

Correcting chromatic aberrations using a diffraction grating in a camera lens

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1 Lens aberrations

In a camera a lens is used to create an image of an object on the image plane, where the light is recorded by a light-sensitive device. This light-sensitive device is usually a photographic film or an electrical sensor called a charged couple device (CCD). The lens is made from one or more pieces of a transparent material, often glass but sometimes plastic or an encased liquid. Each of these pieces is called a lens element. Refraction of the light as it crosses the boundaries between glass and air causes light from the object to form the image. An ideal lens (fig 1) “would reproduce every object point of light as an exact point on the properly positioned sensitive material or focusing screen, and reproduce every straight line as a fine straight line” [1].

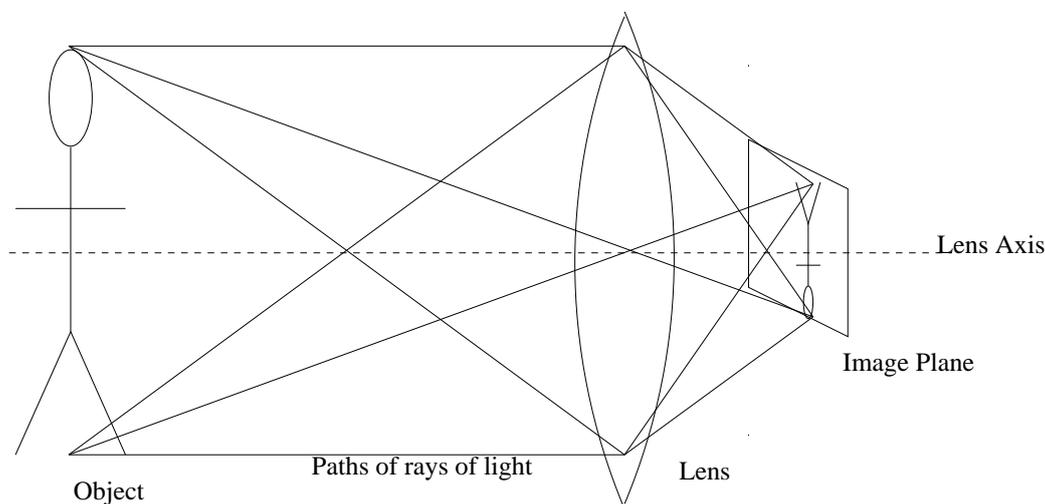


Figure 1: A hypothetical ideal lens

It is however impossible to manufacture an ideal lens, so a real lens must be designed to match the properties of a hypothetical ideal lens as closely as possible. This is usually done by using multiple elements in a lens. The simplest, and therefore cheapest, type lens element to manufacture is one where the surfaces form part of a sphere. This means the curvature is uniform across the face of the glass, and it can therefore be ground and polished with a simpler tool. Aspherical elements have surfaces with elliptical, parabolic or higher order curves, but these are rarer as they need special tools to manufacture to the precision required for a camera lens.

The differences between a real lens and an ideal lens are called the aberrations, and are often categorised into seven groups : “spherical, coma, astig-

matism, field curvature, distortion, chromatic and lateral colour” [2]. Spherical, coma, astigmatism and field curvature result in sharp points on the object becoming blurs in the image. This tends to be worse further from the axis of the lens. These aberrations are minimised by adding more lens elements, especially aspheric ones. Distortion is a drawing error, meaning that a straight line on the object is drawn as a curved line in the image. This can be minimised fairly easily using multiple lens elements, corrected with post-processing on a computer, or left uncorrected or even exaggerated for a fish-eye effect.

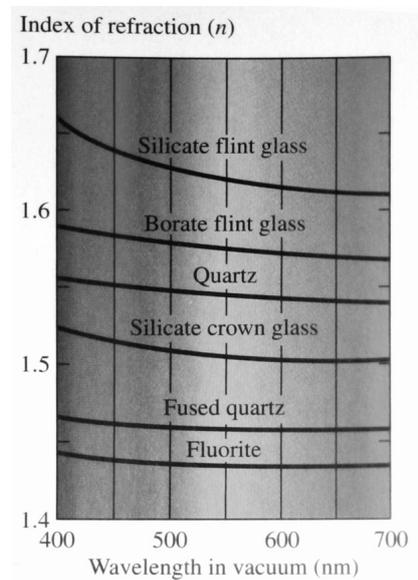


Figure 2: A graph shown dispersion of several common glasses [3]

The chromatic and lateral colour aberrations are of a different type from the above problems. They cannot be corrected with any shape or number of lenses of the same type of glass. They are a result of the different indices of refraction of a material for different wavelengths of light; the indices are larger for shorter wavelengths. This is called dispersion and is shown for a number of glasses in fig. 2. Blue light bends more strongly at the air/glass boundary than red light, as a result different colours will take different paths through a lens and be focused at different points.

Chromatic aberration is when some colours focus in front of or behind the image plane, and lateral colour is where different colours focus at different points on the image plane. Chromatic aberration is shown in figure 3. They result in coloured halos appearing around high contrast edges in the image.

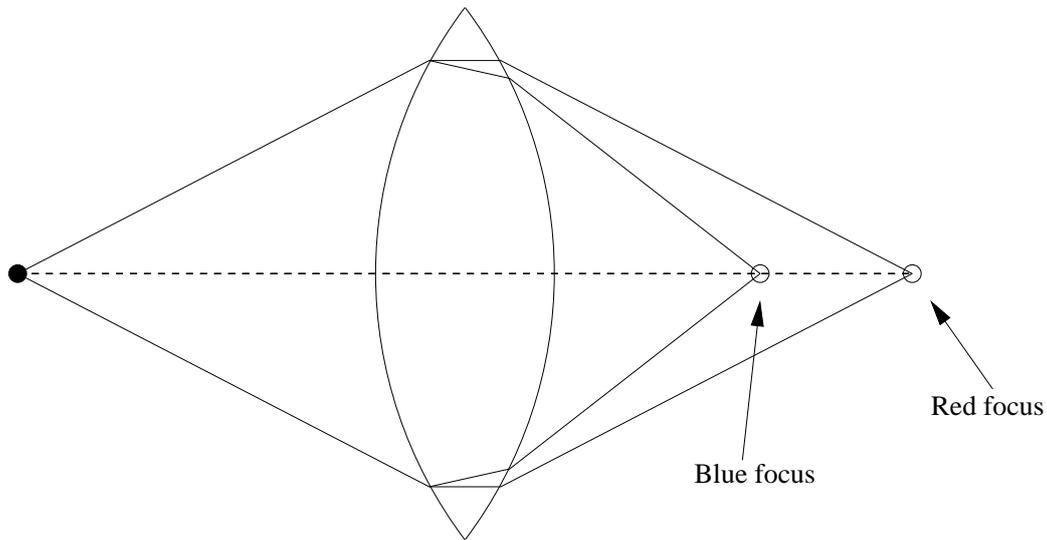


Figure 3: Chromatic aberration of a convergent lens element. Blue light is focused nearer to the lens than red light

This essay will describe two methods of correcting this aberration. The first is a compound lens called an achromat; the second is a modern method using diffractive optical elements in the lens. The discussion will be mostly qualitative and make use of diagrams rather than equations to explain the systems.

2 Traditional Corrections

An achromat makes use of the fact that different types of glass have different dispersive properties. A glass with a high dispersion will spread different coloured rays of light more than one with a low dispersion, as it has a larger difference between index of refraction for red and blue light. It is common to refer to the power of a lens, which is a function of its shape and refractive index. The power is the reciprocal of the focal length (fig 4), the distance it takes for parallel rays entering the lens to meet, and is measured in diopters. Convergent elements have positive powers, and divergent ones have negative power. The combined power of two lens elements in series is the sum of the individual powers. A lenses power will be different for different colours of light.

An achromat uses two elements, both shown in figure 5. The first is convergent, with a low dispersion and a high power; the second is divergent,

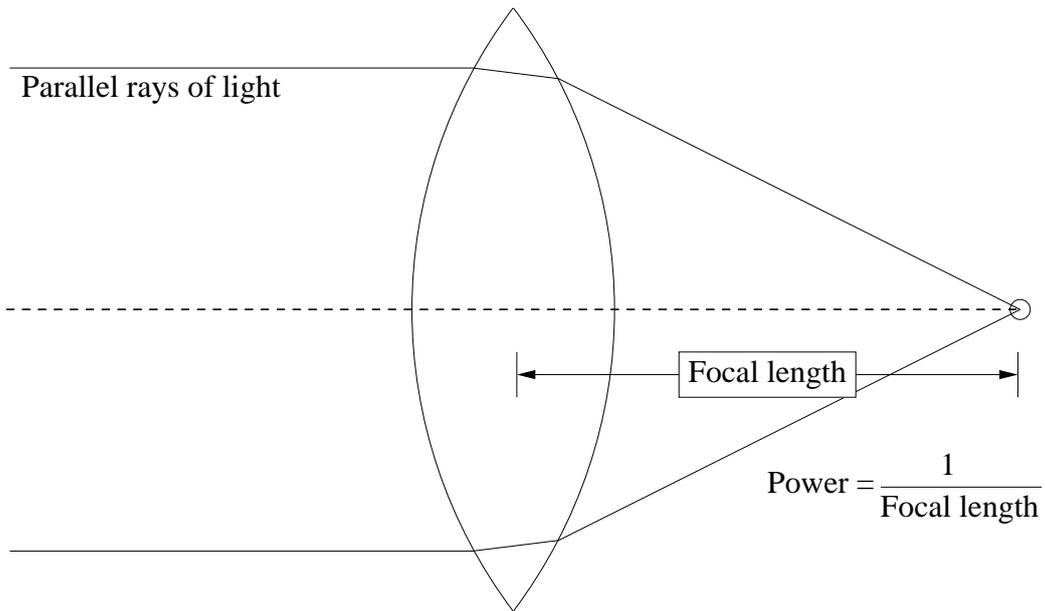


Figure 4: Focal length and power

with a high dispersion and a low power. Their individual effects are shown below. The convergent lens brings rays of light closer, and the divergent pushes them apart. They both have a higher power at the blue end of the spectrum.

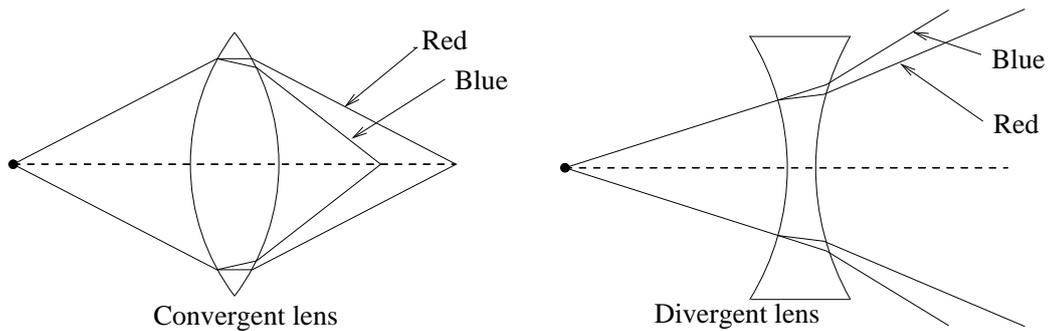


Figure 5: The two components of an achromat lens

When the divergent element is placed behind the convergent one, light focuses further away from the first element than it would otherwise. To focus red and blue light to the same point the total power for red and blue must be equal. Also to make the light light focus to a point this total power must

be positive. Each lens must have to same difference in power between red and blue light. If both were made of the same glass then this would require them to be of the same power, but the high dispersion glass gives the same amount of dispersion at a lower power. This make all the above conditions possible and brings red and blue light together at the same point(fig 6).

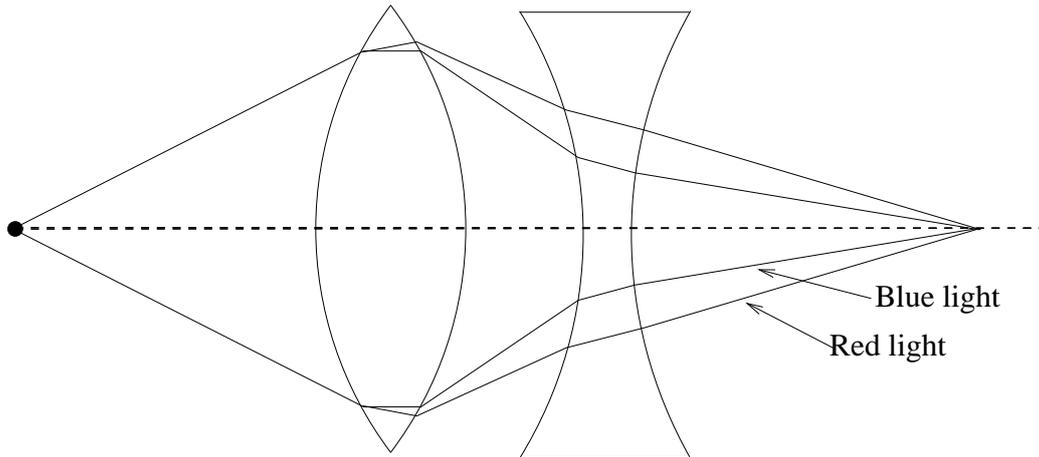


Figure 6: An Achromat. Blue light is refracted more strongly by each element, and focuses at the same point as the red light

3 Diffractive Optics

In 1800 Thomas Young demonstrated interference patterns in light [3]. He shone monochromatic light at two screens. The first had one narrow slit in it, which had the effect of only letting light from a small part of the source through, and resulted in the transmitted light being fairly coherent. The second screen had two slits in it. The light then reached a screen on which an interference pattern was visible. The set-up is shown in figure 7.

This experiment showed that light behaves as a wave. The current interpretation is that photons of light travel as a probability wave, with the square of the amplitude of the wave being the probability of a photon arriving. As the number of photons becomes large, the probabilistic effects are smoothed out, and a classical wave model becomes accurate.

The bright fringes on the screen are areas where the waves of light from each slit have arrived in phase. The lengths of the paths the light takes must differ by an integer number of wavelengths. The central fringe is numbered 0, as the paths differ by 0 wavelengths. For the n^{th} fringe on each side the

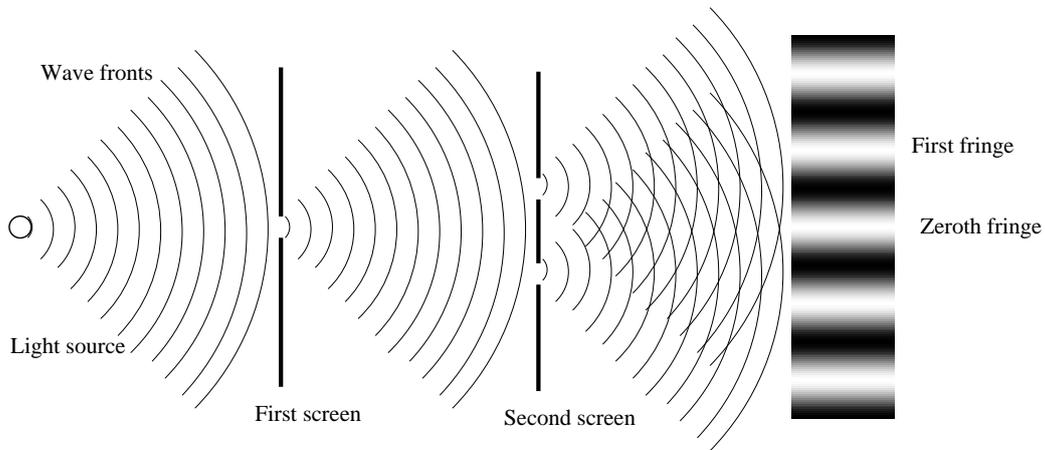


Figure 7: Youngs Slits, light fringes occur where the wave fronts from each of the slits arrive at the same time

paths differ by n wavelengths. This is shown for the 1st fringe in figure 8. The interference is the same if the two slits are replaced by many slits, which are called a diffraction grating.

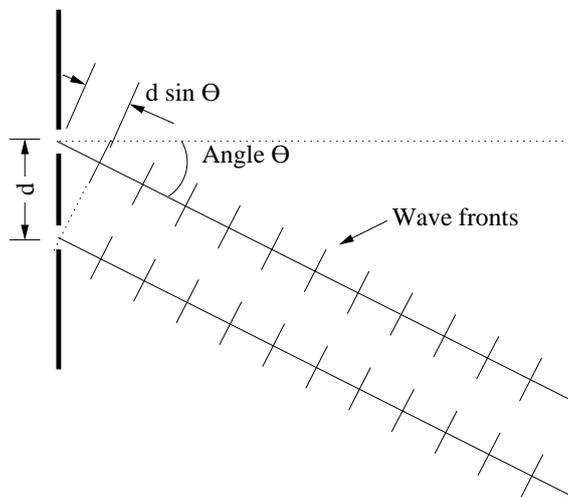


Figure 8: Light takes the path where wave fronts are in sync

The angle θ of the maxima of the n^{th} fringe, measured from the normal, is given by $\sin\theta = \frac{n\lambda}{d}$, where d is the distance between slits and λ is the wavelength of the light [3], or just $\theta = \frac{n\lambda}{d}$ using the small angle approximation. The dependence on the wavelength of light means that a diffraction will split

a beam of white light into a spectrum (fig 9). This effect is used in accurate spectroscopes. If the light arrives at the grating at an angle ϕ rather than along the normal, then the term $\sin\phi$ must be added to right-hand side of the above equation. This accounts for the difference in phase at different slits.

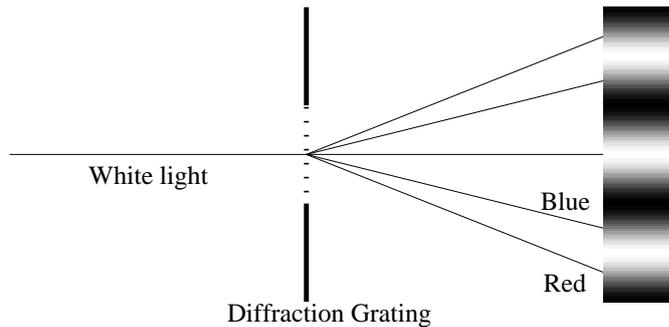


Figure 9: Red light is diffracted more than blue light as it has a long wavelength

In an idealised grating with perfectly symmetrical slits the light intensity of each of the fringes would be of equal intensity. In reality the “grating is often made with little ‘sawtooth’ cuts [in a piece of glass, and] by arranging the ‘sawteeth’, more light may be sent into one particular [fringe]” [4]. Sending most of the light to the first fringe on one side gives the most useful spectrum (fig 10).

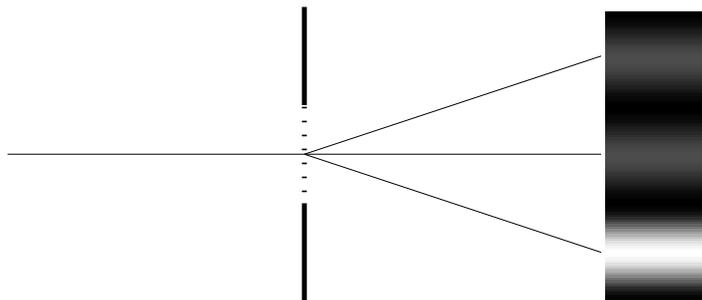


Figure 10: Shape of slits biases diffraction to the first fringe

We now have a device which alters the path of light according to its wavelength and has the greatest effect at large wavelengths, i.e. red light. To make this useful in a lens it the grating must be circular. This can be

used to counter the effect of chromatic aberration from a single converging lens. The diffraction grating is etched or moulded onto the surface of the convergent lens (fig 11).

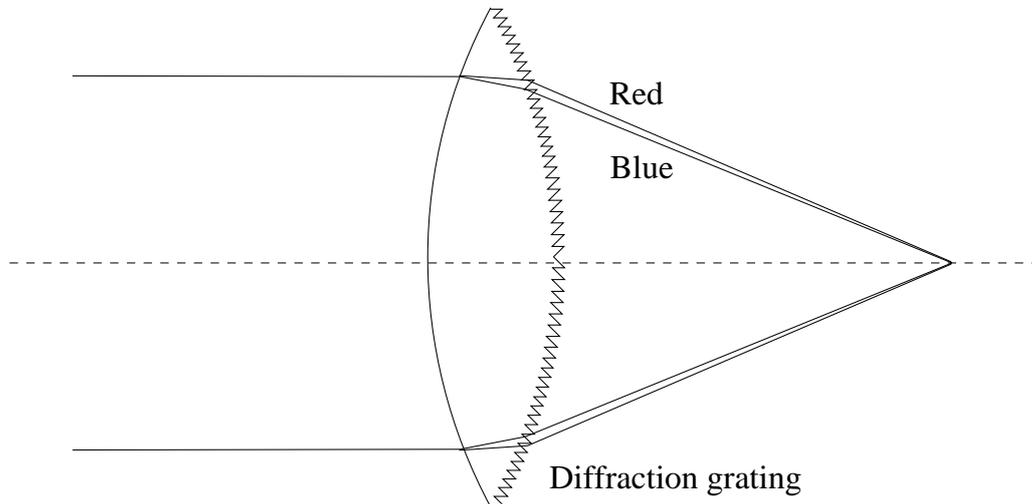


Figure 11: A lens element with a diffraction grating etched into it

The advantage of using diffractive optical elements in a lens is that it corrects a chromatic aberration without requiring extra glass elements. This can reduce the size and mass of large lenses. This is especially useful in professional telephoto lenses which can typically be several kilograms. Canon have been the first company commercially manufacture diffractive optics (DO) lenses. They claim their 400mm f4 DO is 26% shorter and 36% lighter than a "comparable lens having a conventional design" [5], the two lenses are shown in figure 12.



Figure 12: Diffractive optic lens compared to traditional lens[5]

A final point to mention is that neither achromats nor diffraction gratings can be used to completely eliminate chromatic aberrations. This is because the dependence on wavelength of refractive index is not a simple linear one. The best that can be achieved is to correct at two wavelengths, for example red and blue. Wavelengths in between red and blue will focus close to the image plane, and if this is close enough then chromatic aberration is minimised. As stated at the beginning, it is impossible to manufacture a perfect lens, but a lens corrected for two wavelengths is accurate enough for most purposes.

References

- [1] Arthur Cox, *Photographic Optics*, 13th Ed, Focal Press (1966), Page 27.
- [2] Geoffrey Crawley, *Squaring the circle, Amateur Photographer*, IPC Media, 10th April 2004.
- [3] Hugh D Young & Roger A. Freedman, *University Physics*, 11th Ed, Pearson Addison Wesley (2003), Chapters 33 -36
- [4] Richard P. Feynman, *Lectures on Physics I*, Addison Wesley (1963), Part 30-2.
- [5] Canon Inc., Technical report 2001.6, <http://www.canon.com/camera-museum/tech/report/200106/report.html>, 5th May 2004.
- [6] W. T. Welford, *Aberrations of Optical Systems*, Adam Hilger (1991)