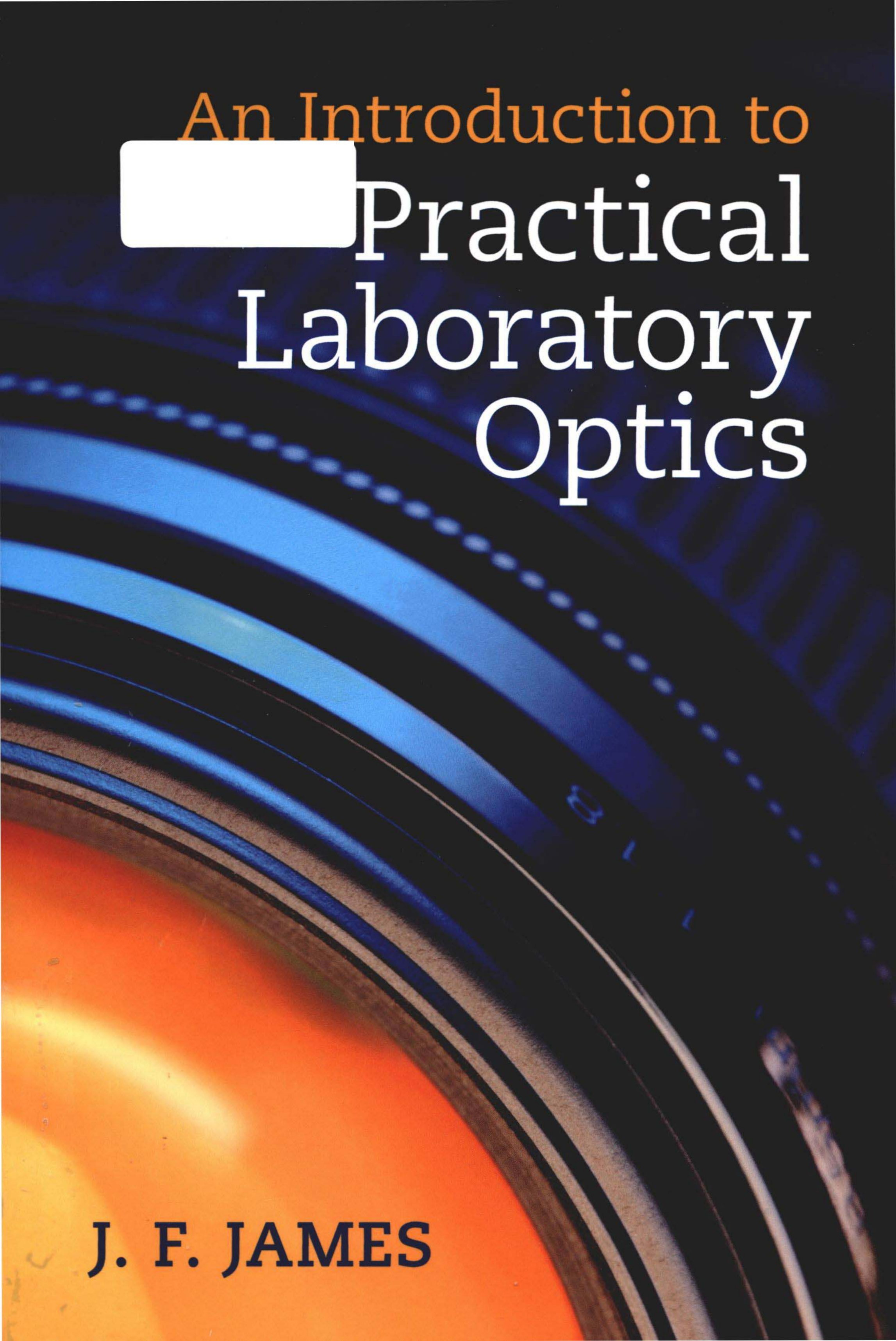

An Introduction to Practical Laboratory Optics

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An Introduction to Practical Laboratory Optics

Aimed at laboratory workers and students taking laboratory courses in experimental optics, this book introduces readers to optical instruments and their uses.

The book explains the basic operation of lenses, mirrors, telescopes in the laboratory and under field conditions, how to use optical instruments to their maximum potential and how to keep them in working order. It gives an account of the laws of geometrical optics which govern the design, layout and working of optical instruments. The book describes the interactions of polarized light with matter and the instruments and devices derived from this, and discusses the choice of spectrometers and detectors for various spectral regions, with particular attention to CCD cameras.

The emphasis throughout is on description, with mathematical precision confined to the appendices, which explain the ray transfer matrix and outline the Seidel theory of optical aberrations. The appendices also introduce Fourier methods in optics and Fourier transform infra-red spectrometry.

J. F. JAMES has held teaching positions at The Queen's University, Belfast, and the University of Manchester, and is one of the pioneers of Fourier spectroscopy. He is the author of *A Student's Guide to Fourier Transforms*, now in its third edition, and *Spectrograph Design Fundamentals* (Cambridge University Press, 2011 and 2007 respectively).

Preface

The most famous and illustrious mis-user of an optical instrument is Sherlock Holmes. There is an iconic figure of him with Inverness cape, deerstalker hat and calabash pipe, peering though a magnifying glass, the latter held at arm's length, to inspect a possible blood stain.

This is the wrong way to use a magnifying glass – which incidentally should always have a plano-convex lens rather than the biconvex lens with which many cheap versions are provided. The glass should be held close to the eye, plane side facing, and the object brought in until it is in clear focus at a comfortable distance for viewing. This gives the clearest image, the widest field and the minimum of optical aberrations. It is the attention to small detail like this which helps ensure success. Watchmakers do it properly, with a *loupe*, a lens held, like a monocle, in the eye socket.

In experimental science, especially in physics laboratories, it is sometimes found, when beginning a new piece of basic research, that no appropriate apparatus exists and that it is necessary to improvise. The traditional laboratory stand-and-clamp then comes into its own, followed, after some experimentation, by a properly designed system with an optical bench or table with lenses, mirrors and other basic optical elements for measuring and analysing radiation. Skills in the design and assembly of such provisional devices are part of the true experimenter's art.

In any field of science, a large part of experimentation involves light, be it photography, photometry, polarimetry, microscopy or spectroscopy, and the proper selection and application of optical elements and devices may have a great effect on the satisfactory outcome of experimental work. Much can be done with standard, versatile 'common-user' instruments such as cameras and microscopes, but all too often there is a particular measurement to be made where apparatus must be designed and constructed before the experiment can be done.

No mention is made here of individual manufacturers of optical equipment. Even famous firms come and go or are swallowed by other, bigger fish. But they advertise in the various scientific journals and their catalogues provide valuable information about their products and much useful background information on optics generally.

What follows here is an account of the basic principles of common optical instruments, the elementary laws of optics affecting them and descriptions of some of the ingenious devices which have been invented over the last few centuries and which are of particular use in the laboratory, in the workshop and in the field. [1]

I make no apology for presenting theorems and useful equations without proof. This is a handbook, not a treatise, and there are many learned works on library shelves which will supply the deficiency if a more thorough explanation is needed. The list of further reading at the end of this book will point the inquirer in the right direction.

Finally, a warning! Geometrical optics is a dangerous subject and I have left it to the end. For most sensible people it is a miserably boring agglomeration of tedious, elementary calculation, arithmetic and geometry, but to others it is an obsession like chess or golf or computer programming. The victim is sucked into a quagmire of invention, ingenuity and improvement, forever trying to achieve the perfect lens or telescope or whatever. The lucky designer is the one who knows when to stop calculating and start building. Yet there is an immense sense of achievement when the last element of the new system is put in its place, the last adjustment is made, and one's final fears evaporate as a clear, sharp image appears in its proper place, just as calculated. This is invention at its most satisfying.

Beppu, Japan
Beppu, Japan, October 2013 J. F. James

[1] 'Field', here, is the usual euphemism for mosquito-ridden swamp or bare, windswept mountain-top where some deranged scientists choose to do their data-gathering.

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Introduction: centred optical systems

1.1 The common properties of optical instruments

Optical instruments come in all shapes and sizes, from fly-on-the-wall surveillance cameras to 10 metre segmented astronomical reflecting telescopes, and in shapes from microscopes to sextants to periscopes to spectrographs to cine-projectors.

Whatever their purpose, they all have two things in common.

(1) They are *image-forming* devices, intended to make a picture, to form an image of a luminous source. The image may be on a cinema screen, on a photographic emulsion, on a CCD surface or on the retina of an eye.

(2) They are, with one important exception, *centred systems*. That is to say they comprise a series of curved surfaces of transparent materials or reflecting materials or both. The centres of curvature of the various elements all lie on a straight line called the *optic axis*. Light passes from the object, through successive elements until it emerges to form an image.

This is a slight over-simplification of course. There are occasional plane reflectors along the path, as in a periscope for example, but these are for convenience rather than for any peculiar optical properties they possess.

1.2 Optical elements

There are four basic optical elements: the lens, the mirror, the diffraction grating and the prism. What follows now concerns the first two of these. The others have chapters of their own.

1.2.1 The lens

Lenses have been known since antiquity. The word lens is the Roman word for a lentil. A lens may be simple as in a magnifying glass or composed of several *elements* as in a telescope or camera, and the word is used indiscriminately. We are concerned for the moment with the simple element, which is a disc of glass with two polished surfaces, one or both of which may be curved. The curved surfaces are usually spherical, although non-spherical surfaces are becoming commonplace at the time of writing.

Its chief properties are (a) its *aperture* and (b) its focal length. The aperture is the diameter of the transparent area. The focal length is the distance from the *vertex*[1] of the lens of the image formed of an object at $-\infty$. If the curvature is concave the focal length is negative and no real image can be formed. Negative lenses are almost invariably part of a more complex lens system which does form a real image.

Lenses may be described as *biconvex*, *plano-convex* or *meniscus*, depending on the direction of curvature of the two surfaces. Two lenses may have the same aperture and focal length, but focal length depends only on the *difference* in the two curvatures, so that two lenses of the same focal length but different front surface curvature may have different image-forming properties. As a simple guide to these image-forming properties, remember that as a general rule refraction should be equally distributed among the various surfaces for a good sharp image. For example, the image quality of a plano-convex lens will depend markedly on which surface faces the object side.

Lenses are traditionally made of glass and much research has gone into making high quality optical glass, free from bubbles, striae[2] and stones (which cause scattering), free from stresses (which cause birefringence) and of high homogeneity (to avoid aberrations). Rare earths such as thorium and lanthanum have been incorporated to achieve high index and low dispersion (both desirable properties), and refractive indices between 1.4 and 1.9 are available (at a price); but polymer materials such as polystyrene and polycarbonates, with refractive indices ~ 1.6, are also available for ordinary optical instruments.

Instruments which consist only of lenses, such as refracting telescopes and microscopes, are called ‘dioptric’ systems; those comprising only mirrors are ‘catoptric’ and when both are used they are ‘catadioptric’. Reflecting telescopes and Cassegrain long-focus camera lenses come into this latter category.

[1] The word is used loosely here. Strictly *surfaces*, not lenses, have vertices, and the vertex is the point where the optic axis meets the surface.

[2] Known as sleaks in the trade.

1.2.2 The mirror

Early mirrors were of bronze. In the seventeenth century alloys were found which were hard enough to be ground and polished like glass, and eventually *speculum metal* was perfected, an alloy of approximately two-thirds copper and one-third tin. With a high polish it reflected about 70% of the incident light. In 1835 Justus von Liebig (1801–1873) of the University of Giessen described a method for precipitating colloidal silver from an ammoniacal solution of silver nitrate[3] and it then became possible to deposit highly reflecting silver surfaces on to polished glass. These surfaces, when newly deposited, had a reflectivity of about 92% but as the industrial revolution expanded they tended to tarnish in the sulphurous atmosphere which developed around coal-burning cities.

With the development of vacuum techniques, evaporation of metals became possible and reflecting surfaces of aluminium were found to be chemically durable and with a reflectivity of about 88%. These were improved further by *overcoating* them with evaporated films of silicon monoxide to give a hard and washable surface finish. Reflectivity improves in the infra-red, and gold surfaces, as well as being chemically durable, show a reflectivity in the region of 99%. In the far ultra-violet aluminium may be overcoated with magnesium fluoride to improve its reflectivity which otherwise falls rapidly as the wavelength shortens.

Mirror surfaces may be plane, spherical, paraboloidal or elliptical, and some current mirror-forming techniques allow various, even more elaborate surfaces to be formed by computer-controlled grinding and polishing, chiefly for large astronomical telecopes.

1.3 Concepts in optical instrument design

Let us consider first some features common to all optical instruments, which we need in order to understand how they work. We begin with the description of light.

1.3.1 Rays of light

First of all is the assumption that light travels in straight lines, *rays*, emitted by an object, passing through various lenses and mirrors and converging finally to form an image on a focal surface: a screen, a photographic plate, a CCD or a retina.

[3] An early version of Tollens' reaction.

This assumption is one of the 'convenient fictions' of physics, useful for describing what happens and for predicting the behaviour of light in instrument design; but the model fails in the end to take account of diffraction and interference in the *minutiae* of image formation. Modern optical design requires the *wave theory* of light propagation to account for the fine detail in an image.

Wave theory supposes that light is an electromagnetic field which propagates outwards from a point source in *wavefronts*, spherical surfaces on which the electric field is a maximum, and which expand outwards at the speed of light. The perpendicular distance between successive wavefronts is the wavelength, measured either in angstrom units (1 Å $= 10^{-10}$ m, roughly the diameter of an atom) or in nanometres (10^{-9} m), the standard SI unit.[4]

A lens or a concave mirror can be used to convert part of these diverging wavefronts into spherically converging wavefronts. In a lens, the process is governed by *refraction*, the speed of light being less in a dense transparent medium than in air.

However, it is easier to describe the process of refraction by connecting an object and its image by a ray, the direction changing at each refracting surface.

1.3.2 Optical ray diagrams

It is a convention, not always observed, that diagrams showing rays passing through optical systems show the optic axis horizontal, and show rays coming from the left, the object side or input side, and leaving the system on the right, the image or output side. The usual Cartesian formalities are observed and lengths measured to the left of the lens – the input side – are considered to be negative and those measured to the right are considered positive.

1.3.3 Refraction and the law of sines

The earliest known exposition of the law governing the refraction of light at a surface was by the mathematician Ibn Sahl (940–1000) of Baghdad in the tenth century. It was rediscovered several times in Europe following the Renaissance and today is known in English-speaking countries as *Snell's law* after Willebrord Snel van Royen (1580–1626) of Leiden. It is also more simply known as the 'law of sines'.

In 1657 Pierre de Fermat (1601–1665) published his *Principle of Least Time*, which asserts that light travels from object to image by that path which takes

[4] Physicists tend to use nanometres, while astronomers cleave to the old angstrom unit. Both units will be found in this book.

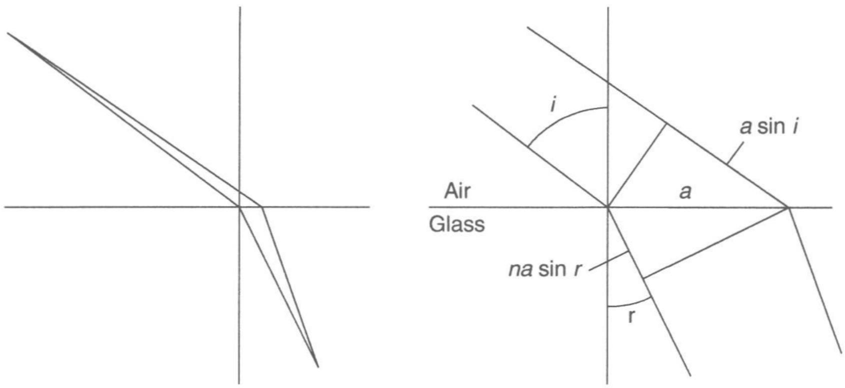

Figure 1.1 The law of sines (Snell's law). When the optical path length is near a minimum, a small change in direction makes no change in the total path length. The small extra path in air is exactly matched by the small diminished path in glass. When the total change is zero, the law of sines follows immediately.

the shortest time. From Fermat's principle it is a simple exercise in differential calculus[5] to derive Snell's law, that the sine of the angle of incidence divided by the sine of the angle of refraction is a constant, the *refractive index*, usually[6] denoted by the letter n:

$$n = \frac{\sin i}{\sin r}$$

The derivation of the 'law of sines' is simple. The small change of *time*, Δt, is given by:

$$\Delta t = a \sin i - n.a \sin r$$

since the speed of light is less in glass by a factor n. At a minimum the change in time is zero, which gives the 'law of sines' immediately.

1.3.4 Optical paths

We occasionally need three different path lengths to describe the passage of light through refracting media.

(1) The *geometrical path*, the path actually laid out on the drawing board.
(2) The *optical path*, the geometrical path multiplied by the refractive index of the medium through which each section of the path the ray is travelling.

[5] And is evidence that Fermat had the idea of the *differential* calculus before Newton and Leibnitz, even though he never made the connection with integration.

[6] But in many older books by the Greek letter μ.

Alternatively (and more accurately), it is the number of wavelengths of light between object and image, multiplied by the vacuum wavelength of the light. All the rays between an object point and its image point must have the same optical path length.

(3) The *reduced path*, the geometrical path *divided* by the refractive index. This is the path length you would measure if you were using a rangefinder to find the apparent distance to an object at the bottom of a swimming pool.

1.3.5 Apertures and stops

The *aperture* of a lens is self-evident. It is the diameter of the transparent part of the lens. The *physical* diameter is a millimetre or two greater than this to allow for 'turn-down' at the circumference in the manufacturing process, and to allow for the 'cell' or retaining device which holds the lens in place.

Stops are opaque screens normal to the optic axis, with circular holes to limit the size of the ray bundle passing through the instrument. They may fulfil several purposes. They may be positioned to control the aberrations of the system, they may be 'anti-glare' stops, used to reduce scattered light from various internal surfaces which would otherwise reduce the contrast of the image and prevent accurate photometry, and if they are variable in diameter as in a camera iris diaphragm, they control the intensity of light forming the final image.

1.3.6 Pupils

There is always one defining stop in an optical instrument, the *iris*. It may simply be the rim of a lens or it may be somewhere inside the sytem, in which case its image, seen through all the elements on the input side, is the *entry pupil* of the system and the corresponding image on the output side is the *exit pupil*. Pupils are not necessarily inside the system. In a telescope for instance, the exit pupil is several millimetres to the right of the last element of the eyepiece: it is where you put your eye-pupil when inspecting a distant object. All the rays of a ray bundle must pass through the pupils of a system.

1.3.7 Relative aperture

This is popularly referred to as 'focal ratio' or 'F-number' and is denoted by F. It is the ratio of the lens focal length to its aperture. As such it is a measure of the intensity of light at an image point and consequently is useful in photography and photometry. It is usually expressed as a fraction of the focal