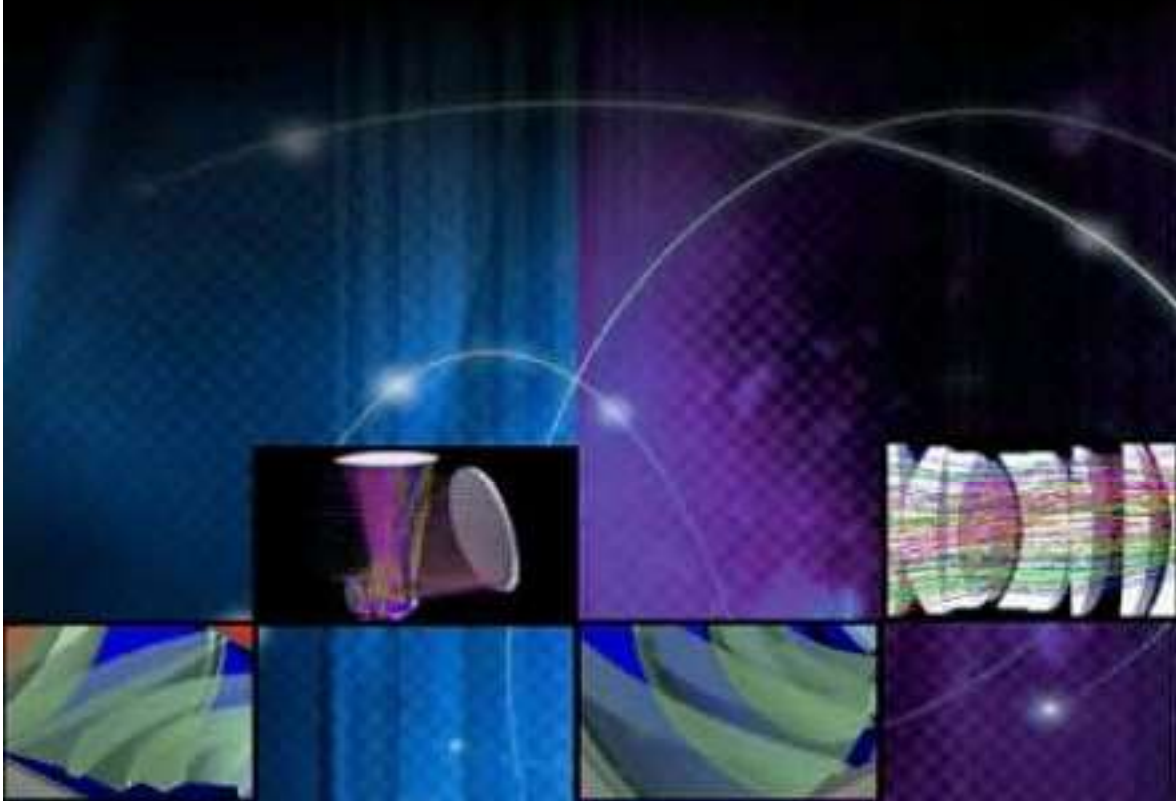


Lens Design Fundamentals

SECOND EDITION

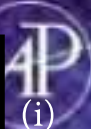


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Rudolf Kingslake
R. Barry Johnson

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*To my dearest wife Marianne Faircloth Johnson
and our remarkable son Rutherford Barry Johnson
for their gentle encouragement and support.*

*In memory of my parents,
J. Ralph and Sara F. Johnson,
for their enduring tolerance of my often trying inquisitiveness.*

And

*In memory of Rudolf Kingslake (1903–2003),
who taught me to appreciate the beauty in well-designed lenses.*

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Table 1.2
Optics Manufacturing Tolerances for Plastics

Attribute	Tolerances (rotationally symmetrical elements less than 75 mm in diameter)
Radius of Curvature	$\pm 0.5\%$
EFL	$\pm 1.0\%$
Center Thickness	± 0.020 mm
Diameter	± 0.020 mm
Wedge (TIR) in Element	< 0.010 mm
S1 to S2 Displacement (across the mold parting line)	< 0.020 mm
Surface Figure Error	≤ 2 fringes per inch (2 fringes = 1λ)
Surface Irregularity	≤ 1 fringe per inch (2 fringes = 1λ)
Scratch-Dig Specification	40–20
Surface Roughness Specification (RMS)	< 50 Å
Diameter to Thickness Ratio	$< 4:1$
Center Thickness to Edge Thickness Ratio	$< 3:1$
Part to Part Repeatability (one cavity)	$< 0.50\%$

Source: Reprinted by permission of G-S Plastic Optics.

1.1.6 Design Tradeoffs

The lens designer is often confronted with a variety of ways to achieve a given result, and the success of a project may be greatly influenced by his choice. Some of these alternatives are as follows: Should a mirror or lens system be used? Can a strong surface be replaced by two weaker surfaces? Can a lens of high-index glass be replaced by two lenses of more common glass? Can an aspheric surface be replaced by two spherical surfaces? Can a long-focus lens working at a narrow angular field be replaced by a short-focus lens covering a wider field? Can a zoom lens be replaced by a series of normal lenses, giving a stepwise variation of magnification? If two lens systems are to be used in succession, how should the overall magnification be divided between them? Is it possible to obtain sharper definition if some unimportant aberration can be neglected?

1.2 THE DESIGN PROCEDURE

A closed mathematical solution for the constructional data of a lens in terms of its desired performance would be much too complex to be a real possibility. The best we can do is to use our knowledge of optics to set up a likely first approach to the desired lens, evaluate it, make judicious changes, reevaluate

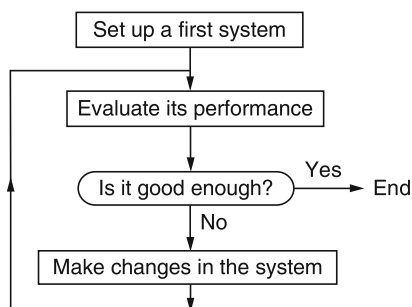


Figure 1.4 Lens design flow chart.

it, and so on. The process may be illustrated by a simple flow chart (Figure 1.4). These four steps will be considered in turn. Throughout this book, a plethora of guidance for design techniques is presented. In Chapter 17, the elements of automatic lens design are discussed along with a brief discussion of the historical evolution of methods of ray tracing and performing optimization.

1.2.1 Sources of a Likely Starting System

In some cases, such as a simple telescope doublet, a lens design can be generated from first principles by a series of logical operations followed in a prescribed order. This is, however, exceptional. Far more often we obtain a likely starting system by one of the following means:

1. A mental guess. This may work well for an experienced designer but it is hopeless for a beginner.
2. A previously designed lens in the company files. This is the most usual procedure in large companies, but most firms not strongly involved in lens development will not have such files.
3. Purchase of a competing lens and analysis of its structure. This is laborious and time-consuming, but it has often been done, especially in small firms with very little backlog of previous designs to choose from.
4. A search through the patent files or of a (commercial) lens design database.

There are literally thousands of lens patents on file, but often the examples given are incomplete or not very well-corrected; such a starting point may require a great deal of work before it is usable, not to mention the necessity of avoiding the claims in the patent itself! A classic book by Cox²² includes an analysis of 300 lens patent examples, which many lens designers have found quite useful. Today, there are tens of thousands of patents on lens designs,

which makes a conventional patent search a rather daunting endeavor. Fortunately there are few databases that can be of significant assistance to the lens designer in looking for a potential starting point.^{23,24}

1.2.2 Lens Evaluation

This is generally performed by tracing a sufficient number of rays through the lens by accurate trigonometrical methods. At first only two or three rays are required, but as the design progresses more rays must be added to provide an adequate evaluation of the system. There are a variety of graphs that can be plotted to represent the various aberrations, and a glance at these will often suggest to the designer what is wrong with the system. In addition to ray error plots, the ray data can be used for a number of purposes including analysis of wavefront error, encircled energy, line scans, optical transfer function, point spread function, and so on (see Section 8.4).

At the time of the first edition of this book, it was unthinkable to be able to perform most of these complex analyses on anything less than a mainframe computer, and then at a nontrivial cost. Today, such analyses can be performed on a laptop costing under a thousand dollars, in a very timely manner, and the cost per run is essentially nil if the costs of the laptop, software license, and annual support are ignored.

1.2.3 Lens Appraisal

It is often very difficult to decide whether or not a given lens system is sufficiently well-corrected for a particular application.²⁵ The usual method is to trace a large number of rays from a point source in a uniformly distributed array over the vignetted entrance pupil of the lens, and then plot a “spot diagram” of the points at which these rays pierce the image plane. It may be necessary to trace several hundred rays before a realistic appearance of the point image is obtained (see Section 8.4). Chromatic errors can be included in the spot diagram by tracing sets of rays in several wavelengths, the spacing of the rays as they enter the lens being adjusted in accordance with the weight to be assigned to that wavelength in the final image.

To interpret the significance of a spot diagram, some designers calculate the diameters of circles containing 10, 20, 30, . . . , 100% of the rays, and thus plot a graph of “encircled energy” at each obliquity. An alternative procedure is to regard the spot diagram as a point spread function, and by means of a Fourier transform convert it into a curve of MTF (modulation transfer function) plotted

against spatial frequency. Such a graph contains very much information both as to the resolving power of the lens and the contrast in the image of coarse objects. Moreover, in calculating the MTF values, diffraction effects can be taken into account, the result being the most comprehensive representation of lens performance that can be obtained. If the lens is then constructed with dimensions agreeing exactly with the design data, it is possible to measure the MTF experimentally and verify that the lens performance has come up to the theoretical expectations.

1.2.4 System Changes

When working by hand or with a small computer, the designer will have to decide what changes he should make to remove the residual aberrations in his lens. This is often a very difficult problem, and in the following chapters many hints are given as to suitable modifications that should be tried even when using a lens design program. Often a designer will make small trial changes in some of the lens parameters and determine the rate of change, or “coefficient,” of each aberration with respect to each change. The solution of a few simultaneous equations will then indicate some reasonable changes that might be tried, although the extreme nonlinearity of all optical systems makes this procedure not as simple as one would like.

Today there are many programs for use on a high-speed computer in which a large number of aberrations are changed simultaneously by varying several lens parameters, using a least-squares technique. In spite of the enormous amount of computation required in this process, it can be performed remarkably cheaply on today’s personal computers (see Chapter 17). A skew ray trace through a spherical surface would take an experienced human computer using a Marchant mechanical calculator about 500 seconds per ray surface (pre-1955). Today, the time has been reduced using a multiprocessor personal computer to about less than 10 ns or about fifty billion times faster!

1.3 OPTICAL MATERIALS

The most common lens material is, of course, optical glass, but crystals and plastics are frequently used, while mirrors can be made of essentially anything that is capable of being polished. Liquid-filled lenses have often been proposed, but for many obvious reasons they were practically never used until recently.^{26,27,28,29} Optical materials in general have been discussed by Kreidl and Rood³⁰ and others.^{31,32}

Automatic Lens Improvement Programs

Many of the methods of lens design outlined in this book were the only procedures available up to about 1956, when electronic computers that had sufficient speed to be used for lens design became available. Many people in several countries then began work on the problem of how to use a high-speed computer, not only to trace sufficient rays to evaluate a system but to make changes in the system so as to improve the image quality. A brief history of this evolution is presented in [Section 17.7](#). It is our purpose in this chapter to indicate how such a computer program is organized and how some “boundary conditions” are handled.^{1,2}

When using this type of program, a starting system is entered into the program, and the computer then proceeds to make changes that will reduce a calculated “merit function” to its lowest possible value. The starting system need not be a particularly good lens, and often a very rough approximation to the desired system can be used. Indeed, some designers have even submitted a set of parallel glass plates to the computer, leaving it up to the program to introduce curved surfaces where necessary. Lenses designed in this way are not likely to be as good as those in which the initial starting system is already fairly well corrected. To gain further knowledge in the use of any of the automatic lens design programs, we suggest that the reader consult the user manual for the program of interest and consult the books cited in [Section 17.8.2](#).

Mastery of the material contained in this treatise can serve the lens designer well by providing a solid foundation of the fundamentals of lens design. Blind use of a lens design program can and has at times provided useful results; however, the resulting design may be difficult to manufacture or align, or it may have marginal performance. Application of lens design fundamentals will almost always result in a preferable design and also provide guidance for the lens designer to control/redirect the optimization path being taken by the lens design program. For example, in Chapter 7 we showed there can be four solutions for a spherically corrected achromat. Which of the solutions is best for a particular

optical system design project will be difficult for almost any lens design program to select because it doesn't "know" there are multiple solutions. The designer can interject his knowledge and assist the program to follow a better path.

Perhaps in the future, knowledge engineering and artificial intelligence will achieve adequate capability that can be integrated with a lens design program to produce acceptable designs from the engineer/designer providing just the desired detailed requirements.³ Even with methodologies to search merit-function space to find the global minimum, the resulting design achieved by one designer may be quite different from that of another designer if they should have, as is often the case, different merit functions. Arguably, the skill, experience, and creativity of the lens designer will be important in lens design for the foreseeable future.

17.1 FINDING A LENS DESIGN SOLUTION

The basic lens design optimization program includes modules for ray tracing, aberration generation, constraints, merit function, and optimization. Programs also include a variety of analysis modules to aid the lens designer in assessing progress other than by the merit function. In this section, we will present a basic understanding of optimization methods, generation of a merit function, and constraints. The lens designer should carefully study the user manual for the lens design and evaluation software being used. A certain commonality in structure, terms, parameters, optimization, and so forth, exists between the various programs, but often subtle and significant differences are present and must be understood by the lens designer for successful utilization.

17.1.1 The Case of as Many Aberrations as There Are Degrees of Freedom

We will consider first the simple case of a lens having the same number of degrees of freedom, N , as there are aberrations to be corrected. By degrees of freedom, or variables, in a lens we refer to the surface curvatures, air spaces, and sometimes lens thicknesses, although thickness changes do not generally help very much.

We first evaluate all the aberrations of our starting system. Next, small experimental changes in each of the N variables are made in turn, and we evaluate the change in each aberration resulting from this small change in each variable. (This procedure was followed in the design of a telephoto lens in Section 14.2.)

To remove all the aberrations we must now solve N equations of the form

$$\begin{aligned}\Delta ab_1 &= \left(\frac{\partial ab_1}{\partial v_1}\right)\Delta v_1 + \left(\frac{\partial ab_1}{\partial v_2}\right)\Delta v_2 + \left(\frac{\partial ab_1}{\partial v_3}\right)\Delta v_3 + \dots \\ \Delta ab_2 &= \left(\frac{\partial ab_2}{\partial v_1}\right)\Delta v_1 + \left(\frac{\partial ab_2}{\partial v_2}\right)\Delta v_2 + \left(\frac{\partial ab_2}{\partial v_3}\right)\Delta v_3 + \dots\end{aligned}$$

where ab represents an aberration and v represents a variable, or degree of freedom, in the lens. There are, of course, N equations in N unknowns, with N^2 coefficients that we must evaluate by making small experimental changes.

Provided the variables have been chosen to be effective in changing the particular aberrations so that the equations are well conditioned, then the N equations can be solved simultaneously. If everything were linear, the solution would tell us how much each variable should be changed to yield the desired changes in the aberrations. Unfortunately, a lens is about as nonlinear as anything in physics, and it will probably happen that at least some of the calculated changes are far too large to be used, and well out of the linear range. Consequently, we take a fraction of the changes, say 20% to 40%, and apply these to the lens parameters. This should yield an improved system, but nowhere near the desired solution. Then we repeat the process, and we must now reevaluate the N^2 coefficients because the changes that we have introduced will alter the path of all the traced rays and hence all the subsequent coefficients. In the next iteration we shall be closer to the solution and the changes will be smaller, so we can take a much larger fraction, say 50% to 80%. After a third iteration we should be so close to the solution that the whole of the calculated changes can be applied. This process can be manually applied, but becomes challenging when N is very large.

17.1.2 The Case of More Aberrations Than Free Variables

Suppose we have M aberrations and only N variables, where M is greater than N . Then our procedure will yield M equations in N unknowns, and a unique solution is impossible. The equations to be solved can be written in simple form:

$$\begin{aligned}y_1 &= a_1x_1 + a_2x_2 + a_3x_3 + \dots \\ y_2 &= b_1x_1 + b_2x_2 + b_3x_3 + \dots \\ &\vdots\end{aligned}$$

where the y are the desired changes in the aberrations and the x are the changes in the variables. The quantities a , b , ... are the coefficients determined by making small experimental changes in the variables.

Although an exact solution is now impossible, we can ascertain a set of changes x that will minimize the sum of the squares of the aberration residuals R , where

$$\begin{aligned} R_1 &= a_1x_1 + a_2x_2 + a_3x_3 + \dots - y_1 \\ R_2 &= b_1x_1 + b_2x_2 + b_3x_3 + \dots - y_2 \end{aligned}$$

Obviously the R s are in the nature of aberrations. Our problem is to find the set of x values that will minimize the sum

$$\phi = R_1^2 + R_2^2 + R_3^2 + \dots$$

there being as many R as there are aberrations and as many x as there are variables. The sum ϕ is called a *merit function*, and our aim is to reduce its value as far as possible.

There are two reasons that we sum the squares of the residuals instead of the residuals themselves. One is that all squares are positive, and of course we do not wish to have one negative aberration compensating some other positive aberration. Another reason is that any large residual will be greatly increased on squaring so that it will receive most of the correcting effort of the program, while a small residual when squared becomes smaller still and is ignored by the program. Eventually all the residuals end up at about the same value and the image of a point source will then be as small as it can become. However, the values of the quantities a , b , $\dots$ can vary many orders of magnitude, which can cause computation problems, and the solution obtained may not actually yield the best image performance achievable for that lens configuration.

17.1.3 What Is an Aberration?

“What is an aberration?” may seem like an odd question to ask, but actually it is rather important to an understanding of the optimization problem. Perhaps a better term for aberration would be *defect*. Throughout this treatise we have discussed many image aberrations and measures of image quality. We could use the conventional aberrations, provided they are all expressed in some comparable terms such as their transverse measure, but this will often be found to be inadequate in achieving an acceptable solution.

Almost always, it is desirable to have significantly more defects than parametric variables, as will be explained in the following section. It has been found useful to trace a number of rays and regard as an aberration the departure of

each ray from its desired location in the image plane. In a like manner, the optical path difference (OPD) for each ray can be computed and used, but it should be recalled that the OPD and transverse ray error are related. The OPD states the departures of the wavefront from the ideal spherical form while the transverse ray error uses the slope of the wavefront, the second being the derivative of the first. One can also use various forms of chromatic errors, differential ray traces,⁴ aberration coefficients, Strehl ratio, *MTF*, encircled energy, and so on, for image defects. Combining the image defects into the merit function must be done with care since the magnitude of the errors can be dramatically different. For example, the Strehl ratio and *MTF* for a well-corrected system are somewhat less than unity while the wavefront error will be a fraction of a wavelength.⁵ To compensate for the numerical disparities of the constituents of the merit function and relative importance to the lens designer, an appropriate weight is assigned to each defect.

17.1.4 Solution of the Equations

For the merit function ϕ to be a mathematical minimum, we must solve a set of equations of the form

$$\frac{\partial \phi}{\partial x_1} = 0, \quad \frac{\partial \phi}{\partial x_2} = 0, \quad \frac{\partial \phi}{\partial x_3} = 0, \dots$$

with there being as many of these equations as there are variables in the lens. Differentiating our expression for ϕ , we get the appropriate set of equations

$$\frac{\partial \phi}{\partial x_i} = 2R_1 \left(\frac{\partial R_1}{\partial x_i} \right) + 2R_2 \left(\frac{\partial R_2}{\partial x_i} \right) + 2R_3 \left(\frac{\partial R_3}{\partial x_i} \right) + \dots = 0$$

for $i = 1, 2, \dots, N$.

Entering the successive derivatives of the R with respect to x_1 for the first equation gives

$$\frac{1}{2} \frac{\partial \phi}{\partial x_1} = (a_1 x_1 + a_2 x_2 + a_3 x_3 + \dots) a_1 + (b_1 x_1 + b_2 x_2 + \dots) b_1 + \dots = 0$$

or

$$x_1(a_1^2 + b_1^2 + \dots) + x_2(a_1 a_2 + b_1 b_2 + \dots) + \dots - (a_1 y_1 + b_1 y_2 + \dots) = 0$$

Carrying out this differentiation in turn for each of the N variables, we obtain the so-called normal equations. They are simultaneous linear equations and have a unique solution. This is the well-known least-squares procedure invented by Legendre in 1805.