The Spectacle Vendor by Johannes Stradanus, engraved by Johannes Collaert, 1582.

A History of Imaging:

Revisiting the Past to Chart the Future

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It's hard to keep up with the recent explosion of imaging applications, from medical cameras small enough to swallow to municipal cameras for detecting speeders and red-light runners. How has the history of optics in general, and imaging in particular, informed where we are and where we will be next? This article explores the interplay between scientists' understanding of the physical world through the ages and subsequent imaging materials, applications and trends.

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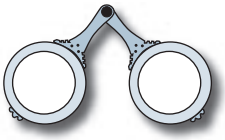
300 BCE

Euclid's *Catoptrics* correctly notes that the angle of reflection is equal to the angle of incidence.

1270



Spectacles, the first practical optical instrument, appear in Florence, Italy.

1590

Father and son team Hans and Zacharias Janssen introduce the compound microscope, a two-element optical system.

Physical understanding begins with observation. Indeed, reflection, refraction and the ability of an appropriately shaped crystal to magnify an image were all observed in antiquity. Even Euclid's *Catoptrics*, written around 300 BCE (Before Common Era), correctly notes that the angle of reflection is equal to the angle of incidence. Refraction, on the other hand, was observed but not understood. Plato attributed it to man's flawed perception of reality.

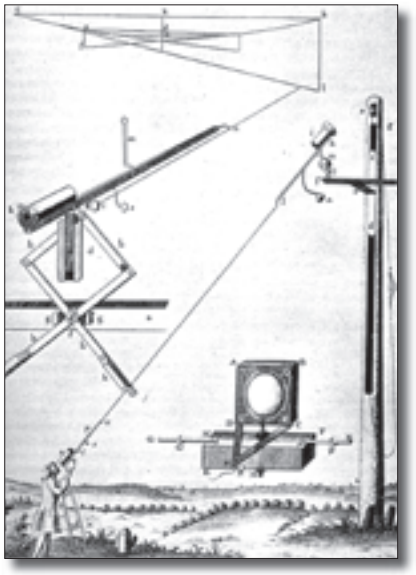
The appearance in 1270 of a Latin translation of Alhazen's *Opticae Thesaurus*, written at the turn of the first millennium, provided Europeans with explanations of other imaging phenomena, but refraction remained elusive. That same year, Vitello, a Polish mathematician who studied in Italy, published a compendium of measured refracted angles. Unfortunately, however, his work was fraught with errors.

The first practical optical instrument—namely spectacles—appeared in 1270 as well, in Florence, Italy. Interestingly, spectacles do not represent a development in optics as much they do an advance in packaging. As evidenced by the writings of Bacon, Europeans were already aware of a lens's ability to magnify images. It was the application of this knowledge to the improvement of human vision—through a metal frame that held two lenses in front of a person's eyes—that made spectacles unique.

The introduction of spectacles demonstrated the maturity of two technologies necessary for producing optical instruments—metallurgy (packaging) and glass making. Venice was well known for the quality of its glass. In fact, between 1287 and 1291, the hazards associated with numerous glass furnaces in Venice forced the town council to move all glass factories to Murano—an island to the north. This act of zoning had the effect of protecting the Venetians' secret of high quality glass manufacturing. Protection of these secrets was so important to the Venetian economy that the city's Council of Ten issued the following edict in 1547:

> If a [glassmaking] workman transports his art into a foreign country to the injury of the republic, a message shall be sent to him to return; if he does not obey, the persons most nearly related to him shall be put into prison. If, notwithstanding the imprisonment of his relatives, he persists in remaining abroad, an emissary shall be commissioned to put him to death.

Venetians carried out this ultimate penalty on two occasions.



Telescope lengths increased to accommodate long focal length objectives that increased magnification and minimized defects.

Magic lanterns, microscopes and multi-lens systems

The fabrication of lenses for spectacles may have also influenced the development of the first image projection system in the 16th century. Known as the magic lantern, this system used an oil lamp and lens to project images painted on glass plates onto a screen. (Whether or not this application was also used by painters is a topic of considerable debate among art historians.) Given the presence of

1610
Two different telescopes are introduced by Lippershey and Galileo.

1611
Kepler's *Dioptrice* and Neri's *Art of Glass* are published.

1621
Snell works out the law of refraction, the first comprehensive description of this phenomenon.

1670
Newton derives the imaging equation, a keystone in optical design that relates the focal length of a lens to the distance between it and the object and image planes.

spectacles and magic lanterns in the early renaissance, it is puzzling that the development of the first multi-element optical instrument was so long delayed.

In 1590, the father and son team of Hans and Zacharias Janssen introduced the compound microscope, a two-element optical system. Apparently society was ready. Within 20 years of the microscope's invention, Lippershey and Galileo introduced two different telescope types, and Lippershey developed the binocular as well.

Two significant publications also appeared at this time, Kepler's *Dioptrice* in 1611 and Antonio Neri's *L'arte vetraria* (*The Art of Glass*) the subsequent year. Whereas Kepler provided the basics of first-order optics, Neri revealed the proper proportions of sodium, lime and silicates needed to manufacture high-quality glass. Together, these publications provided the means and motivation for widespread optical design. Neri's work made the Venetian edict obsolete.

Kepler's publication contains the first analysis of multi-lens systems. It also reveals a continued lack of understanding of refraction. Kepler's attempts to derive a law of refraction failed primarily because he relied on Vitello's error-ridden data. Lacking a general law of refraction, Kepler restricted his analysis to small angles. It wasn't until Snell worked out the law of refraction in 1621 that the phenomenon was completely explained. The law of refraction also appeared independently in Descartes' *Dioptrique*, published in 1637.

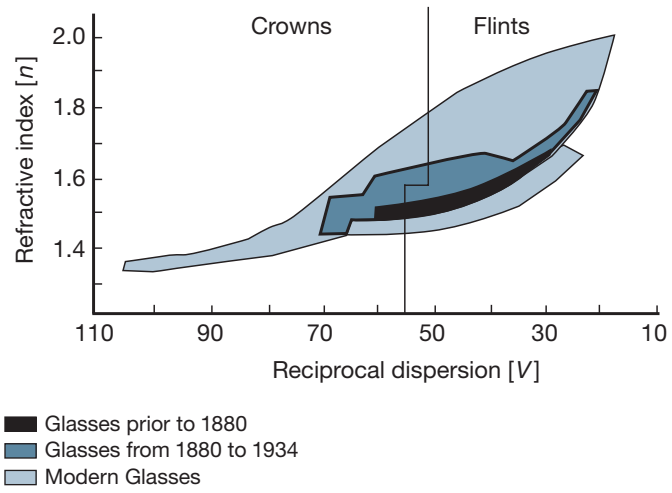
The birth of optical design

The law of refraction is the key that unlocked optical design. With it, Descartes derived the shape of a lens that would be needed to correct spherical aberration. In 1647, Cavalieri linked the focal length of a lens to the curvatures of the lens' surfaces and refractive index in what we now refer to as the lensmaker's formula. Finally, around 1670, Newton derived the imaging equation, a keystone in optical design that relates the focal length of a lens to the distance between it and its object and image planes.

Concurrently, several experiments were performed that revealed deeper aspects of the nature of light. Grimaldi's observations on white light diffracting through a pinhole appeared posthumously in 1665, and Newton recorded his observations of white light dispersed by a prism the following year. Near the end of that decade, Bartholinus observed double refraction in calcite. By 1678, Huygens suggested that light travels as a wave. Later, in 1704, Newton declared that it travels as a ray. Newton's declaration carried considerable weight in the scientific community.

Given the extent of geometrical optics theory, improvements in optical instruments depended primarily on the properties of glass and mirrors, and people's ability to shape such elements. To compensate for material deficiencies, designs relied on multiple elements and distances

[Glass Map Representation of the Historical Development of Glasses]



From C. R. Kurkjian and W. R. Prindle, "Perspectives on the History of Glass Composition," Journal of the American Ceramic Society, **81**(4), 795-813 (1998).

1674
Ravenscroft patents flint glass.

1678
Huygens suggests that light travels as a wave.

1704
Newton declares light travels as a ray.

1733
Hall corrects chromatic aberration using crown and flint glasses.

to improve image quality. Telescope lengths, for example, increased to accommodate long focal length objectives that increased magnification and minimized defects. Further, the limited examples of glass led Newton to believe (erroneously) that chromatic dispersion was the same in all glasses. He therefore pursued the design of reflecting instruments since refractive solutions to correcting chromatic aberrations did not seem possible.

The appearance in 1662 of an English translation of Neri's book may have affected the work of British glassmaker George Ravenscroft, whose decision to add lead to the chemical composition of glass had a significant impact on optical glass. In 1674, Ravenscroft patented a method for making flint glass.

However, Newton's influence remained strong, and designs based on reflective elements dominated telescopes for years. In 1733, nearly 60 years after Ravenscroft's introduction of flint glass, amateur astronomer Hall used the disparate dispersion properties of crown and flint glasses to correct chromatic aberration.

Loosening Newton's grip

Compared with the 17th century—which was marked by numerous advances in science and technology—the 18th century was quiet. Optical instruments made significant impacts on the fields of biology and astronomy. However, no deep gains in understanding were made in optical physics itself. That changed after the turn of the 19th century, when the production of homogenous glass propelled optics further.

The collaboration between Guinand and Fraunhofer at a Bavarian glass melting workshop in 1809 led Fraunhofer to experiment with the material composition of glass. As a consequence, Fraunhofer not only produced high quality achromats, he characterized the dispersive properties of different glass compositions using his nascent spectroscopic techniques.

Fraunhofer's work in turn prompted the British Royal Society to support a similar British effort on glass. British support of Faraday led to further improvements in glass homogeneity. However, Faraday did little to advance the link between glass composition and its optical properties. Instead, advances in glass chemistry were conducted outside the mainstream. For example, Harcourt, an English clergyman, experimented with many of the new elements discovered in the 1830s, including cadmium, fluorine and magnesium, to determine their impact on the optical properties of glass.

Hall's invention of the achromat, combined with Fraunhofer's improvements in glass making, did much to loosen Newton's longstanding grip on optical design. Young's demonstration of light interference in 1801 further diminished Newton's dominance by bolstering the wave nature of light. A quarter century after the first evidence emerged to counter the particle theory, the wave nature of light was firmly established; it was validated with mathematical models for diffraction and polarization, culminating in 1865 with Maxwell's equations and his description of light as an electromagnetic wave.

From optical science to optical engineering

Armed with more and better materials, and a deeper understanding of optical physics, the optics community was poised in the 1870s to make significant strides in imaging. These advances were realized through a partnership of theory, application and materials expertise embodied by Abbe, Zeiss and Schott. Abbe's 1873 wave optical interpretation of image formation enabled a non-materials-based improvement to optical imaging. At the same time, Abbe and Schott studied the relationship among materials, their proportions and their influence on optical properties.

As a consequence of this productive collaboration, 19 of the 44 glasses described in the first Schott catalog in 1886 were new. Two years later, their first catalog supplement included 24 more new glass types. The confluence of physical understanding and materials moved optics into the realm of engineering and made Zeiss an international leader in optical instruments.

Modern imaging

At the turn of the 20th century, scientists were slowly revealing the quantum nature of matter and its links to light, and turning the argument of waves versus particles completely on its head. The discovery of the electron and its subsequent applications were to have a profound impact on imaging.

Just as scientists and engineers exploited the ray and wave nature of light to great effect in the past, recent research-

1801
Light interference is demonstrated by Young.

1809
Fraunhofer produces high quality achromats and characterizes the dispersive properties of different glass compositions.

1837
Daguerre introduces an early form of photograph—the daguerreotype—in which an image is exposed on polished silver. The invention of photography has little impact on optical design.

1865
Maxwell's equations help to firmly establish the wave theory of light.

ers have applied optics' quantum nature to new imaging modalities—for example, quantum coincidence imaging. Coincidence imaging is an indirect form of imaging that does not use optical elements to map object points to image points.

Rather, it relies on a pair of quantum entangled photons that travel two different optical paths, one of which contains the object to be imaged, and the other with no object. The photon that traverses the object path is collected by a single photodetector, while the one in the non-object path is collected by a photodetector array.

An image is formed by correlating the output from the photodetector with that from the photodetector array. In some respects, the configuration resembles a holographic recording wherein coherent signal and reference beams are mixed on film. (Holography is another indirect method of imaging; it is made possible through the marriage of wave optics and film.) In coincidence imaging, "mixing" occurs using electronic correlation.

Electronic fabrication technologies have also recently impacted the fabrication of optical materials. For most of optics' 400-year history, chemistry and large-scale geometry have provided the means for controlling light. By contrast, in the early 20th century, ruling engines and holography stressed small-scale geometry to bend light via diffraction. Modern diffractive optics is one of the first optical technologies to benefit from precision patterning borrowed from the fabrication of electronics.

As minimum feature sizes have shrunk from several wavelengths to a wavelength or less, precision patterning can be used to engineer the dispersive properties of a material. Consequently, the fabrication of materials with negative indices of refraction is now possible. This realization has led the optics community back to the basics—to take a close look at the law of refraction.

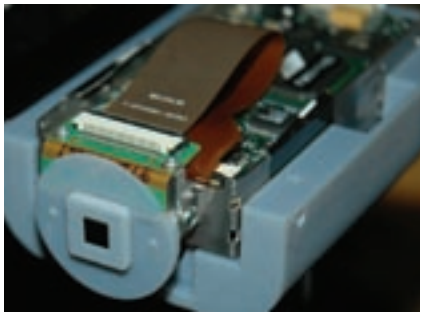
The use of a flat slab of negative index material for imaging is a significant application in this area that leads to resolutions of less than a wavelength. Optical elements formed out of negative index materials are predicted to produce smaller degrees of aberration than their positive counterparts. The engineering of these new materials could therefore expand the glass map and take the work of Abbe, Schott and Zeiss to a totally new level.

Perhaps the most powerful advance in the 20th century was the marriage of the physicist's elementary particles (the electron and the photon) with Shannon's elementary particle of information (the bit). Shannon's theory of information, which emerged in the late 1940s, did much to influence how people thought about images, the imaging process and optical systems in general. At that time, electronic processing was analog and one-dimensional, and required a collection of discrete components; optics offered considerable advantages in throughput and parallel processing.

But the invention of the charged coupled device detector in 1969 contributed to a shift away from optical processing. Electronic detection allowed optical

[Modern Imaging Systems]

Courtesy of the University of Arizona



Courtesy of Duke University

These imaging systems were designed to be thin without compromising optical performance using computational imaging techniques. (a) The visible imager (lower right) next to a conventional imager with comparable performance. (b) The optics for this infrared imager are no more than 3.5 mm in depth.

1873 Abbe's wave optical interpretation of image formation enables a non-materials-based improvement to imaging.

1900 Planck describes the quantum nature of radiation.

1948 Shannon develops his theory of information, which states that messages can be transmitted over a noisy channel, and introduces the bit.

1968 Veselago postulates the impact on electromagnetic phenomena due to materials with negative indices of refraction.

1969 Smith & Boyle invent the charge coupled device. *

image data to be transformed into an electronic format to which one can apply digital electronic processing.

Signal processing: The next paradigm?

The final advance in imaging research that I consider does not rely on materials or physics but on the efficient application of signal processing. As indicated by the quantum imaging example, electronics and signal processing offer new dimensions in imaging that were not previously thought possible.

The potential for advances in digital imaging is often referenced to Moore's Law—that the number of transistors per area in an integrated circuit doubles every 18 months. However, the fervor with which Moore's Law is so often repeated can lead to a skewed view of the future of imaging and imaging systems. Although electronic signal processing is capable of much, information that is not collected cannot be recovered without *a priori* information—for example, aliased frequencies and wavefront phase.

To understand completely the impact of electronic detection of light on imaging, consider that spatial resolution in a film-based imaging system is limited solely by the optics. Film is merely a detector that introduces noise, limits dynamic range, and affects sensitivity.

With electronic-based imaging, image formation and its detection are no longer separable. Since the size of a typical detector pixel is such that it cannot capture the resolution provided by the optics, the detector now limits resolution in addition to being the primary source of noise. It therefore no longer makes sense to limit the concept of imaging to an optical front-end followed by a detector followed by post-detection digital signal processing.

A design philosophy more in tune with today's technology is computational imaging, which attempts to balance the processing capabilities of optics and electronics through concurrent design and joint optimization of all elements. Individual elements are no longer designed independently. The word "computation" underscores that the burden of forming an image does not fall solely to the optics but also to the optoelectronics and the post-detection signal processing.

The extended depth of focus system developed by Cathey and Dowski is a good example of a successful computational imaging system. They showed that introducing a cubic phase function into the pupil plane of an imaging system renders its optical transfer function invariant to range. Although the cubic phase aberrates the image, the aberration is independent of the object's location. Therefore, only a single filter is required in post-detection to correct this unique aberration.

It is important to distinguish this work from adaptive optics, which also depends heavily on signal processing. The field of adaptive optics differs in concept from computational imaging by placing the burden of image formation on the optics; electronics are used as an adjunct to the process as needed. In computational imaging, on the other hand, the goal is to achieve a particular imaging objective with minimal resources. Quantum imaging is an example of a computational system that exploits the quantum nature of light, but is not adaptive. Perhaps the greatest potential for imaging would be realized by designing adaptive optical systems using a computational approach.

For most of the history of imaging, progress has been driven by advances in optical materials and physical understanding. The enlightened application of signal processing in both the optical and electronic domains could unlock the next revolution in optics. The potential for further development has only just begun.

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*The National Academy of Engineering recently awarded Smith & Boyle the 2006 Charles Stark Draper Prize for their invention, which was described as "at the heart of digital cameras and other widely used imaging technologies."

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