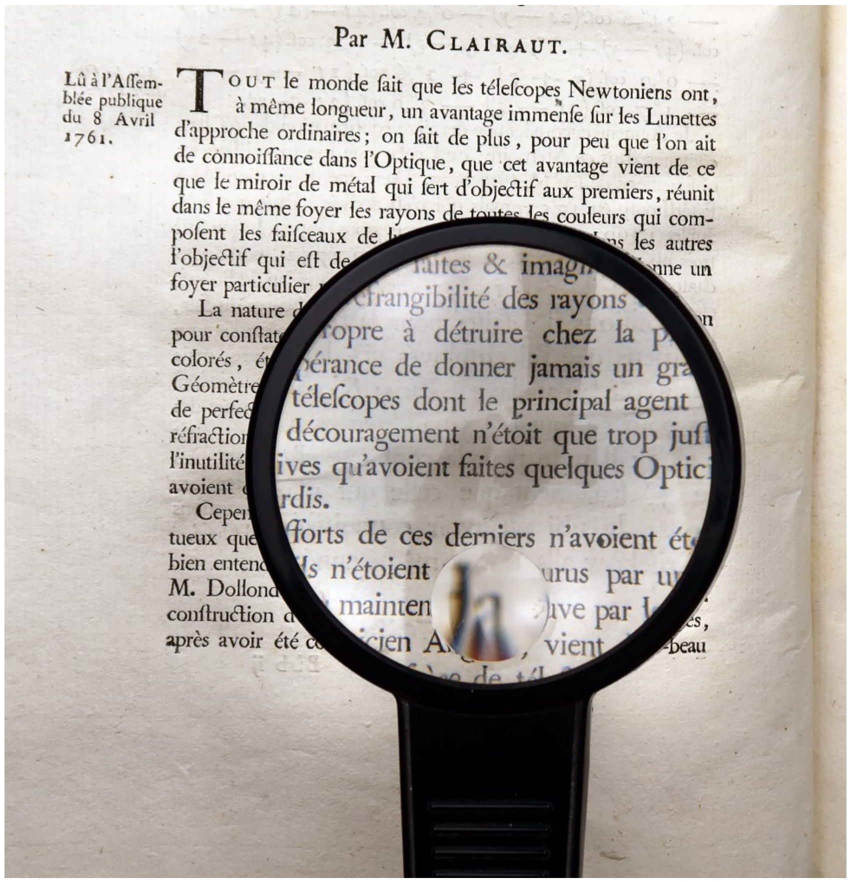
The Lens

A Brief History of Our Understanding of its Function
and Use as Evidenced in Antiquarian Optics Books



Issued from the Bibliotheca Opticoria
To Mark the Festive Season of 2022

A Casual Sunday Afternoon Diversion
Presented to Curious Bibliophiles

The Lens

As with any advanced ubiquitous technology, the lens is now an essential but unobserved part of our lives. Set in frames perched on our nose or floating on a layer of tears on our cornea, lenses overcome blunted sight. Lenses provide revelatory views of the microscopic and the galactic, allowing us to apprehend the vanishingly small and the unimaginably distant. Using lenses, we capture, share, and preserve images. And with lenses, we harness light to be our swiftest messenger.

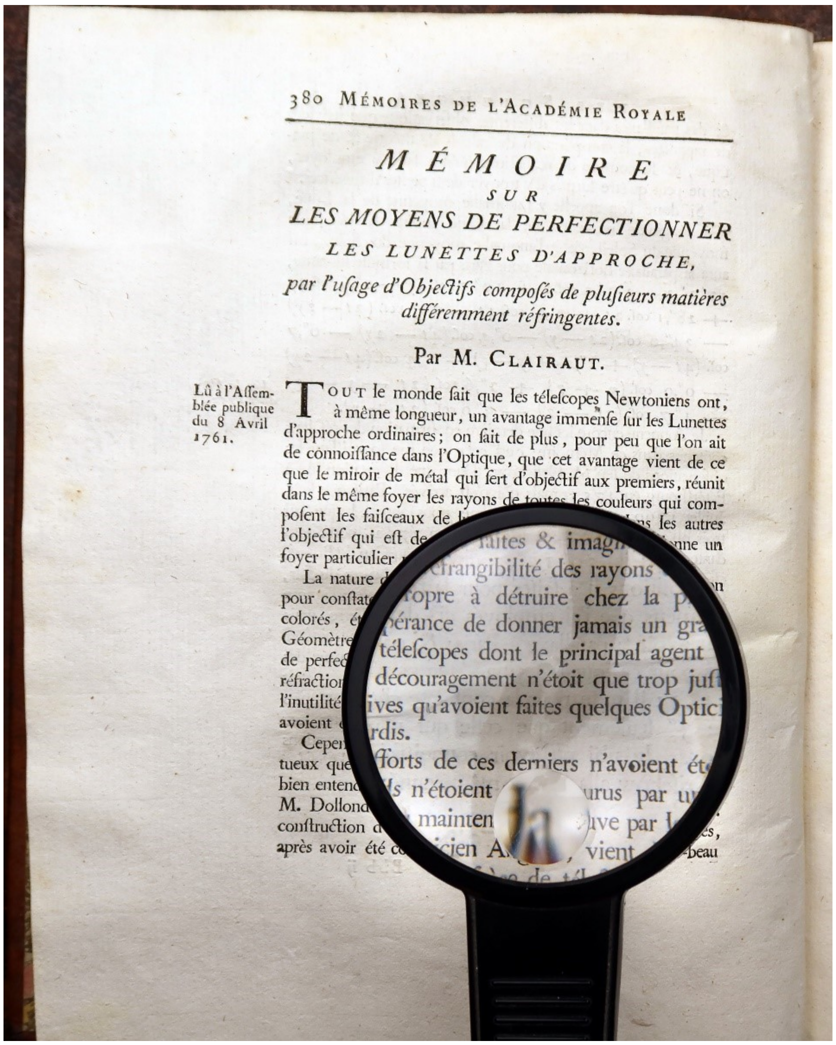


Fig. 1. Alexis Clairaut's memoir of 1762 on constructing lenses that do not exhibit chromatic aberration, viewed through a magnifying glass with two simple biconvex lenses, the smaller more powerful embedded in the larger. At the distances used for this photograph, the magnification is about a factor of two for the large lens and about five for the small lens.

Lenses occur in many visual systems in nature and are among evolution's most elaborate outcomes. In the human eye, lenses produce an inverted, focused image of viewed objects at the back of the eye, where it is encoded into electro-chemical signals sent to the brain. The result is visual perception, recognition, cognition, and behavior. The *optical* part of this sequence begins at the front of the eye with the cornea and ends at the retina at the back.

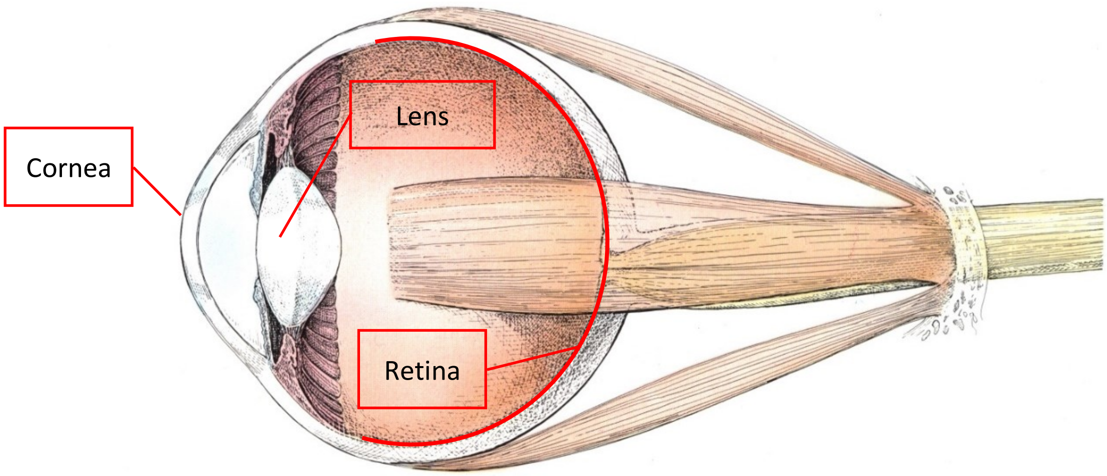


Fig. 2. The principle optical components of the eye. Cornea: transparent bulged part of the outer eye. Lens: transparent, flexible body providing accommodation; that is, focusing. Retina: triple layer of cells for absorbing light and producing electro-chemical signals.

“Focusing” is the fundamental function of lenses. It comes about this way. Light refracts (changes propagation direction) at the interface between media of different densities. Refraction and the shape of the interface can be combined to collect and the change direction of incoming rays. Incoming parallel, or nearly parallel, rays can be brought to a point in front by a convergent lens, or dispersed from an apparent point behind by a divergent lens. The human eye has two types of lenses. (See Figure 3). The Cornea is a positive meniscus and the Lens is a double convex. Interestingly, the Cornea provides most of the focusing power of the eye, while the Lens adds a smaller but variable power.

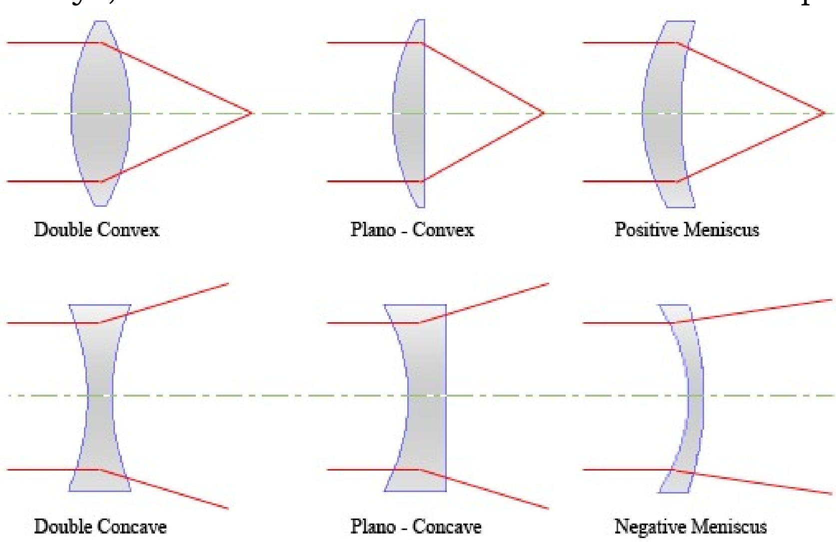


Fig 3. Basic types of simple lenses, showing the light ray paths. Magnifying glasses are usually double convex lenses. Spectacles to correct for farsightedness and presbyopia generally use positive meniscus lenses. Those to correct for nearsightedness generally use negative meniscus lenses.

Focusing power of a lens is expressed in terms of how close to the lens is the focal point it creates – that it, how much it bends the light path. The distance from the lens to the focal point, (focal distance for parallel incoming rays) is measured and the *inverse* of this distance, in meters, expresses the power of the lens in *Diopters*. The stronger the lens, the smaller the focal distance, the greater the inverse, and the larger the resulting Diopter value. Reading spectacles that many of us use have Diopter ratings between 1.5 – 3.0 Diopters. That is, the focal point is between 0.66 and 0.33 meters from the lens. Divergent lenses power is expressed in negative Diopters, since the focal distance is behind the lens.

When the eye is functioning normally, the Cornea and Lens together produce a focused image on the retina at the back of the eye. If the eyeball is too long or too short, a focused image cannot be produced for some visual objects, and vision is blurred. Myopia and Hyperopia, respectively. (See Figure 4.) It is estimated that 15-20% of the human population have these vision limitations to varying degrees.

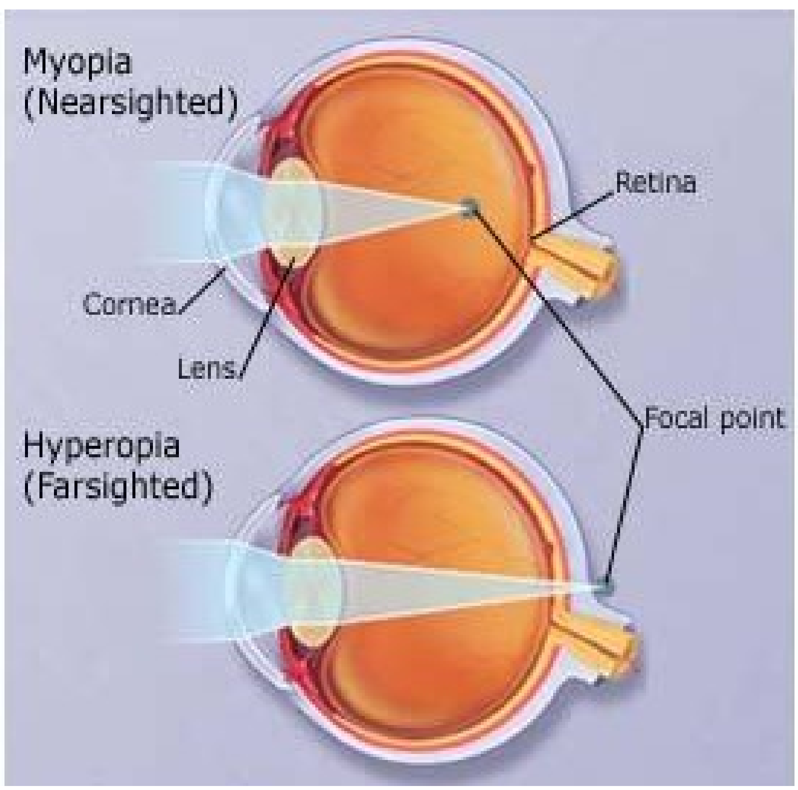
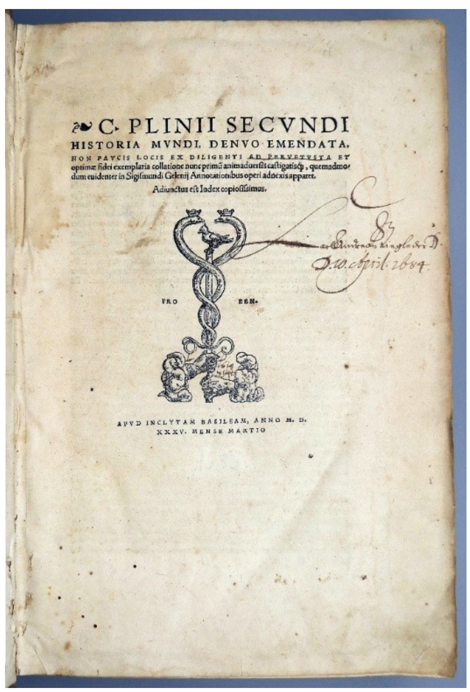


Fig. 4. Unfocused images due to Myopia and Hyperopia. The nearsighted require an object to be close to eye which, given the least focusing power of the cornea/lens, moves the focused image back onto the retina. The farsighted require an object to be far from the eye which, given the maximum focusing power of the cornea/lens, moves the focused forward onto the retina.

Though near- or farsightedness affect some, vision begins to become limited after the age of about 40 years for *all* humans. The Lens begins to lose it flexibility, the combined focusing power of the Cornea/Lens decreases, and for close objects vision is blurred since the focused image is behind the retina. This diminishment continues for about 20 years and is called Presbyopia, farsightedness due to age. The term is from Greek πρέσβυς *presbys* meaning "old" and ὤψ *ōps* meaning "sight."

Pliny's wide-ranging but uncritical assembly of information gathered from many sources and forming an encyclopedia of all knowledge of the ancient world.

It is Presbyopia which, when partially corrected, first showed the power lenses can have to aid vision. This was known to the ancients. In his *Naturalis Historia*, **Pliny the Elder** (23 AD-79 AD) makes the earliest reference to shaped quartz or gems to correct vision and notes the magnifying power of water-filled glass globes.



1535
Gaius Secundus Pliny (Pliny the Elder)
Naturalis Historia
Gaius Pliny the Second, History of the World, Emended anew. Selected from a Collection of not a few Ancient and most Faithful Copies, Corrected and Attended to now for the First Time, in a Manner Apparent from the Annotations of Sigismund Gelenius Attached to the Work. A Copious Index is Attached.

Late edition (First in 1469)
Printed at Basel by Hieronymus Froben, Nicolaus Episcopius, and Johann Herwagen
Format: 2° in 6s
250 x 375 mm
A-C^6 a-z^6 A-Z^6 Aa-Kk^6 aaa-ccc^6 ddd^8 a-g^6 h^8 A-B^8
[36] 1-671 [1] [52], [132]
Binding: Contemporary Blind Stamped Pig Skin Over Wooden Board With Decorations Of Portraits Of Allegorical And Mythological Females, Within An Outer Border Of Medallion Male Portraits.

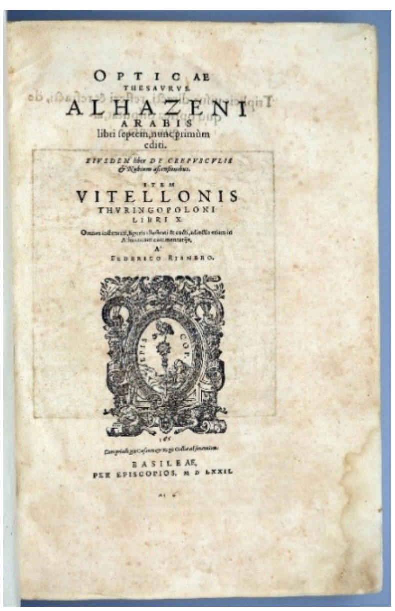
Half-spheres of glass, "reading stones," were known in early Medieval times and in 13th century Northern Italy, these developed into spectacles. From Venice, a center for glass production, spread the craft of making lenses for spectacles. "Almonds of Glass," as they were called, shaped to correct presbyopia, far-sightedness and, later, near-sightedness.

Given the ubiquity of Presbyopia and the general availability of glass lenses, spectacles became common. The craft, and eventually the Guild, was entirely empirically based. With the mistaken ideas of how the optical part of vision worked, and the lack of theoretical knowledge of optics, only experiment demonstrated how lenses could help vision. Mystery though they might have been, lenses were widely known and used.

It was the optical part of vision that **Johannes Kepler** (1571-1630), German mathematician and astronomer, addressed in 1604 in his *Ad Vitellionem Paralipomena, quibus Astronomiae parts Optica Traditur.* “A Supplement to Witelo, in which the Optical part of Astronomy is Propounded.” The reference is to Witelo of Silesia who, in the late 13th century, produced his *Perspectiva*, an elaborate recension of *De Aspectibus*, “On Vision,” which was, in turn, the 12th century Latin translation of the *Kitāb al-Manāẓir*, “The Book of Optics,” an 11th century work by the great Arabic polymath **ibn al-Ḥasan ibn al-Haytham** (965-1040). The third edition of the printed version of Witelo’s work, along with the first printed edition of *De Aspectibus* were both edited by Friedrich Risner (1522-1580). Risner, a German mathematician and student of Petrus Ramus, used Ramus’ manuscripts to produce the *Opticae Thesaurus* of 1572, containing the *De Aspectibus* of “Alhazen” and the *Peri Optikes* of Witelo.

Risner's editing of Witelo's *Perspectiva*, a widely used redaction of *De Aspectibus*, the 13th century Latin translation of the Arabic original ***Kitāb al-Manāẓir***, of Ibn al-Haytham. Prefaced by a significant exposition of necessary mathematics.

Ibn al-Haytham’s work was based, in part, on the optical work of Ptolemy. The *De Aspectibus* is an example of ancient Greek knowledge re-entering the West via Islamic scholarhip and Latin translation.



1572
“Alhazen”
Opticæ thesaurus

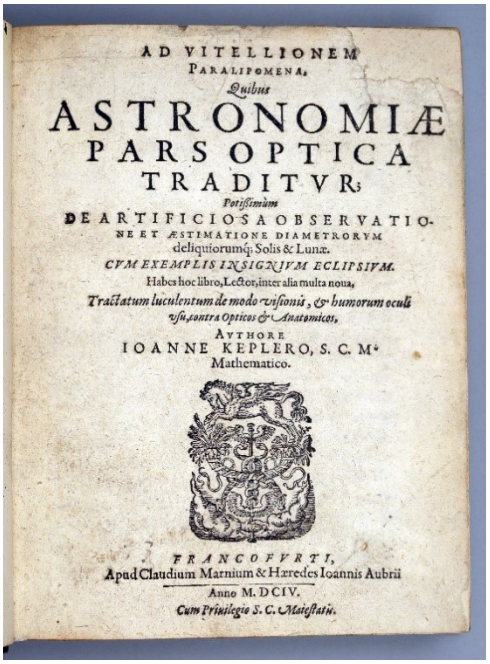
A Treasury of Optics. The Seven Books of Alhazen of Arabia, now Edited for the First Time. By the Same Author: A book on Twilight and the Height of Clouds. Also, Ten books of Vitelo of Thuringopolis. All restored, Augmented and Illustrated with Figures, and Augmented with Commentary on Alhazen as Well. By Friedrich Risner.

First edition
Printed at Basel by Nicholas and Eusebius Episcopius
Format: 2°
340 x 220 mm
α^4 a-z^6 zz^6; $*^4$ A-Z^6 Aa-Rr^6
[8] [1] 2-288; [8] 1-474 [2]
Colophon on Rr_6^v
Binding: Contemporary 1/2 Calf Over Drab Boards Rebacked
Nonce Volume: Bound with Witelo 1572

It was this book Kepler had studied and this book to which he wished to make a Paralipomena – “an addressing, by way of supplement, of things neglected or omitted.”

Establishes the beginning of modern optics. Contains advances in the nature of light, images from pinholes, mirrors and lenses, and the optics of the eye.

Kepler's work marked the final separation of Light from Sight. It also marked the end of Medieval *Perspectiva* (the combined study of Light-Sight) and the advent of early modern optic.s



AD VITELLIONEM
PARALIPOMENA,
Quibus
ASTRONOMIÆ
PARS OPTICA
TRADITVR;
Potissimum
DE ARTIFICIOSA OBSERVATIO-
NE ET ÆSTIMATIONE DIAMETRORVM
deliquiorumq; Solis & Lunæ.
CVM EXEMPLIS INSIGNIVM ECLIPSIVM.
Habes hoc libro, Lector, inter alia multa noua,
Tractatum luculentum de modo visionis, & humorum oculi
vsu, contra Opticos & Anatomicos,
AVTHORE
IOANNE KEPLERO, S. C. M.
Mathematico.
FRANCOFVRTI,
Apud Claudium Marnium & Hæredes Ioannis Aubrii
Anno M. DCIV.
Cum Priuilegio S. C. Maiestatis.

1604
Johannes Kepler
Ad Vitellionem Paralipomena
A supplement to Vitelo, in which the Optical Part of Astronomy is Propounded. Above all, on the Skillful Observation and Appraisal of the Diameters of Eclipses of the Sun and Moon. With Examples of Important Eclipses. In this Book, Reader, You have, among many other new things, A Lucid Treatment of the Means of Vision, and the Use of the Humors of the Eye, against the Opticians and Anatomists. By the author Johannes Kepler, His Imperial Majesty's Mathematician.

First edition
Printed at Frankfurt by Claude de Marne and Jean Aubry
Format: 4°
200 x 150 mm
)(^{4} (:)^4 A-Z^4 Aa-Zz^4 Aaa-Mmm^4 Nnn^2
[16] 1-449 [19]
Plates [1] Tables [2]
Binding: Modern 1/4 Morocco Over Marbled Boards

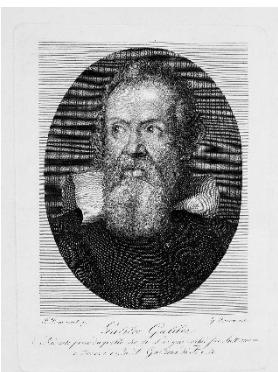
Among the most important of these things was the theory of the optical function of the eye, which Kepler would not supplement, but rather replace. The two prevalent theories of vision at that time were intromission of visible species and intromission of rays. The former posited that objects were continuously radiating thin, laminar simulacrums ("species") which were received by the eye. That later posited that rays were emitted from objects, struck the cornea, and (only) those striking it perpendicularly entered the eye. In both cases the entering visual entity was conducted to the "crystalline lens"—considered to be the seat of vision—and there produced "visual spirit" that was conducted to the brain by the optic nerve. The organ "crystalline lens" had its name not from an understanding of it function but rather from its lenticular shape.

Kepler swept all this away. Adhering strictly to the axiom that light travels in straight lines unless it is reflected or refracted, Kepler showed how rays from an object entered the eye, were refracted by cornea and lens, and focused on the back of the eye. The result was an inverted image of the object "painted" on the retina. Kepler was not troubled by the image inversion – stating that in some as-yet unknow way, the subsequent process of perception made things right.

By the late 16th century, the Netherlands had become a center for optical craft. It is generally held that Hans and Zacharias Janssen first

developed the compound microscope; that is, a convex lens at either end of a tube. It provided magnification of about 10× but with poor resolution. Not long after, in 1608, **Hans Lippershey** (1570-1619) filed for a patent for his instrument "*for seeing things far away as if they were nearby.*" A *kijker* (“looker”), as he called it. This was one of several near-simultaneous announcements of the invention of the telescope.

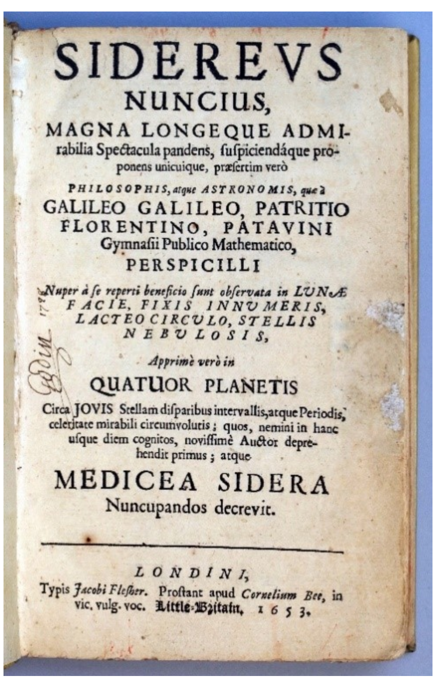
News of these developments, followed by working examples, traveled to the rest of Europe. Originally thought useful for land use (in particular, military applications and surveying) and as an aid to navigation (sighting ships and oncoming shorelines), they were a source for wonder. One such example came into the hands of **Galileo Galilei** (1564-1652). He, apparently, was the first to use the new instrument to view the heavens.



Modeled after the instruments from the Low Countries, Galileo made his own lenses, grinding glass discs in spherical molds and on shaped mandrels. After considerable practice and effort, he made a telescope that provided 20× magnification. It used a double convex lens at one end—the “objective lens”—and a double concave lens at the other—the “eye piece.” With this he viewed the moon—discovering its mountainous nature—, the planets—discovering the moons of Jupiter and the phases of Venus, and the stars—discovering that the Milky Way was comprised of many small stars. He published his findings as the *Sidereus Nuncius* in March 1610.

This edition was modeled on the pirated Frankfurt edition of 1610. 40 years after its appearance, the *Sidereus Nuncius* was essentially unobtainable and so Peter Gassendi included it and Kepler’s *Dioptrice* with his *Institutio Astronomica*, forming a nonce volume devoted to important developments in astronomy.

It presented Galileo's telescopic discovery of the moons of Jupiter, the topography of the moon, and the starry enumeration of the Milky Way.



SIDEREVS
NUNCIUS,
MAGNA LONGEQUE ADMI-
rabilia Spectacula pandens, suspiciendáque pro-
ponens unicuique, præsertim verò
PHILOSOPHIS, atque ASTRONOMIS, quæ à
GALILEO GALILEO, PATRITIO
FLORENTINO, PATAVINI
Gymnasii Publico Mathematico,
PERSPICILLI
Nuper à se reperti beneficio sunt observata in LUNÆ
FACIE, FIXIS INNUMERIS,
LACTEO CIRCULO, STELLIS
NEBULOSIS,
Apprimè verò in
QUATUOR PLANETIS
Circa JOVIS Stellam disparibus intervallis, atque Periodis,
celeritate mirabili circumvolutis; quos, nemini in hanc
usque diem cognitos, novissimè Auctor depre-
hendit primus; atque
MEDICEA SIDERA
Nuncupandos decrevit.

LONDINI,
Typis Jacobi Flesher. Prostant apud Cornelium Bee, in
vic. vulg. voc. Little-Britain, 1653.

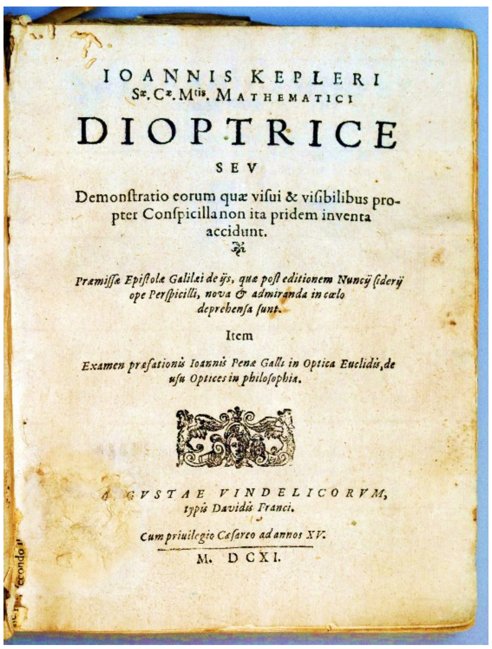
1653
Galileo Galilei
Sidereus Nuncius
The Starry Messenger, Unfolding Great and Boundlessly Astonishing Spectacles, and Presenting to Everyone for Admiration, but Especially Philosophers and Astronomers, by the Telescope of Galileo Galilei, Patrician of Florence, Public Mathematician of the School at Padua. Recently Invented by him and by its Help Observations are made of the Face of the Moon, Innumerable Fixed Starts, the Miky Way, Clouded Stars. But Especially About the Four Planets Revolving around the Star of Jupiter with Marvelous Swiftness in Unequal Intervals and Periods, Which, Known to no one Until Now, the Author Discovered First, and Determined to Name the Medicean Stars.

Second edition (First in 1610)
Printed at London by James Flecher for Cornelius Bee
Format: 8°
175 x 110 mm
A-L^8
[1-2] 3-173 [3]
Binding: Contemporary Vellum
Nonce Volume: Bound with Kepler Dioptrice
Provenance: Godain 1798' inscribed on the titlepage.

Galileo’s announcement broke like a thunderclap over natural philosophy in Europe. It challenged the accepted architecture of the heavens, etched deeply into the armor surrounding Scholastic teaching, and showed how evidence concerning the unseen world could be apprehended. Though first to show its power, there is little evidence that Galileo understood in any detail how his telescope worked.

Among the very first to respond to the *Sidereus Nuncius* was Johann Kepler with his *Dioptrice* of 1611.

The *Dioptrice* was prompted by Galileo's Sidereus Nuncius and is the earliest complete analysis of dioptrics. Axioms, principles, and experimental results about the refraction of light are applied to lenses, explaining image formation, magnification and its measurement, image inversion, and the operation of the telescope.



IOANNIS KEPLERI
Sæ. Cæ. Mtis. MATHEMATICI
DIOPTRICE
SEU
Demonstratio eorum quæ visui & visibilibus propter Conspicilla non ita pridem inventa accidunt.

Præmissæ Epistolæ Galilæi de iis, quæ post editionem Nuncij siderij ope Perspicilli, nova & admiranda in cœlo deprehensa sunt.

Item

Examen præfationis Ioannis Penæ Galli in Optica Euclidis, de usu Optices in philosophia.

AUGUSTAE VINDELICORUM, typis Davidis Franci.
Cum privilegio Cæsareo ad annos XV.
M. DCXI.

1611
Johannes Kepler
Dioptrice
Dioptrics, or A Demonstration of those things that happen to vision and visibles because of the Conspicilla invented not long ago.

First edition
Printed at Augsburg by David Franck
Format: 4°
190 x 145 mm
)(^{4} a-c^4 d^2 A-K^4
[8] 1-80
Binding: Contemporary Vellum
Provenance: Stamp of 'Doctor Mario E. Spada' on front pastedown

In March of 1610, Kepler had learned of Galileo’s discoveries from his friend Johannes Matthaeus Wacker von Wackenfels, and in April the ambassador from Tuscany, Giuliano de' Medici, provided Kepler with a copy of the *Sidereus Nuncius* and asked him, via a letter from Galileo, to provide a response. The result was Kepler's *Dissertatio* of May 1610, praising Galileo and defending his claim to have discovered Jovian satellites and lunar mountains. In August and September 1610 Kepler verified Galileo's observations, using a telescope the Medici's had provide the Archbishop of Cologne, and described them in his *Narratio* of October 1610. The *Dissertatio* and *Narratio* were incorporated in the *Dioptrice*.

Kepler considered refraction, measurement of refractive index, refraction at curved surfaces and lenses; making a complete study of the convex lens and the concave-convex lens combination. All this is finally used to describe the operation of the telescope. In addition, Kepler proposed a telescope using two convex lenses. The analysis is entirely in the context of vision and what is observed; lenses make objects appear larger, inverted, distinct.

Though not the analytic geometrical optics of images that would appear 60 years later in Isaac Barrow's *Lectiones Opticae* of 1674, The *Dioptrice* was a significant advance.

Euclid (fl. 300 BC) held that the eye emitted rectilinear vision rays from the eye, with perception resulting from a haptic-like apprehension of objects by these rays. Treated as lines, these rectilinear rays could be analyzed with geometry – the advent of geometrical optics, with its initial use in the analysis of mirrors.

Euclid's theory of vision, like all those of the ancients, considered light and sight deeply intertwined–essentially the same thing. But eventually *sight* was separated from *light*. In ibn al-Haytham's *Kitāb al-Manāẓir* of the 11th century, light was understood to be necessary for vision but it was considered a separate physical entity. It became the universal custom to consider the ray as light's smallest, fundamental manifestation. The geometric analysis of rays, with paths altered by reflection and refraction, allowed the study and analysis of optical instruments, and a slow stepping away from purely empirical methods.

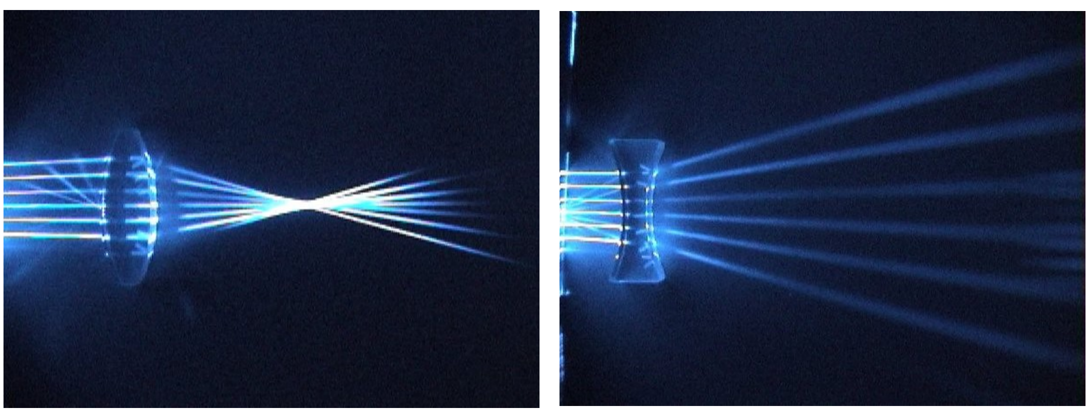
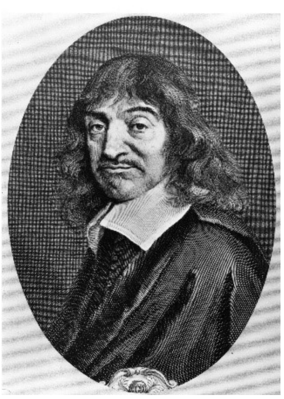


Fig. 5. Rays of light, produced by a special, multiple-beam-producing source off to the left, passing through a convex and concave lens.

How light reflected from mirrors was know to the ancients. Using geometry and the assumption that light rays travel in straight lines, Euclid establish the first principle of geometric optics. The angle the incoming ray formed with the perpendicular to the mirror (the angle of incidence) was always equal to the angle the reflected ray made with the same perpendicular (the angle of reflection).

Ptolemy of Alexandria (c100 - c170 AD) was the first to record measurements of the angles involved in refraction of light from air into water, air into and glass, and water into glass. Unlike reflection, the relationship between the angle of incidence and refraction was not obvious; though Ptolemy did posit that, for a given material, an approximate proportion existed between incidence and refraction angle. The refracting power of a material came to be called its Index of Refraction.

At the time of Kepler, a millennium and half later, there was still no concise way to predict the change in a ray's direction due to refraction. He used an approximation that suited his purpose of analyzing ray paths through lenses, but he understood that a fundamental law of refraction was missing.



Such a law of refraction was first discovered in 1602 by **Thomas Harriot**, (1560-1621) English mathematician and astronomer. He did not publish his discovery and though he corresponded with Kepler, Kepler was unaware of it. In 1621, the Dutch astronomer **Willebrord Snell** (1580–1626) derived the law (in a form equivalent to that of Harriot) but he, too, never published it. **René Descartes** (1596-1650) independently derived the law and expressed the result with the ratio of the sines of the angles the incident and refracted rays make with the refracting surface perpendicular. This law of refraction appeared in his essay *La Dioptrique*, one of three essays in his *Discours de la méthode* of 1637.

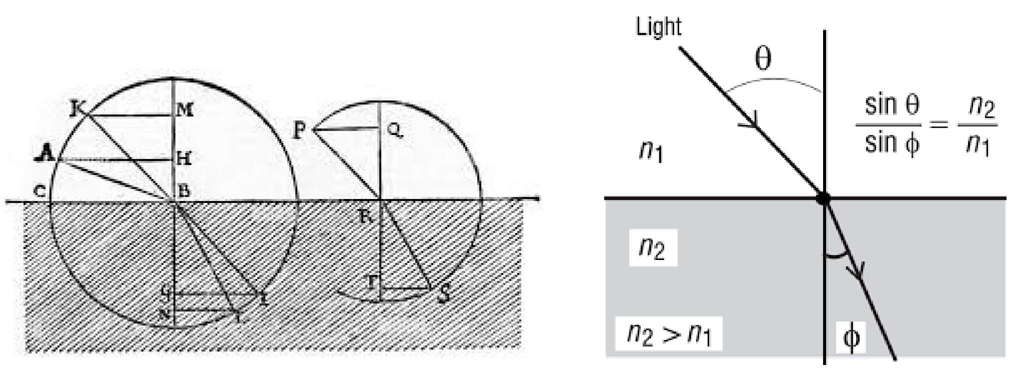
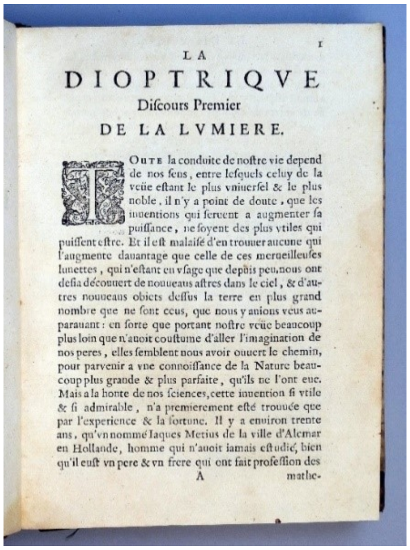


Fig. 6. Law of Refraction. Left: From Descartes' La Dioptrique showing his explanation. Right: The incident and refracted angles. In the case shown here, the density of the second material is greater than that of the first. That is, it's Index of Refraction is greater: $n_2 > n_1$. The law is universally called "Snell's Law." The simple equation made it possible to mathematically describe refraction.

It it known that the *Discours de la méthode* took a year to print and was done it parts. The first two of its three essays, *La Dioptrique* and *Les Meterores,* being written and printed first. *La Geometrie* and the *Discours* itself, written and printed last.

Before the book appeared, Descartes circulated printed copies of these first two essays, seeking reactions. These copies ended up in the library of Count Riccati.



LA
DIOPTRIQVE
Diſcours Premier
DE LA LVMIERE.

TOUTE la conduite de noſtre vie depend de nos ſens, entre leſquels celuy de la veüe eſtant le plus vniuerſel & le plus noble, il n'y a point de doute, que les inuentions qui ſeruent a augmenter ſa puiſſance, ne ſoyent des plus vtiles qui puiſſent eſtre. Et il eſt malaiſé d'en trouuer aucune qui l'augmente dauantage que celle de ces merueilleuſes lunettes, qui n'eſtant en vſage que depuis peu, nous ont deſia découuert de nouueaus aſtres dans le ciel, & d'autres nouueaus obiects deſſus la terre en plus grand nombre que ne ſont ceus, que nous y auions veus auparauant: en ſorte que portant noſtre veüe beaucoup plus loin que n'auoit couſtume d'aller l'imagination de nos peres, elles ſemblent nous auoir ouuert le chemin, pour parvenir a vne connoiſſance de la Nature beaucoup plus grande & plus parfaite, qu'ils ne l'ont eue. Mais a la honte de nos ſciences, cette inuention ſi vtile & ſi admirable, n'a premierement eſté trouuée que par l'experience & la fortune. Il y a enuiron trente ans, qu'vn nommé Iaques Metius de la ville d'Alcmar en Hollande, homme qui n'auoit iamais eſtudié, bien qu'il euſt vn pere & vn frere qui ont fait profeſſion des

A mathe-

1637
René Descartes
La Dioptrique et Les Meteores
Dioptrics and Meteorology

Two of the three essays written to demonstrate his new method of natural philosophy: Optics and vision, and atmospheric phenomena.

First edition
Printed at Leiden by Jan Maire
Format: 4°
190 x 140 mm
π^1 A-Z^4 Aa-Oo^4
[2] 1-294 [2]
Binding: Old 1/2 Calf Over Marbled Boards Spine Gilt
Provenance: Bookplate from the library of Count Jacopo Francesco Riccati (1676 – 1754)

Snell's Law allowed for the analysis of lenses, but advances were slow. Optics was still a craft and the best instruments had the best lenses. And these, in turn, were the result of craft: creating clear glass blocks, proper shaping by grinding, use of lathes, smoothing and polishing. Within 50 years of Galileo's telescope, lens making advanced considerably. Carlo Manzini (1599-1678) published his *L'occhiale all'occhio, dioptrica practica,* "Glasses for the Eye. Practical Dioptrics" in 1660. It was the earliest complete manual for lens making, describing the craft of the greatest lens makers of the time: Francesco Fontana (ca 1580-1656), Eustachio Divini (1610-1685), Anton Maria Schyrleus of Rheita (1604–1660), and Giuseppe and Matteo Campani (1635-1715).

Early, detailed guide to manufacturing lenses for telescopes, spectacles, and microscopes. Though citing and influenced by the theory in Kepler's Dioptrice of 1611, the material is based on perfected practice and experience.

L'OCCHIALE ALL'OCCHIO
DIOPTRICA PRATICA
DEL CO. CARLO ANTONIO MANZINI
DOTTORE COLLEGIATO &c.
Doue ſi tratta della Luce; della Refrattione de Raggi; dell'OCCHIO; della Viſta; e de gli aiuti, che dare ſi poſſono à gli OCCHI per vedere quaſi l'impoſſibile.
Doue in oltre ſi ſpiegano le Regole Pratiche di Fabbricare OCCHIALI à tutte le Viſte,
E CANNOCCHIALI da oſſeruare i PIANETI, e le STELLE FISSE, da TERRA, da MARE,
Et altri da ingrandire Migliaia di volte i minimi de gli Oggetti vicini.

In Bologna per l'Herede del Benacci. 1660. Con Licenza de' Super.

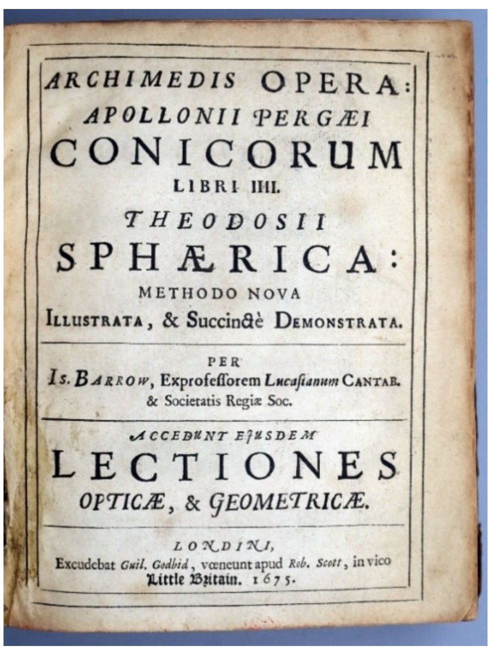
1660
Carlo Antonio Manzini
L' Occhiale all'occhio
Eye Glasses: Practical Dioptrics. Which deals with Light, Refraction of Rays, Vision and its Aid, and that Which Can Permit Your Eyes to See Almost the Impossible. Besides which explains the Practical Rules for Making Eye Glasses for All Views, and Telescopes to Observe the Planets, and the Fixed Stars from the Earth from the Sea, and Others to be Magnified Thousands of Times the Minimum of Nearby Objects.

First edition
Printed at Bologna by Heirs of Vittorio Benacci
Format: 4°
200 x 140 mm
✠^{6}(✠$_3$ signed ✠$_2$) A-Z^4 Aa-Ll^4
[12] 1-268 [4]
Binding: Contemporary Calf Rebacked
Provenance: With the author's dedication on the titlepage
Notes: Portrait of Eustachio Divini drawn by Johann Paul Schor and engraved by Joseph Testana on recto of x^1

By the last quarter of the 17th century, Geometry and the law of refraction were brought to bear on problems in lens analysis and (very importantly) lens design. The culmination of this geometric effort is found in the optical lectures of **Isaac Barrow** (1630-1677). Barrow was (among other things) a mathematician keenly interested in optics, Lucasian Professor of Mathematics at Cambridge University, and teacher of Isaac Newton. In 1675 he published his *Lectiones Opticae & Geometricae,* “Optical and Geometric Lectures.”

The title implies the inseparability of geometry and optics and the book is the first complete, detailed analysis of *image formation* by mirrors and lenses. The lens analysis is entirely theoretical, but advanced lens design considerably.

Barrow’s *Lectiones* is the first, elaborate development of the theory of optical images. It Includes preliminaries on the nature of light and color and a full mathematical treatment of images formed by mirrors and lenses.



ARCHIMEDIS OPERA:
APOLLONII PERGÆI
CONICORUM
LIBRI IIII.
THEODOSII
SPHÆRICA:
METHODO NOVA
ILLUSTRATA, & Succinctè DEMONSTRATA.
PER
Is. BARROW, Exprofessorem Lucasianum CANTAB.
& Societatis Regiæ Soc.
ACCEDUNT EJUSDEM
LECTIONES
OPTICÆ, & GEOMETRICÆ.
LONDINI,
Excudebat Guil. Godbid, vœneunt apud Rob. Scott, in vico
Little Britain. 1675.

1674
Isaac Barrow
Lectiones opticæ & Geometricæ

The Works of Archimedes: The Four Books of Conics of Apollonius of Perga, The Spherics of Theodosius. Illustrated and Succinctly Demonstrated by a New Method. By Isaac Barrow, ex Lucasian Professor at Cambridge and Member of the Royal Society. Optical and Geometric Lectures of the same (author) are added.

First edition
Printed at London by William Godbid for Robert Scott
Format: 4°
195 x 155 mm
π^2 A^2 B-X^4; ^{2}B-D^4; x^1 ^{2}[A]-O^4; ^{3}B-F^4; x^4 a^2 ^{4}B-R^4; x^1 ^{5}B-T^4 V^2 x^1 X^2
[8] 1-285 [2]; [8] 1-104; 1-38 [2]; [12] 1-127 [1]; [2] 1-147 [148]; [2] 149-151 [1]
Plates [1-14]; Plates [15]; Plates[3]; Plates [1-15]; Plates [1-12]
Binding: Contemporary Calf Rebacked

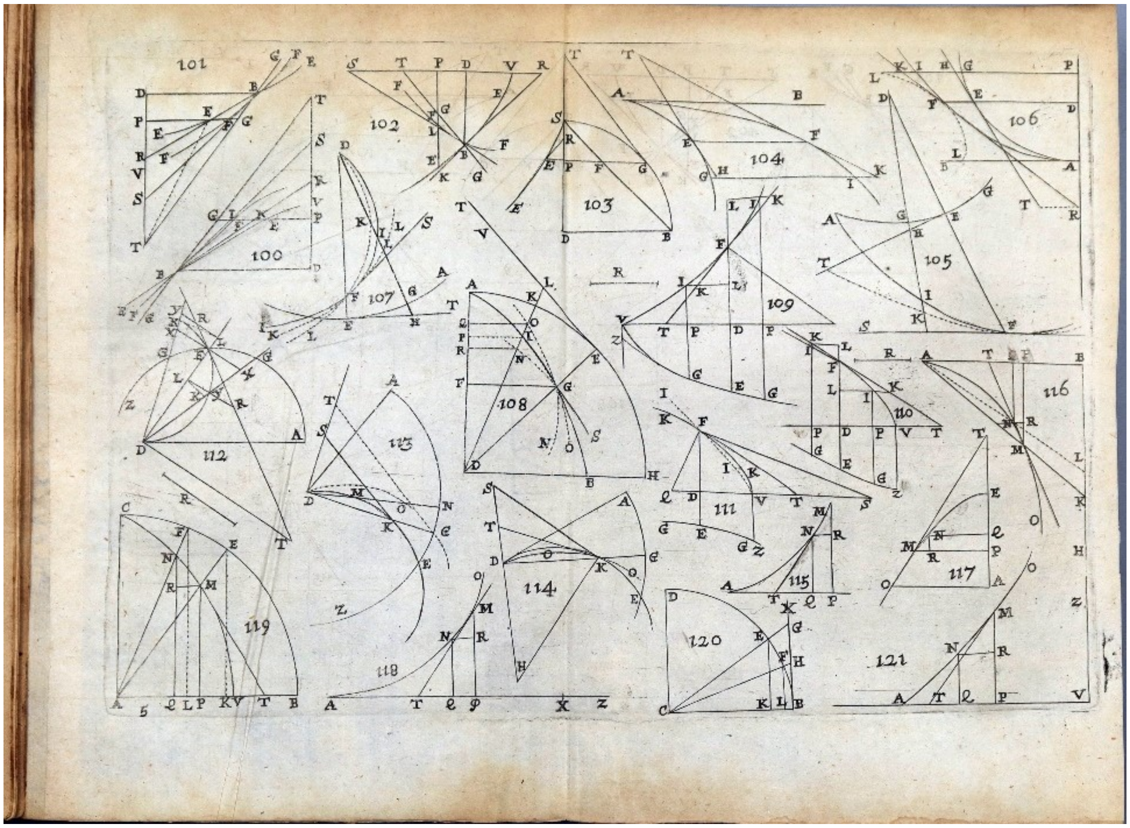


Fig. 6. Geometric analysis and design of lenses, from Barrow's Optical Lectures. More than 200 geometric figures bristle from the plates and show the complete and entire reliance on geometry used in lens analysis.in Barrow's time.

Geometric Optics was remarkably successful. It made clear how simple lenses worked (See Figure 7), aided lens design, and made clear an important limit to lenses and what was required to correct it: Spherical Aberration.

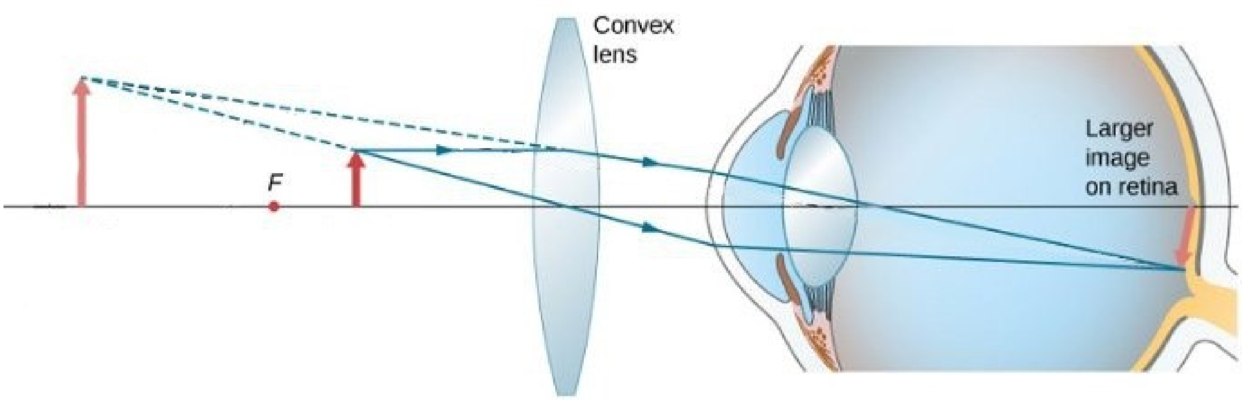


Fig. 7. Magnification by a simple lens. Rays from every point on the object (red arrow) are refracted by the lens and, when viewed by the eye, appear to be coming from points on a larger object (pale red arrow). A larger image is produced on the retina and magnification results. The solid blue rays trace the light path from the object to the retina of the eye. Their dashed extensions show that the rays appear *to be emanating from a point further back on a larger virtual object.*

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Lenses with spherical surfaces are the most straightforward to make. If a glass plate is moved against another, grinding will naturally give nested convex/concave spherical shapes. Similarly, using a lathe or a mandrel can easily produce spherical surfaces. But it was known since Kepler's time that a lens with a spherical surface does *not* bring parallel incident rays to a point. The further the incident rays are from the axis of the lens, the closer is their focus. The result is a blurred image. See Figure 8.

Kepler showed that a hyperbolic surface *did* bring all rays to a single focus, but hand griding such a surface is all but impossible. Descartes tried and failed to design a machine for grinding hyperbolic surfaces. But even a hyperbolic lens won't help if the incident rays aren't all parallel to the lens axis. Full correction for spherical aberration would require modern developments.

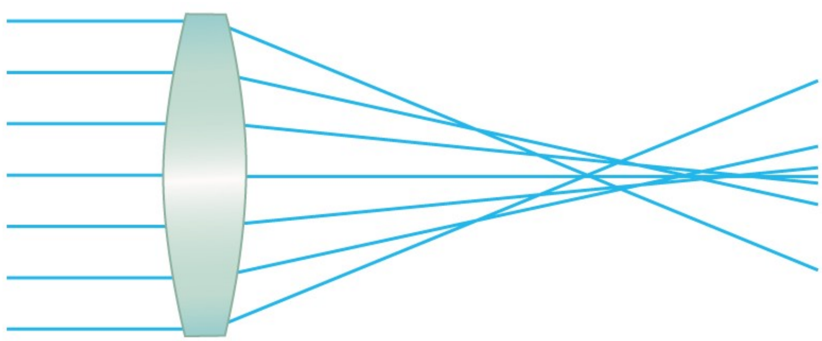


Fig. 8. Spherical Aberration. Spherical surfaces do not produce a sharp focus. The differences between different focal points is exaggerated here for clarity.

Another difficulty found with all lenses was the presence of colored rings and fringes. See Figure 9. This was called chromatic aberration. Its origin was unknown an all attempts to correct it failed.

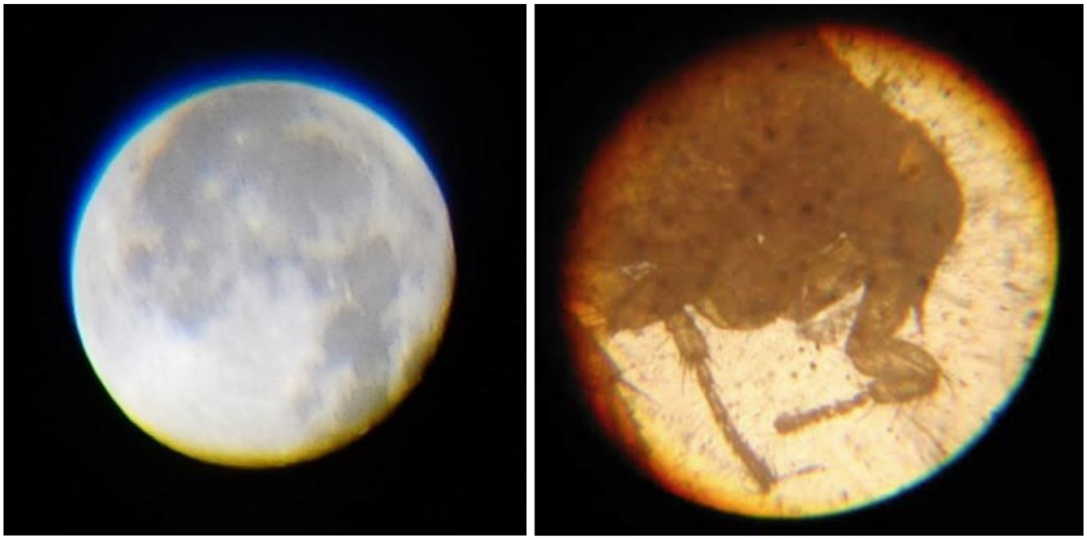
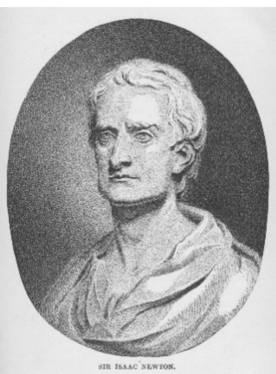
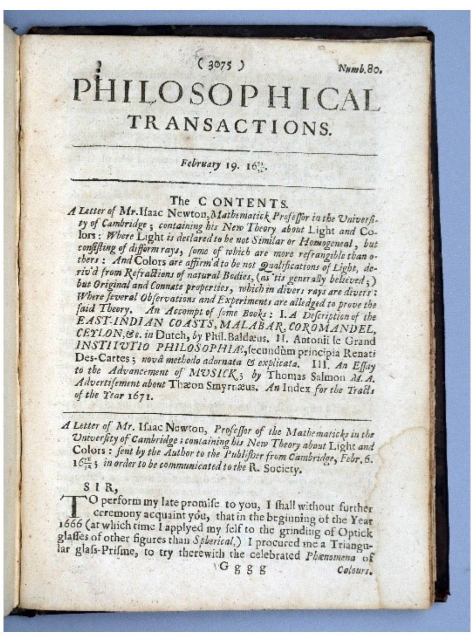


Fig. 9. Chromatic Aberration. Colored rings and fringes in images produced by lenses. Left: Image of moon from a set of simple telescope lenses. Right: Color blurring and detail-obscuring in a microscope image.



Isaac Newton's (1643-1727) theory of light and color offered an explanation. In his famous letter that appeared in the Transactions of the Royal Society of 1672, he proposed that white light was a composite of lights of different colors. Objected to by most natural philosophers of the time, Newton continued to experiment in optics and work on a large optical treatise for thirty years.

Newton's letter describing his new theory of light and color,
was based on his interpretation of results from experiments he had begun in 1666, claiming that white light was a heterogeneous mixture of all colors.



(3075) Numb. 80.

PHILOSOPHICAL TRANSACTIONS.

February 19. 16$^{71}_{72}$.

The CONTENTS.

A Letter of Mr. Isaac Newton, *Mathematick Professor in the University of Cambridge; containing his New Theory about* Light *and* Colors: *Where* Light *is declared to be not Similar or Homogeneal, but consisting of difform rays, some of which are more refrangible than others: And* Colors *are affirm'd to be not Qualifications of Light, deriv'd from Refractions of natural Bodies, (as 'tis generally believed;) but Original and Connate properties, which in divers rays are divers: Where several Observations and Experiments are alledged to prove the said Theory. An Accompt of some Books: I. A Description of the EAST-INDIAN COASTS, MALABAR, COROMANDEL, CEYLON, &c. in* Dutch, *by* Phil. Baldæus. II. Antonii le Grand *INSTITUTIO PHILOSOPHIÆ,* secundùm principia Renati Des-Cartes; *novâ methodo adornata & explicata.* III. *An Essay to the Advancement of MUSICK; by* Thomas Salmon *M. A. Advertisement about* Thæon Smyrnæus. *An* Index *for the Tracts of the Year* 1671.

A Letter of Mr. Isaac Newton, *Professor of the Mathematicks in the University of Cambridge; containing his New Theory about* Light *and* Colors: *sent by the Author to the Publisher from Cambridge, Febr. 6.* 16$^{71}_{72}$; *in order to be communicated to the* R. Society.

SIR,

TO perform my late promise to you, I shall without further ceremony acquaint you, that in the beginning of the Year 1666 (at which time I applyed my self to the grinding of Optick glasses of other figures than *Spherical*,) I procured me a Triangular glass-Prisme, to try therewith the celebrated *Phænomena* of

Gggg *Colours*,

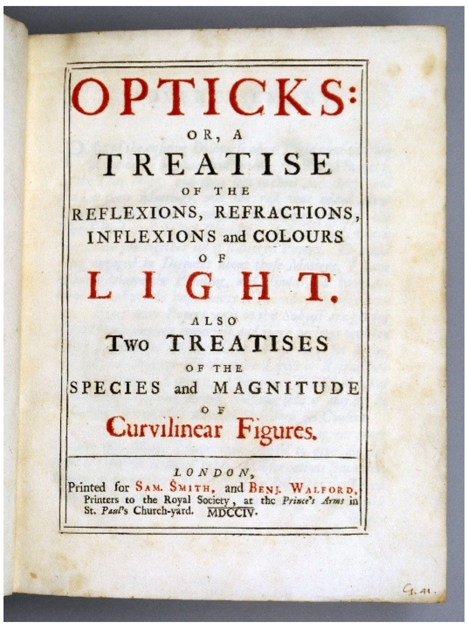
Isaac Newton
New Theory about Light and Colors

First edition
Printed at London by Possibly Thomas Roycroft or Thomas Ratcliffe for John
Martyn
Format: 4°
215 x 155 mm
π^2 Rr-Zz^4 Aaa-Zzz^4 Aaaa-Iiii^4
[2] (2087)-(2299) (3000)-(3095) [3]
Plates [1-2 (No 69), 1-2, (No 75), 1-2 (No 78)] all 6 folding
Binding: Contemporary Smooth Calf, Blind Ruled, Worn
Provenance: With the contemporary ink signature of Abigail Swayne

Europe learned of Newton's extensive work in his *Optice* of 1706, the Latin translation of his Opticks of 1704. For lenses, the news was not good. Newton described two experiments which appeared to demonstrate that the amount of dispersion in glass (how differently light of different colors was refracted) was inextricably linked to its refractive power. This meant that any attempt to counter the chromatic aberration—with another lens or prism, say—would necessarily require undoing the refraction that produced the image. And so, any image produced by a lens or series of lenses was uncorrectably color-fringed by the very nature of the process that produced it. See Figure 10.

Newton's long-gestated record of optical experiments and their results, which he used to deduce the nature of light, refraction, diffraction, and color. The work's three books deal exclusively with physical optics.

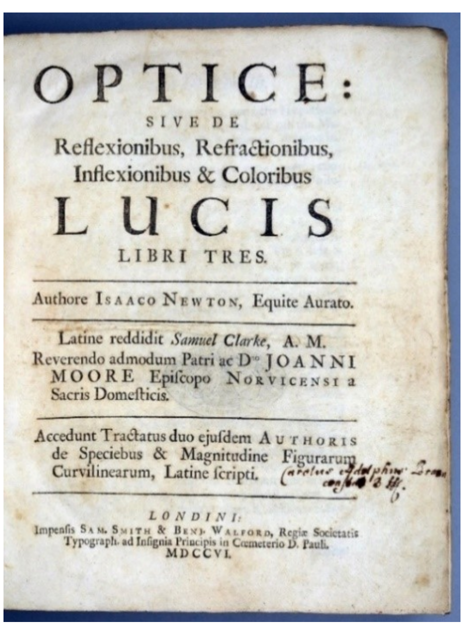
'Queries' appear at the end, being rhetorical questions proposing ideas about the nature of light and color.


OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS, INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.
LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD, Printers to the Royal Society, at the Prince's Arms in St. Paul's Church-yard. MDCCIV.

1704
Isaac Newton
Opticks

First edition
Printed at London by Printers to the Royal Society for Samuel Smith and
Benjamin Walford
Format: 4°
245 x 185 mm
π^2 A-S^4 Aa-Bb^4 Dd-Zz^4 Aaa-Ddd^4 Edd^2
[4] 1-144, 1-137 [1] 138 [1] 130-211 [1]
Plates [19] folding
Binding: Contemporary Calf Cambridge Style Binding
Provenance: The bookplate Tixall Library on inside front cover.

Samuel Clarke's Latin translation of the *Opticks* of 1704. Seven new queries are added to the sixteen that appeared in the *Opticks* of 1704. These queries famously dealt with the nature of light and related aspects of natural philosophy. This copy without the cancel at Ss1 involving the changed text that refers to God's Sensorium.


OPTICE:
SIVE DE
Reflexionibus, Refractionibus, Inflexionibus & Coloribus
LUCIS
LIBRI TRES.
Authore ISAACO NEWTON, Equite Aurato.
Latine reddidit Samuel Clarke, A. M. Reverendo admodum Patri ac Dno JOANNI MOORE Episcopo NORVICENSI a Sacris Domesticis.
Accedunt Tractatus duo ejusdem AUTHORIS de Speciebus & Magnitudine Figurarum Curvilinearum, Latine scripti.
LONDINI:
Impensis SAM. SMITH & BENJ. WALFORD, Regiæ Societatis Typograph. ad Insignia Principis in Cœmeterio D. Pauli. MDCCVI.

1706
Isaac Newton
Optice
Optics:
Or Three Books on the Reflections, Refractions, Diffractions, and Colors of Light.
Author: Sir Isaac Newton
Rendered into Latin by Samuel Clarke, MA, Chaplain of the Most Reverend Lord John Moore, Biship of Norwich. Added are Two Tracts of the same Author on the Type and Magnitude of Curvilinear Figures, Written in Latin.

First edition
Printed at London by Printers to the Royal Society for Samuel Smith and Benjamin Wlaford
240 x 185 mm
A^4 b^4(-b$_4$) Aa^4 B-Z^4 Aa-Oo^4 Pp^1 Qq-Xx^4 Yy^1 Aaa-Bbb^2 Ccc^2 Ddd-Ttt^2
[14] 1-348, [2] 1-24 [2] 1-24, 21-43
Plates [I-V, I-IV, I-II ,I, I-VI, I] all folding
Binding: Contemporary Calf Cambridge Style Binding
Provenance: Owner name on title page 'Carolus Adolphus Broan'
Notes: Without the cancel at Ss$_1$ and so missing the famous 'tanquam' (as if) regarding space being the sensorium of God.

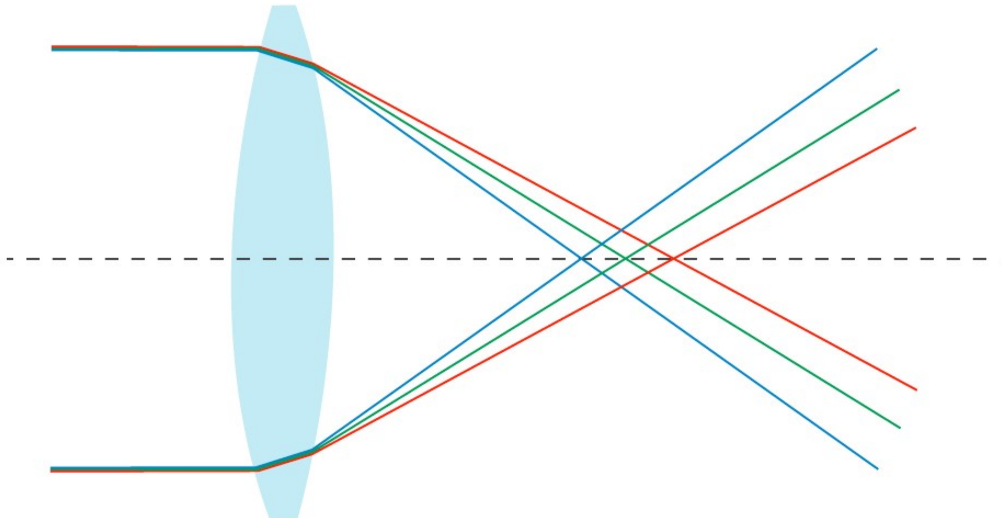


Fig. 10. Chromatic Aberration. White light is a composite of lights of different colors. Each is refracted by a different amount by a lens. The result is spread of colors, different focal points for different colors of light, and therefore a chromatically blurred image. The differences between the paths of light of different colors is exaggerated here for clarity.

Such was Newton's authority and influence that most attempts at dealing with chromatic aberration were abandoned for 50 years. Indeed, Newton himself considered it necessary to abandon the use of lenses in telescopes, and so invented and produced a reflecting telescope—an instrument that used a parabolic mirror rather than a lens to produce an image. It was this instrument which brought Newton onto the world stage and a fellowship in the Royal Society of London.

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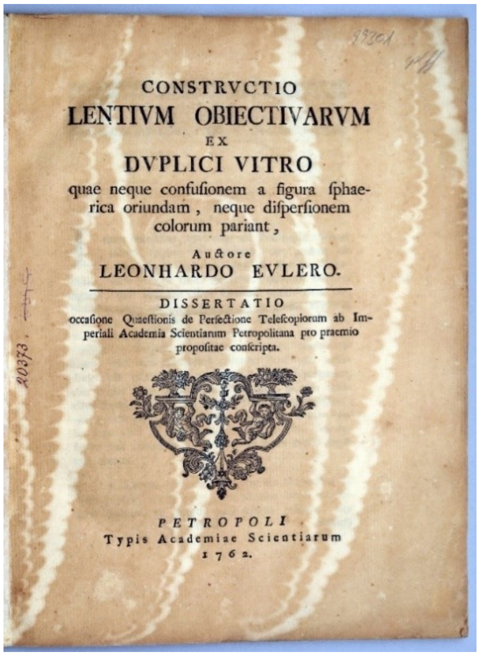
A remarkable series of events, in quick succession, changed lenses, lens making, and optical instruments. It was found that Newton's inference regarding dispersion and refraction was incorrect.

In 1747 **Leonhard Euler** (1707-1783), renowned Swiss mathematician, first suggested that chromatic aberrations could be corrected with a glass and water lens. He presented several subsequent papers to the St. Petersburg Academy regarding achromatic lenses and in 1762 published a summary of his work, *Constructio Lentium Objectivarum ex Duplici Vitro*, "The Construction of Objective Lenses from Two Glasses"

Euler addresses the problem of simultaneously minimizing chromatic and spherical aberration in telescope lenses.

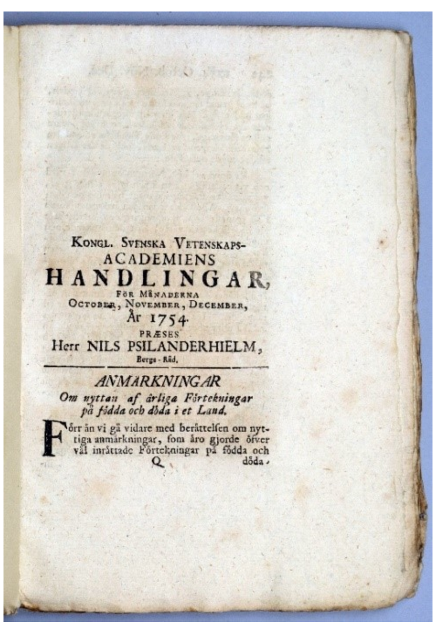


Leonhard Euler
Constructio lentium obiectivarum ex duplici vitro
Construction of Objective Lenses from Two Glass (types), Such that no Confusion Arises From Spherical Shape nor Produced by Color Dispersion. Author: Leonhard Euler. A Dissertation Written on the Occasion of the Prize Question Proposed by the Imperial Academy of Sciences on the Perfection of Telescopes.

First edition
Printed at Saint Petersburg by Press of the Academy of Science
Format: 4°
240 x 175 mm
A-D[4]
[1-3] 4-31 [1]
Plates [1] folding
Binding: Contemporary Paper Wrappers
Provenance: Bookplate of the Tiflis Magnetic and Meteorological Observatory
Library (in Russian)

In 1754 the Swedish mathematician and scientist, **Samuel Klingenstierna** (1698 – 1765), published a remarkable geometric demonstration that implied that, indeed, Newton's conclusion regarding dispersion and refraction could not be correct. The article appeared in the quarterly publication of the Swedish Academy and was immediately translated in German and notice of it spread through Europe.

Samuel Klingenstierna's remarkable paper disproving Newton's assertion that chromatic dispersion and refraction were linked such that no series of refractions could bring light of 'different colors' to the same point of focus.



Samuel Klingenstierna
Anmärkning vid Brytnings-Lagen af särskilta slagsLjus-strålar
Note on the Refraction of Particular Light Rays When They Exit Several Different Transparent Materials; by S. Klingenstierna. In: Acts of the Royal Swedish Academy of Sciences, for the Months of October, November, December, 1754. Edited by Mr. Nils Psilanderhielm, Bergs-Råd.

First edition
Printed at Stockholm by Lars Salvius for Royal Swedish Academy of Sciences
Format: 8°
220 x 150 mm
Q-U[8] X[4]
[241] 242-322 [6]
Plates [IX] in facsimile
Binding: Later Paper Wrappers, Unopened, Untrimmed
Notes: Issue 4 covering October, November, and December 1754. Index for
the entire year 1754 in gathering X

Though initially objecting to Euler's ideas, citing Newton's work and authority, **John Dolland** (1706-1761) English optician, learned of Klingenstierna's work and conducted experiments of his own with glass and water prisms. In 1757 he reported his results in the Philosophical Transactions of the Royal Society: Newton's claim that dispersion could not be overcome was incorrect. Dolland soon managed to produce a doublet lens of two different glasses that exhibited much reduced chromatic aberration. The technique of using multiple glass types soon became common, as did the (near) achromatic lens.

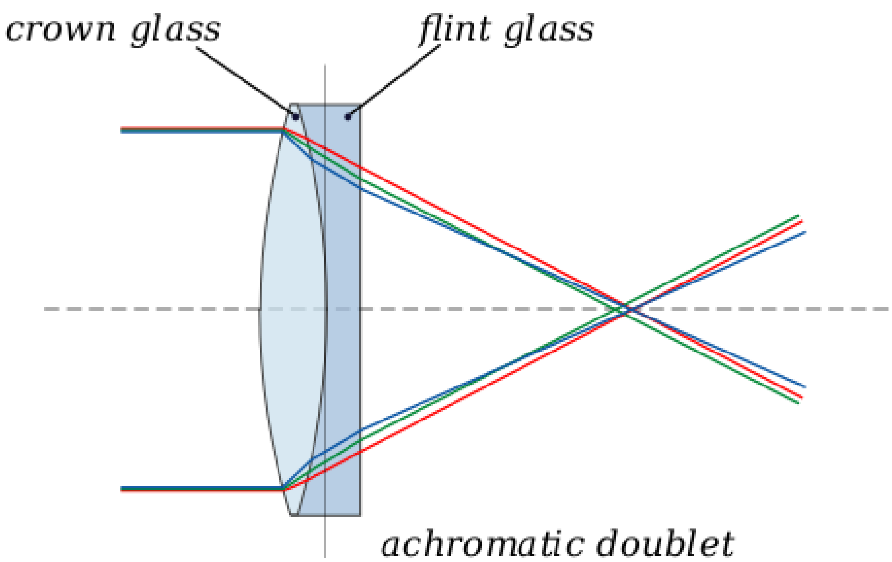
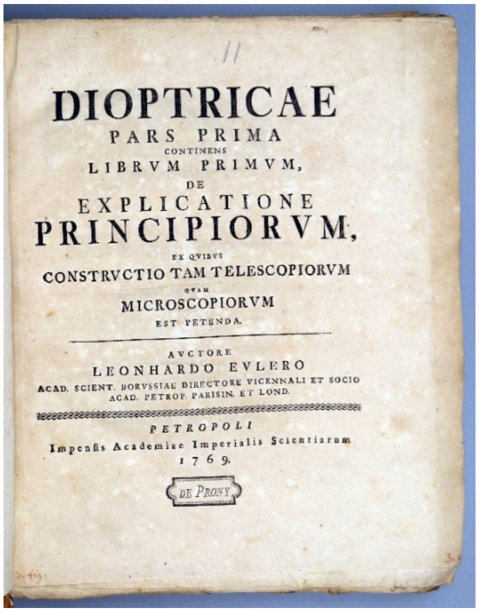


Fig. 11. Reducing Chromatic Aberration. Two types of glass are used: soft crown glass, and hard flint glass. The refractive power of flint glass is greater than that of crown glass and it has a different dispersive properties.The combined effect to significantly narrow the range over which light of different colors come to a focus.

By the middle of the 18th century, Calculus and Algebra began to replace geometry in lens design. It was possible to mathematically express the relationships between all the aspects of lens performance: the shapes of a series of lens' surfaces, the index of refraction and chromatic dispersion of the material from which they are made, and the spherical and chromatic aberrations the lenses produce. Leonhard Euler based his elaborate exposition on lens design, the *Dioptrice* of 1769, on these ideas.

Leonhard Euler, with the help of a student, gathered his works on geometrical optics from between 1746 and 1760 and put them into textbook form: A complete text on geometric optics, his three-volume *Dioptricae*.



DIOPTRICAE
PARS PRIMA
CONTINENS
LIBRVM PRIMVM,
DE
EXPLICATIONE
PRINCIPIORVM,
EX QVIBVS
CONSTRVCTIO TAM TELESCOPIORVM
QVAM
MICROSCOPIORVM
EST PETENDA.

AVCTORE
LEONHARDO EVLERO
ACAD. SCIENT. BORVSSIAE DIRECTORE VICENNALI ET SOCIO
ACAD. PETROP. PARISIN. ET LOND.

PETROPOLI
Impenſis Academiae Imperialis Scientiarum
1769.

DE PRONY

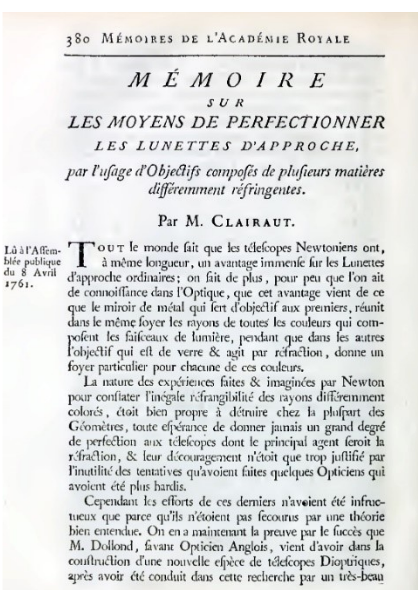
1769
Leonhard Euler
Dioptricae
The First Part of Dioptrics, Containing Book One, on the Explication of the Principles by which the Construction of Telescopes as well as Microscopes is attained. The Second Part of Dioptrics, Containing Book Two, on the Construction of Dioptric Telescopes with an Appendix on the Construction of Catadioptric Telescopes. The Third Part of Dioptrics, Containing Book Three, on the Construction of Microscopes, Simple as well as Compound. By the Author Leonhard Euler, Twenty Year Director of the Russian Academy of Sciences and Fellow of the Academies of St. Petersburg, Paris, and London.

First edition
Printed at St. Petersburg by Press of the Imperial Science Academy
Format: 4°
280 x 220 mm
Binding: Contemporary Paper Spine Over Marbled Boards
Multivolume: 3 Volumes
Provenance: Stamp of De Prony on titlepage recto. Small red stamp on titlepage verso.

But Euler was no optician and his work was limited and purely theoretical. **Alexis Clairaut** (1713-1765) a French mathematician and practicing astronomer, had significantly clearer and more practical ideas. Between 1756 and 1762 he read three long papers to the French academy on the design of achromatic lenses. There were published in the Mémoires de l'Académie royale des sciences between 1761 and 1764. His mathematical work was accompanied by experiment to test his equations and showed the power of mathematics when brought to the problem of lens design. This advance of mathematics was part of the general mathematization of science that began in the middle of the 18th century.

Clairaut's method for designing achromatic telescope objective lenses using multiple glass types. He was among the first to invoke the use of Calculus to solve for lens design equations.

He considered both spherical and chromatic aberrations, both on and off the axis of the lens.



380 MÉMOIRES DE L'ACADÉMIE ROYALE

MÉMOIRE
SUR
LES MOYENS DE PERFECTIONNER
LES LUNETTES D'APPROCHE,
par l'uſage d'Objectifs compoſés de pluſieurs matières différemment réfringentes.

Par M. CLAIRAUT.

Lû à l'Aſſemblée publique du 8 Avril 1761.

TOUT le monde ſait que les téleſcopes Newtoniens ont, à même longueur, un avantage immenſe ſur les Lunettes d'approche ordinaires; on ſait de plus, pour peu que l'on ait de connoiſſance dans l'Optique, que cet avantage vient de ce que le miroir de métal qui ſert d'objectif aux premiers, réunit dans le même foyer les rayons de toutes les couleurs qui compoſent les faiſceaux de lumière, pendant que dans les autres l'objectif qui eſt de verre & agit par réfraction, donne un foyer particulier pour chacune de ces couleurs.

La nature des expériences faites & imaginées par Newton pour conſtater l'inégale réfrangibilité des rayons différemment colorés, étoit bien propre à détruire chez la pluſpart des Géomètres, toute eſpérance de donner jamais un grand degré de perfection aux téleſcopes dont le principal agent ſeroit la réfraction, & leur découragement n'étoit que trop juſtifié par l'inutilité des tentatives qu'avoient faites quelques Opticiens qui avoient été plus hardis.

Cependant les efforts de ces derniers n'avoient été infructueux que parce qu'ils n'étoient pas ſecourus par une théorie bien entendue. On en a maintenant la preuve par le ſuccès que M. Dollond, ſavant Opticien Anglois, vient d'avoir dans la conſtruction d'une nouvelle eſpèce de téleſcopes Dioptriques, après avoir été conduit dans cette recherche par un très-beau

1761
Alexis Clairaut
Memoire

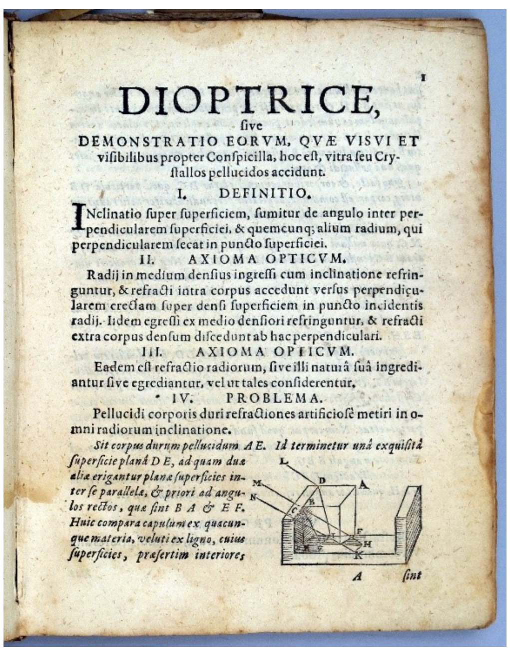
Memoire on the means to perfect telescopes by the use of objectives composed of multiple materials of different refractions

It became clear from the work of Clairaut and others that the power of the new mathematical tools to design lenses depended critically on knowing the properties of the glasses from which they were made.

Since the time of Ptolemy, a single value of the Index of Refraction was used to define the degree to which light was bent when it entered a material more dense than air. Water has an index of refraction of 1.33; soft glass 1.52; hard glass 1.62; diamond 2.4. These values could be used with Snell's Law to predict the paths of light rays through lenses.

But Newton's experiments showed that the Index of Refraction varied with the color or species of light. For a given material, red light was refracted least and blue light refracted most. This was the dispersion, and it varied from glass to glass. Snell's Law would have to be used with a different index of refraction for each color of light.

The determination of the index of refraction had always been problematic. Angle measurements in glass are difficult, though Kepler did devise an ingenious way – even if it did require a carefully made block of glass. See Figure 12.


1

DIOPTRICE,

ſive

DEMONSTRATIO EORVM, QVÆ VISVI ET viſibilibus propter Conſpicilla, hoc eſt, vitra ſeu Cryſtallos pellucidos accidunt.

I. DEFINITIO.

Inclinatio ſuper ſuperficiem, ſumitur de angulo inter perpendicularem ſuperficiei, & quemcunq; alium radium, qui perpendicularem ſecat in puncto ſuperficiei.

II. AXIOMA OPTICVM.

Radij in medium denſius ingreſſi cum inclinatione refringuntur, & refracti intra corpus accedunt verſus perpendicularem erectam ſuper denſi ſuperficiem in puncto incidentis radij. Iidem egreſſi ex medio denſiori refringuntur, & refracti extra corpus denſum diſcedunt ab hac perpendiculari.

III. AXIOMA OPTICVM.

Eadem eſt refractio radiorum, ſive illi naturâ ſuâ ingrediantur ſive egrediantur, vel ut tales conſiderentur.

IV. PROBLEMA.

Pellucidi corporis duri refractiones artificioſè metiri in omni radiorum inclinatione.

Sit corpus durum pellucidum A E. Id terminetur unâ exquiſitâ ſuperficie planâ D E, ad quam duæ aliæ erigantur planæ ſuperficies inter ſe parallelæ, & priori ad angulos rectos, quæ ſint B A & E F. Huic compara capulum ex quacunque materia, veluti ex ligno, cuius ſuperficies, præſertim interiores

A ſint

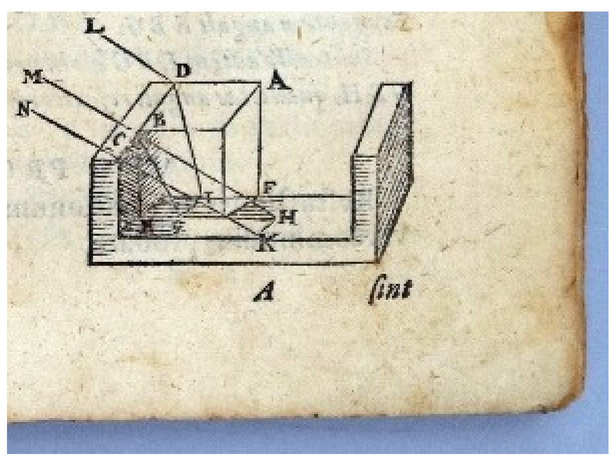
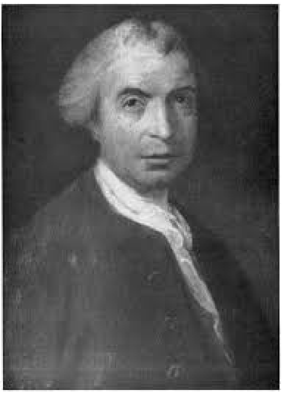
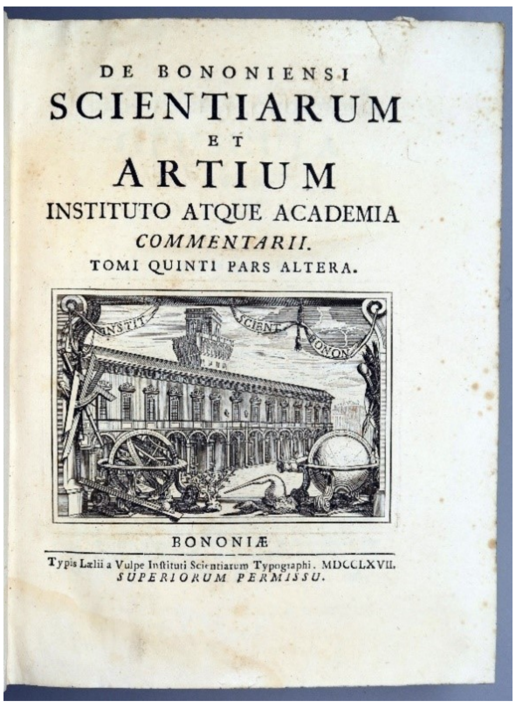


Fig. 12. Kepler's method for measuring refraction in glass. A figure on the first page of his Dioptice *of 1611. A glass block (A) is placed in an opaque cradle and place in a beam of light. The angles of incidence and refraction can be determined simply from the lengths of the shadows of the cradle inside and outside the glass block. The 'A' at the bottom of the page is the signature of the first quire, 'sint' is the catch word.*



The measurement of indices of refraction for different colors of light was a formidable problem. It was clearly understood and first addressed by **Roger Boscovich** (Rudjer Josip Bošković, 1711-1787), from what is now Croatia, developed a “Vitrometer” (Glass Meter) for measuring indices of refraction. It and its use was described in two long articles dealing with chromatic aberration in lenses that appeared in the proceeding of the *Accademia di Bologna* in 1767. Though advancing the measurement art, the Vitrometer was not able to provide the necessary data with the necessary precision.

Boscovich presents theory, mathematics, and examples for designing achromatic lenses with two and three elements.

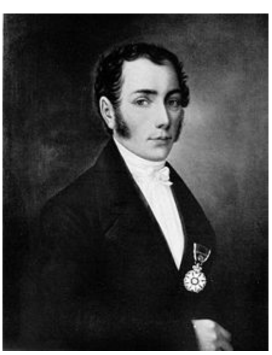


DE BONONIENSI
SCIENTIARUM
ET
ARTIUM
INSTITUTO ATQUE ACADEMIA
COMMENTARII.
TOMI QUINTI PARS ALTERA.

BONONIÆ
Typis Lælii a Vulpe Instituti Scientiarum Typographi. MDCCLXVII.
SUPERIORUM PERMISSU.

1767
Rudjer Josip Bošković
De unione colorum aliorum post alios per binas substantias, ac unione multo majore per tres
On the Union of Colors one After Another by Means of two Substances, and the Union of Many More by Three.

First edition
Printed at Bologna by Laelii a Vulpe
Format: 4°
270 x 200 mm
a^4 A-Z^4 Aa-Zz^4 Aaa-Xxx^4
[1-2] 3-535 [1]
Plates: [27] all folding.
Binding: Contemporary Vellum



It was not until the work of **Joseph Fraunhofer** (1787-1826), an optician working at the Bavarian Optical Institute, that a singular advance was made in the refraction measurement problem. In the *Annalen der Physik* of 1817, Fraunhofer published his *Bestimmung des Brechungs- und des Farbenzerstreungs-Vermögens verschiedener Glasarten,* "Determination of the refractions and color-dispersion properties of various types of glass, with respect to the improvement of achromatic telescopes." He described his discovery of the narrow dark lines in the solar spectrum—now call Fraunhofer Lines—and the process and instruments by which he used them to accurately determine glass's dispersion. That is, the accurate determination of the indices of refraction of light of different wavelengths. Fraunhofer's paper was internationally influential and changed optical measurement practice throughout the technical world.

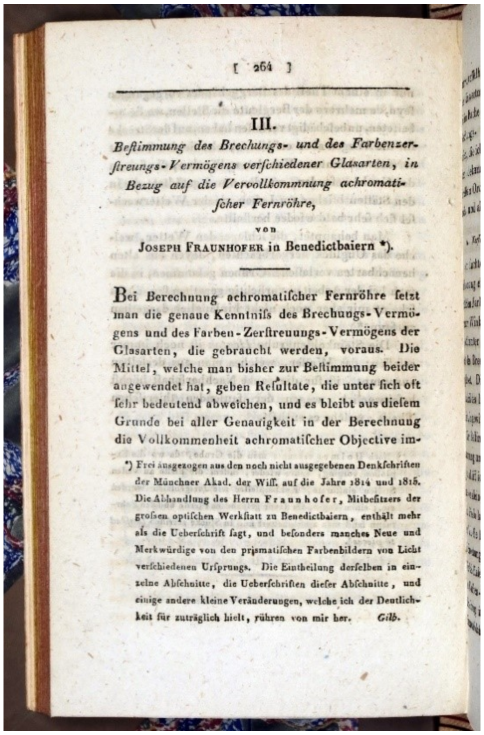
By Fraunhofer's time, the wave theory of light had advanced in the general natural philosophy community, and displaced the particle theory. Different colors of light were now thought to be caused by light of different wavelengths, moving in an all-pervading medium that came to be called the Luminiferous Æther.

Fraunhofer describes his discovery of the narrow dark lines in the solar spectrum—the Fraunhofer lines.

He showed how they could be used as very precise markers of light's wavelength and their shift by various glasses reveal a glass' index of refraction for that wavelength.

The *Annalen der Physik* was widely read throughout Europe and news of Fraunhofer's discovery spread rapidly.

This paper is sometimes cited as the "beginning of Astrophysics." This is incorrect and a prime example of "precursoritis." It was 50 years later that the dark lines were recognized as abdorption lines—the optical signature of specific chemical elements. This allowed chemical analysis at a distance—part of modern Astrophysics. Fraunhofer knew nothing of such things.


[264]

III.

Beſtimmung des Brechungs- und des Farbenzerſtreungs-Vermögens verſchiedener Glasarten, in Bezug auf die Vervollkommnung achromatiſcher Fernröhre,

von

JOSEPH FRAUNHOFER in Benedictbaiern *).

Bei Berechnung achromatiſcher Fernröhre ſetzt man die genaue Kenntniſs des Brechungs-Vermögens und des Farben-Zerſtreuungs-Vermögens der Glasarten, die gebraucht werden, voraus. Die Mittel, welche man bisher zur Beſtimmung beider angewendet hat, geben Reſultate, die unter ſich oft ſehr bedeutend abweichen, und es bleibt aus dieſem Grunde bei aller Genauigkeit in der Berechnung die Vollkommenheit achromatiſcher Objective im-

*) Frei ausgezogen aus den noch nicht ausgegebenen Denkſchriften der Münchner Akad. der Wiſſ. auf die Jahre 1814 und 1815. Die Abhandlung des Herrn Fraunhofer, Mitbeſitzers der groſsen optiſchen Werkſtatt zu Benedictbaiern, enthält mehr als die Ueberſchrift ſagt, und beſonders manches Neue und Merkwürdige von den prismatiſchen Farbenbildern von Licht verſchiedenen Urſprungs. Die Eintheilung derſelben in einzelne Abſchnitte, die Ueberſchriften dieſer Abſchnitte, und einige andere kleine Veränderungen, welche ich der Deutlichkeit für zuträglich hielt, rühren von mir her. *Gilb.*

1817
Joseph Fraunhofer
Bestimmung des Brechungs- und des Farbenzerstreungs-Vermögens verschiedener Glasarten

"Determination of the refractions and color-dispersion properties of various types of glass, with respect to the improvement of achromatic telescopes."

First edition
Printed at Leipzig for House of Johann Abrosius Barth
Format: 8°
190 x 110 mm
π² ⋆⋆⁴ A-Z⁴ Aa-Ee⁴
[12] [(1)] (2)-(440)
Plates [I-V]
Binding: Later 3/4 Gray Calf Over Marbled Boards
Provenance: Stamp of the British Museum of Natural History and 'Withdrawn' stamp

The dark lines in the solar spectrum observed by Fraunhofer were very narrow and therefore marked positions, equivalent to wavelengths, in the spectrum very accurately. The *shift* in these lines produced by refraction in a glass under study revealed the precise index of refraction for that glass, for that wavelength. Fraunhofer was able to determine glass dispersion with unprecedented accuracy. See Figure 13.

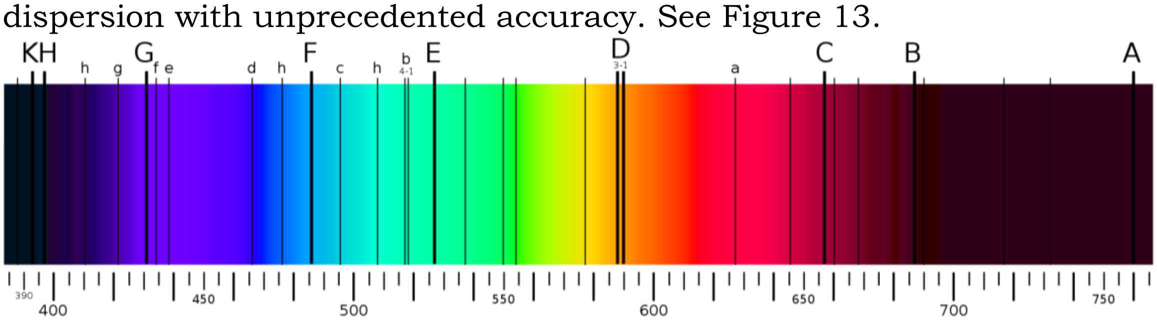


Fig. 13. Fraunhofer Lines: The dark lines that appeared in the solar spectrum Because they were very narrow, they marked places (wavelengths) very precisely. Fraunhofer labeled these with upper and lower case letters. The wavelength of the light involved is show at the bottom, expressed in nanometers (10^{-9} m).

Accurate dispersion measurements allowed Fraunhofer to produce lenses with significantly reduced chromatic aberration. His skill in griding and polishing, along with reduced chromatic aberration allowed him to produce near achromatic and aspheric lenses. They were the best lenses then available anywhere in the world.

Along with accurate glass dispersion data came advances in correcting the other types of aberrations that affected lenses. By the end of the 19th century, limits to lens performance were well understood and only technological difficulties of manufacture had to be overcome. The 20th century saw advances in glass chemistry and manufacture, lens coating capabilities, computer-aided simulation for lens design, and computer-driven manufacturing processes, and significant cost reductions and increased availability of even very complex lens systems.

Augustin-Jean Fresnel (1788-1827), French engineer and mathematical-physicist, produced a wave theory of light that correctly predicted light diffraction and polarization phenomena and by 1830 was universally accepted. Being an engineer, his day-job in 1819 was working for the French Commission on Lighthouses. Combining the urgent need to improve lighthouse effectiveness and his knowledge of optics, Fresnel proposed an ingenious sectioning or stepping of a lens to allow lighthouses to produce strong, collimated beams of light from small sources. See Figure 14.

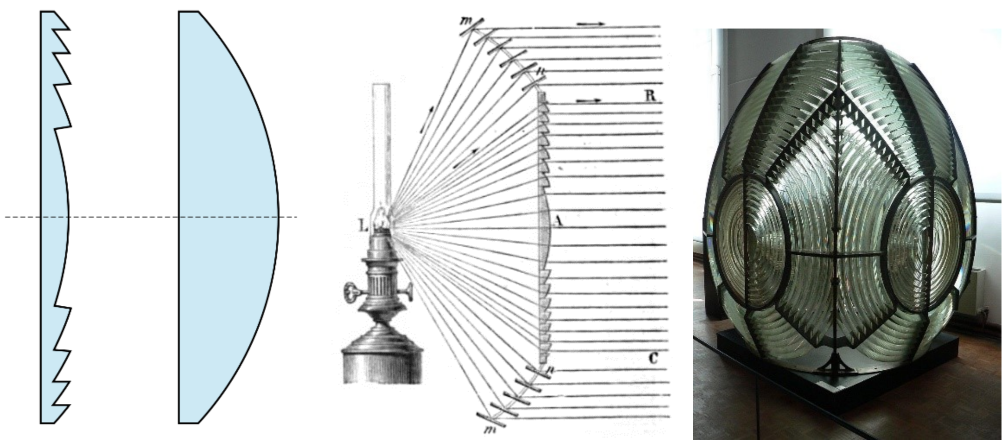


Fig. 14. The Fresnel Lens. Left: A large, heavy plano-convex lens can be compressed into a sectioned, more practical lens. Center: Light emitted into many directions from a small source is redirected into a beam by the compressed lens. Right: An example of a lighthouse Fresnel lens in use in 1870.

In the case of lighthouse lenses, the goal was not to produce accurate magnified images—indeed, it cannot do that. Rather, to simply redirect light. This use of lenses, and other optical material came to be known as non-imaging optics. A modern example is the use of lenses to inject light into the end of a specially clad glass thread that conducts light by refraction along its length. The basis for modern fiberoptics communication systems.

The use of lenses for telescopes came to an end late in the 19th century. One of the last and largest telescope lenses ever made was an achromatic doublet, 40" in diameter (!), for the Yerkes Observatory outside of Chicago. It was made by the foremost opticians in the United States at the time, Alvan Clark & Sons in 1897

Fig. 15. The 40" refracting telescope at the Yerkes Observatory. The lens was made by Alvan Clark & Sons, the tube and mounting by Warner & Swasey Co. of Cleveland. It remains the largest operating refracting telescope in the world. The focal length of the lens was 63 feet, so the tube had to be at least that long.

The cost, difficulty in manufacture, and light-loss due to absorption of light in the thick glass of larger lenses made them impractical for astronomical use. Reflecting telescopes (of which Newton's was among the first) would eventually become the basis for virtually all astronomy.

Lenses continue to be important in numerous other applications, including photography or image-capturing in general. George Eastman pioneered the large-scale manufacture and use of flexible roll film and lenses in portable cameras. Lens systems of the very highest quality and remarkably small size can now be mass manufactured and coupled with nanotechnology-based image capturing chips. Their presence in mobile phones has, for better or worse, made photographers of us all.

In microscopy, significant advances in lens system were made early in the 20th century, increasing the magnification and resolution attainable. It was learned, for example, that the light diffracted from the object being studied had to be gathered into the image, if an accurate view was to be obtained. The best optical microscopes provided images of objects about 10^{-6} meters in size. Modern advanced microscopical instruments combine nanotechnology with conventional lens systems to produce images of objects that are only 5×10^{-8} meters in size.

Operating on the same principle as a simple convex lens, but at sizes and distances difficult to image, an entire galaxy can bend light and bring it to a focus. Rather than a path changed by refraction, light's path is moving through space that has itself been bent by gravity. A phenomenon first predicted by Einstein; gravitational lenses have produced remarkable images of distant objects.

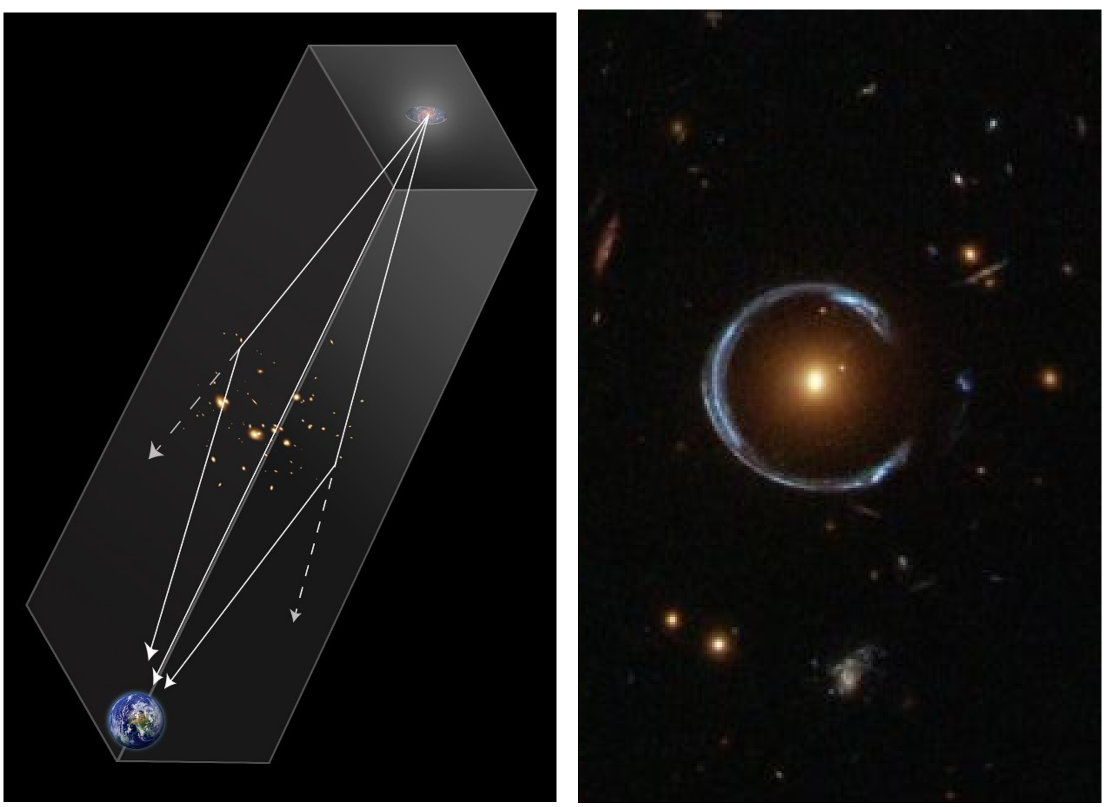


Fig 16. Gravitational Lens. Left: Light from the much more distant object spreads out but encounters space itself bent by the strong gravitational field of the nearer galaxy. The light is bent and, by chance of distance and alignment, is (nearly) focused on the earth. Right: The blue streaks are images of a galaxy far beyond the nearer, yellow galaxy in the center.

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Knowing how lenses work deepens our understanding of their role in the most quotidian parts of our lives and enables us to appreciate how essential they are to our quest to apprehend the world in which we live—from the microscope to the macroscopic. And it is gratifying to know of the role that printing has had in presenting, preserving, distilling, culling, and testing the theories, practice, and discoveries that formed the basis for our modern understanding and use of the lens.