ABERRATIONS

Seven Primary aberrations that lead to imperfect images

1. SPHERICAL ABERRATIONS
   Longitudinal and transverse spherical aberration
   Minimizing spherical aberrations
     By optimizing lens’ shape
     By exploiting the existence of conjugate points in spherical lenses (their use in oil-immersion microscope objectives)

2. COMA
   Meridional or tangential plane, sagittal plane, tangential coma, saggital comma
   Skew rays

3. ASTIGMATISM
   Meridional or tangential focal surface
   Sagittal focal surface

4. PETZVAL FIELD CURVATURE

5. DISTORSION

6. LONGITUDINAL CHROMATIC ABERRATION

7. LATERAL CHROMATIC ABERRATION
   Correcting CA: The design of an “achromatic doublet”
ABERRATIONS (section 6.3)

Seven primary lens aberrations that lead to imperfect imagery.

"PERFECT" LENS

REAL LENS
1. Spherical Aberrations

(1) Paraxial ray
(2) Non-paraxial ray (marginal ray)

When using a lens with spherical aberration,
- Each zone or annulus of the lens has a slightly different focal length
- Rays from zones farther from the axis are focused short of the paraxial focal point F.

The lack of a common focal point for all zones of the lens is referred to as spherical aberration.
Longitudinal spherical aberration of ray (2)

\[ f = 90 \text{ mm} \]
\[ f/\# = 3 \]

Aperture

"Circle of least confusion"

\[ \Sigma_{lc} : \text{best place to observe the image} \]

Paraxial focal plane
- When a screen is moved from the paraxial focal plane to the $\Sigma_{lc}$ plane, the image blur will have its smallest diameter. This is known as the circle of least confusion.

- Notice, the previous graph suggests: spherical aberration decreases when the aperture decrease.

  More general: the greater f/#, the less spherical aberration.

- Spherical aberration pertains to image analysis of an object point located at the optical axis.
NOTE 1: Minimizing spherical aberration

We saw above that increasing the f/# minimizes spherical aberrations.

For the cases where the f/# is fixed, there are other ways to minimize spherical aberrations: optimizing the shape of the lens.

A striking example is presented by a planar-convex lens: simply turning the lens around, markedly reduces the spherical aberration.

EXPLANATION: This can be understood by considering the lens as composed of 2 prisms joined at their bases.
When a ray strikes a prism, it undergoes a net deviation $\delta$.

- $\delta$ increases with the index of refraction $n$.

Since $n = n(\lambda)$, then $\delta$ depends on the wavelength of the incident light.

$n(\lambda_{\text{blue}}) > n(\lambda_{\text{red}})$ implies the deviation $\delta$ is less for red light.

- For a given prism (i.e. $n$ and $a$ fixed), $\delta$ is a function of the incident angle $\theta$. 

For $\eta = 1.5$, $\theta = 60^\circ$, $\delta = \delta_{\text{min}}$. 
Rays for which the deviation $\delta$ is minimum, traverses the prism parallel to the base.

A reinterpretation of this result, (in terms of our purposes of interpreting a lens as two prisms joined at their bases) is as follows:

The incident ray will undergo a minimum deviation when it makes, more or less, the same angle as does the emerging ray.
Note 2 Minimizing spherical aberration

Remember that aspherical lenses were completely free of spherical aberration for a specific pair of conjugate points.

P is a perfect image of Q when the proper oval surface is used.

Huygens may have been the first to discover that two such axial points exist for spherical surfaces as well.

Such a situation happens only when Q is located at the proper position.
Let’s consider a spherical interface surface of radius “R”.

The ray indicated in the figure image point “Q” at point “P” (but not necessarily all the rays emanating from Q will be imaged at the same point “P”.

**CASE: \( n_i > n_r \)**

Let’s express the position of Q and P, with respect to C, in units of R.
\[ \overline{a} = \overline{ac} + \overline{r} \]
\[ a^2 = \overline{ac}^2 + R^2 + 2 \overline{r} \cdot \overline{ac} \]
\[ = \overline{ac}^2 + R^2 + 2R \overline{ac} \cos \chi \]

Let's measure \( \overline{ac} \) in units of \( R \).
Thus let's consider \( \overline{ac} = q \cdot R \) (\( q \) a real number) \( \Rightarrow \)
\[ a^2 = q^2 R^2 + R^2 + 2R^2 q \cos \chi \]
\[ a^2 = R^2 \left( q^2 + 1 + 2q \cos \chi \right) \]

Notice also in the figure that
\[ \alpha \sin \alpha = R \sin \chi \]

From (3) and (2)
\[ \sin \alpha = \frac{\sin \chi}{\left( q^2 + 1 + 2q \cos \chi \right)^{1/2}} \]

Notice, giving the angle \( \chi \) and the position of \( A \) relative to \( C \) (that is given the value of \( q \)), the angle \( \alpha \) is determined.

Now, given \( \chi \) and \( q \), the position of the image \( P \) must be determined. Let's find it.
In \( \triangle PCB \) : \[ \overline{PC} \sin \beta = R \sin \theta_r \Rightarrow \eta_r \overline{PC} \sin \beta = \eta_r R \sin \theta_r \]
In \( \triangle QCB \) : \[ \overline{QC} \sin \alpha = R \sin \theta_i \Rightarrow \eta_i \overline{QC} \sin \alpha = \eta_i R \sin \theta_i \]
Snell's law implies: \[ \overline{PC} = \frac{\eta_i \sin \alpha}{\eta_r \sin \beta} \overline{QC} \]

\[ (5) \]
If we express $\overline{PC}$ also in units of $R$, 
\[ \overline{PC} = p \cdot R \quad (p \text{ a real number}) \quad (6) \]
result (5) becomes
\[ p = \frac{n_i \sin \alpha}{n_r \sin \beta} q \quad (7) \]

In addition, we should obtain for $\sin \beta$ an expression similar to (4). That is,
\[ \sin \beta = \frac{\sin \chi}{(p^2 + 1 + 2p \cos \chi)^{1/2}} \quad (8) \]

**Summary:**
For a given point $Q$ whose distance from $C$ in terms of $R$, $q/R$ (i.e. $q$ is given), we want to find the location of its image $P$. For that purpose, we send a generic ray $QB$.

The position of $B$, with respect to the center $C$, is determined by $\chi$.

Given $q$ and $\chi$, then we find $\alpha$ using (4) and $\beta$ using (8).

From expression (7) we find $p$, which allows to locate the image point $P$ since $\overline{PC} = p \cdot R$.

Let's find a more explicit expression for (7).

From (4) and (8),
\[ \frac{\sin^2 \alpha}{\sin^2 \beta} = \frac{p^2 + 1 + 2p \cos \chi}{q^2 + 1 + 2q \cos \chi} \]

In (7)
\[ \frac{p^2}{q^2} = \left( \frac{n_i}{n_r} \right)^2 \frac{p^2 + 1 + 2p \cos \chi}{q^2 + 1 + 2q \cos \chi} \quad \text{Given } \chi \text{ and } q \text{, the value for } p \text{ is implicit in this formula.} \quad (9) \]

We may wonder if we can wisely choose the position of the point $Q$ (or choose $q$) such that the corresponding position of the image $P$ (given by $p$) ends up being independent of $\chi$.
\[
\frac{p^2}{q^2} = \left( \frac{n_i}{n_r} \right)^2 \frac{p^2 + 1 + 2p \cos(\chi)}{q^2 + 1 + 2q \cos(\chi)} \quad (9)
\]

Given \( q \) and \( \chi \) (that is, given the position of Q and B), the value of \( p \) (the position of point P) is implicit in this formula.

**Summary:**

For a given point “Q”, whose distance from C (in terms of R, is \( qR \) i.e. \( q \) is given), we want to find the location of its image P. For that purpose, we send a generic ray QB. The angular position, with respect to the center C, is determined by the angle \( \chi \).

Given \( q \) and \( \chi \),

- we calculate \( \alpha \) using expression (4)
- calculate \( p \), using (9), and \( \beta \) using expression (8)

Notice, for the same Q:

different values of \( \chi \) (i.e. a different point B) will give different values for \( p \) (i.e. a different point P).

**Looking for aberration-free imaging**

We wonder if the position of Q can be wisely chosen, such that for any point B, the corresponding position of P is the same?

That is, can we choose the value of “\( q \)” wisely enough, such that “\( p \)” (in expression (9)) becomes independent of \( \chi \)?
If that were the case, then $P$ and $Q$ would become conjugate points free of spherical aberrations. (In the figure, the position of $P$ would be independent of the position of $B$)

For that matter,

Let's keep working out expression (9)

$$p^2 + q^2 + 2pq \cos \chi = \left(\frac{m_i}{n_r}\right)^2 q^2 + \frac{m_i}{n_r} q^2 + \frac{m_i}{n_r} q^2 \cos \chi$$

$$\Rightarrow \left[\left(\frac{m_i}{n_r}\right)^2 - 1\right] q^2 + \left[\frac{m_i}{n_r} q^2 - p^2\right] + 2pq \cos \chi \left[q \left(\frac{m_i}{n_r}\right) - p\right] = 0 \quad (10)$$

or

$$\left(2q^2 + 1 + 2q \cos \chi - r^2 q^2\right) p^2 - \left(2r^2 q^2 \cos \chi\right) p - r^2 q^2 = 0 \quad \text{given $q$, solve for $p$} \quad (11)$$

In general, $p$ will depend on $\chi$

However, notice in (10) that

If $q = \left(\frac{m_i}{n_r}\right)^2$, we obtain

$$\left[1 - \left(\frac{m_i}{n_r}\right)^2\right] p^2 + \left[1 - p^2\right] + 2p \left(\frac{m_i}{n_r}\right)^2 \cos \chi \left[\left(\frac{m_i}{n_r}\right) - p\right] = 0$$

which is satisfied by the following solution for $p$:

$$p = \frac{m_i}{n_r}$$

In effect

$$\left[\left(\frac{m_i}{n_r}\right)^2 - 1\right] + \left[1 - \left(\frac{m_i}{n_r}\right)^2\right] + 2 \cos \chi \left[0\right] = 0 \quad !$$
So, we have found the locations of a pair of conjugated points that are free of spherical aberrations.

**CASE: \( n_i > n_r \)**

![Diagram showing conjugated points for \( n_i > n_r \)]
Instead of using the bulky sphere, we can use a converging meniscus:

Grind another spherical surface with center in \( Q \). Radius is not critical as far as it is smaller than \( QV \).

Notice this inner spherical surface does not affect the trajectories of the rays emanating from \( Q \).
For the case $n_i < n_r$, find the position of the pair of conjugated points (along the x-axis) that are free of aberrations. Show explicitly all the derivation.
Alternatively, a diverging meniscus lens can also be constructed for the same purpose.

(see also Fig. 6.17 on page 266)

Notice, this surface does not affect the outgoing rays reflected from the surface of radius R.

\( \eta_i > \eta_r \)
Thus, similar to aspherical lenses, spherical lenses can be constructed to have zero spherical aberration for a pair of conjugated points $P$ and $Q$.

**APPLICATION**

Spherical meniscus lenses free of spherical aberration (for two conjugated points) are used oil-immersion microscope objective lenses.

Object under study is placed at $Q$

$Q$ and $P$ are the conjugate points (for zero SA) for the first lens

$P$ and $P'$ are conjugate points for the second lens
2. COMA ■ Aberration that afflicts off-axis light bundles

Each annulus focuses onto the image plane at a slightly different height and with a different spot size.

A lens with coma produces images of different magnification depending on the aperture.

Rays 2 and 3 passing through the edge portion of the lens are imaged at a different height than the rays 3 and 4 passing through the central annulus.
NEGATIVE COMA

POINTS ON THE LENS

POSITIVE COMA

CORRESPONDING POINTS ON THE IMAGE PLANE
Points on the lens

The distance $OA$ is the tangential coma

The distance $OB$ is the sagittal coma

Meridional or Tangential Plane
It contains the optical axis and the chief ray of the bundle of rays leaving the object point $P$
The sagittal plane is a plane that contains the chief ray and perpendicular to the meridional plane.

Notice: A sagittal plane change slope as the chief ray navigates through the optical system.

Meridional ray: One in the meridional plane. It intersects the optical axis.

Skew ray: One that doesn't intersect the optical axis.

Sagittal rays: Skew rays from the object point lying in a sagittal plane.

Hence the names meridional or tangential coma and sagittal coma.
• COMMA depends on the shape of the lens

\[ \text{object at } \infty \rightarrow \quad ) \quad ) \quad ) \quad ) \quad ( \quad ( \text{ negative coma positive coma} \]

Note: A well-connected lens for the case in which one conjugate is at \( s_o = \infty \), may not work well when the object is at a finite position.

Solution:
Use two infinite conjugate lenses

Two infinite conjugate lenses yield a system that operates at finite conjugates.
3. ASTIGMATISM

Rays from an off-axis object point P focus on different focal points.

When P is located on the optical axis, the symmetry of the spherical lens makes unnecessary the distinction between meridional and sagittal rays. (Both "see" the same thing).

When P is located off-axis, meridional rays are tilted more than the sagittal rays, and thus have shorter focal length. This focal difference, so called "astigmatic difference, increases rapidly as P moves farther off the optical axis.
**Measuring Astigmatism**

For different points $P$, located at different height from the optical axis, the $z$-coordinate of the corresponding tangential and sagittal image points describes a paraboloidal surface centered on the optical axis.
A measurement of astigmatism is the distance between the tangential and sagittal image points for a particular chief ray.

4. **PETZVAL FIELD CURVATURE**

**APLANAT** is a lens corrected for spherical aberration and coma.

**ANASTIGMAT** is an aplanat lens corrected also for astigmatism. In an anastigmat the tangential and sagittal surfaces collapse to a single image surface called the **PETZVAL SURFACE**.
The Petzval field curvature aberration refers to the imaging of a flat surface onto a paraboloidal surface.

5. **Distortion**

Unique aberration that does not affect the quality of the image in terms of sharpness or focus.

Rather, distortion affects the shape of the image.
object

lens
Chromatic Aberration (CA)

6. LONGITUDINAL CA
   \[ f = f(\lambda) \]

7. LATERAL CA

Chromatic aberration results from the fact that

- The focal length of a lens depends on the index of refraction \( \eta \)

\[
\frac{1}{f} = \frac{\eta_{\text{lens}} - \eta_{\text{air}}}{\eta_{\text{air}}} \left( \frac{1}{R_1} - \frac{1}{R_2} \right)
\]

and

- \( \eta \) depends on the wavelength of wavelength \( \lambda \) of the light

\[
\eta = \eta(\lambda)
\]

That is, different colors refract at different angles

Thus,

focal length \( f = f(\lambda) \)
How to correct this chromatic aberration?

Option 1

Option 2
The previous ray-tracing diagrams suggest that chromatic aberration might be corrected by properly combining a converging lens with a diverging lens.

Indeed that is the case in the design of the achromatic doublet lens.

**ACHROMATIC DOUBLET**

Consisting of a crown equiconvex lens cemented to a negative flint glass lens

Let’s assume we want an “achromat doublet” of 15 cm focal length. Let’s call it \( f_{\text{desired}} = 15 \) cm. Since, in general, the focal length depends on the wavelength, \( f_{\text{desired}} \) is conveniently specified as that associated with yellow light (the Fraunhofer wavelength \( \lambda_D = 587.6 \text{ nm} \)). Thus,

\[
 f_{\text{desired}} = 15 \text{ cm}, \quad \text{at} \ \lambda = \lambda_D
\]

Considering a doublet as two thin lenses, its effective focal length in terms of its lens components can be expressed as,

\[
 \frac{1}{f_{\text{doublet}}} = \frac{1}{f_1} + \frac{1}{f_2} \quad \text{(1)}
\]

The focal length of the individual lenses is given by
The focal length of any doublet is then given by,

\[
\frac{1}{f_1} = (n_1 - 1)\left(\frac{1}{r_{11}} - \frac{1}{r_{12}}\right) = (n_1 - 1) \rho_1
\]  

(2a)

\[
\frac{1}{f_2} = (n_2 - 1)\left(\frac{1}{r_{21}} - \frac{1}{r_{22}}\right) = (n_2 - 1) \rho_2
\]  

(2b)

The focal length of any doublet is then given by,

\[
\frac{1}{f_{\text{doublet}}} = (n_1 - 1) \rho_1 + (n_2 - 1) \rho_2
\]  

(3)

The value of \(1/f_{\text{doublet}}\) in general will depend on \(\lambda\).

The condition of achromaticity, around the wavelength of the yellow light \(\lambda_D\), can be expressed as,

\[
\frac{d}{d\lambda} \left( \frac{1}{f_{\text{doublet}}} \right) = 0 , \quad \text{at} \ \lambda = \lambda_D
\]

Or, equivalently, using expression (3),
\[ \rho_1 \left. \frac{dn_1}{d\lambda} \right|_{\lambda=\lambda_D} + \rho_2 \left. \frac{dn_2}{d\lambda} \right|_{\lambda=\lambda_D} = 0 \] 

The derivative of \( n \) at \( \lambda=\lambda_D \) can be approximated using the red and blue Fraunhofer wavelengths, \( \lambda_C = 656.3 \text{ nm} \) and \( \lambda_F = 486.1 \text{ nm} \),

\[ \left. \frac{dn}{d\lambda} \right|_{\lambda=\lambda_D} \approx \frac{n_F - n_C}{\lambda_F - \lambda_C} \]

In addition, using the reciprocal of the dispersion power \( \Delta \)

\[ V \equiv \frac{1}{\Delta} = \frac{n_D^{-1}}{n_F - n_C} \]

known as “Abbe number”,

we obtain,

\[ \rho_1 \left. \frac{dn_1}{d\lambda} \right|_{\lambda=\lambda_D} = \rho_1 \frac{n_{1F} - n_{1C}}{\lambda_F - \lambda_C} \]

\[ = \rho_1 \frac{n_{1F} - n_{1C}}{\lambda_F - \lambda_C} \frac{n_{1D} - 1}{n_{1D} - 1} \]

\[ = \rho_1 \frac{1}{\lambda_F - \lambda_C} \frac{1}{V_1} \frac{n_{1D} - 1}{1} \]

and using (2a)

\[ \rho_1 \left. \frac{dn_1}{d\lambda} \right|_{\lambda=\lambda_D} = \frac{1}{\lambda_F - \lambda_C} \frac{1}{V_1} \frac{1}{f_{1D}} \]
So, the condition for achromaticity, expression (4), becomes

\[
\frac{1}{V_1 f_{1D}^*} + \frac{1}{V_2 f_{2D}^*} = 0
\]  

(5)

(For two given materials, their corresponding Abbe number values are tabulated.)

Expression (5), together with the designer’s requirement that the doublet has a desired focal length of \( f_{\text{desired}} = 15 \) cm at \( \lambda = \lambda_D \), where

\[
\frac{1}{f_{\text{desired}}} = \frac{1}{f_{1D}} + \frac{1}{f_{2D}}
\]  

(6)

constitute the couple of equations from which \( f_{1D} \) and \( f_{2D} \) have to be determined.

The solution to (5) and (6) is:

\[
\frac{1}{f_{1D}} = -\frac{V_1}{V_2 - V_1} \frac{1}{f_{\text{desired}}} \quad \text{and} \quad \frac{1}{f_{2D}} = \frac{V_2}{V_2 - V_1} \frac{1}{f_{\text{desired}}}
\]  

(7)
DESIGN of an ACHROMAT DOUBLET of 15 cm focal length

DOUBLET

(1) Equiconvex
520/636 crown glass

(2) 617/366 flint glass

<table>
<thead>
<tr>
<th>Catalog code</th>
<th>V</th>
<th>n_C</th>
<th>n_D</th>
<th>n_F</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{n_D - 1}{10V} )</td>
<td>( \frac{n_D - 1}{n_F - n_C} )</td>
<td>656.5 nm</td>
<td>587.6 nm</td>
<td>486.1 nm</td>
</tr>
<tr>
<td>(1) Borosilicate crown</td>
<td>520/636</td>
<td>63.59</td>
<td>1.51764</td>
<td>1.52015</td>
</tr>
<tr>
<td>(2) Dense flint</td>
<td>617/366</td>
<td>36.60</td>
<td>1.61218</td>
<td>1.61715</td>
</tr>
</tbody>
</table>

\[
\frac{1}{f_{1D}} = \left( n_{1D} - 1 \right) \left( \frac{1}{r_{11}} - \frac{1}{r_{12}} \right) = 0.52015 \left( \frac{1}{r_{11}} - \frac{1}{r_{12}} \right)
\]

\[
\frac{1}{f_{2D}} = \left( n_{2D} - 1 \right) \left( \frac{1}{r_{21}} - \frac{1}{r_{22}} \right)
\]
\[
\left( \frac{1}{r_{11}} - \frac{1}{r_{12}} \right) = \frac{0.157}{0.52015} \text{cm}^{-1} = 0.3019 \text{cm}^{-1};
\]

by choosing a equiconvex lens \( r_{12} = -r_{11} < 0 \) gives
\[
\frac{2}{r_{11}} = 0.3019 \text{cm}^{-1}. \text{ Thus, } r_{11} = 6.624 \text{ cm}
\]

Similarly
\[
\frac{1}{f_{2D}} = (n_{2D} - 1) \left( \frac{1}{r_{21}} - \frac{1}{r_{22}} \right) = \left( 0.61715 \right) \left( \frac{1}{r_{21}} - \frac{1}{r_{22}} \right)
\]
\[
\left( \frac{1}{r_{21}} - \frac{1}{r_{22}} \right) = \frac{-0.0904}{0.61715} \text{cm}^{-1} = -0.14649 \text{ cm}^{-1};
\]

by construction \( r_{21} = r_{12} \) (cemented lenses), which gives
\[
\left( \frac{1}{r_{12}} - \frac{1}{r_{22}} \right) = -0.14649 \text{ cm}^{-1}. \text{ Since } r_{12} = -r_{11}, \text{ we obtain } \left( -\frac{1}{r_{11}} - \frac{1}{r_{22}} \right) = -0.14649 \text{ cm}^{-1}. \text{ Thus, } r_{22} = -224.21 \text{ cm}
\]

**Observation**

Although the condition \( \frac{d}{d\lambda} \left( 1/f_{\text{doublet}} \right) = 0, \text{ at } \lambda = \lambda_D \), is quite appealing to use it as a requirement for obtaining a achromatic doublet, such a condition may does not necessarily ensure that 1/f is independent of the wavelength. The graph below is an example of what may happen in some cases.
That is, $1/f$ may still be different for different colors, despite the fact that the derivative of $1/f$ is zero at $\lambda = \lambda_D$.

A stronger condition is to require that, for example, that the focal length of the doublet for the red (C) and blue (F) light (Fraunhofer lines) to be equal,

\[
\frac{1}{f_{\text{doublet},C}} = \frac{1}{f_{\text{doublet},F}} \quad \text{requirement for achromaticity} \quad (8)
\]

Using (1) and (2) we obtain,

\[
\frac{1}{f_{\text{doublet},C}} = (n_{1C} - 1) \rho_1 + (n_{2C} - 1) \rho_2
\]

\[
\frac{1}{f_{\text{doublet},F}} = (n_{1F} - 1) \rho_1 + (n_{2F} - 1) \rho_2
\]

So, the condition (8) is equivalent to

\[
(n_{1F} - n_{1C}) \rho_1 + (n_{2F} - n_{2C}) \rho_2 = 0
\]

This expression is nothing but expression (4).
Indeed, the resemblance can be more direct if we divide by the difference $\lambda_F - \lambda_C$.

$$p_1 \frac{n_{1F} - n_{1C}}{\lambda_F - \lambda_C} + (n_{2F} - n_{2C}) \rho_2 \frac{n_{2F} - n_{2C}}{\lambda_F - \lambda_C} = 0$$

where the fractions are the approximate values of the derivative of $n$ with respect to $\lambda$.

**SUMMARY**

The procedure above ensures that the achromat doublet will have equal focal length for at least the red and blue colors.
Classification of Objective Lenses

1) Achromats. 2) Fluorites. 3) Apochromats.

Added Plan designation to lenses with wide flat field (low curvature of field and distortion).

<table>
<thead>
<tr>
<th>Type</th>
<th>Spherical</th>
<th>Chromatic</th>
<th>Flatness Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achromat</td>
<td>*</td>
<td>2λ</td>
<td>No</td>
</tr>
<tr>
<td>F-Achromat</td>
<td>*</td>
<td>2λ</td>
<td>Improved</td>
</tr>
<tr>
<td>Neofluar</td>
<td>3λ</td>
<td>&lt;3λ</td>
<td>No</td>
</tr>
<tr>
<td>Plan Neofluar</td>
<td>3λ</td>
<td>&lt;3λ</td>
<td>Yes</td>
</tr>
<tr>
<td>Plan Apochromat</td>
<td>4λ</td>
<td>&gt;4λ</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* Corrected for two wavelengths
2λ Corrected for blue and red
3λ Corrected for blue, green and red
4λ Corrected for dark blue, blue, green and red

Fluorites objectives.

- Considerably better corrected than achromats, but not quite as well corrected as the apochromats.
- Uses fluorite crystals (which have lower dispersion) in place of some of the glass elements.
- Correct for spherical aberrations in three wavelengths at considerably lower cost than the apochromats.
Apochromatic objectives.

- Provides the same focal length for three wavelengths, and free of spherical aberration for two wavelengths.
- Magnification still vary with wavelength (a compensating eyepiece is used to cancel the colored fringes).

60x Plan Apochromat Objective

http://www.microscopyu.com/articles/optics/objectivesspecs.html