

Calcite Refractive Indices

- Calcite is used as an example of the formation of the two rays because of the large difference between the refractive indices (birefringence (δ))
- For calcite, **δ = 0.172**
- For minerals with a lower birefringence, e.g. quartz (**δ = 0.009)**, two images are still produced but show very little separation. The quartz would have to be 20-25X as thick as the calcite to see the same separation of the dots

Calcite Refractive Indices

- Can measure the RI of the **ordinary** and **extraordinary** rays using immersion oils
- Ray with the ____ RI is the ____ **Ray** (for calcite this is the _______________ **ray**)
  - $n_\varepsilon = V_{vac}/V$, n_ε=1.486, V=2.02 X 10^{10} m/sec
- Ray with the ______ RI is the _____ **Ray,** (for calcite this is the ____________ **ray**)
  - $n_\omega = V_{vac}/V$, n_ω=1.658, V=1.81 X 10^{10} m/sec

Uniaxial Optic Sign

- For Calcite $n_\omega > n_\varepsilon$ 1.658 vs. 1.486
- For Quartz $n_\omega < n_\varepsilon$ 1.544 vs. 1.553
- This difference in the RI relationship defines the Optic Sign of Uniaxial Minerals
- By Convention:
  - For **uniaxial positive minerals** $n_\omega < n_\varepsilon$
    - quartz, zircon
  - For **uniaxial negative minerals** $n_\omega > n_\varepsilon$
    - calcite, apatite, nepheline, tourmaline

Uniaxial Optic Sign

- Alternatively,
  - If ε ray is the slow ray, the mineral is optically positive
  - If the ε ray is the fast ray the mineral is optically negative
- Whether the **extraordinary ray** has a higher or lower RI then the **ordinary ray** is dependant on the chemical bonding and crystal structure
- More on optic sign later

n_ε Clarification

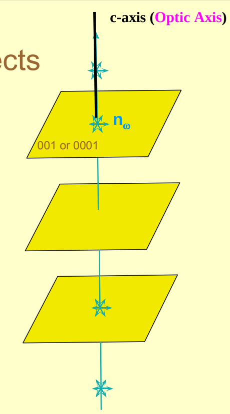
n_ε refers to the maximum or minimum RI for the **extraordinary ray**, the value recorded in the text

- Any orientation through a uniaxial mineral will provide n_ω, but only one orientation cut parallel to the c-axis will yield n_ε
- This orientation is the one which exhibits the highest interference colour, as δ is greatest and therefore Δ is greatest
- n_ε' refers to a RI for the **extraordinary ray** which is between n_ω and n_ε

Crystallographic Effects

- Uniaxial Minerals (Hexagonal and tetragonal) are characterized by a high degree of symmetry about the c crystallographic axis
- Within the 001 or 0001 plane, at 90° to the c-axis, there is uniform chemical bonding in all directions

Crystallographic Effects

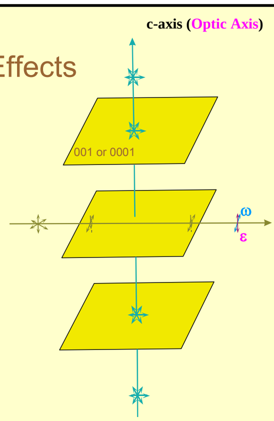


Due to symmetry about the c-axis, light travelling along the c-axis (**Optic Axis**) vibrates freely in any direction within the 001 or 0001 plane

Light travelling along the optic axis vibrates in the (001) plane and passes through the mineral as an **ordinary ray (ω)**, since the electronic configuration is uniform for all vibration directions with (001)

This orientation can be easily recognized as it is the one that exhibits the lowest interference colour - low 1st order (dark grey to black)

Crystallographic Effects



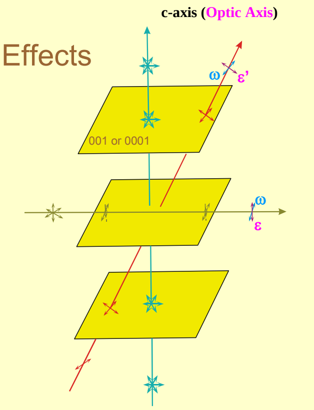
Light travelling at 90° to the c-axis is split into two rays:

Ordinary ray (ω) which vibrates parallel to (001), and

Extraordinary ray (ε) which vibrates parallel to the c-axis

The difference between n_ω and n_ε is at a maximum value, yielding the maximum birefringence and the grain exhibits the highest interference colour

Crystallographic Effects



Light travels at an oblique angle to the c-axis. It consists of:

Ordinary ray (ω) which vibrates parallel to (001), and

Extraordinary ray (ε') which vibrates at some angle to (001)

n_{ε}' is some value between n_{ω} and n_{ε}, so the birefringence is an intermediate value and the resulting interference colour between the minimum and maximum colours exhibited by the mineral

Uniaxial Optics II

Uniaxial Indicatrix

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Uniaxial Indicatrix

- Isotropic Indicatrix is a sphere – 1 RI
- Uniaxial minerals have 2 RIs ($n_{\omega} \neq n_{\varepsilon}$) resulting in the indicatrix forming an __________, the shape (flattened or stretched) is dependant on the orientation of the Optic Axis
  - **Uniaxial Positive** ($n_{\omega} < n_{\varepsilon}$)
    - Z-axis = c-axis = Optic Axis
  - **Uniaxial Negative** ($n_{\omega} < n_{\varepsilon}$)
    - X-axis = c-axis = Optic Axis

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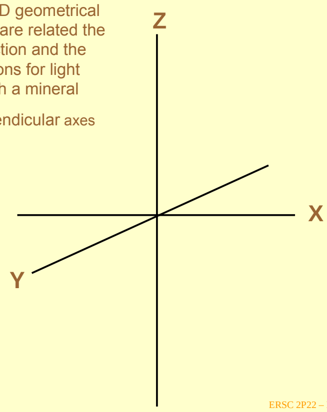
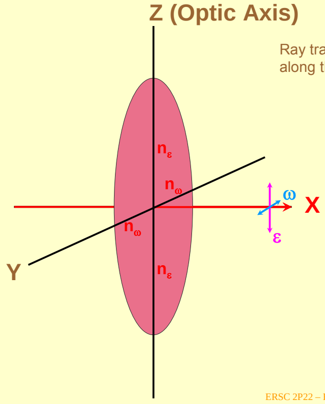
Indicatrix – a 3D geometrical figure on which are related the indices of refraction and the vibration directions for light traveling through a mineral

3 mutually perpendicular axes X, Y and Z



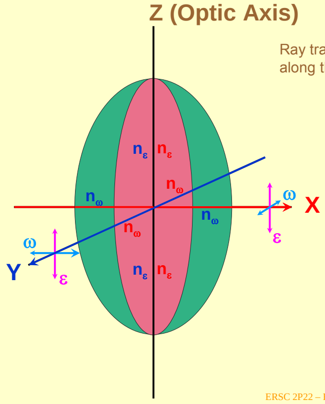
Z (Optic Axis)

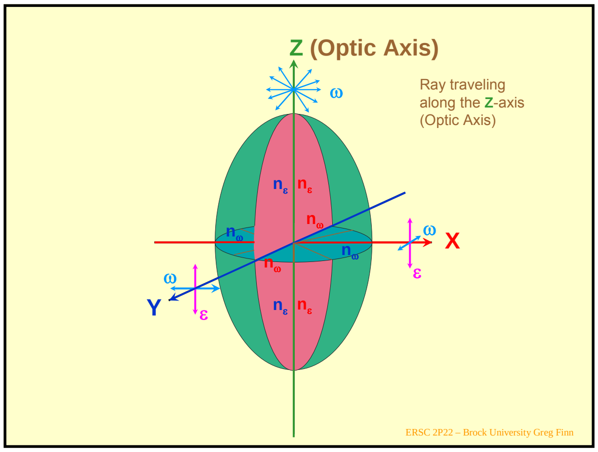
Ray traveling along the **X**-axis



Z (Optic Axis)

Ray traveling along the **Y**-axis




Z (Optic Axis)
Ray traveling along the Z-axis (Optic Axis)
ω
X
Y
ε
n_ε
n_ω
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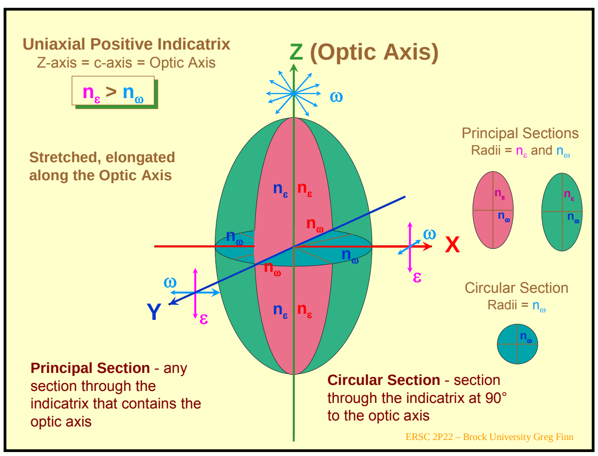
Uniaxial Positive Indicatrix
Z-axis = c-axis = Optic Axis
$n_\varepsilon > n_\omega$
Stretched, elongated along the Optic Axis
Z (Optic Axis)
Principal Sections
Radii = n_ε and n_ω
Circular Section
Radii = n_ω
X
Y
Principal Section - any section through the indicatrix that contains the optic axis
Circular Section - section through the indicatrix at 90° to the optic axis
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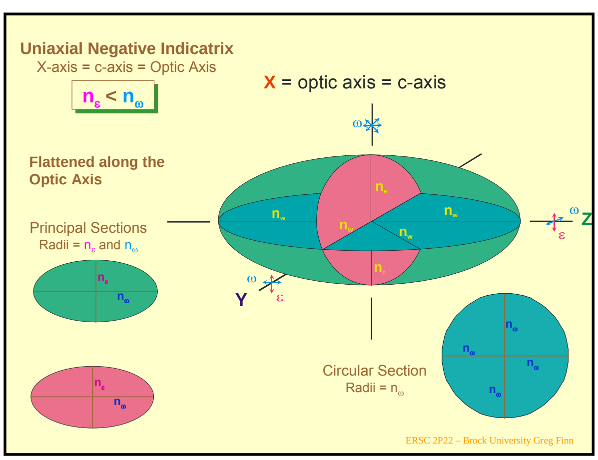
Uniaxial Negative Indicatrix
X-axis = c-axis = Optic Axis
$n_\varepsilon < n_\omega$
X = optic axis = c-axis
Flattened along the Optic Axis
Principal Sections
Radii = n_ε and n_ω
Z
Y
Circular Section
Radii = n_ω
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Uniaxial Indicatrix

- For positive and negative minerals
  - The ________ section through the indicatrix is _____________ to the optic axis, and
  - Has a radius = n_ω
- The _________ of the indicatrix along the optic axis is always n_ε
- **Ordinary Ray (ω)** vibrates at _____ to the optic axis
- **Extraordinary Ray (ε)** vibrates _________ to the optic axis

Uniaxial Indicatrix

- Any section through the indicatrix which includes the optic axis is a _________ section, and produces an ______ with axes n_ε and n_ω
- A section through the indicatrix ___________ to the optic axis produces a ________ section with radius n_ω
- The uniaxial indicatrix is oriented so that the optic axis is ________to the c-crystallographic axis
- Random sections through the indicatrix will produce an ellipse with axes n_ω and n_ε'

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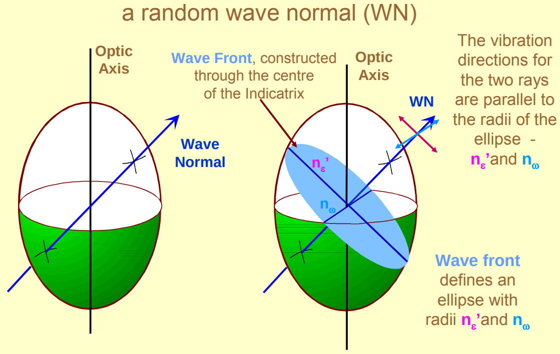
Determining the RIs and vibration directions for a random wave normal (WN)



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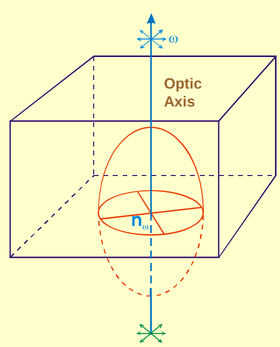
Birefringence and Interference Colours

- The relationship between:
  - _______________ (difference between the RI of the slow and fast rays), and
  - _____________________ (magnitude of the retardation)

  for uniaxial minerals is dependent on the direction that light travels through the mineral, i.e. the orientation with respect to the Optic Axis

Case 1

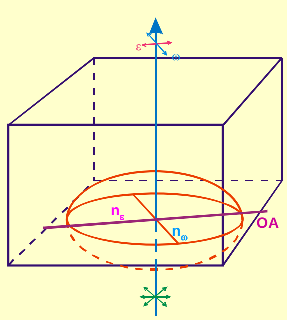


Mineral grain is cut perpendicular to the Optic Axis (OA)

The resulting section through the indicatrix is a circular section. All light passes as the Ordinary Ray and maintains its original vibration direction, i.e. the vibration direction of the lower polarizer

Birefringence (n_s-n_f) is at a minimum (n_ω-n_ω) and the resulting interference colour is 1st Order black

Case 2

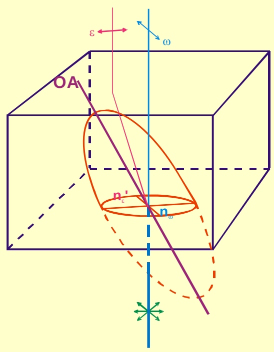


Mineral grain is cut parallel to the Optic Axis (OA)

The resulting section through the indicatrix is a principal section, with axes equivalent to the indices of refraction n_ω and n_ε, with the vibration direction of the Ordinary Ray at 90° to the OA and the Extraordinary Ray parallel to the OA

Birefringence (n_s-n_f) is at a maximum (n_ω-n_ε) and the resulting interference colour is the maximum for this mineral.

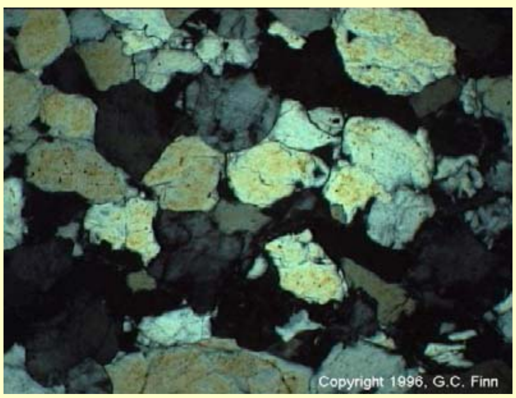
Case 3



Mineral grain is cut in a random orientation wrt Optic Axis (OA)

The resulting section through the indicatrix is an ellipse with axes equivalent to the indices or refraction n_ω and n_ε', with the vibration direction of the Ordinary Ray at 90° to the OA and the Extraordinary Ray parallel to the OA

Birefringence (n_s-n_f) is at an intermediate value (n_ω-n_ε') and the resulting interference colour lies between the maximum and minimum for this mineral.



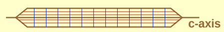
Quartz – various orientations

Extinction

- Uniaxial minerals may exhibit parallel, inclined, symmetrical or 'no cleavage' extinction
- Type is dependant on:
  - The orientation the mineral is cut
  - The presence of cleavage(s) in the grain

Extinction in Tetragonal Minerals

- Prismatic and either elongate or stubby parallel to the c-axis



- Cleavage displayed:
  - Prismatic (parallel to c-axis), or
  - Pinacoidal (90° to c-axis)
- The way in which the grain is cut and the orientation of the indicatrix will dictate what is observed
- Examples
  - Zircon $ZrSiO_4$ poor prismatic
  - Rutile TiO_2 good prismatic

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Extinction in Hexagonal Minerals

- Exhibit the following forms:
  - Prisms, pinacoids, pyramids and rhombohedrons
- Which exhibit:
  - Prismatic, pinacoidal and rhombohedral cleavages
- The way in which the grain is cut and the orientation of the indicatrix will dictate what is observed
- Examples
  - Quartz SiO_2 no cleavage
  - Calcite $CaCO_3$ 1 of 2 cleavages is rhombohedral
  - Apatite $Ca_5(PO_4)_3(OH,F,Cl)$ rare cleavage

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Pleochroism

- Coloured minerals (uniaxial and biaxial) are usually ____________
- For pleochroic uniaxial minerals:
  - Sections cut at 90° to the c-axis will exhibit a ______ pleochroic colour, corresponding to the ω ray
  - Sections cut parallel to the c-axis will exhibit the widest ________ in colour, as both ω and ε are present
- Strong vs. weak pleochroism

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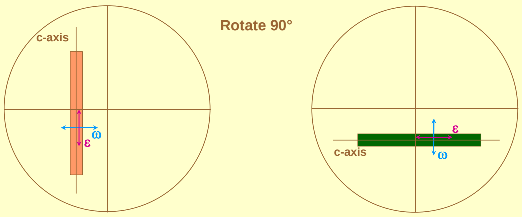
Tourmaline – hexagonal mineral elongated along the c-axis



Pleochroic colour associated with ε, as ε is parallel to the lower polar, is light brown

Pleochroic colour associated with ω, as ω is parallel to the lower polar, is dark green