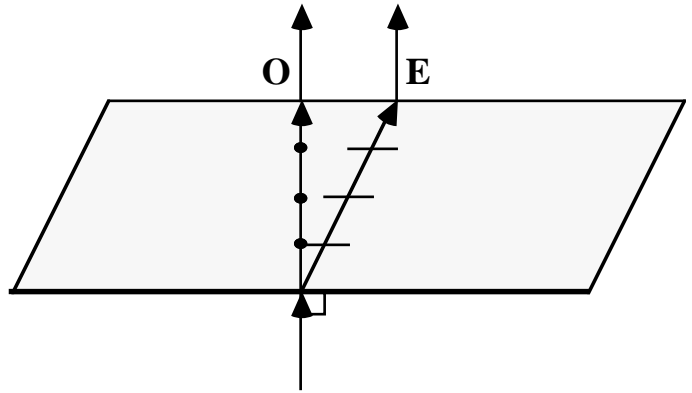


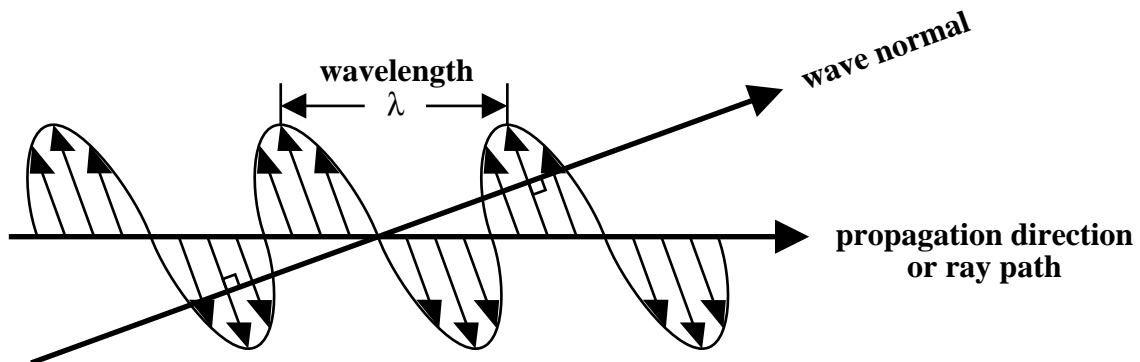
## Lecture Notes - Optics 3: Double Refraction, Polarized Light

- Experiment: observations with optical calcite.
- Light passing through a calcite crystal is split into two rays. This process, first reported by Erasmus Bartholinus in 1669, is called **double refraction**. The two rays of light are each **plane polarized** by the calcite such that the planes of polarization are mutually perpendicular. For **normal incidence** (a Snell's law angle of  $0^\circ$ ), the two planes of polarization are also perpendicular to the plane of incidence.

- For **normal incidence** (a  $0^\circ$  angle of incidence), Snell's law predicts that the angle of refraction will be  $0^\circ$ . In the case of double refraction of a normally incident ray of light, at least one of the two rays must violate Snell's Law as we know it. For calcite, one of the two rays does indeed obey Snell's Law; this ray is called the **ordinary ray** (or **O-ray**). The other ray (and any ray that does not obey Snell's Law) is an **extraordinary ray** (or **E-ray**).



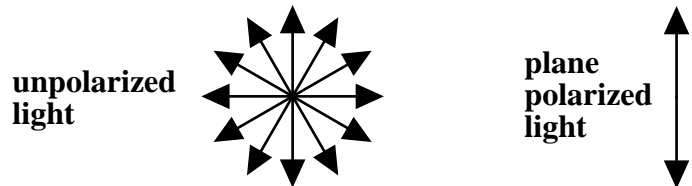
- For ordinary rays the vibration direction, indicated by the electric vectors in our illustrations, is perpendicular to the ray path. For extraordinary rays, the vibration direction is **not** perpendicular to the ray path. The direction perpendicular to the vibration direction is called the **wave normal**. Although Snell's Law is not satisfied by the ray path for extraordinary rays, it is satisfied by the wave normals of extraordinary rays. In other words, the wave normal direction for the refracted ray is related to the wave normal direction for the incident ray by Snell's Law.



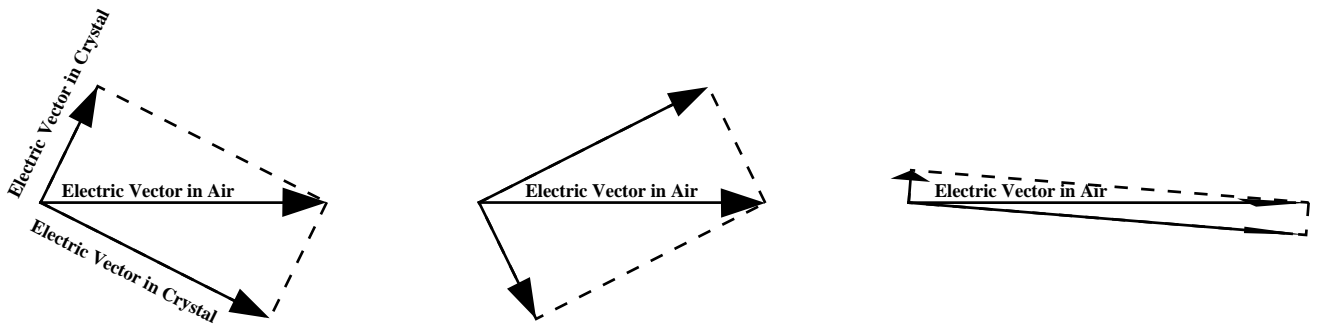
- All transparent crystals except those in the cubic system have the property of double refraction. For most crystals the image separation is not large enough to be visible. However, we will

observe other optical properties that result from the double refraction. For hexagonal and tetragonal crystals, there will be one **O**-ray and one **E**-ray. For orthorhombic, monoclinic, and triclinic crystals, there will be two **E**-rays. In general, the refractive indices for non-cubic crystals depend on vibration direction. Non-cubic crystals are, therefore, said to be optically **anisotropic**. In most cases the refractive indices for the two rays produced by double refraction are not the same. One of the two rays will have a higher refractive index (and a lower velocity); this ray is called the **slow ray**. The other ray is then the **fast ray**.

- Ordinary light is not polarized. Looking along a ray of light, the electric vectors make all angles with the vertical. Light that is plane polarized in the vertical plane has only vertical electric vectors. The plane of polarization is the plane that includes both the vibration direction and the ray path. Light may be polarized by crystals, by polarizing filters, and by reflection. Reflected light is partially polarized, favoring the vibration direction perpendicular to the plane of the ray path (including both the incident and reflected rays).

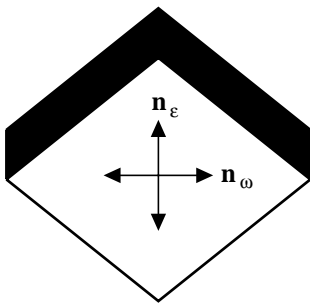


- Polarizing filters **exclude** all light not vibrating in the preferred direction of the filter. Polarizing sunglasses, by orienting their polarizing material vertically, selectively exclude the polarized portion of light reflected by horizontal surfaces. Transparent crystals do not exclude light, whatever its plane of polarization. Transparent anisotropic crystals **resolve** the electric vectors of incident light into two perpendicular electric vectors by the process of double refraction. Upon emergence from the crystal, the two rays add together again according to the rules of **vector addition**. However, because the two rays have not traveled through the crystal with the same velocity, the combined emerging ray will not be identical to the incident ray.

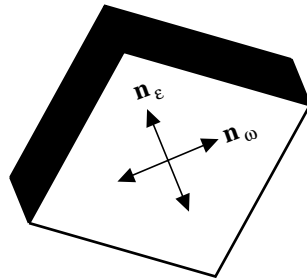
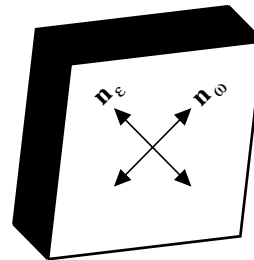
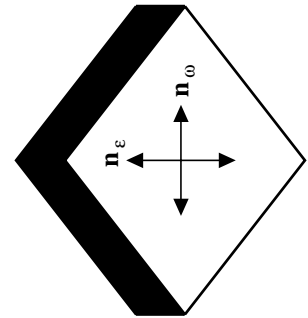


- Polarizing microscopes are equipped with polarizing filters both below and above the stage of the microscope. The lower filter (fixed, but rotatable) is called the **polarizer** and on our microscopes has its direction of polarization oriented E-W when viewed from above. (Beware, some older microscopes have their polarizing filters oriented N-S!) The upper filter (removable, but not rotatable) is called the **analyzer** and has its direction of polarization oriented N-S when viewed from above. Because the polarization directions of these two filters are perpendicular, all of the light passing through the polarizer will be blocked by the analyzer, unless the analyzer is removed or an anisotropic crystal is placed between the two filters.

- Note that if the incident light is already polarized, special orientations exist for which **all** of the incident light is resolved along **one** of the two preferred vibration directions in the crystal. In this special case, there is no double refraction and the emerging ray **will** be identical to the incident ray. If a crystal is oriented so that one of its two vibration directions is "parallel to the polarizer" (that is parallel to the plane of polarization of the polarizing filter), then all light emerging from the crystal would be polarized E-W and would be blocked by the analyzer. When this happens, the crystal appears dark and is said to be "at **extinction**."



extinction

partial  
transmissionmaximum  
transmission

extinction