From Galileo to Abbe: the Contribution of Lenses to the Foundation of Modern Sciences. What is the Role of Lens in the Coming Quantum Era?

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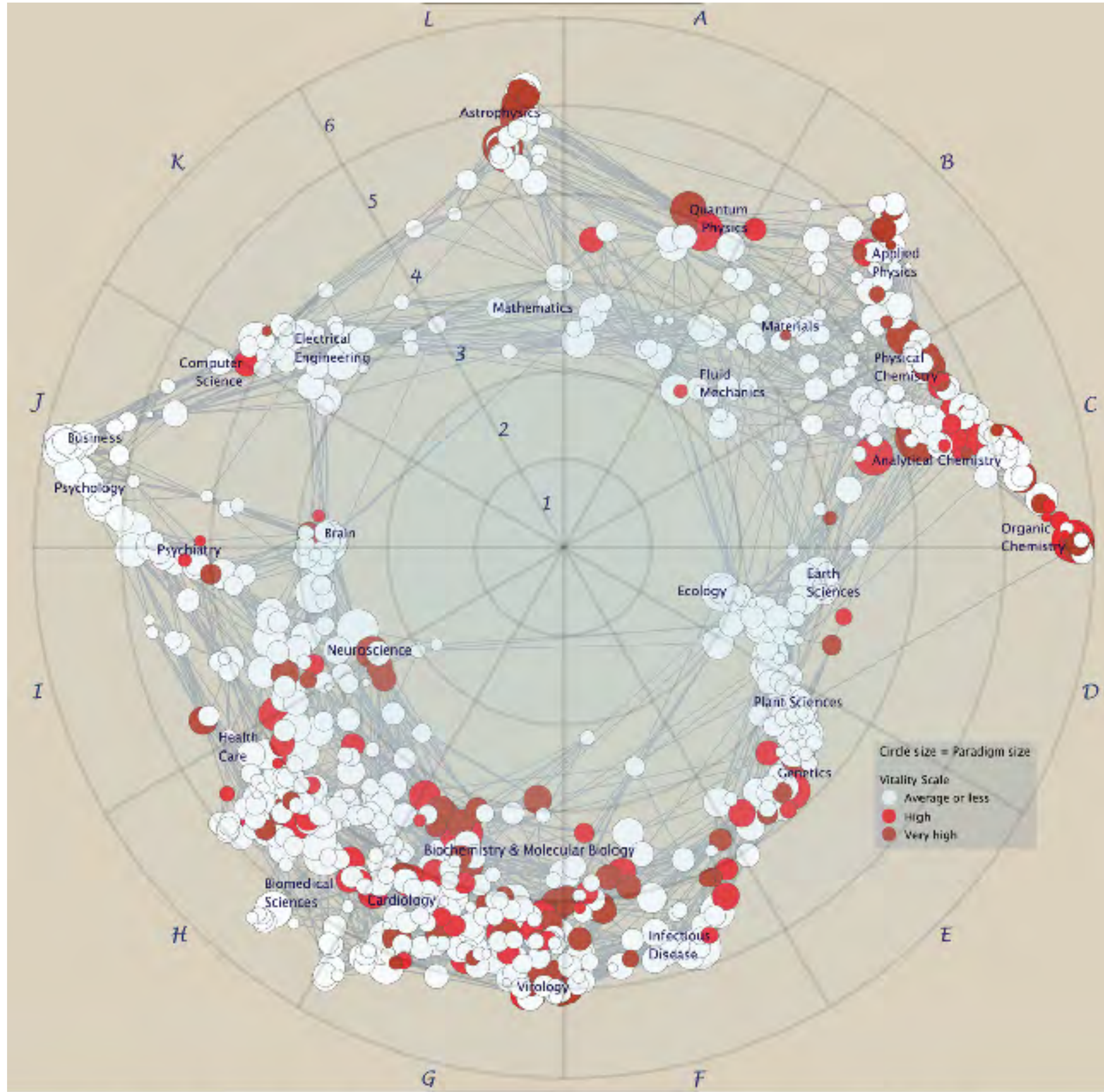
Layout

- Introduction
- The role of Galileo
- Microscopy
- Abbe and the diffraction limit
- Lenses in the past ……

"….photons as a "glue" that demonstrates the interlinking of so many apparently disparate scientific disciplines in natural and life sciences."

Preface H.-J. Lewerenz to Photons in Natural and Life Sciences (Springer, 2012)



Börner, Katy. *Atlas of Science: Visualizing What We Know.* (2010). The MIT

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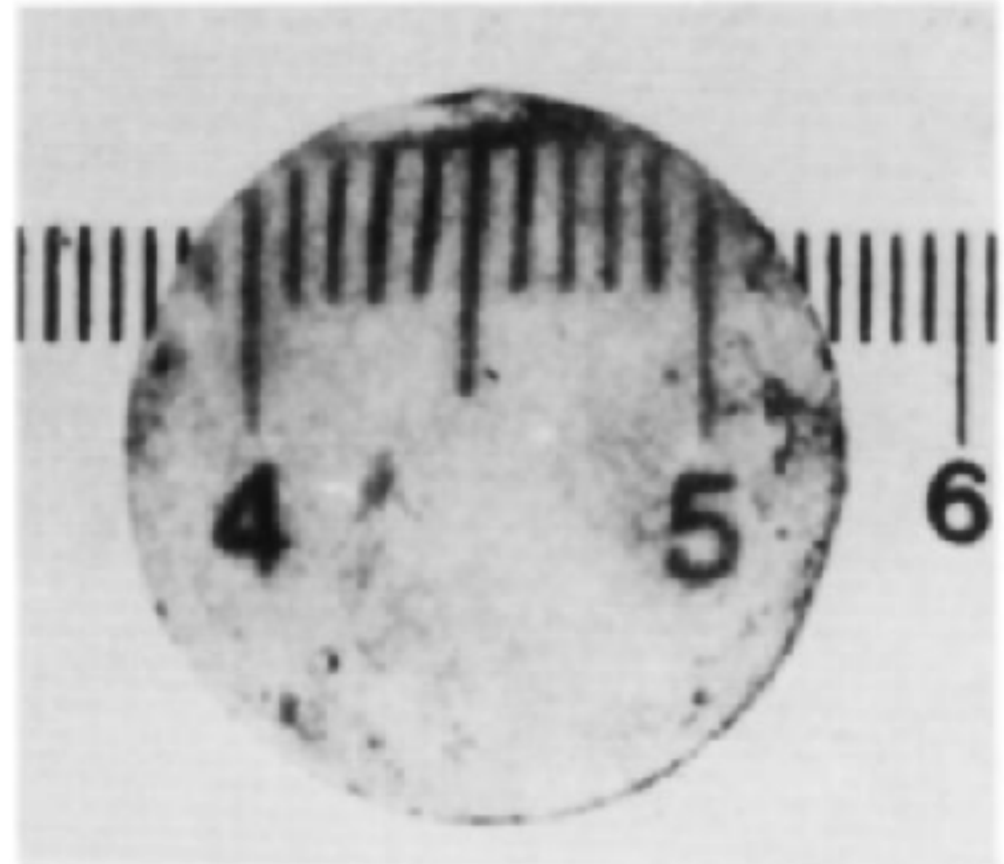
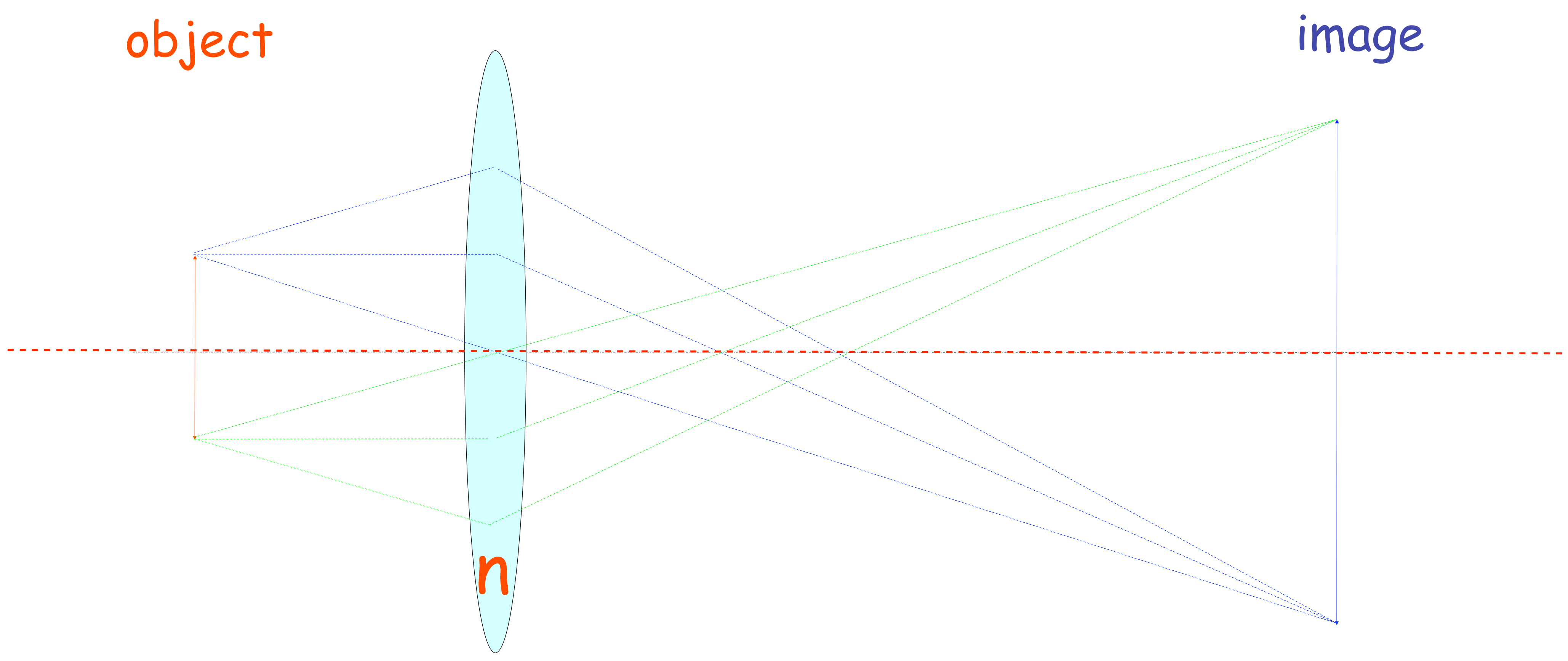


What is a lens?

In physics, a lens can be “considered” a piece of transparent material bound by two spherical surfaces. Lenses can be convex or concave on both sides, or have one flat side. A lens with one side flat and the other convex is termed plano-convex.
A plano-convex lens is perfect for magnification purpouse, but is also great as a burning glass.

Geometrical optics

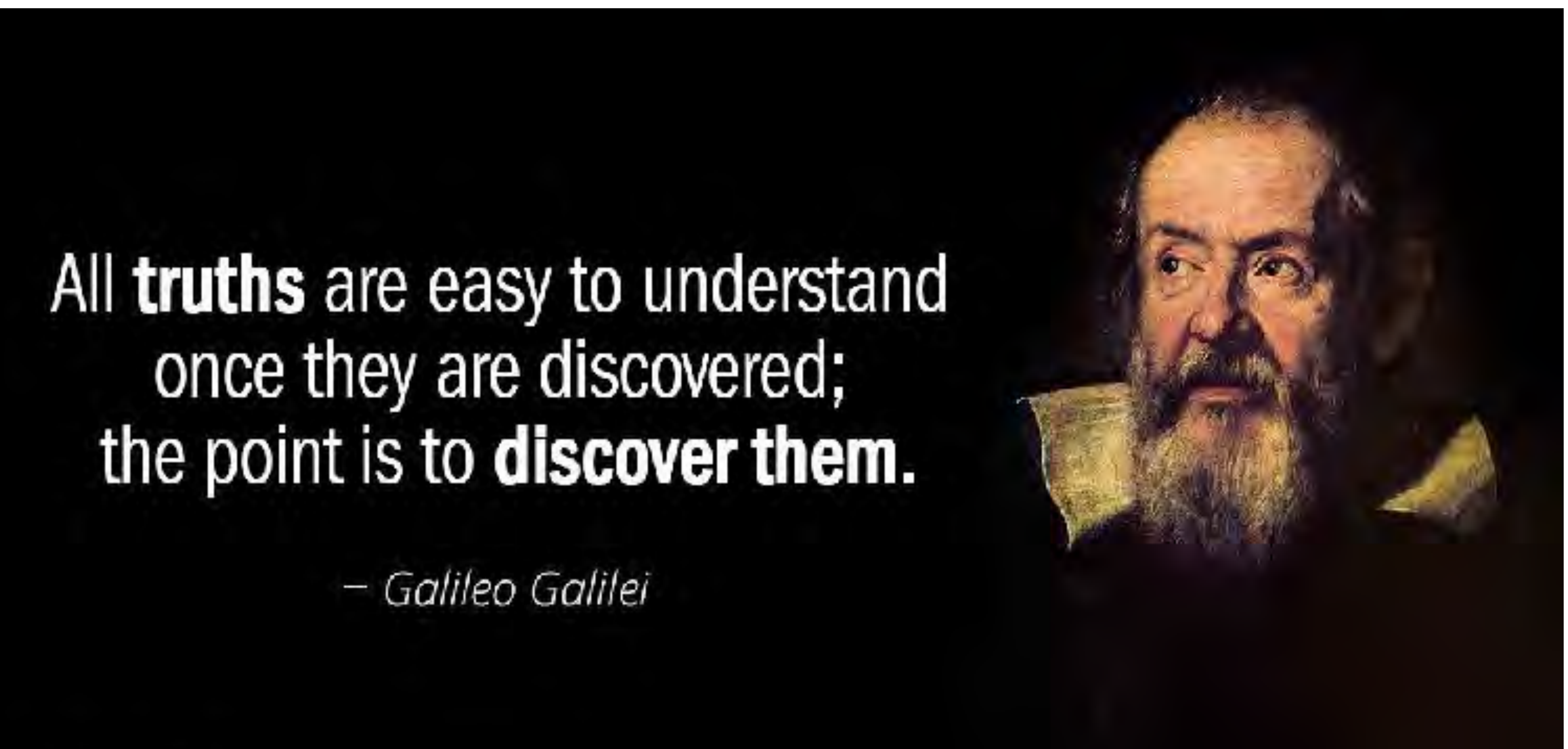
The stigmatic lens: rays emerging from one point all converge in the same point



N.B.: Real lenses are stigmatic only for rays traveling not too far from the optical axes (paraxial rays)

Galileo Galilei (1564–1642) was born in Pisa. (He is just know with his first name!)

In all experiments, Galileo behave as a modern scientist. He knew that his actual measurements were not always exactly the same; sometimes we blink at a bad moment, or the equipment isn't perfect. However, these are the kinds of observations we can make about the real world, and Galileo was always interested in the world as we find it, not in some abstract world where everything was always perfect and exact.



In 1609, he learned of a new instrument that would challenge the ancient way of thinking. This instrument was called the 'telescope', a word that means 'to see far', just as 'telephone' means 'to speak far', and 'microscope' means 'to see small'. Telescopes and microscopes are important tools in the history of science.

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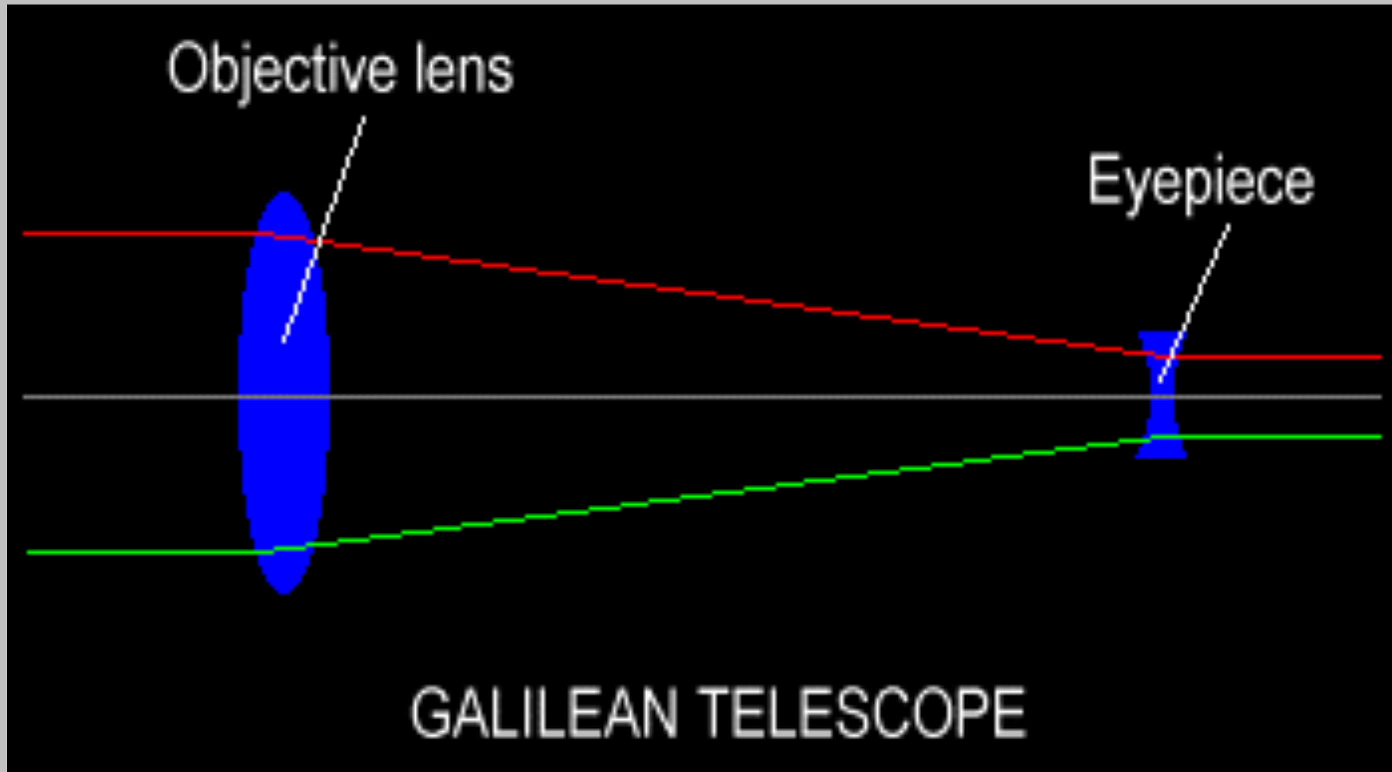
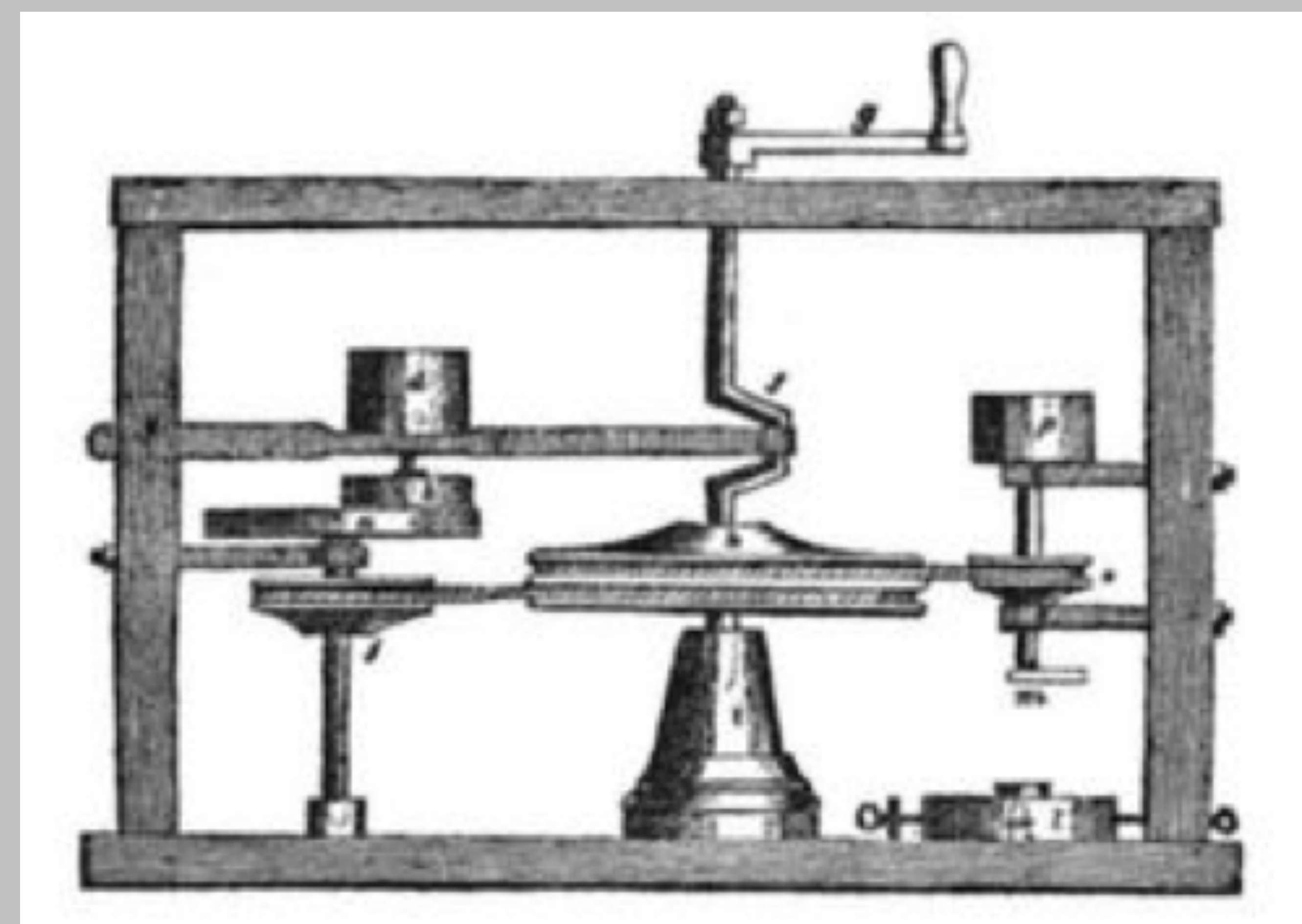


The Galileo's work triggered many natural philosophers. They pushed advancements in the science of astronomy, which were based on advances in the technology of optics and, in particular, of lenses.

Lenses are key elements of the coming revolution, but attention is rarely given to the methods that produced them. Shaping lenses involved increasingly sophisticated use of primitive tools. The use of rotating equipment was an important innovation in lens making, although lenses were entirely grinded by hand in the earliest stages.



Instruments and makers vs. technology

Hubble constant

Lensed quasar images

At some point in any scientific endeavour it becomes necessary to bring philosophy into contact with the real world. The tools for doing this are the scientific instruments: real devices that are used to perform experiments, not just theory. In the case of astronomy, a better instrumentation means better and bigger telescopes: the Hubble space telescope and the Webb telescope in the present days.

In the 17th century it was more of a change in paradigm and the “tools” that are at the origin of the revolution were just few grams of glass - and the genius of Galileo Galilei. In 1609, he published the results of observations he had made using a primitive three-power telescope.

He removed the man from the center of the universe and astronomy became a real science thanks to lenses. Optics changed for ever the view of the universe and the way to run science.

Galileo brought about a revolution that continues to influence our lives after nearly 400 years. With the help of few pieces of shaped glass and his intelligence, he cancelled 2,000 years of ignorance.
He experimentally showed that the Earth is not the center of the universe (in agreement with Copernicus theory) and that the planets are governed by laws we may describe mathematically.

Galileo microscope (1625)

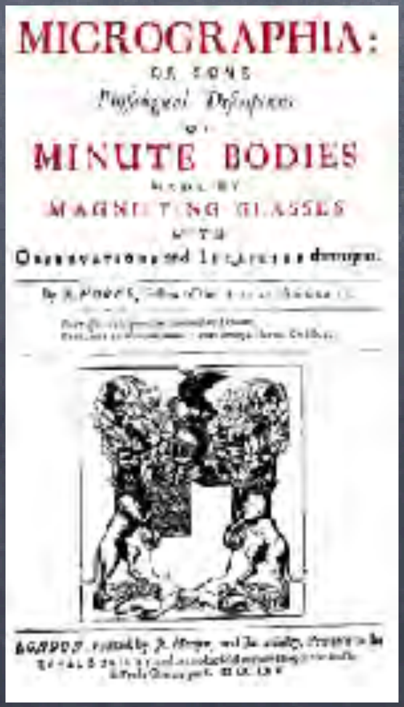
Since Galileo and his telescope, the world has never been the same also at short ….. scale.…

Microscope time-line

- 14th century - born and develop in Italy the lens manufacture technology
- 1595 - Hans e Zacharias Jannsen built the first two lenses microscopy

- 1675 - Anton van Leeuwenhoek observes blood, insects and many other small objects (e.g., cells and bacteria) with a simple microscope
- 18th century - many technological advancements improve microscopy and microscopes (chromatic correction, spherical aberration correction, etc.).
  Abbe introduces in 1878 the equation that determines the maximum resolution of a microscope
- 19th century - diffusion of the microscopy technique. Nobel prizes are awarded to advancements of microscopy and new microscopy techniques

5!

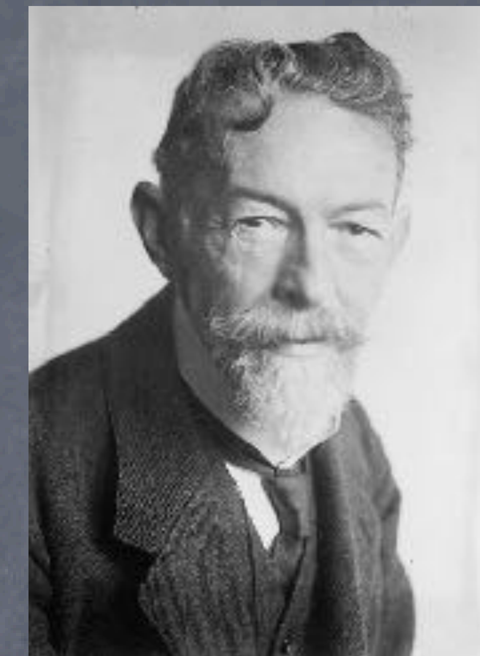

MICROGRAPHIA:

MINUTE BODIES

The microscope

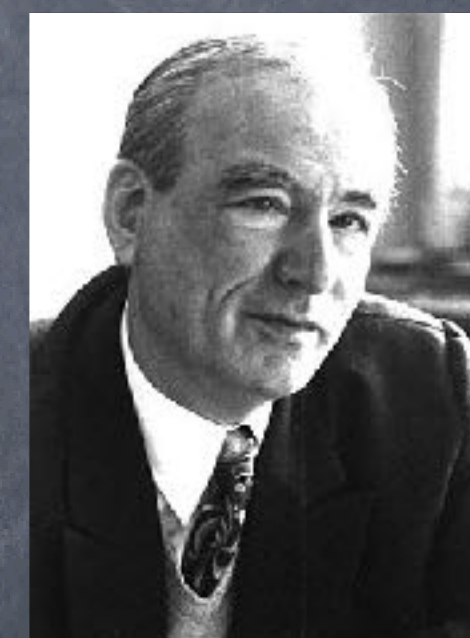
- in a microscope, the radiation emitted by the source is focused on the sample using a "condenser"
- the light transmitted from the sample is collected in the primary focal plane using an "objective" that forms a magnified image of the sample
- the image is then "projected" on the detector

Nobel prizes



1903 - R. Zsigmondy introduces the ultramicroscopy an instrument that allows to investigate objects smaller than the wavelength of the visible light (Nobel in Chemistry - 1925)

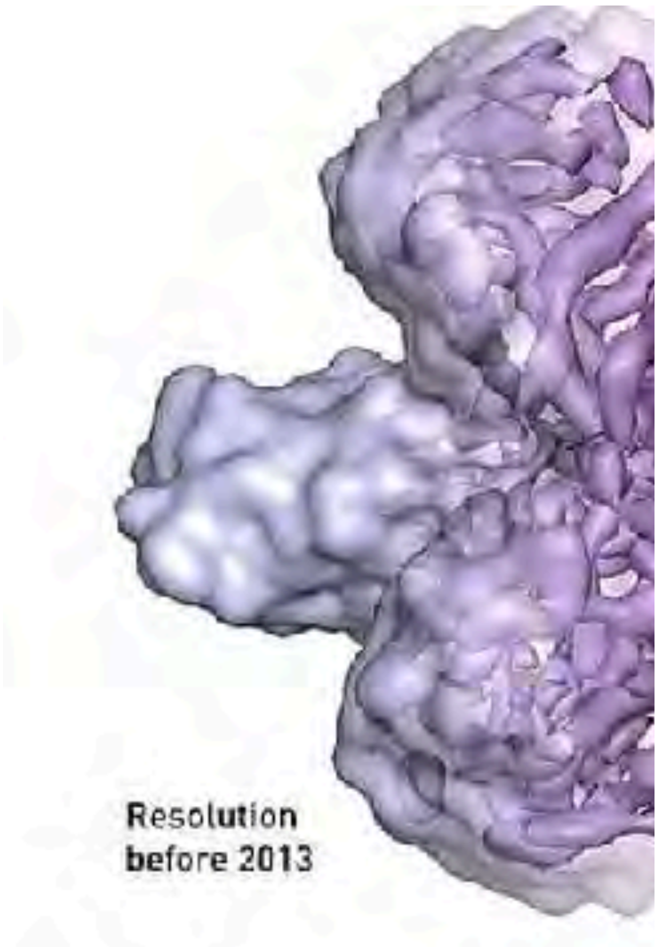
1932 - F. Zernike built the first phase contrast microscope that allows to investigate biological materials (Nobel in Physics - 1953)



1938 - E. Ruska develops the electron microscope. This instrument allows to push forward by several orders of magnitude the achievable spatial resolution of a microscope. (Nobel in Physics - 1986)

1981 - G. Binnig and H. Rohrer set up the first scanning electron microscope. The observation is based on the tunnel effect and allows to collect 3D images at atomic resolution (Nobel in Physics - 1986)

Nobel in Chemistry 2018



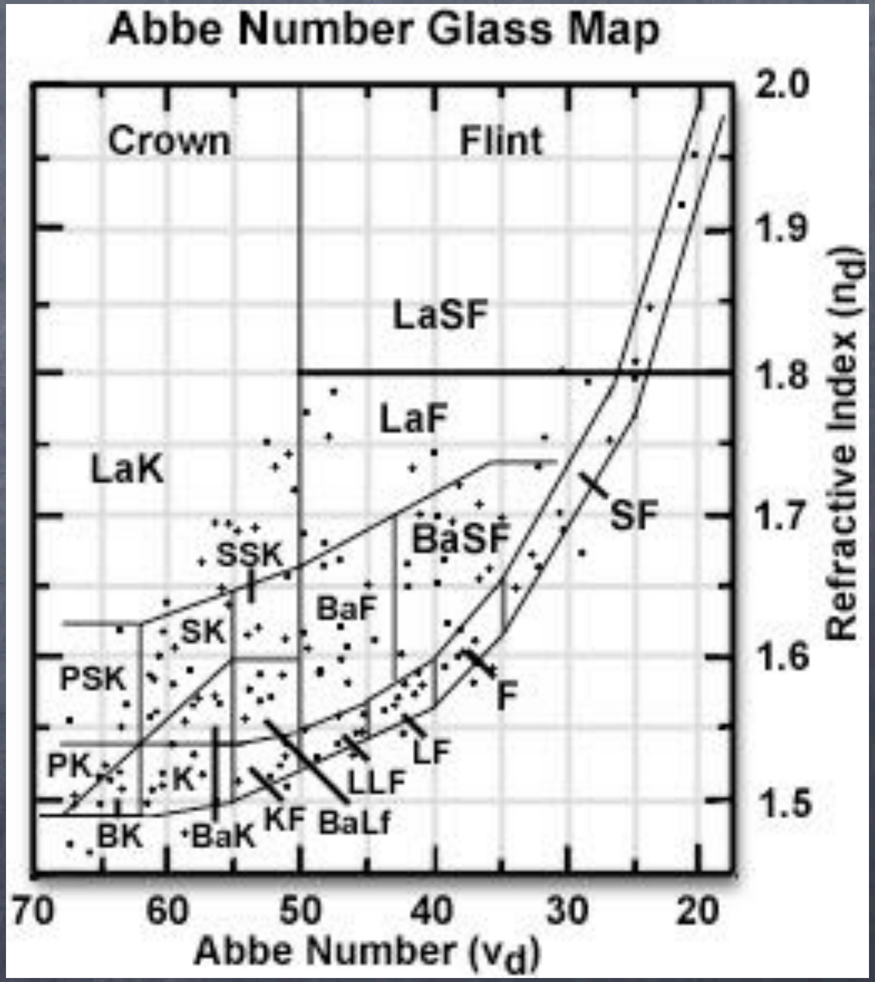
Jacques Dubochet, Joachim Frank and Richard Henderson received the prize for their part in developing cryo-electron microscopy (cryo-EM), a technique that fires beams of electrons at proteins that have been frozen in solution, to deduce the biomolecules' structure even in systems not suitable for X-ray crystallography.

Acceleratorslike microscopies

ADA the first storage ring build in the world dedicated to the interaction of electrons/positrons

Abbe and the concept of the diffraction limit (1873,1884)

- in 1873 Ernst Abbe demonstrated that the resolution of an image is determined by the diffraction of the light from the sample and from the lenses of an objective.
- the "diffraction limit" defines the condition to design a lens whose resolution is limited only by diffraction and not by aberrations (e.g., chromatic and spherical aberrations)
- it determines in a microscope how the resolution of an image is affected by the numerical apertura (NA) of the objective and of the condenser
- it shows that the minimum dimension of the focus of a lens can not be smaller than $\lambda/2n$, being λ the wavelength of the light in vacuum and n the refraction index.



What does it mean?

Resolution = 0.61 λ/N.A.

- larger is the aperture of the objective (and of the condenser) and smaller is the resolution
- Resolution naturally decreases working with shorter wavelengths

Resolution = 0.61 λ/n sen θ

However, an additional parameter to collect more luminous and defined images is increase the refraction index n (e.g., work inside oil).

The position accuracy refers to the precision with which an object can be localized in space.

The spatial resolution is the measure of the ability of an optical system to distinguish two point-like objects from a single object.

The diffraction limit implies that optical resolution is ultimately limited by the wavelength of light.

Super-Resolution

Lateral resolution can be continuously improved and axial resolution can at most be doubled. What happens by increasing both axial and lateral resolution?

If G_A and G_T are the spot size relative to the diffraction limit in the transversal and axial directions, a focal spot has to satisfy this general relation

$$G_A G_T \geq g$$

where g is a geometrical factor depending on the shape of the aperture

$g \approx 0.47$ for circular aperture

If σ_0 is the size of the smallest focal spot that depends only by the NA and λ, where n is the refraction index and θ the semi-angle of aperture of the optical system. [Interestingly not by the geometry of the aperture!] If σ_{DL} is the diffraction limited spot size

$$\sigma_0 = g\,\sigma_{\mathrm{DL}}$$

The minimum possible focal spot (g=0.5) is ~1/2 σ_{DL}, the diffraction limited spot size and represents the lower limit for the reduction of a 3D spot beyond the diffraction limit (voxel information). For a focused beam the spatial distribution is well defined, but its energy content becomes indefinite.

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Smallest Focal Spot

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(Received 19 March 1998)

According to diffraction theory the size of a focused spot is determined by wavelength, numerical aperture, and aperture shape. But even when these parameters are fixed it is possible to achieve super-resolution and reduce the spot size even further. It is shown, however, that the three-dimensional spot size cannot be arbitrarily reduced. The minimum focal spot able to probe high-resolution volumetric information in an optical system is about half of the diffraction-limited spot size. [S0031-9007(98)07535-8]

PACS numbers: 42.25.Fx, 03.50.-z, 41.85.Ct

$\sigma_0 = g\,\sigma_{\mathrm{DL}}$ defines a lower bound for the reduction of the 3D spot size beyond the diffraction limit. Actually σ_0 can be considered as the minimal focal spot able to probe volumetric information. In the analogy with the photon, which can be considered the optical unit of quantum information and for which the photon the energy is well defined while the spatial localization remains ambiguous. In this framework, photons and the minimal focal spots play similar roles in the appropriate quantum and classical limits. For confocal microscopy applications the spatial confinement of the focal beam is an extremely interesting opportunity. Moreover, the Eq. ($G_A G_T \geq g$), is really analogous to the Heisenberg uncertainty principle applied to classical fields. It describes how the access to more information (higher resolution) in a given direction unavoidable leads to a loss of information in another.

When the history of optics began?

When the first lenses have been manufactured for vision/ optical applications?

Ancient lenses tended to be of rock crystal until Carthaginian and Roman times [~4th century BC] after which cheaper glass lenses became more common. Many ancient lenses have been also mis-catalogued in mineral collections and moved to geological museums from archaeological collections being considered 'crystal specimens'.

Nimrud lens (?). Tool created in the ancient Assyria between 750 and 710 BC.

Ancient lenses

Carthaginian Lenses

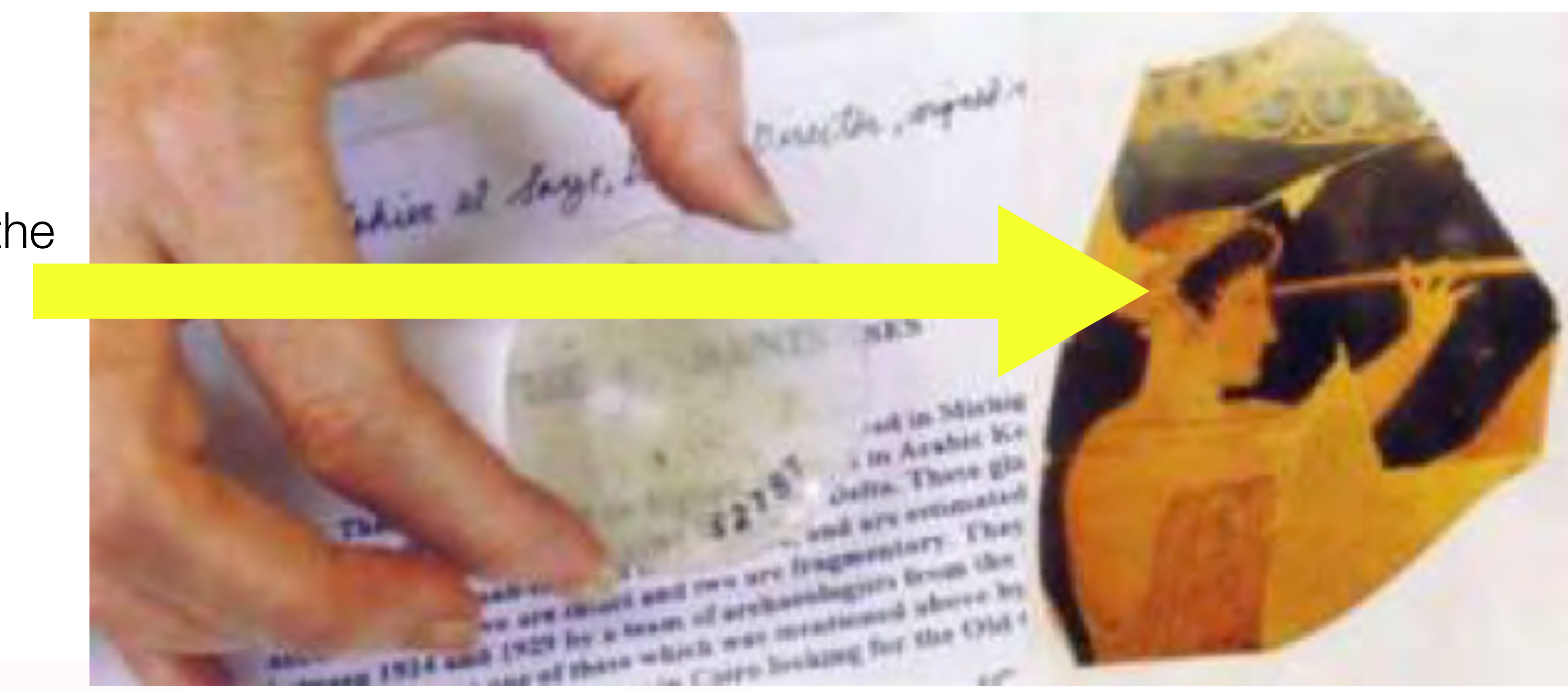
Egyptian Lenses

Cretan Lenses

Assyrian Lenses

The ancient Greek Pythagoreans of the 5th century BC believed that the sun was a gigantic crystal ball larger than the earth, which gathered the ambient light of the surrounding cosmos and refracted it to earth, **acting as a giant lens**.

A fragment of a Greek pot excavated at the Acrocopolis in Athens [6th century BC] shows an ancient image of someone looking through a tool that could be something like a telescope. (?)]



It is not known how long lenses have existed. Egyptian statues dated to 2600 B.C.E. have remarkably lifelike eyes, which incorporate lenses that may have been hand ground or turned on primitive lathes. The earliest clearly documented reference to lenses as burning glasses occurred in The Clouds, a satire by Aristophanes dated 424 BC.

Details on ancient coins and jewelry have led some experts to guess that the magnifying glass was an aid to extremely fine manufactured works dating from a very early time. Primitive lenses were widely used in eyeglasses as early as 1299.

[illegible]

…ابن الهيثم رحمه الله الفصل السادس … [illegible]

[illegible]

How old are human eyes?

The theory nowadays recognised by anthropologists, palaeontologists and biologists claims that the first species of Hominidae is an evolution of proto-primates. The common tree of the evolution from which also come African monkeys dates back ~5-6 millions of years ago while the Homo generae born 2,3-2,4 millions of years ago from Australopithecus. Actually, the origin of primates is set to ~70 millions of years ago.

https://it.wikipedia.org/wiki/Australopithecus

When the early eyes appeared?

Nature Vol. 254 April 24 1975 663

articles

Trilobite eyes and the optics of Des Cartes and Huygens

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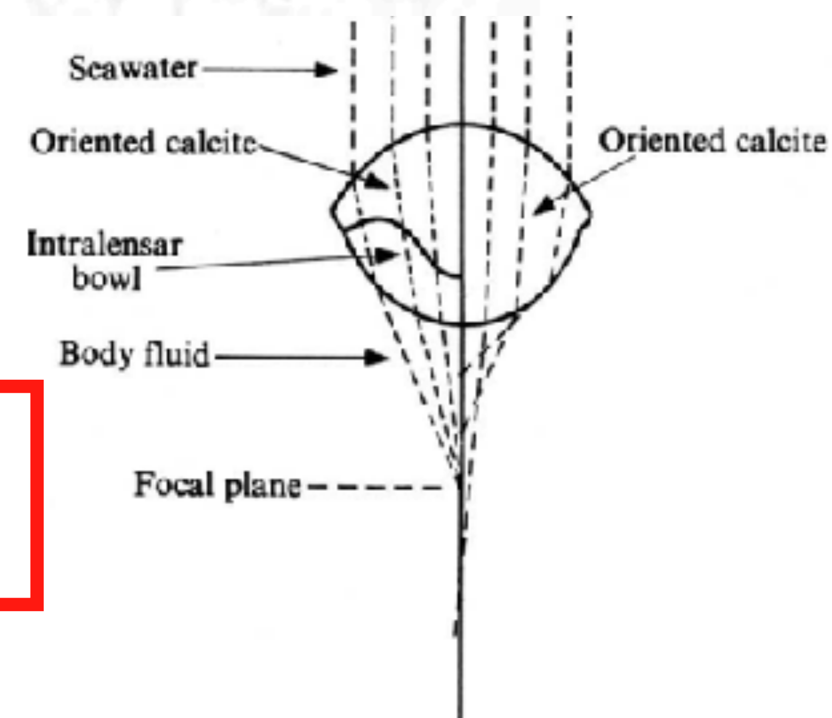
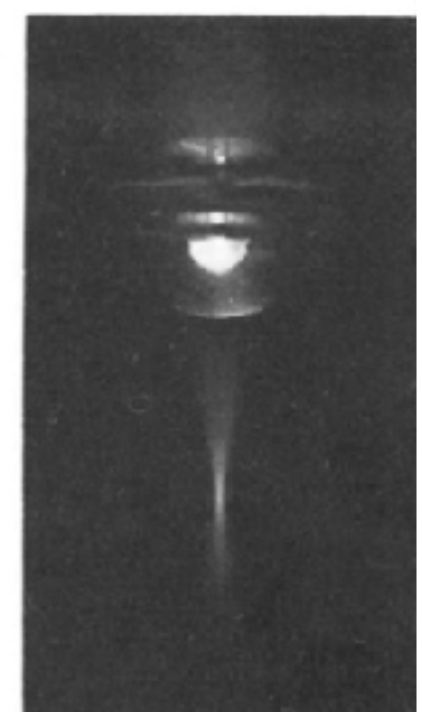
The Department of Physics, and The Enrico Fermi Institute, The University of Chicago, Chicago, Illinois

The thick lenses in the aggregate eyes of a group of trilobites were doublet structures designed to eliminate spherical aberration. The shape of the optically correcting interface is in accord with constructions by Des Cartes and Huygens and is dictated by a fundamental law of physics. Trilobites may have evolved such sophisticated eye-lenses to maximise optic neurone response in a dimly lit environment.





SCIENTIFIC REPORTS

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Discovery of some 400 million year-old sensory structures in the compound eyes of trilobites

SUBJECT AREAS:
ZOOLOGY
CELLULAR IMAGING
NEUROPHYSIOLOGY
PALAEONTOLOGY

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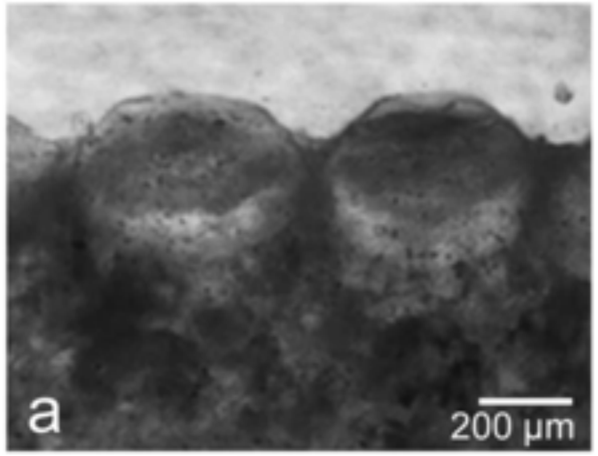

Consideration 1

Nowadays the technology is everything that can achieve labor efficiency, an objective that was unnecessary in antiquity when labor was cheap, but also organic to different political and social structures.
For Seneca (*Ep. 90.7-9*), the task of the scientific knowledge (*philosophia*) was not to create machinery (*fabricae*); moreover, he "disliked" devices designed to economize in labor or promote comfort as they encouraged idleness and complacency (*luxuria*).

Consideration 2

The use of lenses in the past in the "classical" ancient western World (Rome, Greece and the Middle East) is still a matter of controversy and their possible purpose is by no means clarified. Old "lenses" in the form of spherical-like glass object and their purpose could have been for decoration (jewelry), religious purposes, ignition of fire or even magnification. The possible development of optics by other ancient cultures (China, India, the Incas etc.) is certain, but there is a lack of information, source, materials, etc..

Conclusions

No matter of the role played in science and also in the evolution of the species on the Earth, optics will continue to play a great role in the next decades.
It will continue to support the astronomy and the physical sciences, but will certainly contribute also to quantum optics and its applications in all scientific disciplines.

Acknowledgements

A special acknowledgment is due to Adolfo Savoia that introduced me to optical problems long time ago at the LNF.

Thanks to Emilio Burattini who supported many optical researches I performed in THz, IR, UV, soft x-ray and x-ray at Frascati and all over the world.

A lot of friends, sharing with me day & nights at synchrotron radiation facilities running experiments, for the many stimulating discussions, great ideas and the pleasure to talk about the beauty of science.

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Thanks for the attention

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