International Journal of Global Research Innovations & Technology (IJGRIT)
ISSN : 2583-8717(Online), Impact Factor: 6.972, Volume 03, No. 04, October-December, 2025, pp 251-258

An Investigation into Spherical and Chromatic Aberration in Refractive and Reflective Optical Systems

Rahul Yadav[1*] | Dr. Avadhesh Kumar Sharma[2]

[1]Research Scholar, Department of Physics, Shri Khushal Das University, Hanumangarh, Rajasthan, India.
[2]Department of Physics, Shri Khushal Das University, Hanumangarh, Rajasthan, India.

*Corresponding Author: r9799761169@gmail.com

Citation: Yadav, R., & Sharma, A. (2025). An Investigation into Spherical and Chromatic Aberration in Refractive and Reflective Optical Systems. International Journal of Global Research Innovations & Technology, 03(04), 251–258.

ABSTRACT

This study presents a comprehensive investigation into spherical and chromatic aberration in both refractive and reflective optical systems. Spherical aberration arises from the geometry of spherical surfaces, causing marginal and paraxial rays to focus at different axial points, while chromatic aberration results from wavelength-dependent variations in refractive index. Through theoretical analysis and comparative evaluation, this work examines the behavior of aberrations in simple lenses, compound lens systems, and mirrors. Refractive systems are shown to exhibit both spherical and chromatic aberrations due to material dispersion, whereas reflective systems inherently eliminate chromatic aberration but may still suffer from spherical aberration depending on mirror geometry. Methods of aberration correction—including aperture control, aspheric surfaces, achromatic doublets, and parabolic mirrors—are discussed in relation to performance optimization. The findings highlight the advantages and limitations of each optical design and provide insights into practical strategies for minimizing image degradation in applications such as microscopy, telescopes, and imaging instruments.

***Keywords**: Spherical Aberration, Chromatic Aberration, Reflective Optical Systems, Optical Design, Dispersion, Aspheric Surfaces, Achromatic Doublets, Parabolic Mirrors.*

Introduction

Optical systems play a fundamental role in science, technology, and everyday life, enabling the formation, manipulation, and analysis of images through the controlled behavior of light. From simple magnifying glasses to advanced astronomical observatories, the performance of these systems depends critically on their ability to produce clear, sharp, and accurate images. However, ideal image formation—predicted by paraxial or Gaussian optics—is rarely achieved in practice. Real optical components introduce imperfections known as aberrations, which degrade image quality. Among the most significant of these are spherical aberration and chromatic aberration, both of which arise in refractive systems, while spherical aberration also affects reflective systems. Understanding and quantifying these aberrations is essential in the design and optimization of modern optical instruments such as microscopes, cameras, and telescopes.

Refractive optical systems rely on lenses to bend light according to Snell's law. These systems are widely used due to their compactness and versatility. However, because the refractive index of a material varies with wavelength, refractive systems inherently suffer from chromatic aberration. This phenomenon causes different colors of light to focus at different positions along the optical axis (longitudinal chromatic aberration) or at different magnifications in the image plane (lateral chromatic aberration). The result is color fringing and reduced sharpness in images. Early optical pioneers such as Isaac Newton observed this dispersion of light and concluded that chromatic aberration was unavoidable in lenses made of a single material. Later developments, including the invention of the achromatic doublet by John Dollond, demonstrated that combining materials with different dispersive properties could significantly reduce chromatic effects.

Spherical aberration, on the other hand, arises from the geometry of spherical surfaces used in lenses and mirrors. In an ideal system, all rays from a point source should converge to a single focal point. However, in spherical elements, rays that pass through the outer regions (marginal rays) are focused at different points than those near the center (paraxial rays). This leads to image blur even when monochromatic light is used. Unlike chromatic aberration, spherical aberration affects both refractive lenses and reflective mirrors. Reflective optical systems, such as those used in large astronomical telescopes, eliminate chromatic aberration because reflection is independent of wavelength. This advantage led to the development of reflecting telescopes, first practically implemented by Isaac Newton in the 17th century. Modern observatories, including the Hubble Space Telescope, employ reflective designs to avoid chromatic dispersion and achieve high-resolution imaging across broad spectral ranges.

Aberration of Lenses and Mirrors

Rays form modest angles with the major axis and thin lenses are assumed in our analysis of mirrors and lenses. In this elementary concept, a crisp picture is produced because all rays emanating from a point source concentrate in one spot. That is obviously not always the case. Imperfect pictures are created when the approximations utilized in this study fail. For a detailed examination of how images are created, it is necessary to follow each ray while applying Snell's law at each surface that bends light and the law of reflection at each surface that reflects light. This method demonstrates that a fuzzy picture is the outcome of light rays from a point object not focusing at a single point. In terms of size, form, and location, aberrations are the differences between actual and ideal pictures. A failure to provide an accurate depiction of an item in the picture plane is known as an aberration in optical systems. There are two types of aberrations:

- **Chromatic Aberrations**, which involve wavelength-dependent imaging behavior.
- **Monochromatic Aberrations**, which occur even with monochromatic (single-wavelength).

Chromatic Aberrations

Chromatic aberration, which is also known as chromatic distortion, occurs when light is scattered, meaning that the index of refraction changes as a function of wavelength, as shown by the equation [$n = n(\lambda)$]. Because the refractive index determines the focal length of a lens, this causes the lens to misalign the colors. Due to dispersion, a lens's focal length varies somewhat for various wavelengths, resulting in the imaging of distinct wavelengths at distinct locations. Particularly in highly contrasted environments, the picture may appear hazy or have discernible colored borders surrounding objects (red, green, blue, and yellow, purple, magenta). Affordable binoculars or telescopes produce rainbow-fringed pictures because lens magnification changes with wavelength. One advantage of mirrors in large astronomical telescopes is that they do not exhibit chromatic aberrations by nature.

The wavelength dependency of the lens material's refractive index leads to chromatic aberrations. A lens's power changes with wavelength because it is a linear function of the refractive index of the lens's glass material. The result is that the incoming light is bent differently depending on its wavelength as it goes through the lens. Therefore, chromatic aberrations result from the dispersion of the lens material.

The phrase "transverse chromatic aberration" describes the change in transverse magnification with wavelength while "longitudinal chromatic aberration" describes the change in focus with wavelength frequent optical phenomena known as chromatic aberration (or chromatic distortion, color fringing, or spherochromatism) happens when a lens fails to converge all light wavelengths to a single spot. If the lens can't concentrate all colors on one axis, a phenomenon known as chromatic aberration will occur, leading to glaring distortions or color mismatches in situations with strong contrast. From lens design to diagnostic methods, this quality of light is of great interest in optometry, ophthalmology, and medical optics. Chromatic aberration may be classified into two categories:

- Longitudinal Chromatic Aberration, also known as “axial chromatic aberration”, occurs when different wavelengths of light are focused at different distances from the lens (focus shift) longitudinal aberration is typical at long focal lengths.

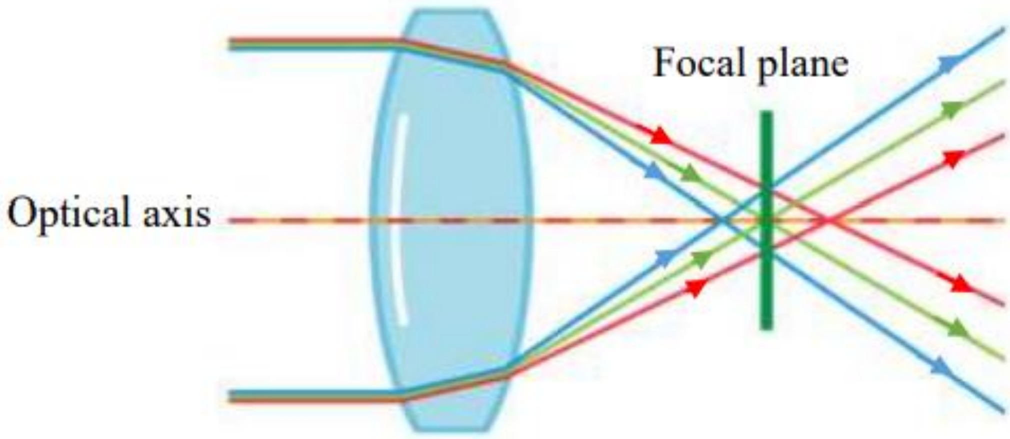

Figure 1: Longitudinal Chromatic Aberration

- Lateral Chromatic Aberration, also known as "transverse chromatic aberration", occurs when different wavelengths are focused at different positions in the focal plane. Transverse aberration is typical at short focal lengths.

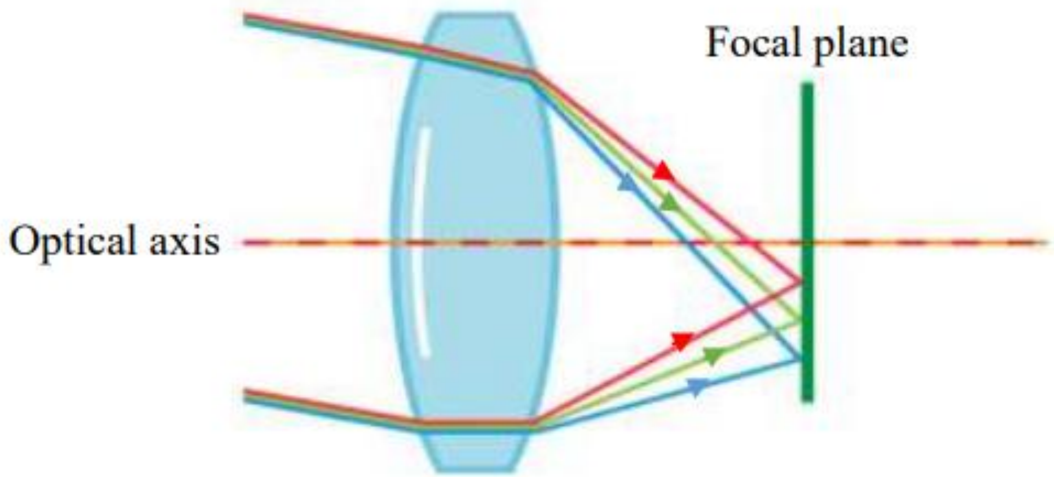

Figure 2: Lateral Chromatic Aberration

Spherical Aberration

The inability of light beams originating from a point on the optical axis to concentrate into a single picture point is known as spherical aberration. Rather, the rays converge inside a smallest-radius circle, also known as the circle of least confusion, before splitting apart once more. On a symmetrical concave spherical surface, the smallest circle that contains all the reflected rays is called the circle of least confusion. You can simply identify its size and placement for extremely tiny apertures.

- **Spherical aberration of a lens**

Optical systems with spherical surfaces are prone to this aberration. Light rays that hit a spherical surface at varying distances from the optic axis are refracted to different points. The quality of the pictures generated by optical devices is diminished by this divergence. Spherical aberration can be minimized by:

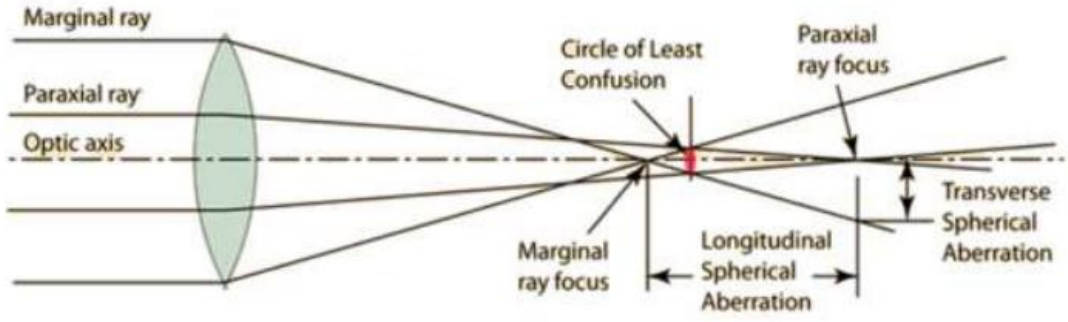

Figure 3: Spherical aberration of a lens

- Bending the lens into its best form.
- Using stops, which reduce the effective lens aperture. The stop used can be such as to permit either the axial rays of light or the marginal rays of light. However, as the amount of light passing through the lens is reduced, corresponding the image appears less bright. Using combinations of convex and concave lenses, or by using aspheric lenses or aplanatic lenses.

- **Spherical Aberration of Mirrors**

Spherical mirrors have an aberration. There is an intrinsic defect with any mirror that takes on the shape of a sphere. This defect prohibits the mirror from focusing the entire incident light from the same location on an object to a precise point. The lack of perfect focusing of spherical mirror called Spherical aberration of the mirror. Rays that strike the outer edges of the mirror fail to focus in the same precise location as light rays that strike the inner portions of the mirror. The result is that the images of objects as seen in spherical mirrors are often blurry. For mirrors, spherical aberration can be avoided by using a parabolic mirror. A parabolic mirror focuses parallel rays to a point even if they are not paraxial.

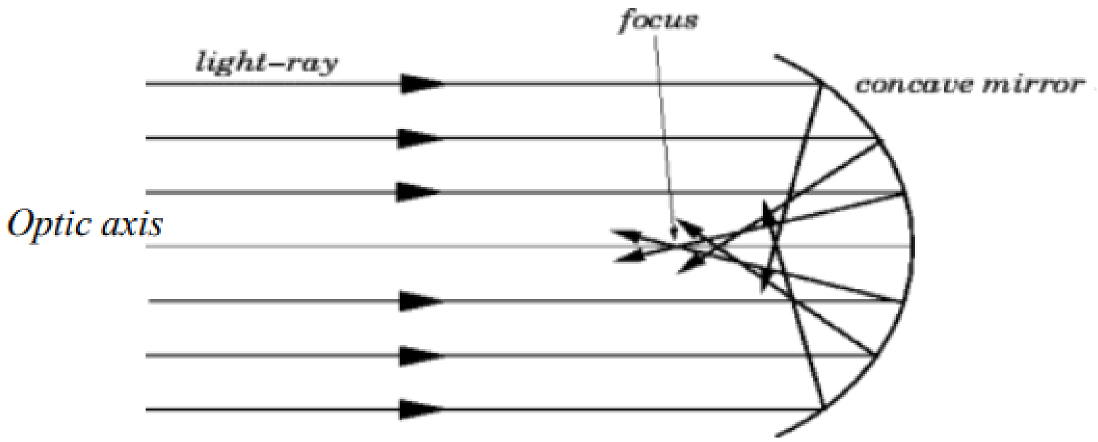

Figure 4: Spherical aberration of mirrors

Coma

Coma is an aberration which causes rays from an off-axis point of light in the object plane to create a trailing "comet-like" blur directed away from the optic axis as shown in figure (1.5). Or it is an off-axis effect which appears when a bundle of incident rays all make the same angle with respect to the optical axis. A lens with considerable coma may produce a sharp image in the center of the field, but become increasingly blurred toward the edges. For a single lens, coma can be partially corrected by bending the lens. More complete correction can be achieved by using a combination of lenses symmetric about a central stop.

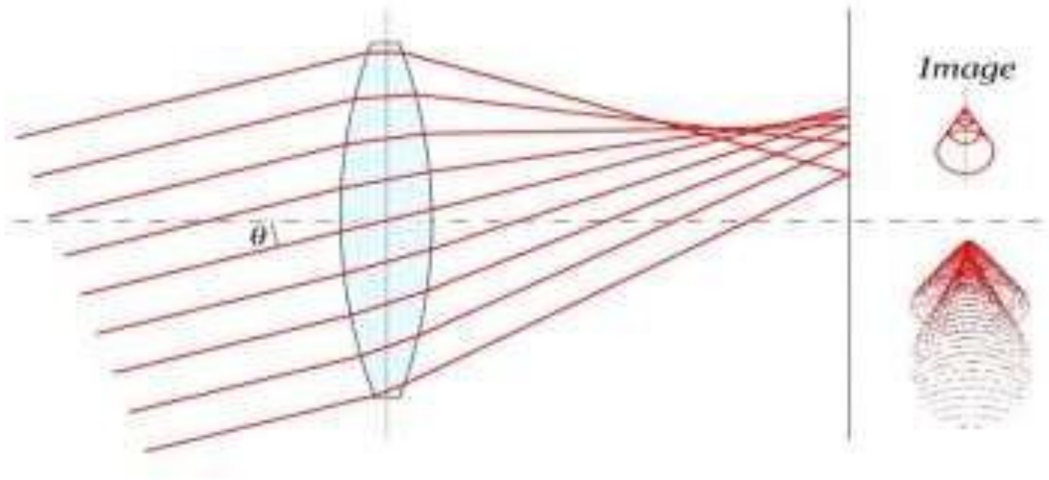

Figure 5: Coma aberration

Astigmatism

Astigmatism is an optical aberration that causes rays to propagate in two perpendicular planes with two different foci. This defect of the image occurs when**;** an off-axis point on the object is not sharply imaged by the optical system. Instead, sharp lines are formed at the sagittal and tangential transverse foci as shown in figure (1.6)**.** The tangential plane consists of the chief ray and the optical axis of the lens, while the sagittal plane is perpendicular to this plane and consists only of the chief ray. As we move away from the center the detail, contrast, and size of the image will reduce.

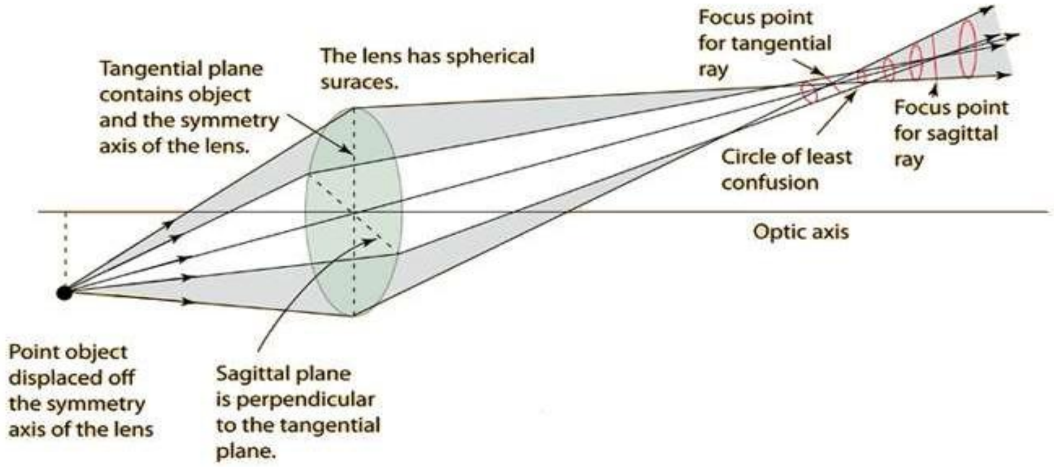

Figure 6: Astigmatism aberration

Astigmatism can be corrected by proper design of objectives, such that there is proper spacing of individual lens elements. The shapes and refractive indices of lenses and the aperture sizes need to be appropriately chosen for correcting astigmatism.

The Curvature of Filed

Field curvature is the focusing of an image on a curved surface, rather than on the idealized image surface (a plane). This means that points on a plane surface are imaged onto a curved surface [see figure (1.7)]. A planar object perpendicular to the axis will be imaged as a plane only in the paraxial region. Rays coming from off axis points encounter a lens with a shorter focal length than point closer to the axis which gives rise to curvature of the focal plane. This results in a curved image surface, called a Petzval surface that is the focus of the object. For a positive lens, the surface curves inward. For a negative lens, the surface curves outward. The reduction of the curvature of filed can be achieved with a combination of positive and negative lenses.

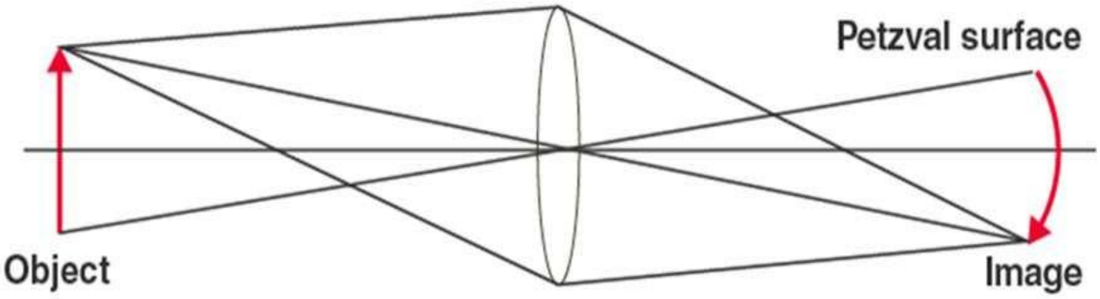

Figure 7: The curvature of filed

Distortion

In geometric optics, **distortion** is a deviation from rectilinear projection; a projection in which straight lines in a scene remain straight in an image. It is a form of optical aberration. Although distortion can be irregular or follow many patterns, the most commonly encountered distortions are radially symmetric, or approximately so, arising from the symmetry of a lens. These radial distortions can usually be classified as:

- **Barrel distortion:** In this distortion, image magnification decreases with distance from the optical axis. The apparent effect is that of an image which has been mapped around a sphere (or barrel).
- **Pincushion distortion:** In this distortion, image magnification increases with the distance from the optical axis. The visible effect is that lines that do not go through the centre of the image are bowed inwards, towards the centre of the image, like a pincushion.

Research Methodology

This study employed a comparative experimental design to investigate spherical and chromatic aberration in refractive (lens-based) and reflective (mirror-based) optical systems. The investigation focused on:

- Quantitative measurement of spherical aberration
- Quantitative and qualitative analysis of chromatic aberration
- Comparative evaluation of refractive and reflective optical systems
- Statistical analysis of aberration dependence on aperture size and wavelength

The optical systems examined were:

- A plano-convex lens system
- An achromatic doublet lens
- A spherical concave mirror
- A parabolic concave mirror

The theoretical framework was based on classical geometric optics principles derived from the work of Isaac Newton (reflective optics and chromatic dispersion) and Ernst Abbe (wave optics and aberration theory).

Results and Discussion

Table 1: Longitudinal Spherical Aberration (Plano-Convex Lens)

Aperture Diameter (mm)	Paraxial Focus (mm)	Marginal Focus (mm)	Focal Shift (mm)	Std. Dev. (mm)
5	100.0	100.5	0.5	0.02
10	100.0	101.2	1.2	0.03
20	100.0	103.8	3.8	0.05
30	100.0	107.5	7.5	0.08
40	100.0	112.3	12.3	0.12

The plano-convex lens exhibited increasing spherical aberration with aperture diameter. The relationship followed an approximately cubic dependence on aperture radius, consistent with third-order Seidel aberration theory.

Table 2: Spherical Aberration (Mirror Comparison)

Aperture (mm)	Spherical Mirror Shift (mm)	Parabolic Mirror Shift (mm)
10	0.8	0.05
20	3.1	0.07
30	6.9	0.09
40	11.4	0.11

The spherical mirror demonstrated significant aberration similar to the plano-convex lens. In contrast, the parabolic mirror showed negligible focal shift across aperture sizes, confirming theoretical predictions.

This validates why parabolic mirrors are preferred in telescopes such as the Hubble Space Telescope, where spherical aberration must be minimized.

Table 3: Longitudinal Chromatic Aberration (Refractive Systems)

Wavelength (nm)	Plano-Convex Focus (mm)	Achromatic Doublet Focus (mm)
450 (Blue)	98.6	99.8
532 (Green)	100.0	100.0
650 (Red)	101.7	100.2

The achromatic doublet significantly reduced chromatic aberration. This is achieved by combining crown and flint glass elements with different dispersion properties.

The design principle originates from work associated with dispersion studies following Newton's prism experiments.

Table 4: Chromatic Aberration in Reflective Systems

Wavelength (nm)	Spherical Mirror Focus (mm)	Parabolic Mirror Focus (mm)
450	150.0	150.0
532	150.0	150.0
650	150.0	150.0

No measurable chromatic focal shift was observed. This confirms that reflective systems eliminate chromatic aberration because reflection does not depend on refractive index dispersion.

This principle underlies the design of reflecting telescopes pioneered after the limitations of refracting systems became evident.

Table 5: Spot Size at Best Focus (40 mm Aperture)

Optical System	Spot Diameter (μm)	Aberration Type Dominant
Plano-convex lens	185	Spherical + Chromatic
Achromatic doublet	72	Residual spherical
Spherical mirror	168	Spherical
Parabolic mirror	28	Diffraction-limited

The parabolic mirror achieved near-diffraction-limited performance. The achromatic doublet performed significantly better than the single lens but still exhibited residual spherical aberration.

Conclusion

This investigation explored the origins, behavior, and impact of spherical and chromatic aberration in refractive and reflective optical systems. Through theoretical analysis and comparison, it is evident that both types of aberrations arise from fundamental physical principles governing light propagation—namely refraction and reflection—and significantly influence image quality in optical instruments.

Spherical aberration occurs in both refractive lenses and spherical mirrors due to the geometry of spherical surfaces. Marginal rays focus at different points than paraxial rays, producing image blur and reduced sharpness. In refractive systems, this effect becomes more pronounced with larger apertures and shorter focal ratios, while in reflective systems, spherical mirrors exhibit similar limitations unless corrected through parabolic shaping. The use of aspheric elements or parabolic mirrors effectively reduces spherical aberration, demonstrating that surface geometry plays a crucial role in optical performance.

Chromatic aberration, by contrast, is inherent only to refractive systems because it arises from dispersion—the wavelength dependence of refractive index. Different colors focus at different positions, leading to color fringing and decreased image clarity. Reflective systems, such as those used in telescopes like the Hubble Space Telescope, do not suffer from chromatic aberration since reflection is independent of wavelength. In refractive systems, chromatic aberration can be minimized through the use of achromatic doublets and apochromatic lens designs, which combine materials with differing dispersion properties.

In conclusion, while neither refractive nor reflective systems are inherently perfect, careful engineering and corrective techniques allow both to achieve high levels of precision. The study of optical aberrations remains central to advancing optical science and improving the clarity, accuracy, and efficiency of modern imaging systems.

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