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Introduction

Motivation and Outline

This book is the first volume of a series of books about lens design. The overall outline of this series is:

Vol 1: Optical System Properties
  Introduction to the basic technical terms of optical systems.
Vol 2: Aberration Theory
  Development of aberration theoretical fundamentals for a better understanding of correction schemes and methods.
Vol 3: Correction Strategy
  Description of the major approaches, rules and methods to lay out, optimize and correct optical imaging systems.
Vol 4: Selected Applications
  Demonstration of how existing and well-known optical systems are developed from the basis of knowledge from volumes 1–4.
Vol 5: Tutorials and Case Studies
  In this last volume a large variety of practical tasks and examples is fully worked out to demonstrate to the reader how to practice the theory

Throughout this series, considerations are restricted more or less to imaging systems. Illumination systems, as the second large category, follow different rules and are not handled here.

In this first volume, the required basic knowledge for lens design is presented. This includes consideration of material parameters, geometrical optics, the technology of simple optical components as well as consideration of compound systems. Furthermore, the basic physics of diffraction theory is presented in scope: how it is useful for lens design. As special important representations to assess the quality of systems including diffraction effects, the point spread function as well as the optical transfer function are discussed in more detail. Finally, some more marginal topics are presented: Gaussian beams as simple representatives of wave optical light fields with an important relation to the modelling of laser light sources; photometry as one relevant consideration of the energetic evaluation of optical imaging systems; the phase space as a very helpful representation of ray as well as wave optics for better understanding their relationship. Last but not least, a chapter is devoted to digital methods in the computation of quasi-realistic images, the properties of a modern digital image acquisition as well as the digital image postprocessing, which nowadays plays an important role in modern systems.

There are many books about aberration theory and optical design [1–33]. This therefore raises the question: why do we need another? I am convinced that a competent working designer needs a deep understanding of aberration theory and huge, concrete practical experience. Therefore, beneath the description of the methods to correct a system, a comprehensive and clear presentation of aberrations is necessary and an application and training related element is required to demonstrate the realization and application of all the theory and methods. In my understanding, there are currently two types of books available: the first is mostly written by colleagues in academia, theory and mathematical treatment is in the foreground and the practical applications are a less pronounced discussion. On the other hand, there are some books that deal with the practical realization without any theoretical foundation. A book that combines both and collects the knowledge more comprehensively appears to be missing. This is the reason why I am convinced that one more book makes sense and helps the community and, in particular, younger colleagues to learn this fascinating profession with a considerable scientific

(Continued)

Lens Design for Imaging: Fundamentals of Optical Systems, First Edition. Herbert Gross.

Motivation and Outline (Continued)

systematic background. No book and nobody is perfect, but owing to a long history dealing with this topic, from applications in industry as well as from an educational position, I believe I know both worlds and will try to combine them as well as possible. Furthermore, it is well known that optical design is an interdisciplinary field between mathematics, physics and engineering. Therefore, a breadth of knowledge is necessary to work successfully. As one option to make learning easier, I always try to visualize as many aspects and information in graphical form as possible. I am sure that this helps a lot and it is one of the main features of this book series.

Rigorous mathematical strictness is not the goal of this book. With the practical approach it is much more important to gain an understanding to be able to bridge to applications. In Chapter 12, as a mathematical appendix, some more details are explained. It seems more meaningful to avoid this in the running text about optics.

There are several sections that are indicated with an asterisk and a short comment. These are topics that are more specialized and I recommend beginners skip them in the first reading. It should be possible to understand the later chapters without knowing these advanced elements.

One dilemma in this first volume was the fact that many visualizations and explanations require certain knowledge about aberrations. Aberrations are explained in detail in the second volume. Nevertheless, I think it makes sense to use these examples. I have tried to refer to the corresponding later chapters and detailed discussions. But, I know, forward referencing is not a good style. I hope the reader forgives me these inconsistencies in didactic sequence.

Of course, it's impossible to write and work out everything fully alone. There are many colleagues I have to acknowledge here for their endless help and support. I have tried to reference every source and figure accurately, but this is sometimes complicated. Therefore, I beg the pardon of anybody who I haven't dignified correspondingly.

1.1 Modelling and Goal of Lens Design

In general, there are two types of calculation scheme and aim in the simulation of optical systems. If the data and parameters of a system are given, a goal can be to analyse the setup, to calculate the functionality and to evaluate the system performance. This is a direct calculation and is quite straightforward. In this task less creativity is needed.

If a specification is known, which is needed for a special application, the question becomes what kind of system fulfils these requirements – and an inverse problem must be solved. In this case, classical optical design work has to be done to find – through experience or creative thinking – which type of system is able to achieve the request taking certain constraints into account. This second task is much more complicated, often not straightforward and sometimes unsolvable. The corresponding scheme is visualized in Figure 1.1.

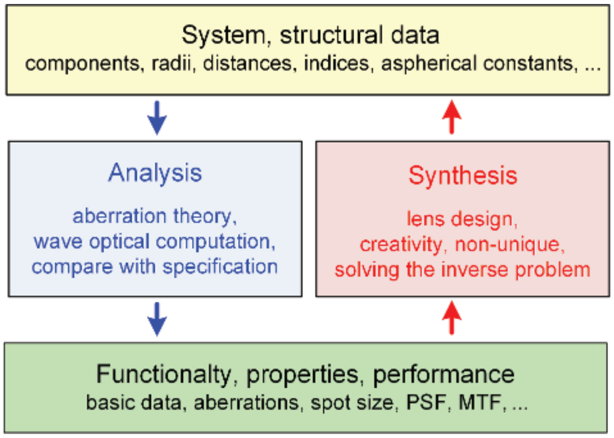

Figure 1.1 Calculation goals for optical system calculations [34].

From the physical point of view, there are several levels of modelling depth used to describe an optical system. On the one hand, a calculation should be fast, effective and accurate. Usually, a more accurate result is needed for deeper physical approaches with fewer approximations. In any case, a decision about a selected model for a specific task must make sure that the investigated effects and results are covered by the approach while, conversely, the computational burden is as small as possible. Figure 1.2 shows certain levels of approximations. Depending on the effects taken into account and the accuracy of the model predictions required, the physical model can be simplified through several approximation steps. Typically, this reduces the computational effort. Furthermore, the simplifications often allow for analytical formulation of solutions, which give much more insight into the dependencies and physical principles.

One of the important questions in simulation or design task reality is: what kind of modelling level is necessary to achieve the necessary accuracy, while keeping the calculation fast and robust.

Optical systems are usually designed, optimized and simulated by raytrace. This kind of approximation level is well established, fast and takes aberrations into account. For the

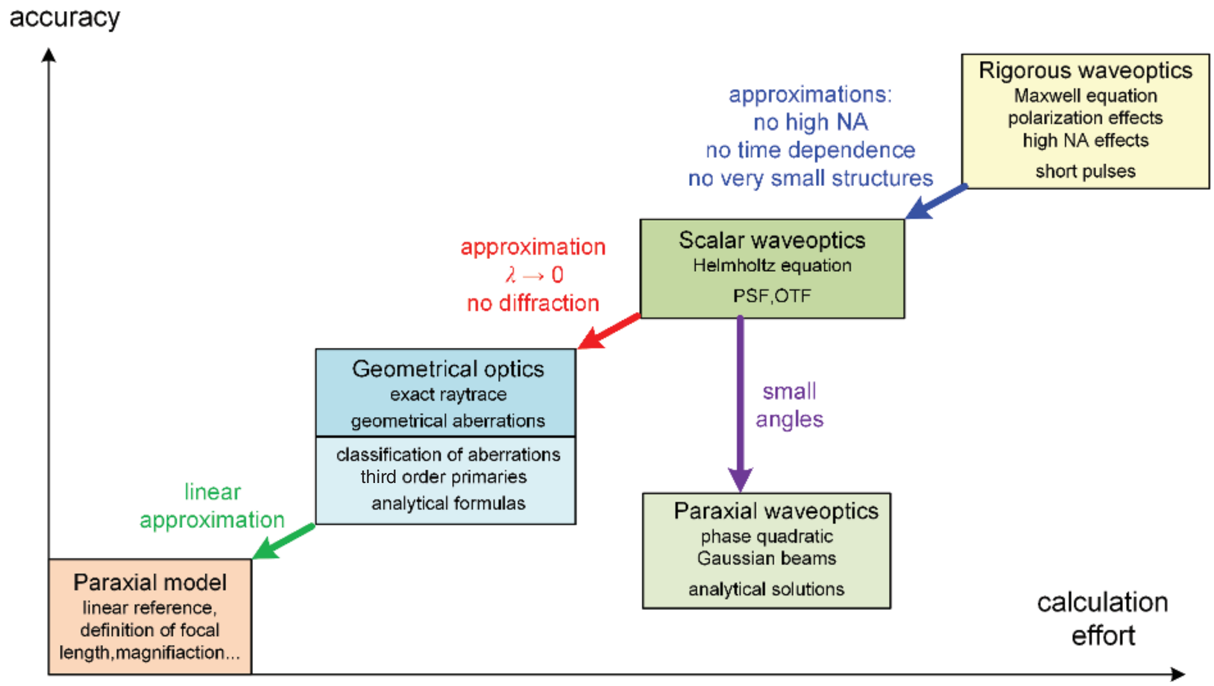

Figure 1.2 Trade-off between calculation effort and accuracy.

majority of systems, this is an acceptable accuracy. In later design phases, if the system is already near the final performance, diffraction related criteria – like the point spread function or optical transfer function – can be included. But the start of calculation with a raw quality is mainly through raytrace. For this purpose, a simple mathematical model is required to describe the essential properties of the system parameters appropriate for this calculation scheme. These include the following.

- Interface surfaces:
  - mathematical modelled surfaces;
  - planes, spheres, aspheres, conics, free shaped surfaces.
- Size of components:
  - thickness and distances along the axis;
  - transversal size, circular diameter, complicated contours.
- Geometry of the setup:
  - special case: rotational symmetry;
  - general case: three-dimensional, tilt angles, offsets and decentrations.
- Materials:
  - refractive indices for all used wavelengths;
  - other properties: absorption, birefringence, non-linear coefficients, index gradients.
- Special surfaces:
  - gratings, diffractive elements;
  - arrays, scattering surfaces.

These data are part of typical system data or the archive files of commercial design software tools. For a concrete reproduction of a calculation, the light data used must additionally be given. These are the wavelengths, the aperture and field size data together with their discrete sampling values and the definition of these properties being used. Furthermore, it can be necessary to fix some more specific cases – like afocal image location, pupil position and telecentricity or vignetting factors – explicitly.

1.2 Optical System Types and Aperture Field Classification

Figures 1.3, 1.7 and 1.10 show some examples as well as the systematic sorting of some special classes of optical systems. These figures should give some idea about the variability and the complexity of real systems. Figure 1.3 is only a small collection of some system types for illustration. Shown are some system types in a diagram indicating the numerical aperture (NA) and the field of view (FoV).

There is a large variety of different optical system types and a long history of developments. To get an overview and a defined structure it makes sense to sort the systems according to their basic properties and characteristic numbers. Since field of view and numerical aperture are very important terms to characterize the imaging capabilities of a system, a diagram with these two properties has been

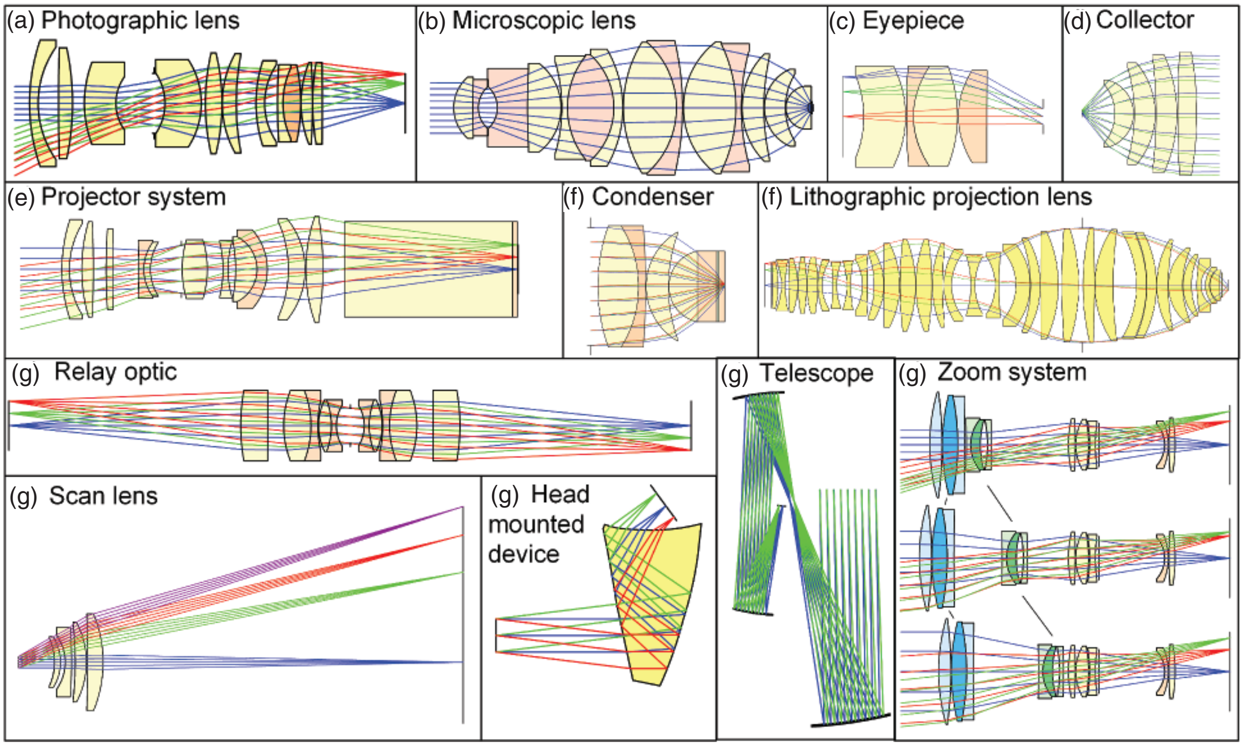

Figure 1.3 Sample systems.

proposed by W. Smith [13]. An example of this diagram is shown in Figure 1.4. For the purpose of comparability, the field angle is used to describe the field of view (FoV) and it is scaled in degree. For telecentric systems, the field is rescaled from the finite field height.

Both properties are essential to describe the imaging options of an optical system. The product of both numbers corresponds to the Lagrange invariant – this is also called etendue or space-bandwidth product. It fixes the complexity of a system and normalizes on the wavelength scales quantitatively the possible information transport capacity. This is discussed and explained in the Chapters 3 and 10 in detail. Therefore, hyperbolic curves describe constant invariants and from practical experience it is known that approximately the same number of lenses is needed for an appropriate correction. Microscopic lenses (large NA, small FoV) and photographic camera lenses (small NA, large FoV) are comparable and roughly contain the same number of lenses. The only exceptions are extremely large apertures (for example in microscopic lenses) or ultra-wide angle fields (fisheye camera lenses); here, the occurrence of many higher orders requires many more lenses.

According to hyperbolic behaviour, systems closer to the origin are easier to correct and simpler in their layout. If a system is placed in the right area, the aperture correction is dominant; spherical aberration correction and marginal ray incidences are most important. In the wide-angle photographic systems, on the other hand, the incidence angles of the chief rays are most prominent and the field-related aberrations are hard to correct. Today's lithographic system has both high field and high NA and they are located in the diagram at an upper right position: the prices are correspondingly high.

It should be mentioned that, in the case of microscopic lenses as well as lithographic projection lenses, field sizes are kept constant due to the application requirements. In particular, for telescopes and EUV lithographic lenses, the field angle is more complicated in reality because the field is arc-shaped and shows certain obscuration effects. Furthermore, the coloured, shaded areas are only raw estimations of the system classes; there is often a huge variety of possible solutions and tradeoffs between field size, aperture and quality. The dots indicate one special realization and are representative, but not unique.

But some aspects are neglected in the classical Smith diagram.

- Spectral range (see Chapter 2): The correction effort for a broadband chromatical correction is higher than for a monochromatic system. Therefore, in reality, one more dimension of complexity is given by $\Delta\lambda$.

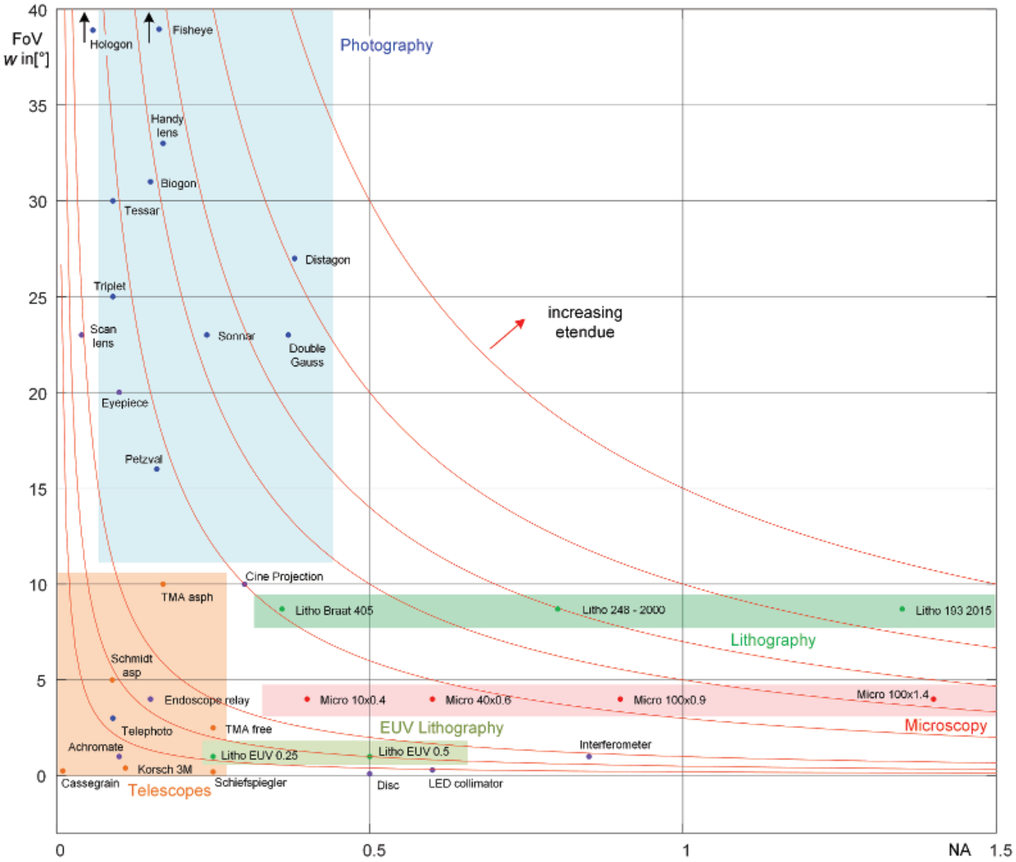

Figure 1.4 Field-aperture diagram according to W. Smith, the red hyperbolic lines indicate a changing etendue value.

- Performance: In principle, the area ranges of the diagram should correspond to the same quality or correction result. But in reality, lithographic lenses, for example, are much better in wavefront correction than usual systems, microscopic lenses are better than photographic lenses and so on. A direct comparison is not trivial.
- The effort of correction also strongly depends on the size, allowed transmission, vignetting and more. Therefore, in the case of an astronomical system with a few mirrors, the comparison of the etendue makes only limited sense; the fabrication complexity is not simply to linear scale with the size. More details are given on this point in Volume 3.
- Dimension: it should furthermore be kept in mind that the systems are working in three dimensions. The simple product of aperture and field is only a one-dimensional simplification and the real energy conservation and information capacity is calculated from the square of this product.
- Definition of FoV and invariant L (see Chapter 3): One additional aspect is the exact definition of the field size. In the original proposal of W. Smith, photographic lenses are mainly considered. These assume the object in infinity and the numerical aperture is measured in the image domain while the field is scaled as an angle in the object domain. This simple definition cannot be taken for finite-finite relay systems or for full afocal systems. Therefore, when comparing systems, this definition should be used carefully.

These facets mean that the diagram is quite useful to classify and compare optical systems, but many special features and a more quantitative evaluation become critical and should be done with care.

Figure 1.5 shows an exemplary diagram, where the one-dimensional etendue is applied as the horizontal axis as only one variable and the wavelength range of the application as the vertical axis. Now it is much easier to see that lithographic lenses have a huge $L^{(1D)}$, but only a small spectral request. The same is true for interferometer lenses, simple scan laser scan lenses and more. The problem of not truly comparing the same quality of correction is still present.

To better visualize this spectral third dimension of correction complexity, in Figure 1.6 the diagram is shown

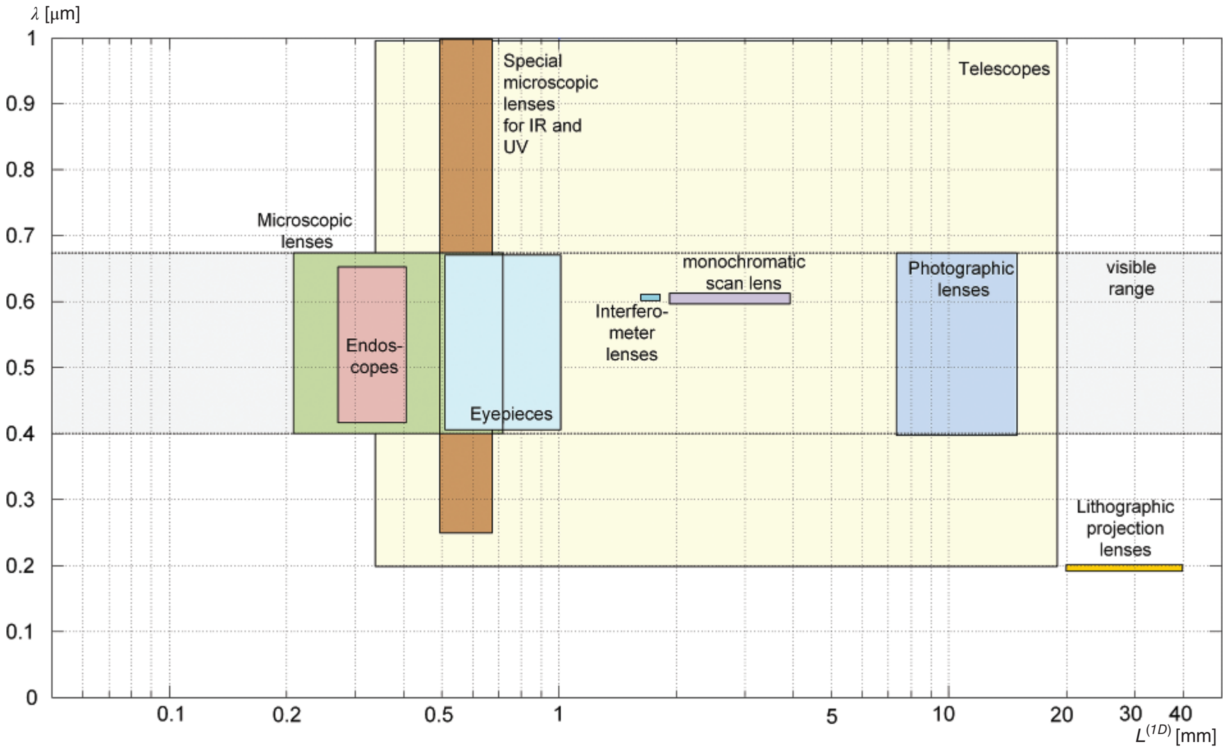

Figure 1.5 Impact of spectral bandwidth correction.

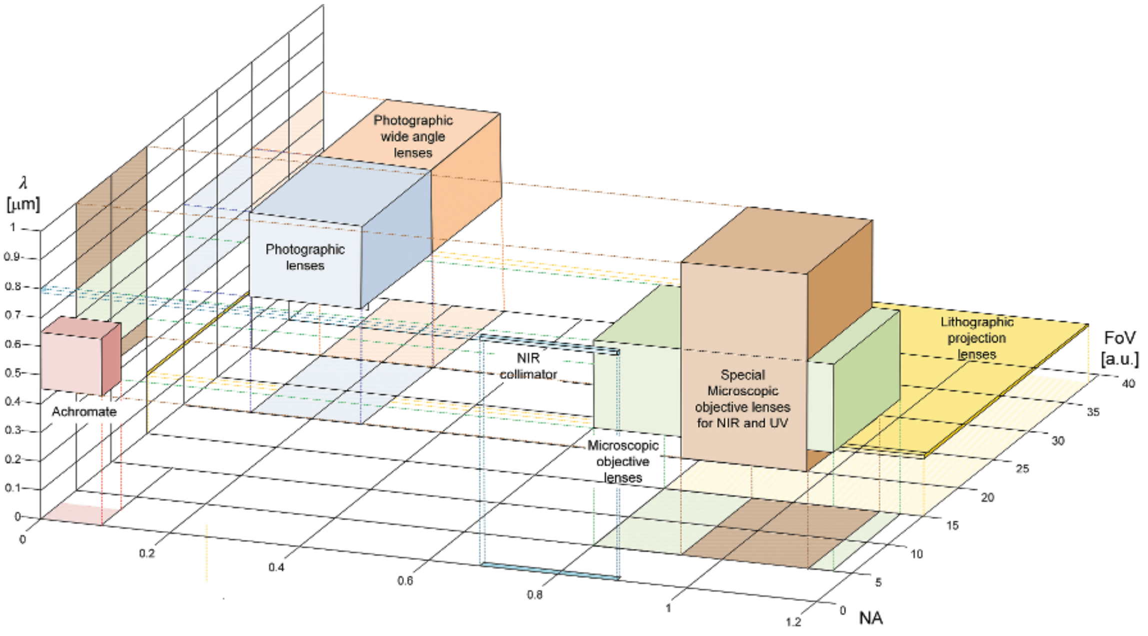

Figure 1.6 Smith's diagram extended by the spectral dimension: the boxes are only raw and schematic.

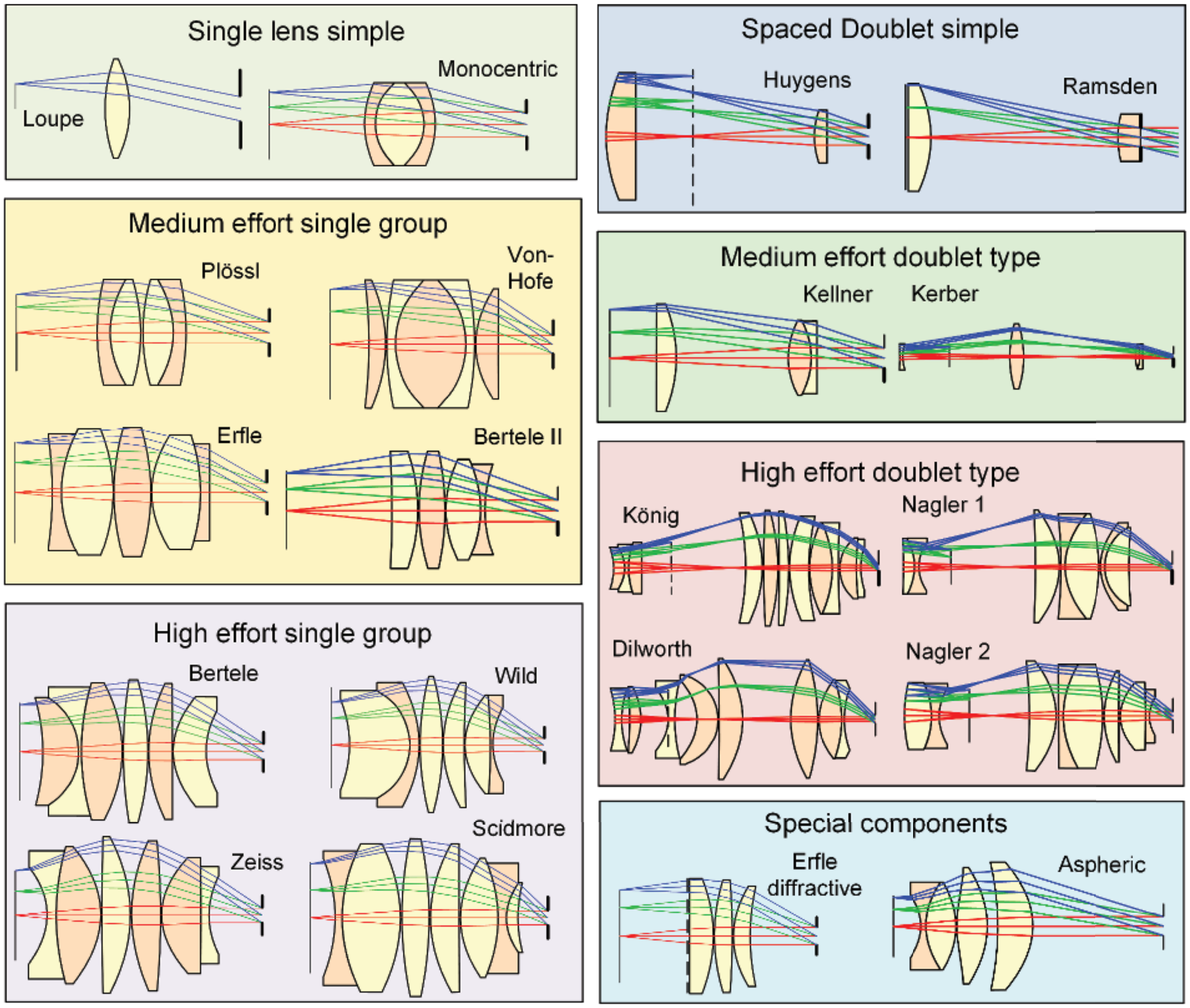

Figure 1.7 Families of eyepiece [35] / with permission of John Wiley & Sons.

in perspective three dimension. For reasons of clarity, only a few system types are included, but it can be seen that, in principle, the volume of the bricks, not just the area in one dimension, is relevant for the correction. This finally shows that the Smith diagram is quite useful for comparisons, but on more detailed examination, some aspects are not considered.

1.2.1 Selected Classes of Systems

In this section, for some examples of system classes the historical development of setups together with the general trend to improve the performance by increasing the number of lenses will be illustrated. These collections and ordering schemes are not fully discussed here; for this, more prior knowledge is required, which cannot be expected in the first chapter of a book. But these figures should give an idea of historical development and the variability of possible solutions. These charts are definitely not complete and different arrangements are possible.

Figure 1.7 shows types of eyepiece with different qualities and complexities. Here, the left column represents the solutions, which come from the one-group approach; the second column on the right side how the results, improve the basic two-lens solution of Huygens with virtual, and Kellner with real, image location.

Figure 1.8 illustrates the families of camera lenses. This very old field has developed over a long period of time. More recent results using aspherical lenses and special new types of glasses, plus the change in detectors from film and photoplates to charge-coupled devices (CCD), deliver different solutions. The main difference is the symmetry of the systems. The larger the field, the more a symmetrical approach helps. Fisheye lenses can be realized only in an asymmetrical setup.

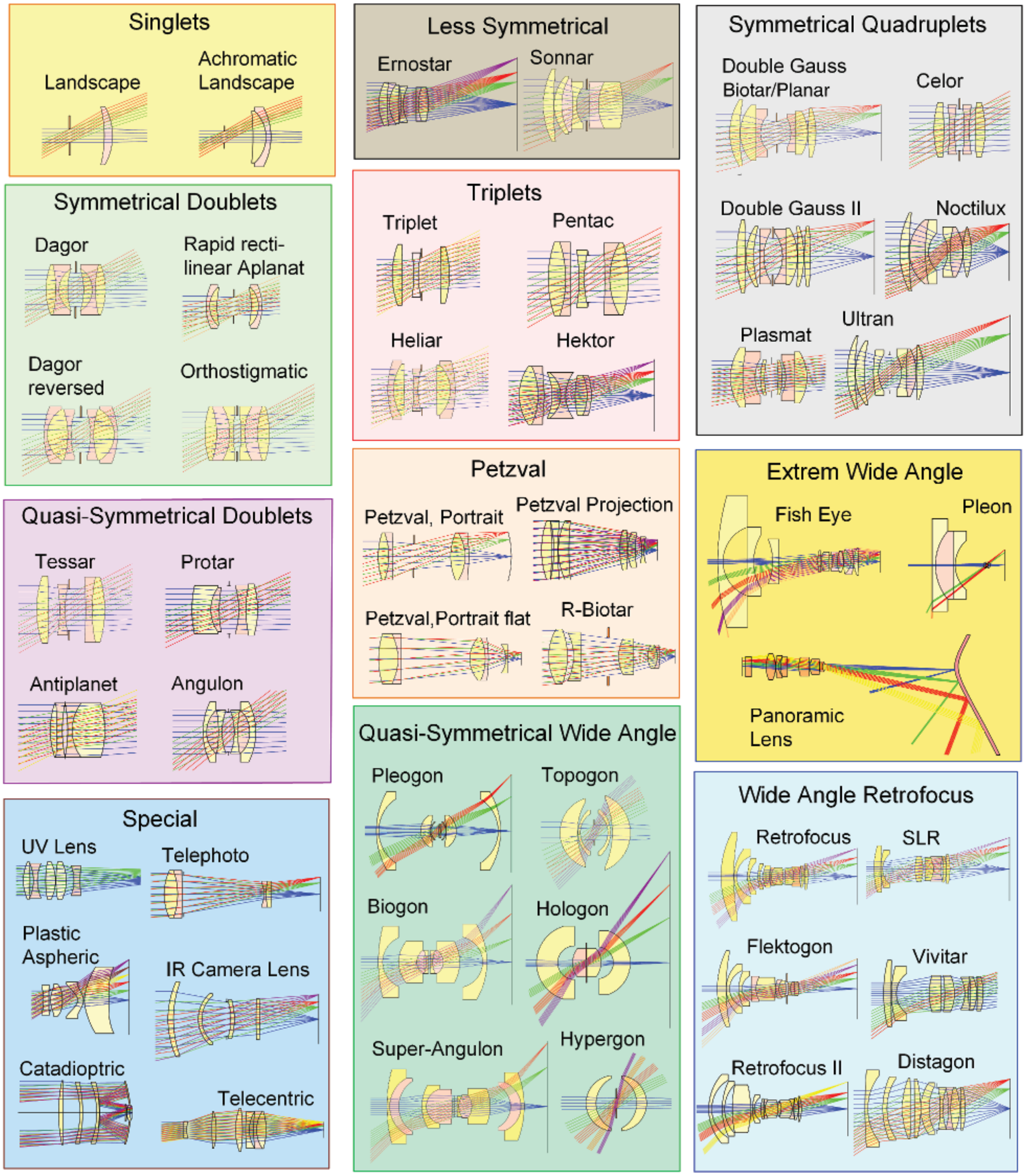

Figure 1.8 Families of photographic lenses.

Figure 1.9 illustrates the development of modern microscope objective lenses for the case of low, medium and high NA with several special aspects. This data basis is extracted from an analysis of 500 patents [36–38]. Most of them come from the four vendors: Olympus, Zeiss, Leica and Nikon. Layouts are typical in every company and correspond to their needs and experiences. The chart should give an idea of the huge variety of possible solutions.

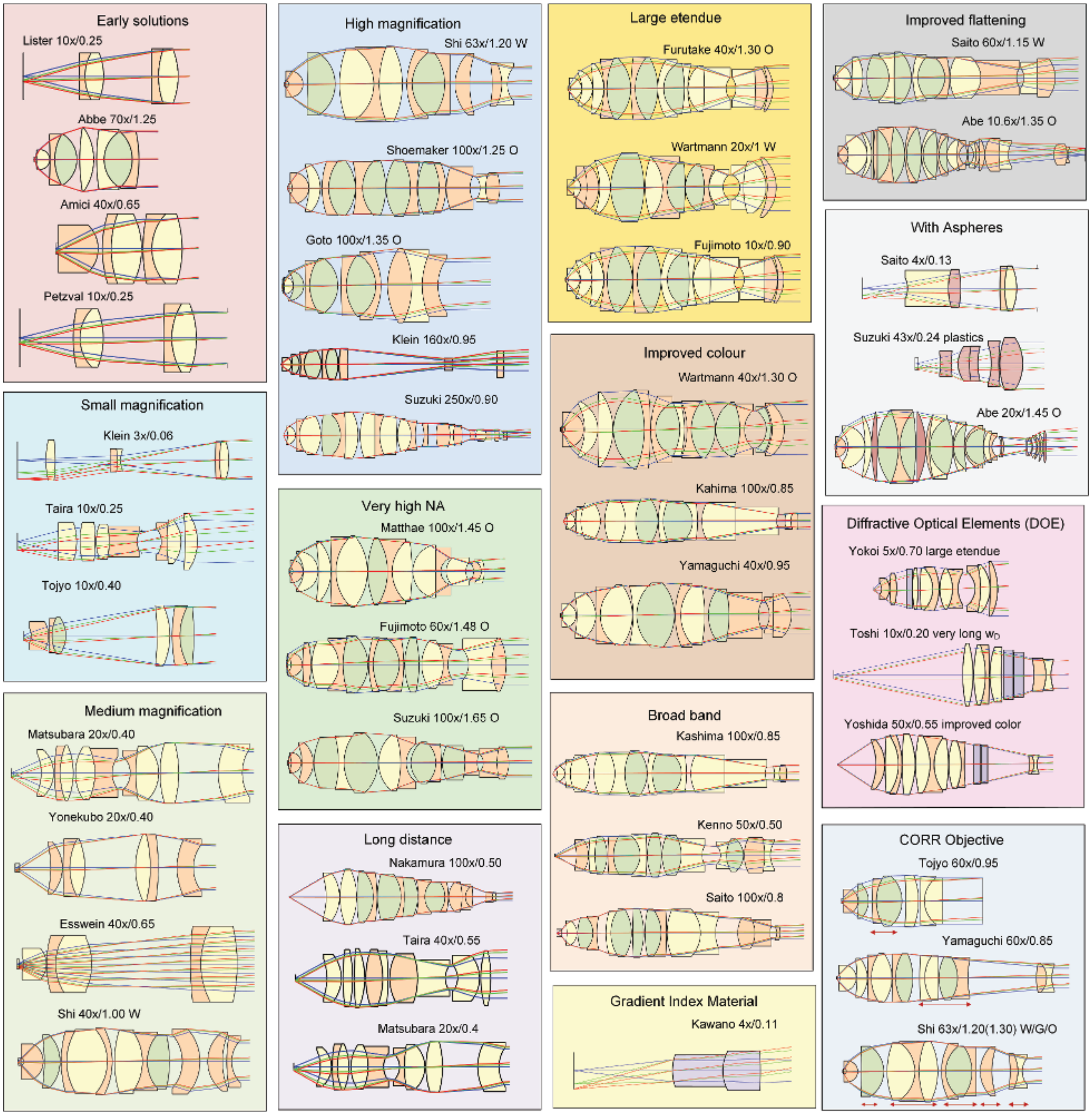

Figure 1.9 Microscopic objective lens types, this overview is far from complete [36–38].

Figure 1.10 illustrates the families of lithographic projection lenses for refractive, catadioptric and fully reflective systems. In the early days, glasses were used, the wavelength was in the visible, no telecentricity was forced, field of view and numerical aperture were moderate in size. Later, the number of waists to correct for field flatness were increased, and then aspheres were used. In the next phase of development, immersion was used to increase the NA and mirrors were used to flatten the field. In the extreme ultraviolet (EUV) mirror solution for lithography, due to the short wavelength of 13.5 nm (soft x-ray), only mirrors can be used. They are used here in nearly normal incidence; therefore, complicated dielectric coatings are necessary to achieve an acceptable throughput.

The overview tables shown here are only examples. They are selective and the list is not complete.

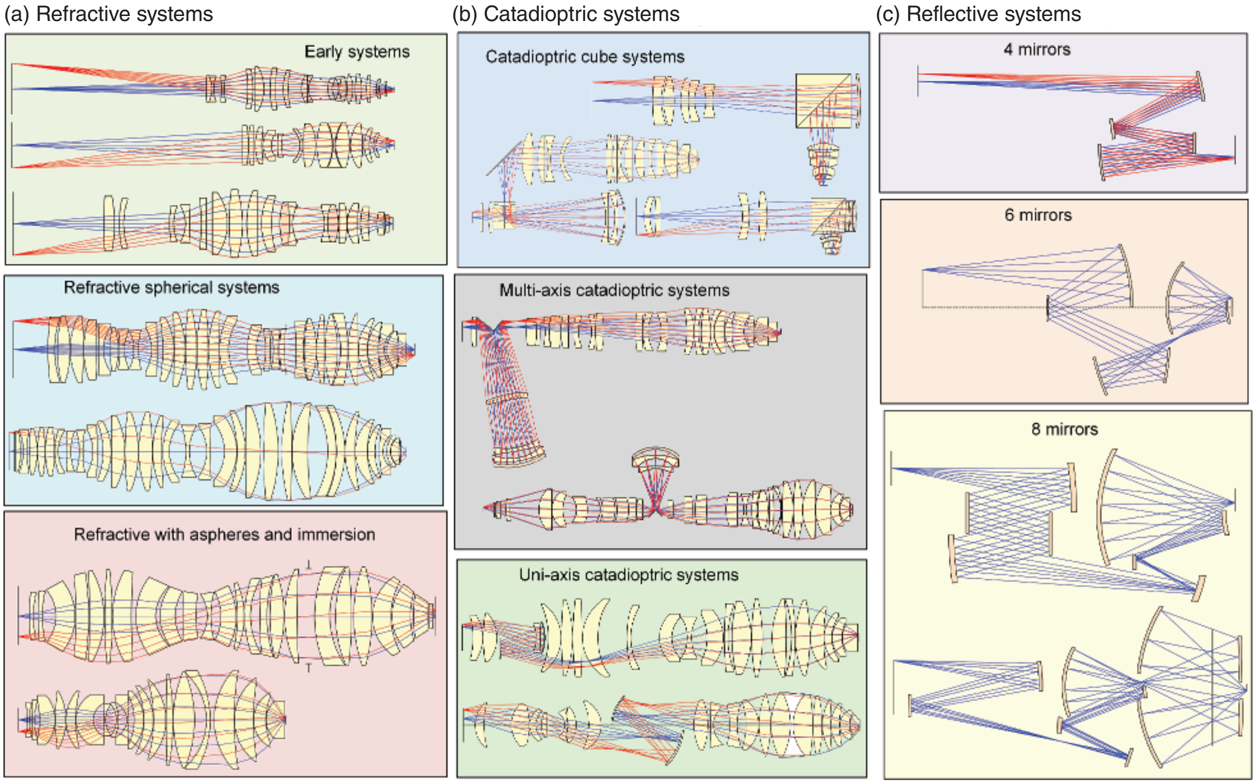

Figure 1.10 Lithographic projection lenses with lenses and mirrors for ultraviolet (UV), deep ultraviolet (DUV) and extreme ultraviolet (EUV) wavelengths, (a) shows purely refractive systems, (b) catadioptric and (c) purely reflective systems.

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