Opti 415/515

Measurement of radii, index, and thickness

Plane-parallel plate

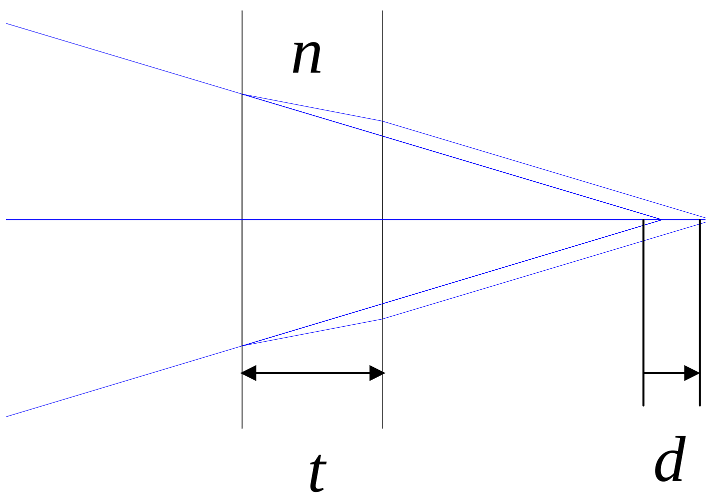
- A plane-parallel plate displaces an image longitudinally
- A plane parallel plate displaces a ray, but does not deviate it
- Reduced thickness → air equivalent thickness: will a filter fit between the last element and the image plane?
  - A plate that is n*air space thick will fit because the image plane is moved
  - Optical path length increases by n^2 * air space thickness on axis

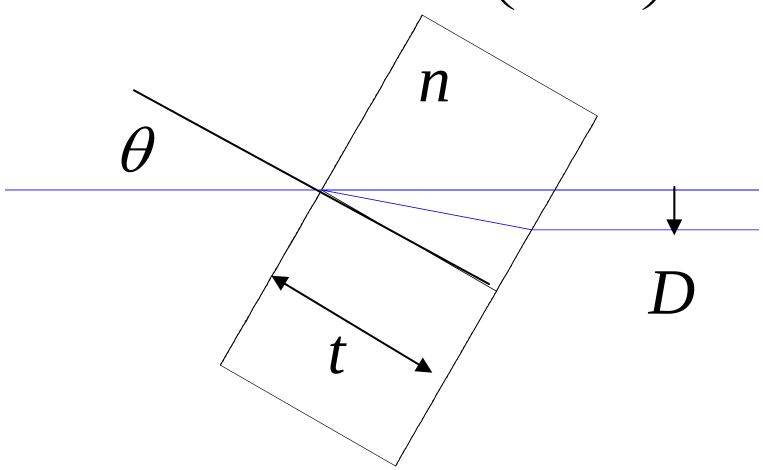
$$d \approx \left(\frac{n-1}{n}\right)t$$

Reduced thickness

$$\tau = t - d = \frac{t}{n}$$

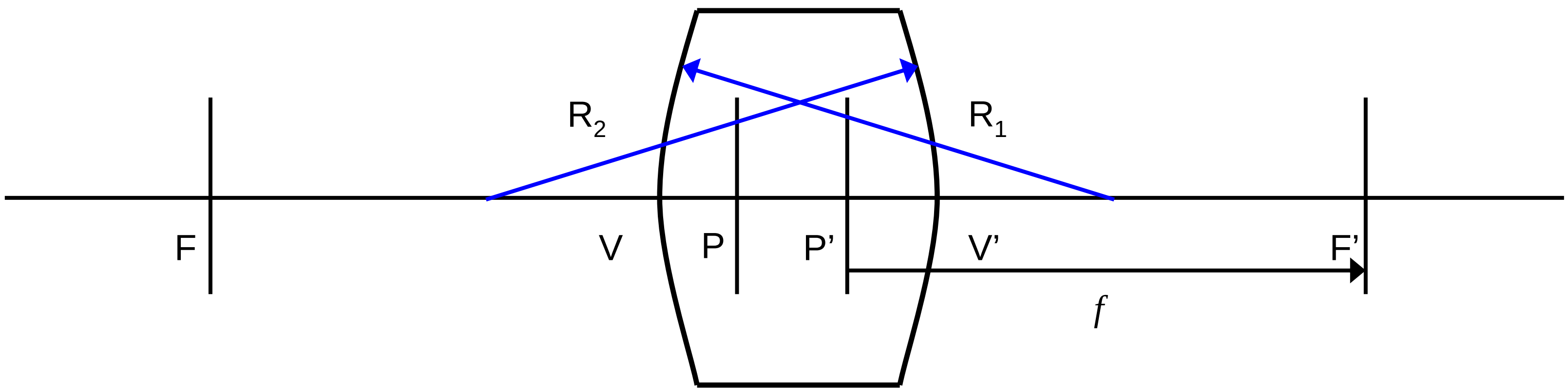
$$D \approx t\theta\left(\frac{n-1}{n}\right)$$





Singlet

- Singlet is the most basic optical system
- First-order properties – focal length and principal plane locations – are defined by radius-of-curvature of two surfaces (R_1 and R_2), thickness (*d*) and index of refraction (*n*)
- How do we measure the four parameters that define a singlet?



$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)t}{nR_1R_2}\right]$$

$$t = \overline{VV'} \quad h_1 = \overrightarrow{PV} \quad h_2 = \overrightarrow{P'V'}$$

$$R > 0$$ For center-of-curvature to right of surface

$$h_1 = -\frac{f(n-1)t}{R_2 n} \qquad h_2 = -\frac{f(n-1)t}{R_1 n}$$

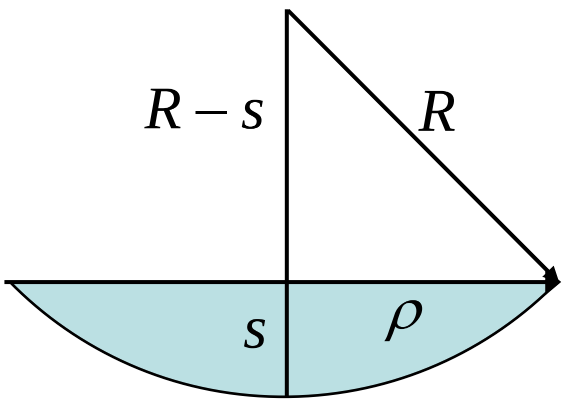
$$h > 0$$ For principal point to right of surface

Sag equation

- Radius-of-curvature of a spherical surface is inversely proportional to sag
- For small sags or large radius can approximate a circle as a parabola
  - Another example of small angle approximation
- Power of a surface (Diopters) is directly proportional to sag, inversely to ROC

$$R^2 = \rho^2 + (R - s)^2$$

$$R = \frac{\rho^2 + s^2}{2s} = \frac{\rho^2}{2s} + \frac{s}{2}$$

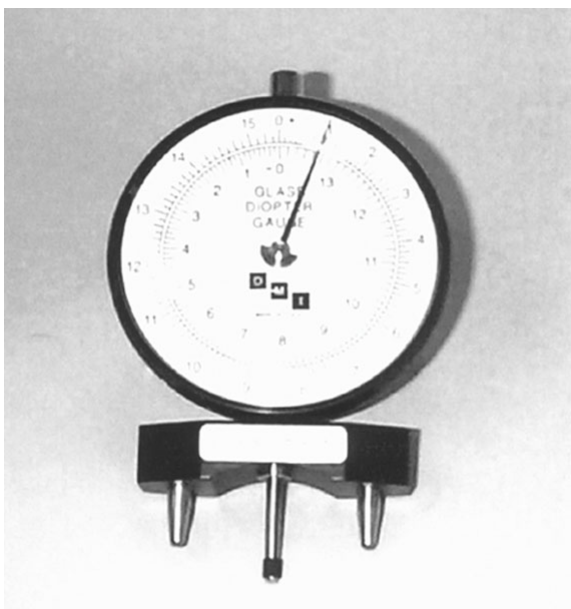


$$R \approx \frac{\rho^2}{2s} \qquad s \approx \frac{\rho^2}{2R}$$

$$\phi = \frac{1}{f} = \frac{n-1}{R}$$

Geneva gauge

- Geneva gauge – depth gauge measures sag between two points and scale calibrated in Diopters (m^{-1})
  - Assuming index of refraction of 1.523
- It is a type of bar spherometer
- Must be held normal to surface
- Typically good to ±0.25 D
- Zero against a flat



Properties of a surface, not an element

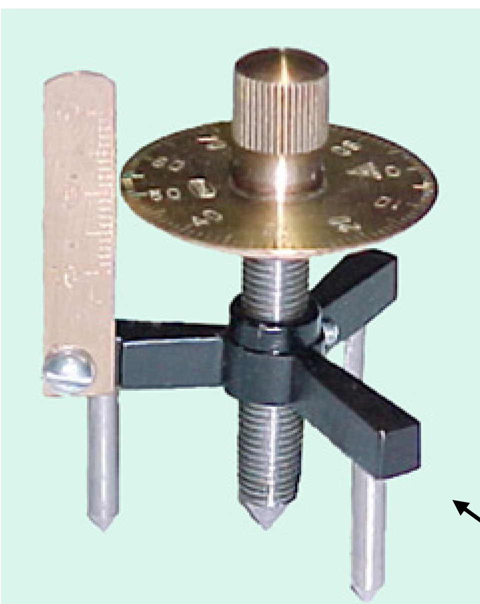
$$\phi_{meas} = \frac{1}{f} = \frac{n-1}{R} = \frac{0.523}{R}$$

$$R = \frac{0.523}{\phi}$$

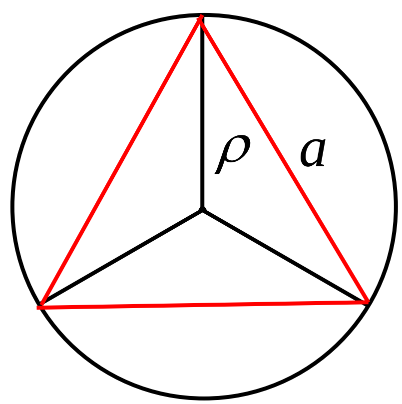
$$\phi_{true} = \frac{n_{lens}-1}{0.523}\phi_{meas} \qquad f_{true} = \frac{0.523}{n_{lens}-1} f_{meas}$$

Spherometer

- Spherometer – measures sag, (not focal length of a surface assuming an index)
  - Usually a spherometer implies 3 points on a circle or a ring for support + depth gauge
    - 3-points might be very small radius tips, or
    - Precision balls having a well-known diameter
  - Bar spherometer – 3-points in a line, measures sag between two points
    - Geneva gauge / diopter meter are essentially a bar spherometer
- Spherometer with circular support is easier to use accurately than a bar spherometer



The Science Fair



$$a = \sqrt{3}\rho$$

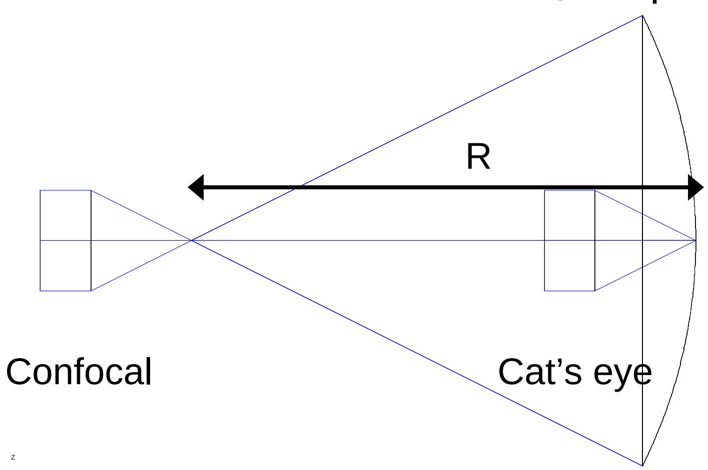
Supports at vertices of an equilateral triangle

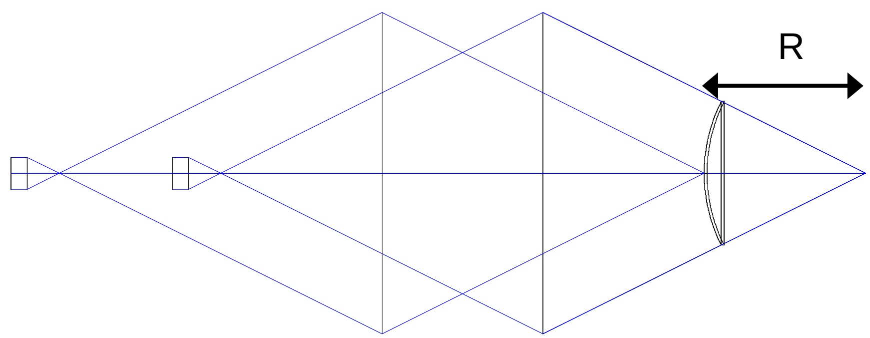
$$R = \frac{\rho^2}{2s} + \frac{s}{2} \pm r$$

r - ball radius, + for concave surfaces, - for convex

Radius bench

- Measure distance from vertex (cat's eye) to center-of-curvature (CC)
- Concave surfaces – need very little working distance:
  - Autostigmatic microscope works well
  - Interferometers
- Convex surfaces need working distance > radius
  - Beam expander + converging optic
  - Auxiliary optic
- Maximize sensitivity to focus by filling aperture of part
- Move instrument or optic on stage with a scale
- Measurement with uncertainty less 0.1% takes care, and 0.01% is quite difficult
- Environment – turbulence, temperature control, can become serious issue





Center thickness

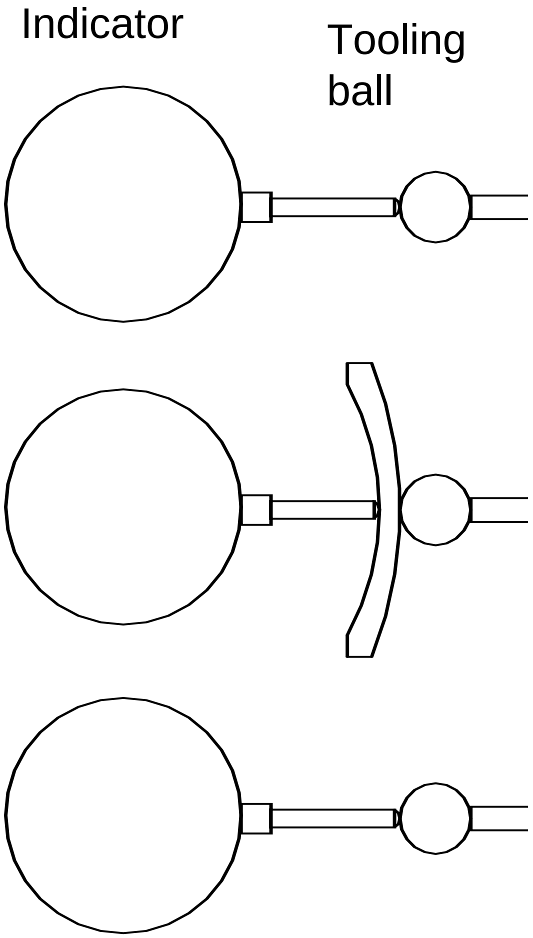
- Many methods are contact based and require care to avoid damaging the component – some materials are easily damaged
  - Indicator on granite
  - Thickness gauge
  - Calipers - think long and hard before putting a piece of glass between the metal jaws of a caliper.
- Non-contact preferable -
- Autostigmatic microscope & stage: zero against reference flat
- Fogale lens meter – essential an optical coherence probe that measures glass thickness along the axis of a stack of lenses

Center thickness (2)

1. Mount indicator and tooling ball, zero the indicator

2. Pull back the indicator shaft and insert the lens. Release shaft to and read the indicator

3. Remove lens, and check that the initial reading repeats.

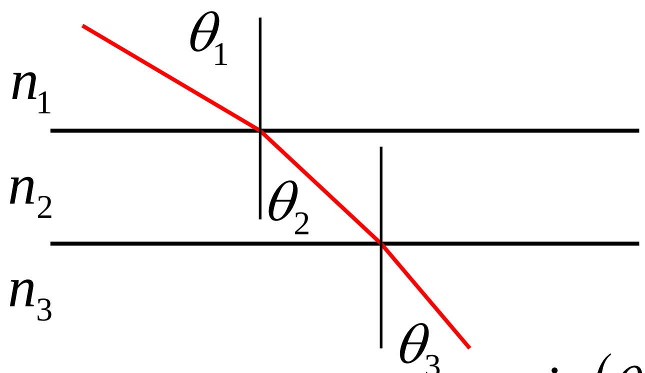


Center thickness (3)

- The lens must be held correctly so that the indicator probe is normal to the surface at the lens vertex and the tooling ball is at the vertex of the other surface. You can establish this by perturbing the lens position slightly and watch the indicator swing through a minimum or maximum.
- For increased precision, perform operation 2) with a gauge block to calibrate the indicator.

Index

- Measurement of index of refraction requires a sample to be prepared and is usually done by glass manufacturers rather than optical fabricators
- Index of refraction is a ration → need two know two numbers
- Minimum angle of deviation through a prism → prism and deviation angle
- Critical angle → critical angle and index of reference glass
- Brewster's angle → angle of incidence and index of reference glass
- Abbe refractometer – measure index and dispersion of index and glasses
  - Eyepiece view has dark-to-light band



Solid $n_3 > n_2 > n_1$

θ_1

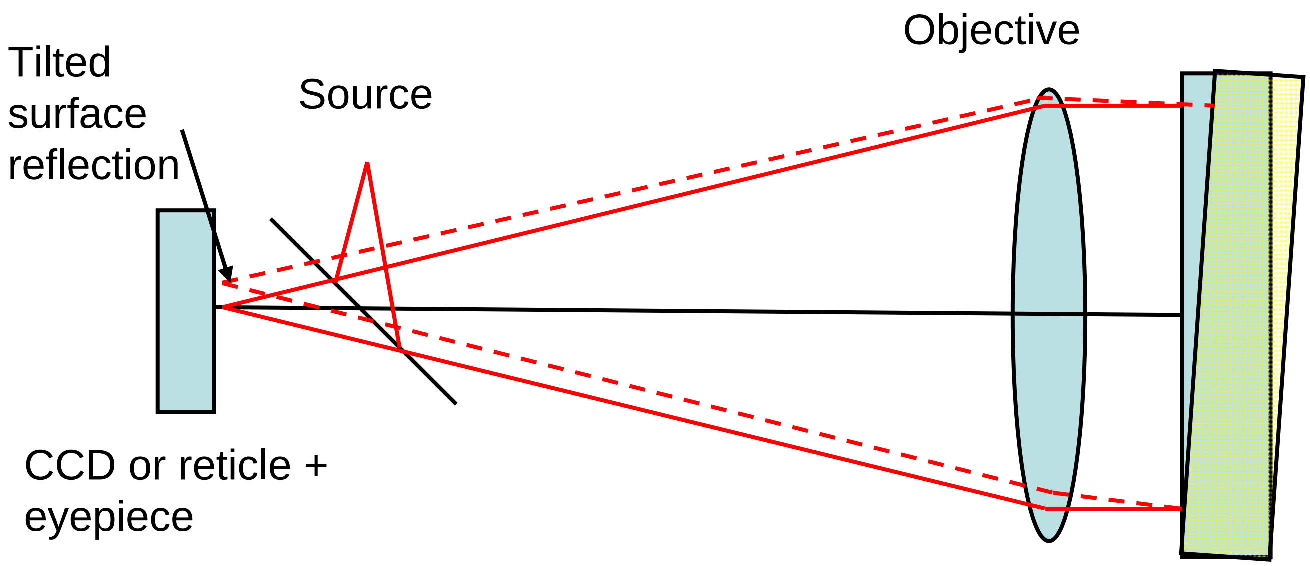
Fluid

Solid (reference)

$$\sin(\theta_1) = n_2 \sin(\theta_2) = n_3 \sin(\theta_3)$$

Autocollimator

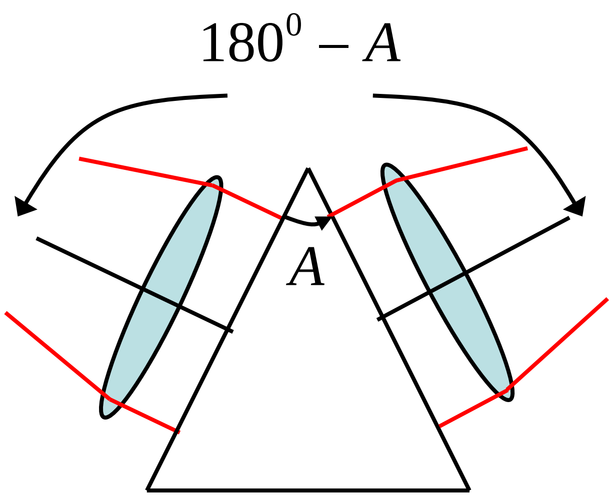
- Autostigmatic telescope – projects source to infinity and images reflected light on to a detector or eyepiece reticle
- Measure angular deviation on reticle or use with a rotary table as a null sensor
- Reflecting surface might be a mirror, uncoated window, AR coated beam splitter face, etc.

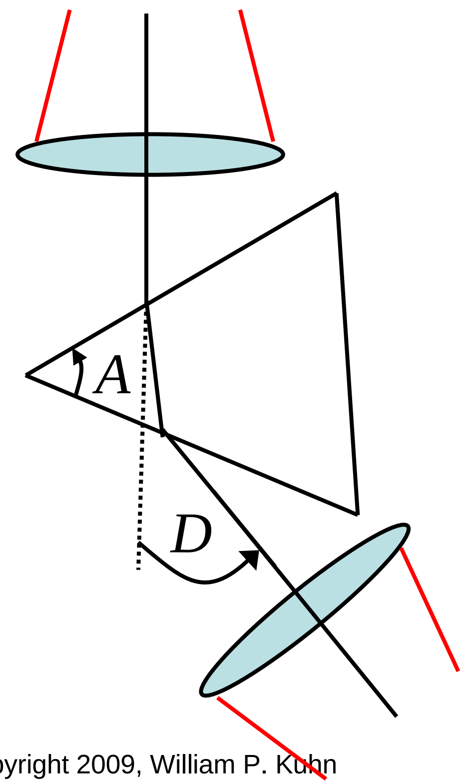


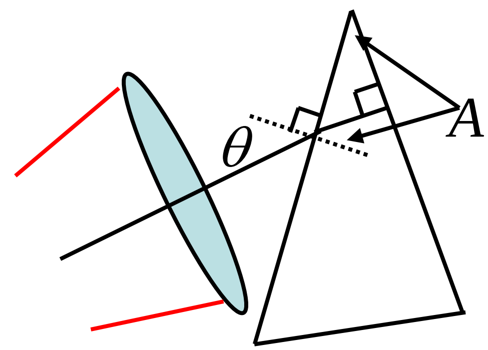
Index (2)

- Autocollimator and rotary table to measure prism angle
  - Can also use angle gauge blocks and autocollimator
- Use two collimators, one as source to measure deviation angle
- Use one autocollimator and rotary table to do it all

Rotate autocollimator or prism to measure prism angle *A*



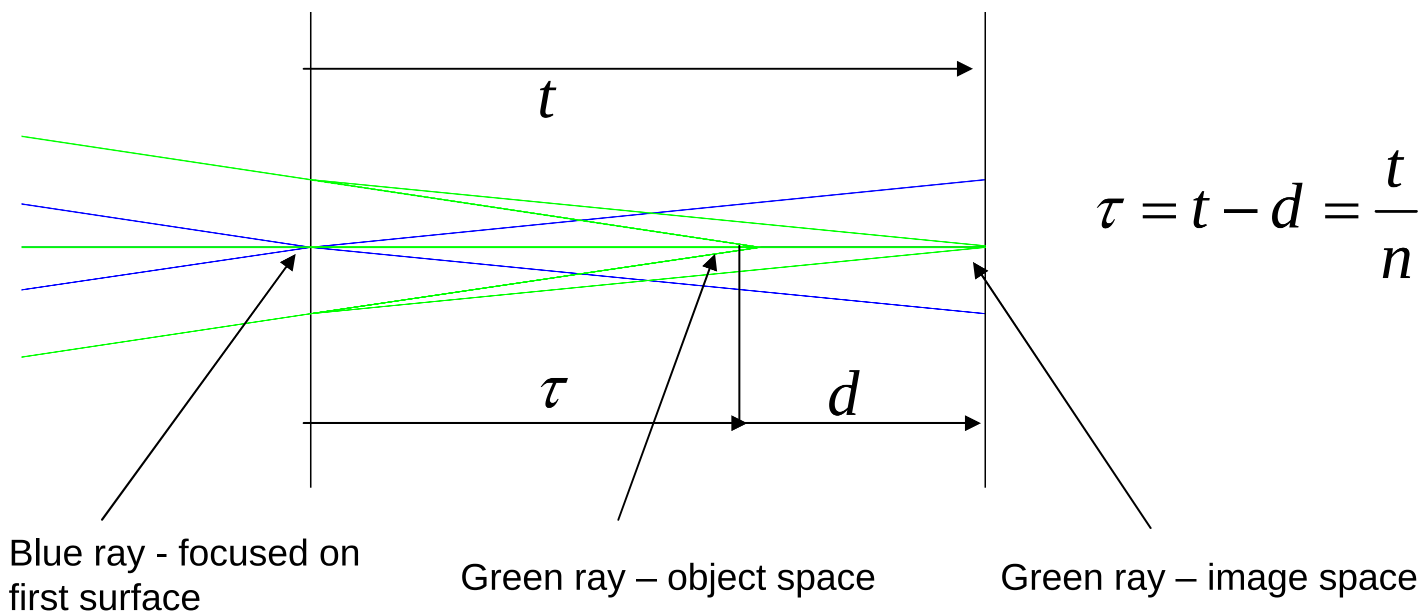




$$n = \frac{\sin(\theta)}{\sin(A)}$$

Index of a plate

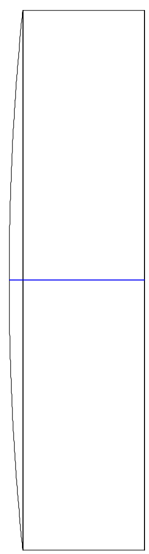
- An autostigmatic microscope and a linear stage can be used to determine the index of refraction of a plate
- Move microscope τ, focus moves t, can calculate n

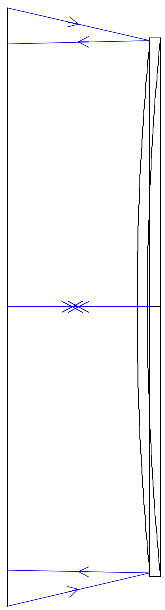


$$\tau = t - d = \frac{t}{n}$$

Measuring the radius of curvature of a lens

- Measuring the radius-of-curvature of a convex surface the converging lens needs a working distance > radius
- If you do not have an objective with a long enough working distance for your interferometer or autostigmatic microscope, how can you measure the radius-of-curvature?





Measuring the radius of curvature of a lens

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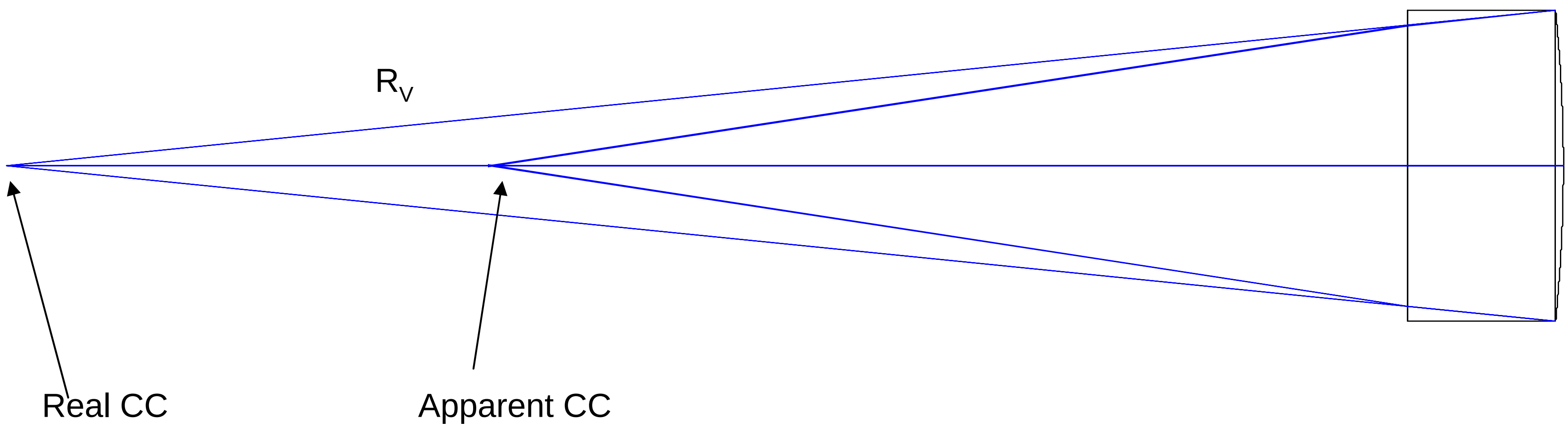
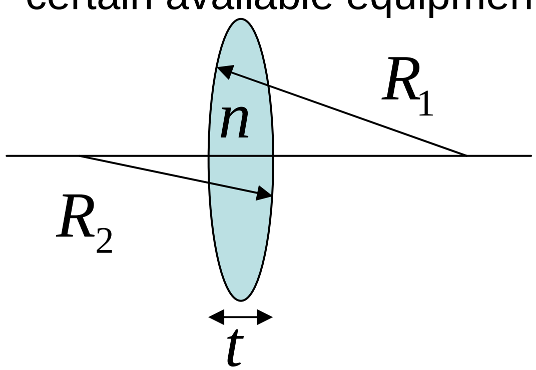
  - Measure the distance from the apparent center-of-curvature to the lens
  - The apparent center-of-curvature is closer to the lens than the actual center-of-curvature
  - Use first-order equations for a lens to calculate the actual radius of curvature



Measuring a singlet another way

- Focal length or power of a singlet are determined by 4 parameters: two radii, a thickness and an index of refraction
- Can one determine parameters defining a singlet by measuring the behavior of a singlet?
- Should be able to since image position can be calculated using paraxial ray tracing equations, object position and the 4 parameters defining a singlet.
- An autostigmatic microscope, flat and a linear stage could be used to measure location, relative to first surface vertex location, of:
  - Center-of-curvature of first surface
  - Center-of-curvature of second surface
  - Apparent thickness – like a window except must consider power of surface
  - Front focal length
- Use paraxial ray tracing equations to calculate required quantities,
  - Note difference between front, back and effective focal lengths
- Use an optimizer: Zemax, CodeV, Matlab, or even Excel
- The point is that there are often many ways in principle to solve a problem, but only a certain available equipment, budget, etc. to get the answer so be open minded.



$$\phi = \frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2} + \frac{t(n-1)}{R_1 R_2 n}\right)$$

Companies with useful products

- No particular company is endorsed, but you will see products from all of these and many more in a shop:
- Classical instruments updated with electronics: Mitutoyo, Starrett, etc.
- Lens thickness via a beam: Fogale, TriOptics, etc.
- Keyence – specialized sensors
- Mahr Federal – high-accuracy probes using LVDT technology