What is light?

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These are notes for a talk given in Waterstone’s bookshop on 27th May 2015 entitled ‘Let there be light’. They were not read out but formed the background to what was said. The aim of the talk was to give an overview of people’s changing perceptions of the nature of light since ‘antiquity’. In particular to highlight how early ideas on the nature of light were wrong and it took some two millennia of questioning before the foundations of today’s views were laid. Although light is now understood to the extent that we can develop impressive light-based technology, the quantum aspect of light still shows it to be a weird phenomenon.

The United Nations (UN) has declared the year 2015 as the International Year of Light and Light-based Technologies – IYL2015. These subjects cover a great sweep of daily and scientific experience. Although this is Café Scientifique, I’m not going to dwell much on light-based technologies. I’d like to invite you this evening in this final meeting of the season to think about the question ‘what is light?’ It’s a subject that’s interested me for a long time. 2015 has been chosen because it celebrates a number of significant anniversaries in the history of understanding the nature of light. I’ll come to these in due course.

To begin where most people begin when talking about light: the 3rd sentence of the biblical creation story is one of the best known sentences in the whole bible. “And God said, let there be light, and there was light”. In this story, light was almost the first thing to be created; the Sun, was only created on the 4th day. In modern cosmology, light also preceded the creation of the Sun by billions of years, for the Sun is a 3rd generation star. But for mankind, sunlight has always been the most important source of light. It was because of sunlight that our evolutionary predecessors developed vision. So closely has light been associated with vision that our ancestors considered that understanding light and understanding vision were one and the same challenge. This was their first mistake.

Imagine yourself not knowing any modern science about light but trying to understand sight, as some of the philosophers of antiquity were trying to do two to three millennia ago. What did they come up with?

When we smell a rose, for example, tiny pieces of the rose diffuse through the air and are detected by our noses and we identify the rose perfume. The pieces are so small that there is really no obvious reduction in the rose itself. Diffusion is a slow process but maybe light and vision are a bit like the sense of smell, only much faster. Objects emit narrow skins or ‘husks’ that define their colour and shape, like almost infinitesimal onion skins. One significant school of Greek philosophy that lasted several centuries called these embodiments of the object the eidola. The eidola travel straight through the air to our eye and we when they reached us we see the shape and colour of the object. It’s not such a preposterous idea. A heat haze above the ground produces a distortion of the eidola as they come to us so looking through a haze we see a distorted and shimmering image. To put it more into modern language, there really are only two possibilities when we see something: either images we see
are transmitted through the air to us or they are formed in our eyes. Eidola were the first hypothesis.

The concept of eidola persisted into Roman philosophy and can be found for example in Lucretius’ *De Rerum Natura* written about 50 BC. In fact using different words the concept lasted a thousand years longer. ‘Eidola’ wasn’t the only idea in Athens and Rome. It had to compete with the alternative idea promoted by Pythagoras, Archytas and many others that some kind of ‘fire’ emanated from our eye to give us the power of seeing. Euclid, the mathematician from around 300 BC, is credited with two works on optics that promote the concept of a ray of sight travelling in straight line. However, Euclid’s rays come from the eye. Euclid’s ideas and those of like-minded philosophers persisted for over 5 centuries. I don’t want to spend any more time on ancient concepts because the fact is that they were confused; they jumbled facts geometric and physical, facts physiological and psychological. It is also quite difficult for us over 2000 years later to correctly translate exactly the concepts that were in the minds of ancient philosophers.

It’s perhaps unfair to say that early scholars simply contributed their fantasies but the fact is that they failed to take what would be the crucial step many, many centuries later, namely to conduct investigations and experiments to find out how light actually behaved. What I take away from reading about early efforts to understand light is that in spite of much introspection on the whole issue of seeing, of colour, of reflection, of the bending of light by water, brilliant minds failed to find the appropriate concepts. Nobody in ancient times knew what light was, or indeed how vision worked.

Unfortunately for many centuries that’s about as far as it got. One needs to look to Arabic scholars for the next stages of enlightenment. Alkindi living in Iraq around 850 AD clearly separated the physical medium ‘light’, emitted by sources and travelling along rays in straight lines, from the physiological processes of vision, which he realised were much more complicated to understand.

The first ‘anniversary’ marked in the International Year of Light is that of 1015, one millennium ago, celebrating the work of the Egyptian scholar Abu Ali Mohammed Ibn Al Hassan Ibn Al Haytham, usually known as Alhazen. Alhazen’s *Optical Thesaurus* is the first book of the last millennium that approached the subject with new thoughts and indeed he conducted experiments to clarify his ideas. For example he observed the appearance on a screen of candles placed in a row in front of a hole. This told him that light from one object didn’t interfere with light from another object, so each object can be treated independently. Indeed each point on each object independently created its own image. His experiments were centuries ahead of what his monastic counterparts in Europe were doing.

Alhazen investigated light as the means of vision. He considered that since refraction bent and weakened light, only the light that came straight from each point on an object caused the image in the eye. He correctly deduced that the whole image was the compound of the images of its composite points. This overcame the objection of how the ‘husk’ of a mountain could get through the tiny pupil of the eye but he still thought that the function of rays of light
was to guide the ‘husks’, somehow. He incorrectly saw the crystalline lens at the centre of the eye as the image detecting organ, since the image was the right-way up on the surface of the lens.

The fact was that 1000 years ago the concept of a ray of light was not clearly formulated. There was something coming in straight lines from objects that steered their husks to the eye. Alhazen was by far and away the most modern in his thinking. He prophetically described the bending during refraction as due to the greater resistance met by light in travelling through denser bodies. Just as a sword cutting wood at an angle is bent from its path by the greater resistance of the wood. Each era has just the analogies available that the broader culture provides.

He interpreted the law of reflection as arising because the velocity parallel to the reflecting surface was unchanged but that perpendicular to the surface was reversed (as we would now say happens to a perfectly elastic ball). Alhazen’s works were intellectual light in the dark ages. Had they been widely disseminated then understanding light might have evolved several centuries faster than it did. Unfortunately Alhazen published in the same century that the Crusades were initiated by Pope Urban II and it was centuries before the Arabic wisdom was translated and influenced the largely Latin reading scholars of Christianity.

The problem with the middle ages, and the late middle ages in particular, was that European scholars became dogmatically obsessed with the ‘great masters’ of antiquity. Writers on philosophical subjects were paralysed by their admiration of the ancient texts. The authority of the masters, Aristotle in particular when it came to studies of nature, trumped all new ideas. Although lenses had been discovered in the late 1200s to help failing eyesight, not by academics but by glass workers, there was a deep suspicion for centuries that lenses, mirrors and prisms were objects of trickery. Perhaps that was a carry-over from the lack of understanding in antiquity. The whole point of vision, they argued, is to allow you to see things where they actually are. Yet you see apparently behind a plane mirror that which you know is in front of the mirror. How can you believe anything that you see with mirrors? Lenses played even worse tricks. In this atmosphere, new insight into light wasn’t going to be found.

I’ll pass quickly by Vitelio, a Polish scholar whose treatise on optics written in 1270 by and large re-states Alhazen’s ideas without crediting him. The person who rightly gets the credit for laying the foundations of modern optics in the West is none other than Johannes Kepler, famed for his 3 laws of planetary motion. Kepler had thought the unthinkable with his planetary laws, planets orbiting the Sun in ellipses not orbits generated by circles. He brought this independence of mind to the subject of light. In 1604 he published an equally perceptive book on light entitled in Latin ‘ad Vitelionem Paralipomena’ (an Appendix to Vitelio). The title deliberately hid its unfashionable originality. Had there been censors in Einstein’s day he might have entitled his work on Special Relativity ‘an Appendix on Newton’s Laws of Motion’, or maybe an appendix on Maxwell’s Equations.
Kepler said pretty well for the first time what we would now teach in any primary school. Sources emit light. It travels in straight lines. It is reflected from objects. Every point on an object reflects light separately. We see the object or image located where the cone of light from a point originates. Kepler followed this in 1611 with his ‘Dioptrice’, discussing refraction and the behaviour of the much maligned lens. Indeed only months after receiving one of Galileo’s telescopes he described a different version using only convex lenses that soon became the version all astronomer’s used. Lenses were not a trick or illusion and their images could be believed. Kepler’s work was the academic foundation that underpinned the believability of what was seen through the new devices such as telescopes, microscopes, the camera obscura and more.

What I find extraordinary is that it took over 2000 years of thought by highly intelligent people to reach what we would today consider as the starting point for trying to understand the nature of light. Even Kepler couldn’t trace accurately the path of light through a lens, for he didn’t know exactly how much bending (refraction) the curved surface of the glass produced. The quantitative law of refraction was found by the Dutch mathematician Willebrord Snell in 1621 but not published until later.

It took time in the 1600s for the cloud of prejudice against optical instruments to disperse. Kepler was a Protestant in spite of being in the employ of the Holy Roman Emperor when he wrote his optical works and many either ignored him or failed to credit him at the time. A big contributor to the trouble that Galileo had with the authorities was that the Cardinals would not believe what they saw through his telescopes. It was all a trick, an illusion, at worst a deliberate deceit, at best a test of their faith.

Over several decades Kepler’s rationality won out and with a belief in images established as well as the laws of reflection and refraction, the scientific instrument maker or the optician could develop optical instruments without really worrying about the nature of light. They just needed to be able to work out the consequences of these laws applied to curved surfaces. Some scholars, though, continued to be interested in the nature of light. Where did these laws come from, they asked? It became apparent in the 1600s that there was much more to the story than had yet been found.

In 1662 the French mathematician Pierre de Fermat described what is known as Fermat’s Principle. This says that of all possible paths that light could take from source to receiver, it takes the path of least time. If the light is reflected from a mirror, application of this law gives the law of reflection; if it goes via a transparent body, application gives the law of refraction. If light consists of corpuscles of some kind as was widely believed, this made sense and surely must embody something fundamental about the nature of light.

When published it was highly controversial for the view of many was that light travelled infinitely quickly. ‘Least time’ implies that light travels at a finite speed but there is no everyday phenomenon that gives any indication that this must be so. Open your eyes and you see immediately the most distant mountain or even the stars. The idea that light travelled instantly was widespread. Every attempt to measure its speed had failed. It wasn’t until 1676
that the speed of light was first measured, by the Danish astronomer Olaf Roemer who was working in Paris.

Our local hero James Gregory, born and brought up in Drumoak and a graduate of Marischal College, was one example of the new breed of optical writers of the 1600s. In his book of 1663 *Optica Promota* (Optics Advanced) he began by saying that *nothing of any great consequence (as far as I know) has been handed down to us from antiquity*. The translation on the web is by former Aberdeen Natural Philosophy graduate Ian Bruce. He described light using the corpuscular model, though his work is largely mathematical. It includes the invention of the reflecting telescope, now the most common type of astronomical telescope.

By the mid-1600s there was a clear dichotomy between a corpuscular view of light – basically light is matter – (supported by Isaac Newton, for example) and a wave theory, promoted by Robert Hooke. Providing huge support for the wave theory in the 1670s, the Dutch natural philosopher and astronomer Christiaan Huygens wrote an astonishingly prescient work *A Treatise on Light*. Light, said Huygens, is motion not matter. Sources impress some kind of motion on a surrounding medium, a motion that spreads out as a wave. He described how such a wave propagated with an idea now called Huygens’ Principle. Huygens’ Principle can also explain the laws of rectilinear propagation, reflection and refraction equally as well as could Fermat’s Principle. It could do more, too. The wave-particle dichotomy of light wasn’t going to be solved easily.

There are no names bigger than Newton in the history of physics. He was, in the original sense of the word, a ‘natural philosopher’ and not someone particularly interested in developing optical instruments. His great contribution to optics was to emphasise the importance of experiments over rhetoric. In the 1660s and 1670s Newton carried out a range of fundamental experiments to try to understand the nature of light, including his famous experiments overturning one of the last of the Aristotelean doctrines to survive, namely that white light was pure light. Newton showed that white-light was a compound of all spectral colours. Newton assembled his work on this and many other experiments into a much read book called, simply, *Opticks*, first published in 1704. It was one of the first science books written in English and is a work full of *Proof by Experiment*.

Throughout the 18th century Newton’s ideas replaced the authority of Aristotle. If Newton said so, it must be true. His experiments were generally excellent and described and interpreted meticulously. However, he needed appropriate concepts both to guide what he did and to interpret what he found. Overall he nailed his flag to the wrong mast by dismissing the wave theory of light and trying to force the corpuscular model into explaining all his observations. For example, having found that different colours are refracted differently he attributed this to the light and not the refracting material such as glass or water. “Lights which differ in Colour, differ also in Degrees of Refrangibility” (p 16) as he put it. It was the erroneous deduction from this that made him devise his own reflecting telescope. Having discovered gravity, he became more and more convinced that light was composed of a stream of tiny corpuscles. He explained refraction by the force of attraction of a surface at close range to the incident corpuscles, a force at right angles to the surface. Such a force
would bend the path of light towards the normal. Since violet light is refracted most, then its corpuscles must be bent more than those of red light and hence must be different. Having been speeded up by the attractive force of the surface, the corpuscles must be travelling through the material faster than in air. Descartes was of a similar opinion. Sound travels faster through materials than through air, so why not light? In his ‘Opticks’ you can see Newton digging a deeper and deeper hole for himself but you can sense that he is thinking ‘this can’t be right’. In fact we know that light travels slower in liquids and solids than in air. No-one in the 18th century made good the defects in Newton’s corpuscular treatment of light.

Several sections within Opticks explore experiments that show the interference of light and the diffraction of light – both phenomena that are archetypical of wave motion. Diffraction involves light apparently bending round obstacles. It had been discovered and named by the Jesuit scholar Francesco Grimaldi who had become absorbed by the detail of shadows. It doesn’t sound a fascinating subject but Grimaldi discovered that when he looked closely at light it didn’t travel quite in straight lines. This was particularly conspicuous when light had to travel through narrow gaps, such as the gaps in a fine comb or through small holes. He had conducted many experiments in the 1640s and 50s and his work was published posthumously in 1665. We should add this to the official list of anniversaries celebrated by IYL2015, the 350th anniversary of Grimaldi’s perceptive work on the ‘physical mathematics of light’ as he called it, ‘de lumine’ as it’s usually abbreviated. Diffraction was his name. Newton carried out his own experiments, came to similar conclusions, called the phenomenon ‘inflexion’ and tried to fit it in to the corpuscular view of light.

In short, diffraction and its accompanying wave phenomenon of interference had been discovered in the 17th century but their significance was not understood. All that changed in the first half of the 19th century. Another anniversary celebrated by the international year of light is Augustin Fresnel’s first memoir on ‘the diffraction of light’ in 1815. He began what would be a series of papers setting out a proper theory of waves using the fairly newly worked out mathematics of waves to describe optical phenomena. Although his work describes a new theoretical approach it was based on a huge number of experiments he had conducted revealing new aspects of diffraction.

Fresnel’s work shows a nice interaction between philosophy and physics. He began with the mental picture that light was transmitted by a tenuous aether and therefore had to be longitudinal waves, just as sound waves were longitudinal waves in air. When he came to make experiments with polarised light that had been discovered by his countryman Malus, he realised that light had to be a transverse wave, for longitudinal waves could not show polarisation phenomena. By the end of Fresnel’s set of papers, some 10 year later, the old dichotomy between waves and particles appeared to be settled. Light was a wave. Of course there were eminent scientists who refused to change their minds but such was the success of Fresnel’s approach that the success of the wave theory was compared with the success of Newton’s theory of gravitation for predicting the motion of planets and moons.
[Malus was a confirmed Newtonian and when he discovered polarised light he attributed the
effect to light corpuscles having poles, like that of a magnet. Hence the word ‘polarisation’
which came from a mistaken view of the nature of light].

By now the physicists had taken over from philosophers and physiologists. In antiquity light
was seen as a subjective phenomenon at the heart of vision. Now light was seen as
something out there, as real as the tables and chairs in front of us with behaviour and
properties to be explained, of which vision was but one modest though important aspect.

The next anniversary is from 1865 and it concerns our greatest local hero, James Clerk
Maxwell. Maxwell was Professor of Natural Philosophy at Marischal College from 1856 to
1860. I’d say that without question he was the greatest professor Aberdeen has ever had, and
that includes our Nobel Prize winners. Had Nobel prizes been awarded in his lifetime he was
surely worthy of at least three. This year is the 150th anniversary of the publication of
Maxwell’s paper answering the question that you may well have asked yourself. If light is a
wave phenomenon, what kind of waves are light? Maxwell’s 1865 answer was that they
were waves of electricity and magnetism. The speed of light in air had been measured to
within a few percent and Maxwell was able to deduce this speed from measurements of
purely electrical and magnetic phenomenon. He also realised that radiant heat was
electromagnetic and in effect predicted a spectrum of electromagnetic waves. Maxwell died
at a young age and never lived to hear of the discovery of radio waves, X-rays and gamma
rays as other parts of the electromagnetic spectrum. Ultra-violet and infra-red had been
discovered earlier in the 19th century and are sometimes referred to as ‘dark light’.

Maxwell comes into this story in another way, too. It was while at Aberdeen that he laid the
foundation for the quantitative science of measuring colour. Colour had been investigated for
centuries but was seen as a largely subjective aspect of vision.

Before coming to Aberdeen Maxwell had made countless experiments with his spinning
‘colour top’ to convince himself that any colour could be matched by a suitable sum of three
primary colours whose intensity could be varied. His top had on the top a card of the colour
he wanted to match and three segments of cards of his chosen primary colours, typically red,
green and blue. The size of each segment could be varied. Spinning the top blurred the
segments together visually, producing a colour that could be compared with the one to be
matched. The idea of 3-colour mixing had been formulated by Thomas Young at the
beginning of the century from his own experiments and the postulate that there were three
kinds of colour receptors in our eyes.

In Aberdeen, Maxwell devised a new way of conducting 3-colour matching, using for this
three primaries three colours selected from the spectrum of sunlight. Different spectral
colours are simply different wavelengths of Maxwell’s electromagnetic spectrum. The
coordinates need to match a colour could be written mathematically and represented on what
is called Maxwell’s colour triangle. Any colour could now be quantified and specified by
three numbers so that someone else could exactly reproduce it. Colour science was born.
Now there was a reproducible way of measuring colour. Maxwell or anyone else could tell if
we all saw colours the same by comparing the colour matches we made. It turns out that about 92% of people do match colours very similarly but 8% are different. The first person in the world to have his colour deficiency measured, in 1859, was one of Maxwell’s students, James Simpson.

Following Maxwell’s work, a beam of light is now seen for many purposes as an electromagnetic wave with just a few properties: Frequency, wavelength, and 4 Stokes parameters that described its intensity and polarisation. That’s it for the non-quantum physicist. There are issues about perceived colour and illumination that bring in physiology and even psychology but they are another story.

Finally, the 20th century opens with Albert Einstein upsetting the unanimous 19th century view that light was just an electromagnetic wave described by Maxwell’s equations. 1905 is the first of the 20th century IYL2015 anniversaries, 110 years ago, the year Einstein introduced the quantum of light, later called the photon. He did so to explain the photoelectric effect. In this effect light shining on a well-chosen material liberates electrons which create a small current that could be amplified and measured. It’s an effect at the heart of modern day opto-electronic devices including still and video cameras, and if it comes to it the working of our eyesight. The photoelectric effect had very curious properties. For example a faint blue light could produce a photo-electric current from a clean metal surface but no amount of intense red light would produce any current even though the red light had very much more energy in it than the blue light. What was going on? Einstein realised that the energy in a beam of light came in discrete packets whose size was proportional to the frequency of the light. Red light has the lowest frequency and photons of red light don’t have enough energy to dislodge and electron from the metal. Since photons are absorbed one-at-a-time, no matter how many you have no photo-electrons will be liberated by red light. Blue light photons can be almost twice as energetic since they have almost twice the frequency and even the most feeble blue light may be able to liberate photo-electrons. Einstein seemed to be saying that light was corpuscular, coming in little quanta of energy, though they were not the corpuscles you knew, Isaac.

The photonic nature of light is why we can’t see into the infra-red. Infra-red photons haven’t the energy to liberate an electron at the back of the eye that starts the neural signal heading towards our brain saying ‘light detected’.

I’ll come back to photons after mentioning the last of the IYL2015 anniversaries involving the nature of light, namely the centenary of Einstein’s first publication on General Relativity in 1915. General relativity is a theory about gravity, light and energy. Two fundamental constants appear in the general relativistic equations, the strength of gravity and the speed of light in vacuum. These equations are at the heart of modern cosmology, our understanding of the universe at large, and in that understanding light plays a key role.

Einstein made other advances in optical science, amongst them finding the basic relationships that later allowed lasers to be developed. However, it was photons that puzzled Einstein throughout his life. They turned out to be very spooky customers. Interference patterns of
light and dark, for example, are described as being due to the interaction of two or more light waves that have been derived from the same original wave. Supposing you send through an apparatus that shows interference light that is so weak that only one photon can be in the apparatus at once. Does the interference pattern disappear? No it doesn’t. Each photon creates one tiny bit of the interference pattern and added up over many photons the whole light and dark pattern appears even though only one photon, the apparently unsplitable corpuscle of light, is in the apparatus at once? What is going on? Photons are weird.

[Another even more spooky property of photons is exhibited by the Einstein-Podolsky-Rosen (usually abbreviated EPR) paradox of 1935 (80th anniversary this year) that applies to any quantum system in which the two particles, photons here, are entangled. Entangled photons are produced together and appear to have linked properties, no matter how far apart they are. This was not mentioned in the talk].

There are yet more unexpected properties of photons and a good place to end this is with a quotation from Einstein himself, made in 1951: *All the fifty years of conscious brooding have brought me no closer to answer the question, “What are light quanta?” Of course today every rascal thinks he knows the answer, but he is deluding himself.*

So, light has gone from being misunderstood in antiquity, to being apparently almost completely understood in the 19th century, back to being seen as a subtle and deep phenomenon in the 20th century. Thanks to today’s understanding we now have astonishingly good telescopes, amazing microscopes, fantastic cameras, lasers and all sorts of optical technology beyond the dreams of our forefathers. Over 20 Nobel Prizes have been awarded related to light science [listed in the appendix], and that excludes many relevant to other parts of the electromagnetic spectrum. As to understanding light, the scientific answer is that light is not exactly like anything else. The closer we look, it seems *curioser and curioser* – as Alice said after one her first experiences in Wonderland.

In this short talk covering some 2500 years of trying to understand light I’ve missed out a good many issues but I’ll take a leaf out of Newton’s treatment in his *Opticks* and not mention explicitly the defects and omissions in what I’ve said. You’ll almost certainly touch on some of them in your queries!

Appendix: Nobel Prizes relevant to light. Physics (18)

2014 - Isamu Akasaki, Hiroshi Amano(Japan) & Shuji Nakamura (USA)  
*“for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources”*

2009 - Charles Kuen Kao *"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"* & Willard S. Boyle and George E. Smith*"for the invention of an imaging semiconductor circuit - the CCD sensor"*
2005 Roy J. Glauber "for his contribution to the quantum theory of optical coherence" & John L. Hall and Theodor W. Hänsch "for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"

1997 Steven Chu, Claude Cohen-Tannoudji and William D. Phillips"for development of methods to cool and trap atoms with laser light"

1971 Dennis Gabor"for his invention and development of the holographic method"

1966 Alfred Kastler"for the discovery and development of optical methods for studying Hertzian resonances in atoms"

1958 Pavel Alekseyevich Cherenkov, Il’ja Mikhailovich Frank and Igor Yevgenyevich Tamm"for the discovery and the interpretation of the Cherenkov effect"

1955 Willis Eugene Lamb "for his discoveries concerning the fine structure of the hydrogen spectrum"

1953 Frits (Frederik) Zernike "for his demonstration of the phase contrast method, especially for his invention of the phase contrast microscope"

1930 Sir Chandrasekhara Venkata Raman "for his work on the scattering of light and for the discovery of the effect named after him"

1923 Robert Andrews Millikan "for his work on the elementary charge of electricity and on the photoelectric effect"

1922 Niels Henrik David Bohr "for his services in the investigation of the structure of atoms and of the radiation emanating from them"

1921 Albert Einstein "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"

1920 Johannes Stark "for his discovery of the Doppler effect in canal rays and the splitting of spectral lines in electric fields"

1918 Max Karl Ernst Ludwig Planck "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta"

1908 Gabriel Lippmann "for his method of reproducing colours photographically based on the phenomenon of interference"
1907 Albert Abraham Michelson "for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid"

1902 Hendrik Antoon Lorentz and Pieter Zeeman "in recognition of the extraordinary service they rendered by their researches into the influence of magnetism upon radiation phenomena"

Nobel Prizes in Chemistry (3)

2014 Eric Betzig, Stefan W. Hell and William E. Moerner "for the development of super-resolved fluorescence microscopy"

2008 Osamu Shimomura, Martin Chalfie and Roger Y. Tsien "for the discovery and development of the green fluorescent protein, GFP"

1988 Johann Deisenhofer, Robert Huber and Hartmut Michel "for the determination of the three-dimensional structure of a photosynthetic reaction centre"

Physiology & Medicine (2)

1981 Roger W. Sperry "for his discoveries concerning the functional specialization of the cerebral hemispheres" David H. Hubel and Torsten N. Wiesel "for their discoveries concerning information processing in the visual system"

1911 Alvar Gullstrand "for his work on the dioptrics of the eye"

JSR