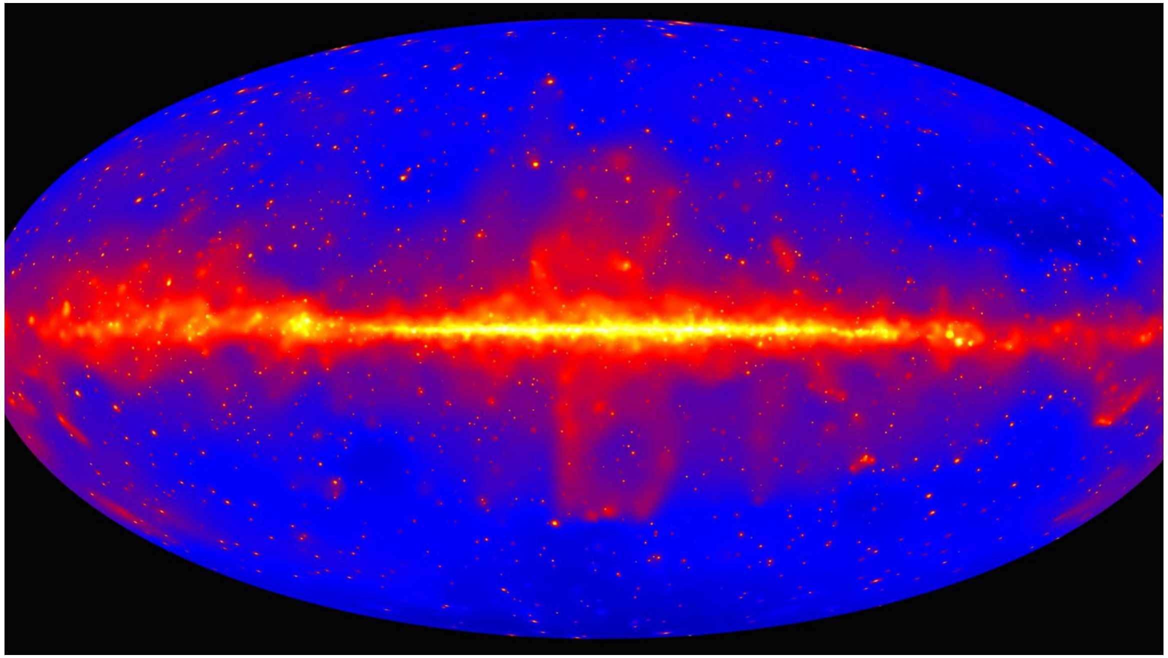
A SHORT HISTORY OF THE PHOTON

Fulvio Parmigiani



«I therefore take the liberty of proposing for this hypothetical new atom, which is not light but plays an essential part in every process of radiation, the name photon.»
Gilbert N. Lewis, 1926

PROLOGUE

- The notion of photon, as well as that of photonics is relatively recent and still debated. Conversely, the notion of light is thousands years old.
- Nonetheless, the roots of this "granular " representation of what today we know as electromagnetic energy is faraway in time, while the idea of “particle of light” does not involve only physics.
- The disciples of a sixth century BC branch of Hindu philosophy called Vaisheshika had a surprising physical intuition about light. Like the ancient Greeks, they used to believe the world was based on ‘atoms’ of earth, air, fire, and water. Light itself was thought to be made of such very fast-moving atoms called *tejas.*

SOME LIGHT PHENOMENA

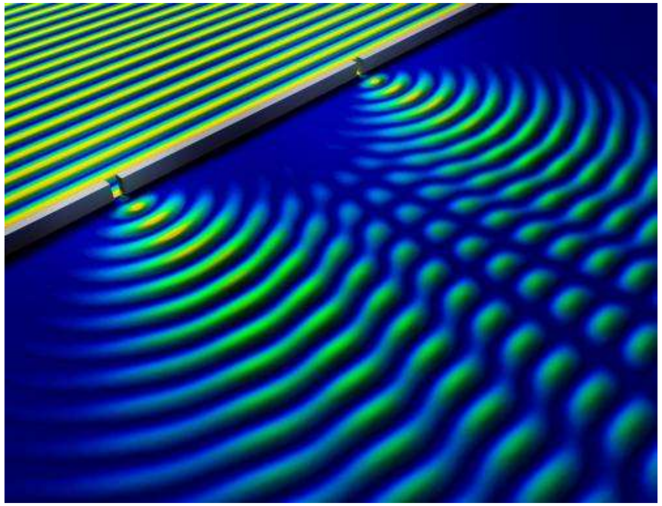
LIGHT DISPERSION

European scientist in the 16th and 17th century or Persian mathematician and physicist al-Farisi (1260–1320)AIP Conference Proceedings **899**, 849 (2007)

LIGHT DIFFRACTION

Known from the ancient times. The effects of diffraction of light were first carefully observed and characterized by Francesco Maria Grimaldi

LIGHT INTERFERENCE



Thomas Young's double slit interferometer in 1803 demonstrated interference fringes when two small holes were illuminated by light from another small hole which was illuminated by sunlight

WHAT WE KNOW TODAY ABOUT PHOTONS

The **PHOTON** is a type of elementary particle. It is the quantum of the electromagnetic field including electromagnetic radiation such as light and radio waves, and the **mediator particle** the electromagnetic **interactions**.
PHOTONS are massless, so they always move at the speed of light in vacuum, 299792458 m/s.
The **PHOTON** belongs to the class of bosons.

PHOTON PROPERTIES

PHOTONS have ZERO MASS and **NO rest energy**. They **only exist as moving particles**.
PHOTONS have **no electric charge but electric and magnetic fields.**
PHOTONS are **spin-1 particles which makes them bosons**.
PHOTONS **carry energy and momentum** which are dependent on the frequency.
PHOTONS can **interact with other particles** such as electrons.
PHOTONS can **be destroyed or created** by many natural processes, for instance when radiation is absorbed or emitted.
WHEN there are **no PHOTONS in a "mode"**, still there is some energy: **the zero field energy**.

CAN WE DEPICT A PHOTON?

PRL **109,** 053602 (2012) PHYSICAL REVIEW LETTERS week ending 3 AUGUST 2012

Adaptive Detection of Arbitrarily Shaped Ultrashort Quantum Light States

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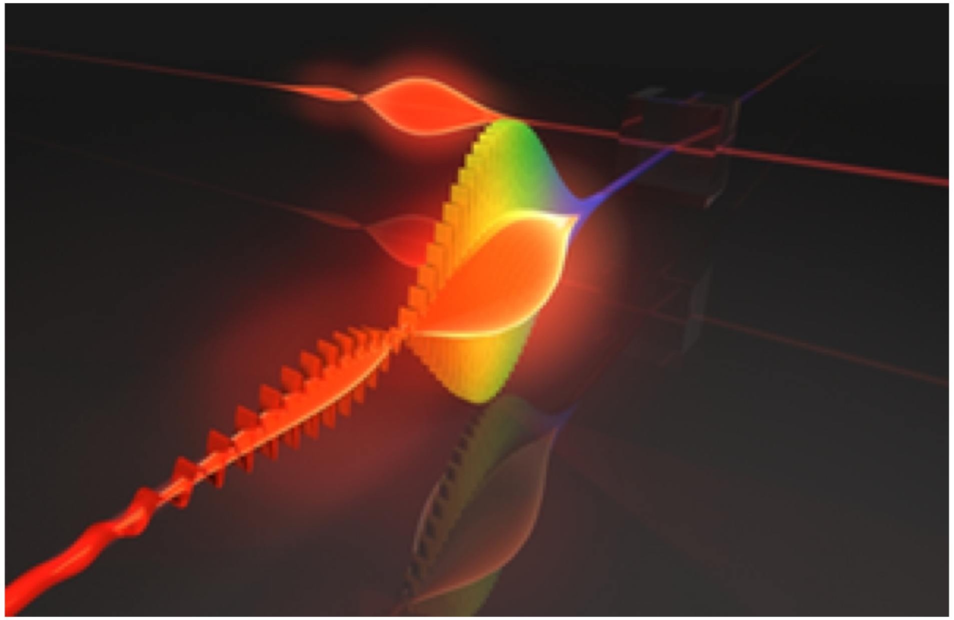
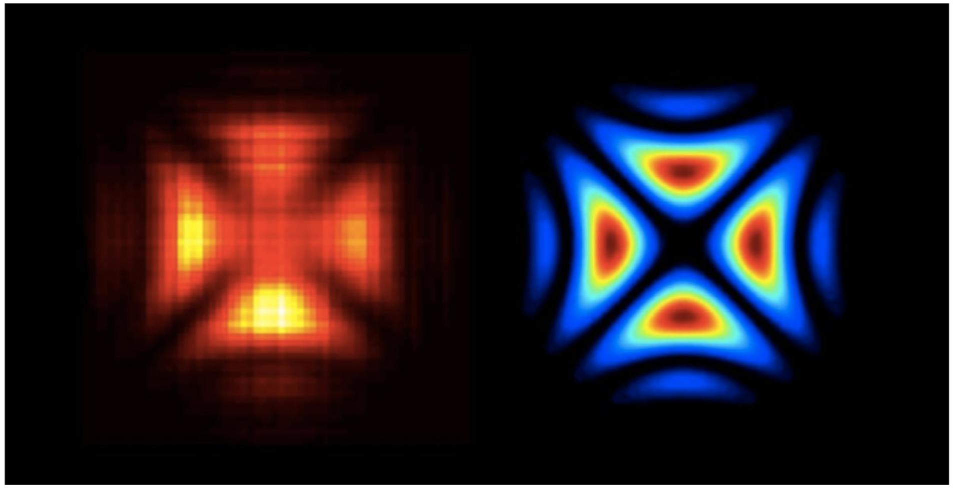
A quantum state of light is the excitation of a particular spatiotemporal mode of the electromagnetic field. A precise control of the mode structure is therefore essential for processing, detecting, and using photonic states in novel quantum technologies. Here we demonstrate an adaptive scheme, combining techniques from the fields of ultrafast coherent control and quantum optics, for probing the arbitrary complex spectrotemporal profile of an ultrashort quantum light pulse. The ability to access the modal structure of a quantum light state could boost the capacity of current quantum information protocols.



LETTERS
PUBLISHED ONLINE: 18 JULY 2016 | DOI: 10.1038/NPHOTON.2016.129
nature photonics

Hologram of a single photon

Radosław Chrapkiewicz, Michał Jachura*, Konrad Banaszek and Wojciech Wasilewski



AN INTRINSIC PROBLEM

Despite the effort to make the modern science, and in particular the physics, ”an objective knowledge”, it **remains anthropocentric**.

2001: A Space Odyssey, S. Kubrick

A FUNDAMENTAL QUESTION

- Nonetheless, our **imagination and creativity** are not intrinsically part of the Universe. Is this what we use for modeling the Universe and the Nature?

2001: A Space Odyssey, S. Kubrick

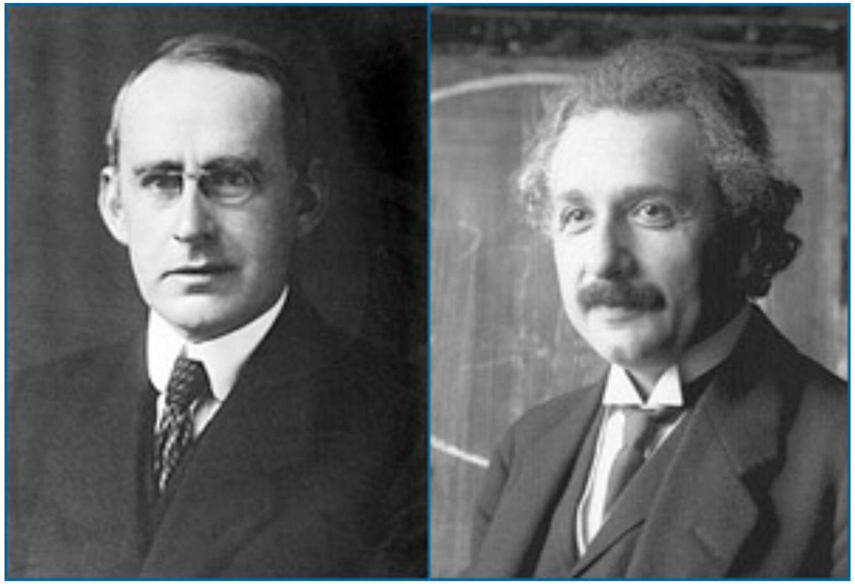
AN ELUSIVE PARTICLE

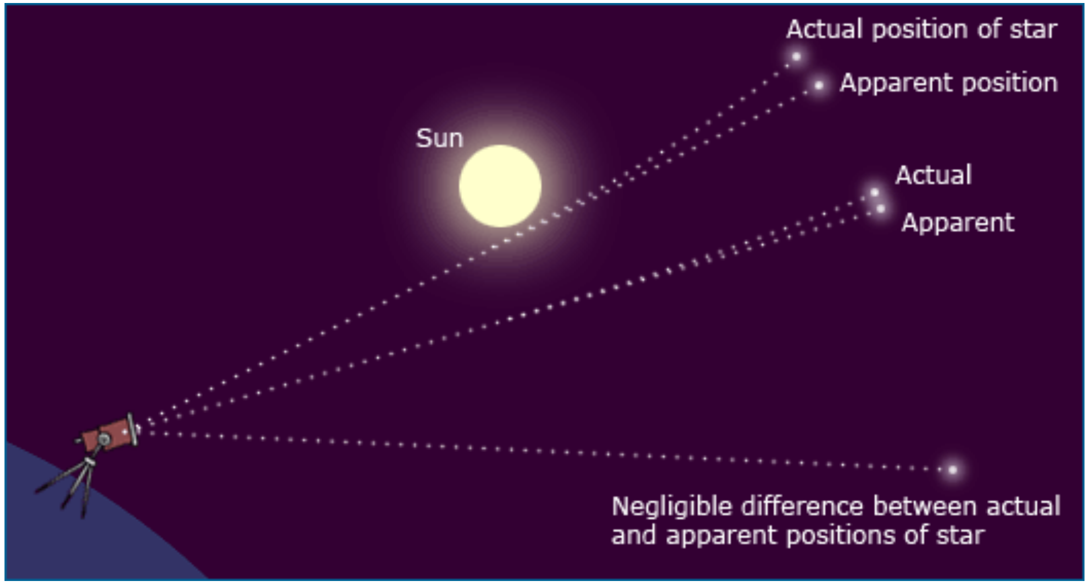
- In spite of all what we know, PHOTON is still an elusive particle, an insuperable sphinx.

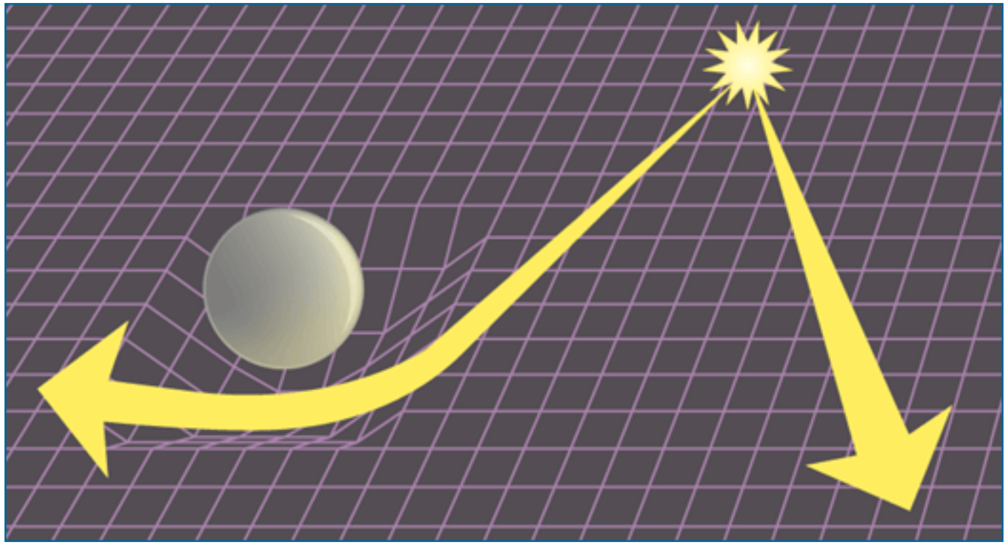
It is enough to allude to the fact that photon has no mass but it is subject to mass effects, as an outcome of the mathematical singularities emerging from the general relativity field equations, today known as black holes, from which gravity even the photon cannot escape.

EINSTEIN'S RELATIVITY AND EDDINGTON'S EXPERIMENT

Eddington experiment that confirmed the prediction of Einstein's general relativity that provides the trajectory of light curved by the presence of a large mass.







LIGHT AND THE BLACK HOLE

The surface $r = r_s$ demarcates what is called the event horizon of the **black hole**. It represents the point past which light can no longer escape the gravitational field. Any physical object whose radius R becomes less than or equal to the Schwarzschild radius has undergone gravitational collapse and become a **black hole**.

LECTURES OUTLOOK

- In the **FIRST LECTURE** I will provide a fresco of the historical and philosophical roots that give rise to the idea of photon. This period will extend from the ancient philosophers to the Newton's Era.

- In the **SECOND LECTURE** we will immerse ourselves in the crucible where classical physics evolved into quantum physics and the history of the photon will be our guide to review opposing ideas in comparison and ideological clashes between the giants of physics of '800 and '900.

- In the **THIRD LECTURE** we will enter the world of the photon with its physical, epistemological, technological and social implications.

- In the **LAST LECTURE**, as in the crescendo of a great polyphonic symphony, we will follow, step by step, what today we can define a fundamental mutation of quantum physics born from the head-on collision between two schools of thought on the completeness of quantum mechanics and therefore two ways of understanding physics. What will emerge is a physics bearer of the idea of zero point energy and then the idea of quantum vacuum, explaining the interference and diffraction produced by single particles (massive and massless) violating the principle of space-time superposition so far used to explain physical phenomena.

However, before starting we need to set some concepts, as a sort of guideline in order to argue on the same logical basis and with the same language.

SOME COMMON CONCEPTS AND DEFINITIONS

❖ SCIENCE

A possible definition is that Science is **organized knowledge.**
In general, the knowledge base of Science is reproducible data, numbers obtained under controlled conditions.
This simple but effective definition set also the boarder line between the ancient definition of science with its aphorisms and what today we call scientific knowledge.

❖ THE SCIENTIFIC METHOD.

The set of procedures that involve not only logical consistency but falsifiable hypotheses (Falsifiability was introduced by the philosopher of science **Karl Popper** in his book *Logik der Forschung* (1934, revised and translated into English in 1959 as (***The Logic of Scientific Discovery***), and their experimental testing as well as exploratory observations. «**A theory is falsifiable if it is contradicted by *possible observations***—i.e., by any observations that can be described in the language of the theory, which must have a **conventional empirical interpretation**. For example, the statement "All swans are white" is falsifiable because "Here is a black swan" contradicts it. »

❖ PHYSICS

Concepts—models of nature—that can be translated into mathematical terms, i.e. into tractable equations. These equations, in turn, allow one **to obtain mathematical formulas with which to predict numerical values that are expected to result from particular measurements (expectation values)**.

❖ MATHEMATICS.

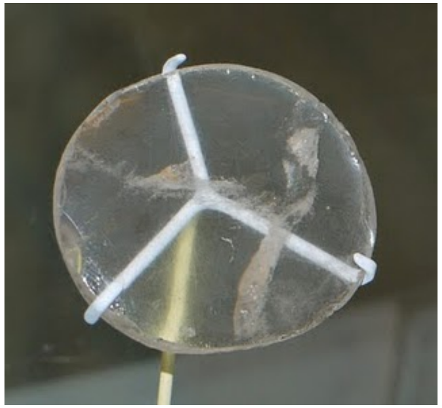
Photon is a physical concept, and physics relies on mathematics, so any understanding of photons must include some understanding of Mathematics. **But math and physics, though linked, do not stand on the same foundations.**
Mathematicians are free to propose any set of axioms, any rules for their symbols, from which they then deduce theorems, corollaries and lemmas—and display their ingenuity. It is only necessary that their structures—the rules of algebras and groups and so on—be free of hindering contradictions.
By contrast, physics is expected to conform to observations of nature, not just to be consistent within their mathematics.

Sometimes mathematics and science converge, but this is not a necessary condition. As I tought to my students of Electrodynamics, Physics is inconsistent with the idea of infinite, size-less objects, zero or empty space.

HISTORY OF LIGHT IN A NUTSHELL

ANCIENT TIMES

Light is derived from the Latin "lux lucis" from the Indo-European root leuk-. The corresponding term in Greek is λευκός, "bright, white." **A particular meaning of light in Greek occurs with φῶς (phaos/phōs)** whose root corresponds to that of the verb phainō, meaning "to show," "to make manifest." The Greek word "**φῶς"** originally denotes not only light as a means of seeing, but also **the light that emanates the truth attained through knowledge.**



To date, the earliest lenses identified in context are from the IV/V Dynasties of Egypt, dating back to about 4,500 years ago (e.g., the superb `Le Scribe Accroupi' and `the Kai' in the Louvre; added fine examples are located in the Cairo Museum). Latter examples have been found in Knossos (Minoan [Herakleion Museum]; ca. 3,500 years ago)

Aristotle (384 B.C.-322 B.C.) was the first to develop a concept of light that, despite its apparent immateriality, **<u>is fundamental to the corporeity of the universe</u>**.
Thus, light is the basis of animate and inanimate physical being.
Vision, and in particular color vision, was of great importance in the speculations of Greek philosophers. Two hypotheses were compared about the origin of images, one emissive, the other intrusive.

Credits: http://www.anisn.it/matita_ipertesti/visione/scienza%20greca.htm

Pythagoras (c 582 - c 500 B.C.) believed that the eye behaved like a beacon of the soul; that is, it emanated light to explore its surroundings and enable knowledge. On the contrary, **the atomists**, whose most significant exponent is Democritus, believed that light moves from the object towards the eye, causing vision.

Plato (427-347 B.C.) supported an intermediate position: there is a double direction of the communicative action of "heat" that impresses the eye, causing the vision; the external heat and the internal one coming from the brain impress the eye determining the perception.

Euclid (IV-V B.C)), in the book Optics formulated the hypothesis that **the visual rays**, which also according to his model came from the eye, **propagated in a straight line** and understood that the apparent size of an object could be calculated based on the angle formed by the straight lines drawn from the apex and base of the object observed to the eye of the observer. He also verified that closer objects appear larger and move apparently faster; and he was able to measure the height of distant objects by the length of the shadow cast by them.

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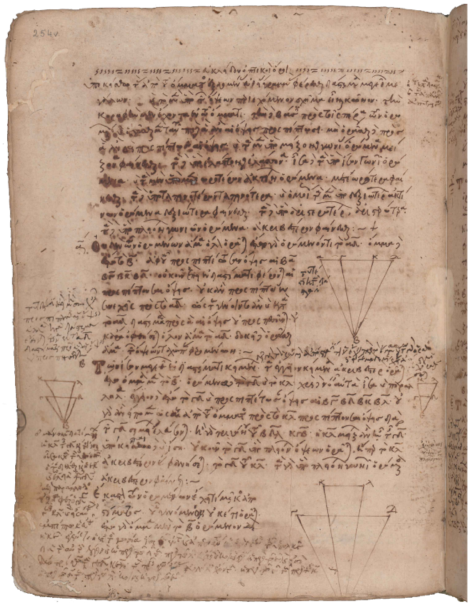

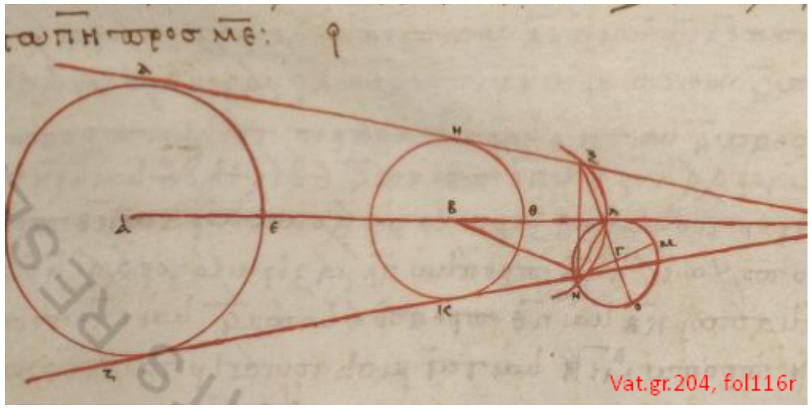

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ARABS

The study of vision and optics was of great interest in the Arab world.
Avicenna (980-1037) and Averroè (1126-1198) deduced from Aristotle that **light is not corporeal**, **because it does not occupy a space**, but when it **multiplies as a multiplicity of points then it materializes in a body**. The universe itself corresponds to its brightness and since matter cannot be infinite, light too stops at a final term.
http://www.anisn.it/matita_ipertesti/visione/scienza%20greca.ht

Imaginary debate between Averroes and third-century philosopher Porphyry. Monfredo de Monte Imperiali *Liber de herbis*, 14th century

THE MIDDLE AGES

The Englishman **Roger Bacon**, who had studied Arabic science, popularized the use of lenses and dreamed of a time when...images could be projected into the air, so that they could be seen by everyone....

Roberto Grossatesta (1168 - 1253), Referring to Genesis, according to which light gives form to matter, he stated:
... Lux est ergo prima forma corporalis ...
For the first time light is considered something material, so it is possible to assume that its characteristics, such as those that allow the vision, can be investigated through natural means. Towards the end of the 1200s spectacles appeared in Italy, the first models of which were perhaps imported by the Arabs. Slowly and laboriously, modernity was making its way.

[Robert Grosseteste: De Luce - On Light]

THE BIRTH OF THE MODERN SCIENCE

Jesuit **Francesco Maria Grimaldi** discovered the diffraction, the problem between the objective "**pictura**" and the subjective world that man distinguishes remained open; hypotheses based on mysterious correspondences between microcosm and macrocosm continued to flourish; suffice it to mention **Robert Fludd (1574-1637)**, a medical alchemist of the time.

Even the use of lenses was considered an artifact: who can say that the lens is not a tool to see things that do not actually exist? It is no coincidence that many Aristotelians refused to look **into G. Galileo's telescope (1564-1642**). In the debate also intervened **Thomas Hobbes (1588-1679)** that in his works argued that **light propagated instantaneously** in a medium through a wave front; according to the English philosopher vision did not consist simply in a response to mechanical stimulation that hit the eye, **but involved a process of active learning**.

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The Dutch physicist **Huygens (1629-1695),** trained at the school of Cartesian mechanics, sketched a wave theory of light in the **Treatise on Light** (1690); the theory was based on the one developed by Hooke in 1665 and helped to open the debate on whether light was corpuscular or made of waves.

John Kepler (1571-1630) formulated the hypothesis that **the crystalline lens played a fundamental role in vision, allowing the rays of light to focus within the eye orbital cavity**. **Kepler's work was fundamental for the subsequent development of modern optics, of which he can rightly be considered the founder.**

Galileo made his earliest observations in 1609, thanks to improvements he had made to the first telescope, developed by Dutch opticians. In the space of a few months, he obtained much sharper images while increasing the telescope's magnification power 30 times. In the autumn of 1609, he was able to contemplate the already known stars and planets in new and greater detail. He observed, for the first time, the Milky Way, the irregular surface of the moon, sunspots and the phases of Venus. Most importantly, he discovered Jupiter's four satellites.
(Christophe Roulet, FHH Journal 2010)

Isac Newton in 1672, as author of **OPTICKS**. In a famous experiment he clarified the nature of colors from a physical point of view and pioneered of the theory that identified the light with corpuscolar. The **corpuscular theory of light**, arguably set forward by Descartes in 1637, states that light is made up of small discrete particles called "corpuscles" which travel in a straight line with a finite velocity and possess impetus. This was based on an alternate description of atomism of the time period. He notably elaborated upon it in 1672.

The father of mechanicism**, René Descartes (1596-1650),** also brought fundamental contributions to the debate, although his ideas were criticized by many contemporaries, such as the great Jesuit Athanasius Kircher.

While the French philosopher **had assumed that light moved at infinite speed**, the studies of **the Danish Ole Rømer (1644 - 1710) allowed to understand that it had a very high but finite speed**; the scientist obtained his data in 1675, thanks to the study of eclipses of Jupiter's satellites

This early conception of the particle theory of light was an early forerunner to the modern understanding of the photon. This theory cannot explain refraction, diffraction and interference, which require an understanding of the wave theory of light of Christiaan Huygens.

THE METHOD AND THE THEORY

GALILEO GALILEI : THE METHOD

SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

ISAC NEWTON: THE THEORY

behind the Glaſs at *a*, from whence any Rays AB, AC, AD, which flow from one and the ſame Point of the Object, do after their Reflexion made in the Points B, C, D, diverge in going from the Glaſs to E, F, G, where they are incident on the Spectator's Eyes. For theſe Rays do make the ſame Picture in the bottom of the Eyes as if they had come from the Object really placed at *a* without the interpoſition of the Looking-glaſs; and all Viſion is made according to the place and ſhape of that Picture.

Fig. 2. In like manner the Object D ſeen through a Priſm appears not in its proper place D, but is thence tranſlated to ſome other place *d* ſituated in the laſt refracted Ray FG drawn backward from F to *d*.

Fig. 10. And ſo the Object Q ſeen through the Lens AB, appears at the place *q* from whence the Rays diverge in paſſing from the Lens to the Eye. Now it is to be noted, that the Image of the Object at *q* is ſo much bigger or leſſer than the Object it ſelf at Q, as the diſtance of the Image at *q* from the Lens AB is bigger or leſs than the diſtance of the Object at Q from the ſame Lens. And if the Object be ſeen through two or more ſuch Convex or Concave-glaſſes, every Glaſs ſhall make a new Image, and the Object ſhall appear in the place and of the bigneſs of the laſt Image. Which conſideration unfolds the Theory of Microſcopes and Teleſcopes. For that Theory conſiſts in almoſt nothing elſe than the deſcribing ſuch Glaſſes as ſhall make the laſt Image of any Object as diſtinct and large and luminous as it can conveniently be made.

I have now given in Axioms and their Explications the ſumm of what hath hitherto been treated of in Opticks. For what hath been generally agreed on I content my ſelf to aſſume under the notion of Principles, in order to what I have further to write. And this may ſuffice for an Introduction to Readers of quick Wit and good Underſtanding not yet verſed in Opticks: Although thoſe who are already acquainted with this Science, and have handled Glaſſes, will more readily apprehend what followeth.

PROPOSITIONS.

PROP. I. Theor. I.

LIGHTS which differ in Colour, differ alſo in Degrees of Refrangibility.

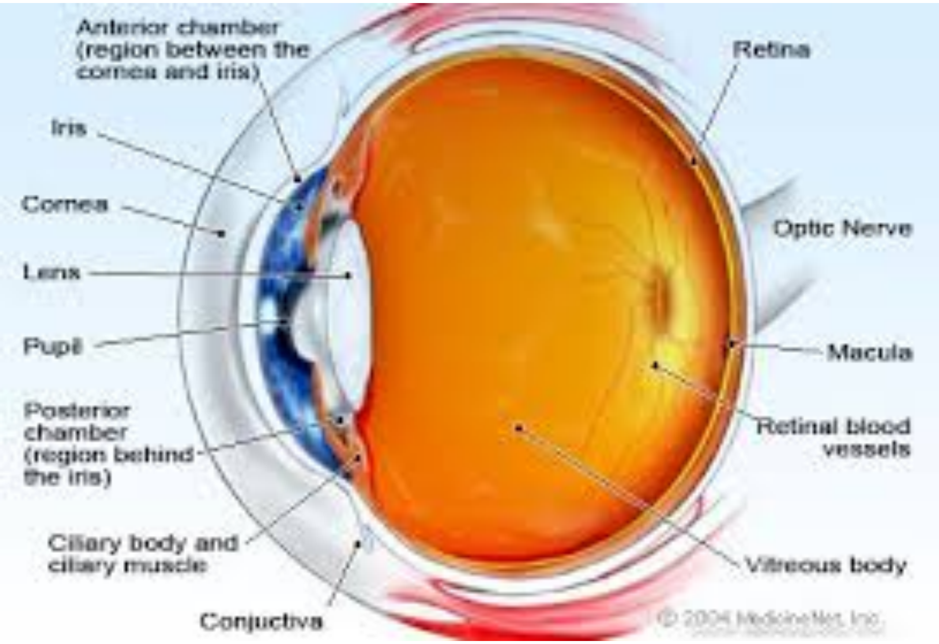
The Proof by Experiments.

Exper. 1. I took a black oblong ſtiff Paper terminated by Parallel Sides, and with a Perpendicular right Line drawn croſs from one Side to the other, diſtinguiſhed it into two equal Parts. One of theſe Parts I painted with a red Colour and the other with a blew. The Paper was very black, and the Colours intenſe and thickly laid on, that the Phænomenon might be more conſpicuous. This Paper I viewed through a Priſm of ſolid Glaſs, whoſe two Sides through which the Light paſſed to the Eye were plane and well poliſhed, and contained an Angle of about Sixty Degrees: which Angle I call the refracting Angle of the Priſm. And whilſt I viewed it, I held it before a Window in ſuch manner that the Sides of the Paper were parallel to the Priſm, and both thoſe Sides and the Priſm parallel to the Horizon, and the croſs Line perpendicular to it; and that the Light which fell from the Window upon

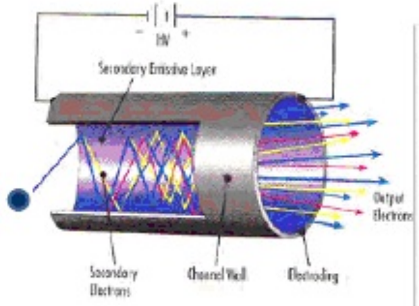
AN EXPERIMENTAL PROBLEM
AND
A CONCEPTUAL QUESTION

HOW NATURE DETECTS LIGHT

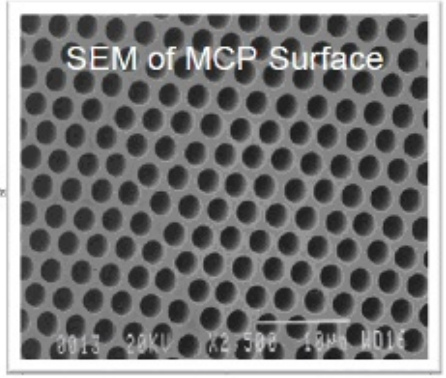
In 1688 **William Molyneux (1656-1698)** entered the debate on the mechanisms of vision, sending a letter to John Locke (1632-1704) in which was formulated a crucial question: can a man blind from birth, once recovered the sight, distinguish objects with the sole help of this?



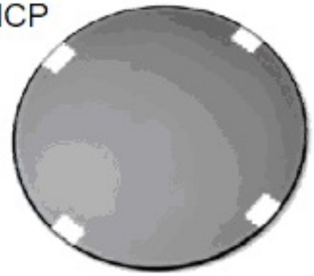
LIGHT DETECTION AND PHOTON DETECTION



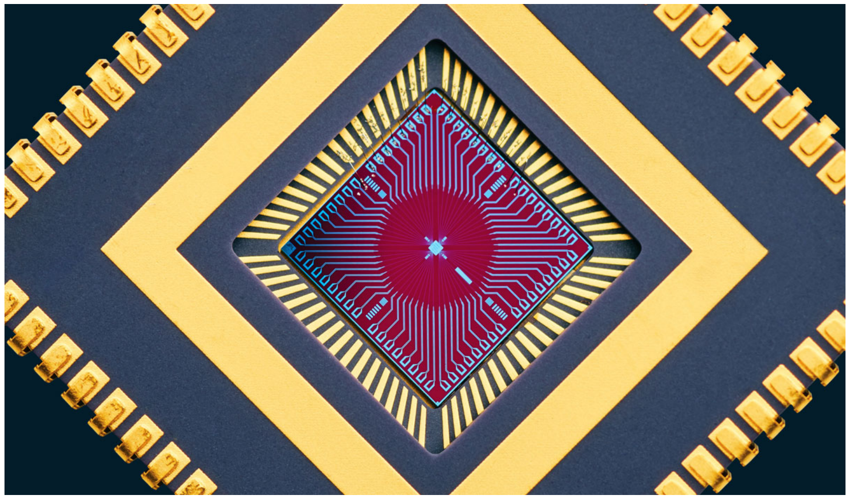
Single MCP Pore



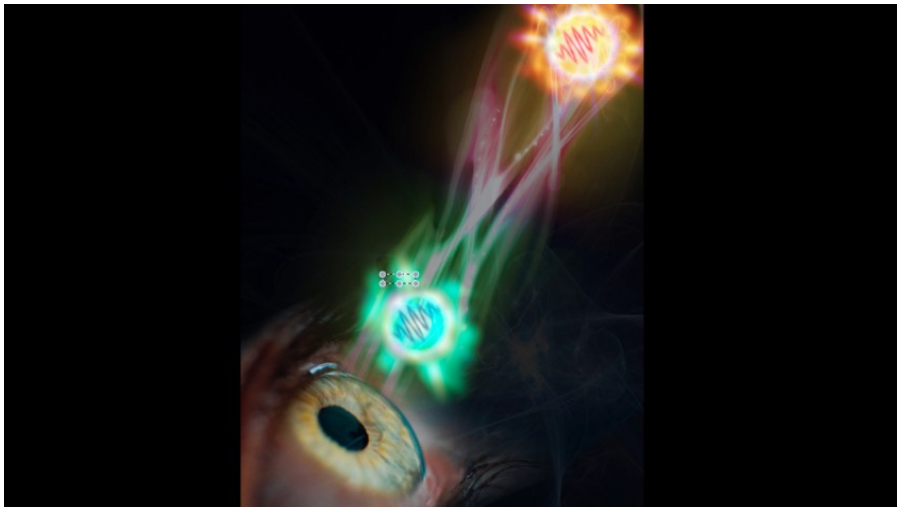
MCP



Photonis Technologies S.A.S



Superconducting Nanowire Single Photon
JET Propulsion Lab. CALTECH



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http://dbserv.ihep.su/hist/owa/hw.fulltextlist_txt downloads of many primary texts
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https://www.mpq.mpg.de/5020834/0508a_photon_statistics.pdf experiments on photon statistics https://www.sheffield.ac.uk/polopoly_rpfs/1.14183!/file/photon.pdf What is a photon?

http://space.mit.edu/home/tegmark/PDF/quantum.pdf http://mediathek.mpiwg-berlin.mpg.de/mediathekPublic/versionEins/Conferences-Workshops/ HQ3/Quantum-Optics/Joan-Bromberg.html

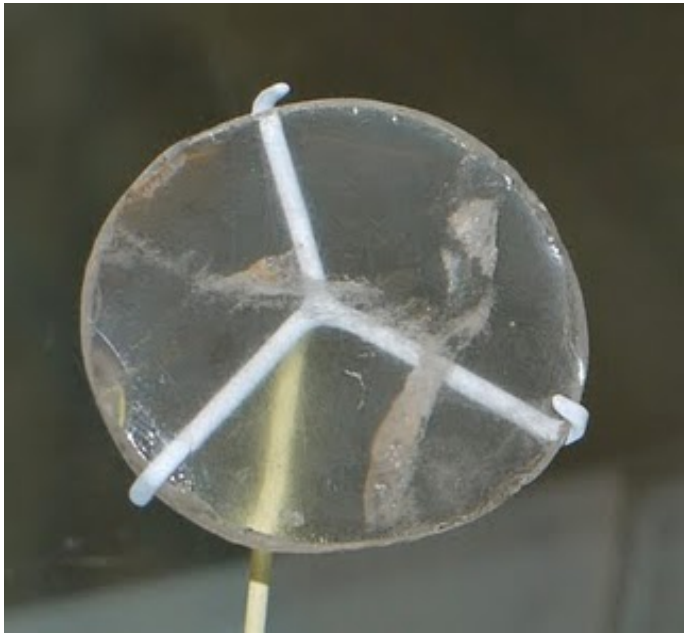
https://www.researchgate.net/post/How_do_you_visualize_a_photon

https://physics.stackexchange.com/questions/273032/what-exactly-is-a-photon

http://www.nature.com/milestones/milephotons/index.html 23 Nature Milestones Photons httpa://indico.cern.ch/event/423687 Proceedings of the Warsaw Conference 2005 on "The Photon: Its First Hundred Years and the Future"

http://inspirehep.net/record/1623145/files/grangier.pdf on Grangier's experiments with single photons 2005

END FIRST LECTURE



To date, the earliest lenses identified in context are from the IV/V Dynasties of Egypt, dating back to about 4,500 years ago (e.g., the superb `Le Scribe Accroupi' and `the Kai' in the Louvre; added fine examples are located in the Cairo Museum). Latter examples have been found in Knossos (Minoan [Herakleion Museum]; ca. 3,500 years ago)