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# dmystify

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The Small Book of Big Thoughts

# Light

## The physics of light and optics explained

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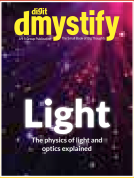
April 2018

## INSIDE






Cover Design
**ANIL VK**

# Credits

The people behind this book:


**Executive Editor & Writer:**
Robert Sovereign-Smith
**Assistant Technical Editor:**
Mithun Mohandas

**DESIGN**
**Sr. Art Director:** Anil VK
**Visualiser:** Baiju NV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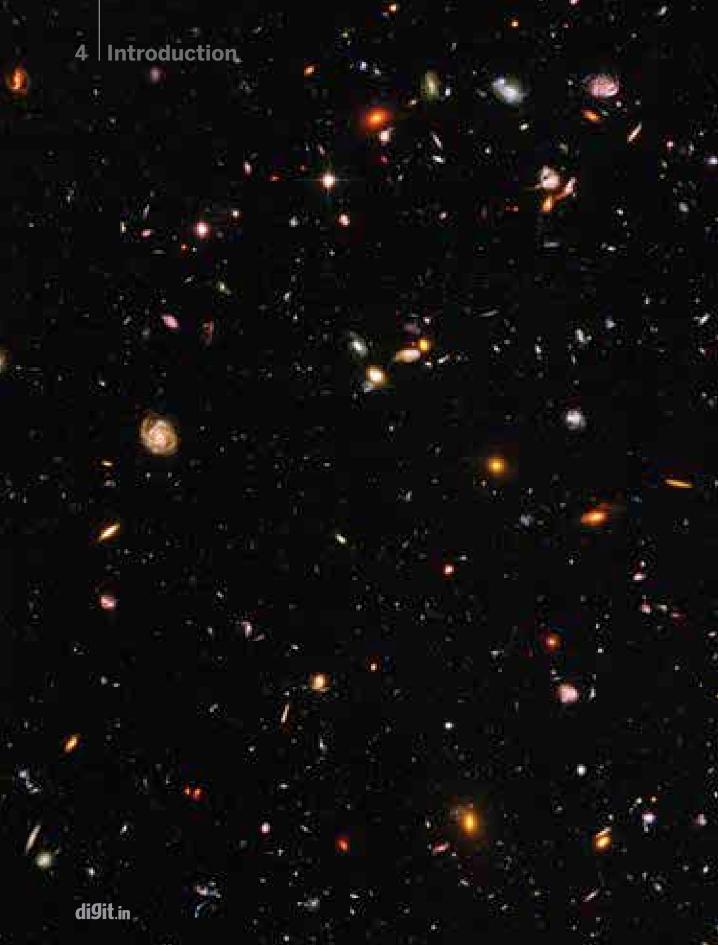


# Electromagnetic Radiation

That's what this book should have been called if we meant to be accurate. But of course you will have to forgive us for taking creative liberties and trying to appeal to a broader audience by using the term "Light". In science, electromagnetic radiation is the term used to describe energy that's transmitted in a certain way (which we will get to later in the book), and light is a subset of that, which is centered around the human eye. Light, also called "visible light", is the type of electromagnetic radiation that we humans can see using our eyes.

This book will cover not just visible light, but the whole spectrum of radiation all the way from gamma rays to long radio waves, and of this spectrum, visible light is but a sliver. We will also look at optics, and some history, to take you on our journey of understanding of light, and also a short detour to the origins of the universe itself!

We hope you like the book, and remember to send your feedback, positive or negative, to **dmystify@digit.in** – you can also send us suggestions for what you'd like to read at the same email address. You can also reach us at facebook.com/digitgeek or twitter.com/digitgeeks if social media is more your style of communication. ■

# History

## The history of light and our understanding of it

We are a very visual species, and a lot of what we do, and the cultures we have formed depend on sight, which is nothing more than our perception of reflected light. The universe is filled with light sources of varying intensities, and although the Earth is the only example of life we have, we're pretty sure that light is an essential ingredient to life.

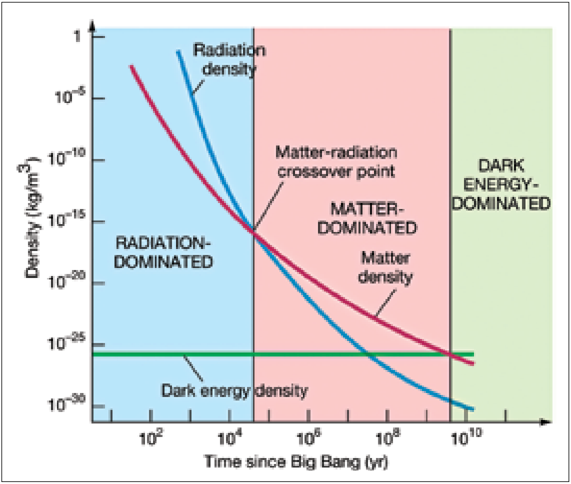
Let's not get ahead of ourselves though, and instead let's look at the very origins of light itself, and then take you on a speedrun you through the human understanding of it.

### Origins

The Big Bang that created everything from nothing, was not really an explosion in space, but more of an explosion of space. Thus, everywhere was the center of the universe then, just as everywhere is still the center of the universe now. It's not a simple concept to grasp, but it's been proven mathematically. Extrapolating from that same math, we get ridiculous figures for temperature and density of the early universe. For example, some estimates of the density of the universe $10^{-43}$ seconds after the Big Bang suggest that it was close to about $10^{95}$ kg/m$^3$.

This is not an easy number to grasp. So consider this. The number of atoms in the entire universe right now is between $10^{80}$ and $10^{82}$.

Source: Pearson Education




**Estimated radiation, matter and dark matter densities over time.**

That's every atom in every star, in every galaxy, in ever supercluster, in the entire known universe! The density of the universe was at least a trillion times more than that in terms of magnitude! The temperature at this same point in time ($10^{-43}$ seconds after the Big Bang) would be a whopping $10^{32}$ K. Contrast that with the hottest part of our sun (the center where all the fusion happens) that's a mere 1.5 x $10^7$ degrees Kelvin (K).

This didn't last long though, and just 100 seconds (one minute and 40 seconds) after the Big bang, the density had fallen to $10^4$ kg/$m^3$, and the temperature had fallen to one billion K.

Today, the density of the universe is a miniscule $10^{-28}$ kg/$m^3$ and the temperature is a mere 3 K.

While there might not have been any visible light sources in the early universe, there was a lot of radiation. Had there been eyes capable of viewing that radiation at the time, it would be blinded. But in terms of visible light, the universe was dark for many hundreds of thousands of years, until the first stars would have formed. However, like we said, if we consider the EM radiation spectrum as "light", then it has existed for as long as the universe has existed. Too bad it's scientifically incorrect to generalise all EM radiation as light.

## Importance to life

For close to a century, it was thought that life started in warm ponds of water thanks to UV radiation, or sunlight, because when our sun was new, it would give off far more UV radiation than it does now, and a newly formed Earth wouldn't have the ozone layer to protect the surface from their bombardment.

This was then changed to the theory that life began at hydrothermal vents at the bottom of the oceans, because that would have all the compounds that life would need in order to get started. And it seemed to be a watertight case that scientists made about hydrothermal vents, until... it wasn't anymore, and new research is bringing back the idea that UV rays were indeed very, very important for at least producing some of the chemicals we think would be necessary to get life started off.

What was thought to be the biggest problem with the UV theory – the fact that UV light breaks down molecules – is actually now the backbone of the rejuvenated UV argument. While still true that UV light breaks down large complex and otherwise stable molecules, it does so in a way that makes smaller much more reactive molecules, which can then combine in many different ways in order to produce more exotic acids, which eventually might have been the precursors to life.

Thus, it seems that the most recent scientific theories do indeed think (again) that light played a vital role in getting life started on Earth, and since there's no reason for us to believe

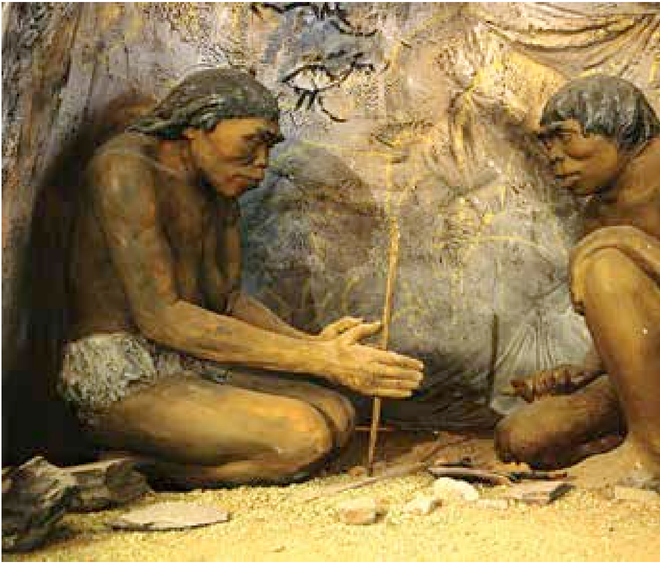
A UV image of the Cygnus Loop nebula taken from space that we're special in anyway, it may very well be true that light has played a role elsewhere in the vast universe and formed a very different type of life.

Regardless of whether light played a role in getting life itself started, we do know for a fact that a lot of the life on Earth does indeed depend on light to survive. The most obvious example are plants and photosynthetic bacteria which literally depend on light to live. Everything else is indirectly dependent on light for food, but a lot of life is directly dependent on light to see. The eye, after all, is considered one of the wonders of evolution. So how did light receptors evolve? We'll get to this later in the book.

## Pre-historic discoveries

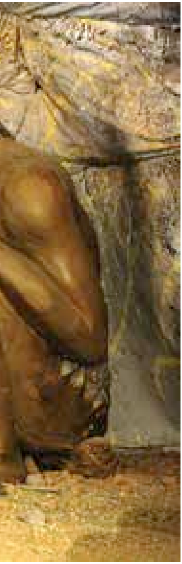
One can only imagine the terror felt by early hominid species as they developed bigger brains capable of more abstract thought, and yet knew nothing of their surroundings and why things happened. It was probably a lot easier being ignorant and incapable of higher thought like their ancient primate ancestors, because with curiosity comes realisation. Can you imagine the first hominid species capable of human-like thought witnessing a lightning strike?

If that lightning happened to strike a dry tree or bush and ignite it, can you imagine the curiosity the hominids would have had, and how they would have burned themselves trying to investigate fire?



**Diorama of a Mongolian caveman starting a fire**

Eventually, however, we do know that some hominid species did tame fire, and learn to cook, and it's the reason we can be sitting here pondering about them. Cooked food was the miracle that allowed



our ancient ancestors to absorb enough nutrients in order to help develop our brains further. We have the biggest brains to body ratio for a reason in the animal kingdom, and fire is the reason for it. However, it's highly unlikely that fire was first coveted by our ancestors as a cooking aid. It's far more likely that the light from the fire is what was desired. Needing to find shelter in caves during the night, in order to get away from predators and the elements, one can only imagine how our ancestors would have clung together in fear as they were unable to see clearly at night, and especially inside dark caves, which although offered protection would have also had dangers of their own. With fire, they would finally be able to bring light into the dark caves, and explore more, and set up homes. Besides, it would also bring some much needed warmth, and probably felt like they were holding a piece of the sun in their torches!

Another important thing fire allowing us to see in caves did was to unleash the creative mind, and is perhaps the reason why we have so many cave paintings from the same period.

It's obvious that light played a huge role in the history of the human race, and especially the ability to artificially produce light by way of starting fires. It's also how humans were able to migrate across large distances and spread out across the world.

## Ancient world

In order to study our understanding of light and electromagnetism, we really have to fast forward quite a bit from hominids discovering fire (between 1.2 million years and 600,000 years ago) to more modern times from when we have records.

Our first stop is about 2800 BC, in Egypt, where electricity was documented. They called the electric eels found in the Nile at the time "thunderers", which means they were equating them to lightning.

Around similar times, all across the globe there were reports of static electricity being observed, or the magnetism of certain ores... though of course no one at the time would have realised they had the same cause.

About 500 BC primitive lenses started appearing, usually using the refractive properties of water held in a near transparent container. It's not clear whether they understood the principles behind the refraction, but our best guess is that they were ignorant of the reasons, and merely liked the oddity of the effect.

Fast forward to about 400 BC, and the famous Chinese philosopher mentioned something similar to a pinhole camera. Again, it's not known if they knew why the pinhole camera effect occurred,

A statue of Euclid outside Oxford

but they certainly knew how to recreate it. 100 years later, Euclid would eventually come up with explanations about reflection and refraction, and the study of light would finally begin!

It was Ptolemy, in 130 AD, who published the first known scientific paper on Optics. He wrote a book about it in which he had painstakingly done experiments to calculate the refraction angles for various different mediums.

## Modern understanding

We have to take a large jump forward in time to 1604 when Johannes Kepler wrote extensively about light, and explained the workings of the eye, and also came up with laws regarding the propagation of light.

We then jump to 1675, when Isaac Newton released his Theory of Light, which was essentially a theory of colour, and he explained why we were able to see colours in the first place. He explained how certain materials and dyes absorbed different colours of the white light, and reflected different colours, and it was the reflected colours that gave objects their colour. Thus, a red cloth was actually absorbing all colours of light except red, and that's why it appeared red to us. It was not widely accepted.

It was three years later, in 1678 that the biggest discovery in the understanding of light came to pass. Christiaan Huygens released what is now popularly known as Huygens principle, which described the wave-like nature of light, and finally explained all the banding of light that was being seen in experiments but not explained. Put simply, Huygen's principle stated that light propagated as waves, and that every point where light was disrupted, itself became a source for spherical waves.

Thus, if you were to shine a light at a sheet of paper with a slit in it, every point on the edges of the slit that light touched, would itself become a light source (in a way) and that light would be emitted in a spherical pattern from every one of those points. Also, like waves, they would interfere, and both cancel and enhance each other, based on an interference pattern, and cause dark and light areas, and the banding that we see when we run a single slit experiment using a point source of light.

For the first time since the entire history of the Earth, a mind was finally comprehending the very nature of radiation and light.

Later, in 1704, Newton would publish his work called Opticks, which would outline with multiple experiments exactly what he had proposed 29 years earlier, which was that white light was composed of many different colours of light. He also extensively covered the refraction of light, and once and for all put to rest the ancient (and somewhat religious) idea that white light was "pure" light that was "tainted" with colour when it interacted with objects.

In 1728, James Bradley, and English astronomer, would use a triangulation method called the aberration of starlight to measure the speed of light. He found it to be 283,000 km/s (it's actually 299,792 km/s). An oversimplified explanation of aberration is to consider how rain that's falling straight down hits you at rest, and when in motion. Aberration because of motion is the reason why rain that is falling straight down appears to come at you from an angle in front, and why you have to tilt your umbrella slightly forwards when moving. The faster you move, the more you tilt the umbrella forward, and in a fast moving car, the rain appears to be almost horizontal. Now imagine measuring the angles at which light hits the Earth from a distant star (differences of tiny fractions of a degree at times). If you know the speed at which the Earth is moving, and consider the star to be stationary relative to Earth (it's not but it makes the math simpler), you can calculate the distance of the star, and the speed of light. This is what Bradley did, and he came pretty close to the answer, and was probably only wrong because of his instruments not having enough fidelity to measure millions of a degree. It's a pity though, that like many scientists before him and after, his work was not truly appreciated until much after his death, because it just didn't fit with accepted theories of light at the time.

In 1746, Leonhard Euler, the Swiss genius who is considered the king of mathematics, proved the wave theory of light put forth by

James Bradley came pretty close to calculating the exact speed of light

Huygens mathematically, and it then overturned Newton's particle theory of light that was the most accepted until Euler. It would remain that way until the quantum theory of light would come along much, much later and prove that both Newton and Huygens were right!

Fast forward to 1820, when Hans Christian Ørsted, the Danish physicist, finally united the fields of electricity and magnetism by conducting an experiment that showed that electric wires generated magnetic fields. In the same year, André-Marie Ampère, the French Physicist, conducted an experiment that showed that a coiled wire with an electric charge flowing through it acted like a magnet.

In 1826 Georg Simon Ohm, the German Physicist, outlines his laws of electrical resistance, and is the reason why the units of resistance is called an ohm.

It was between the years of 1831 to 1833 that Michael Faraday conducted several experiments and then eventually released his law of electrochemical equivalents. He also discovered the effects of a wire passed through a magnetic field, and invented the first electric dynamo. He would also go on to discover all sorts of interesting things via experiments, but we can't make this whole book about Faraday.

Finally, we jump forward to the father of the electromagnetic theory, James Clerk Maxwell, the Scottish theoretical physicist who would finally come up with the modern explanation of electromagnetism, and who would also incorporate discoveries by noted scientists such as Faraday into a grand theory that also showed that light was also electromagnetic in nature.

So great was his contribution to physics that he is considered to be one of the top three physicists of all time, with only Newton and Einstein beating him. Einstein himself considered Maxwell to be second only to Newton in his contributions to physics, though, of course, Einstein would never count himself like we do. ■

# Electromagnetic Radiation

## Physics of radiation

The story of electromagnetic radiation actually begins where we left off… with James Clerk Maxwell. It's why we ended the previous chapter when we did, because his story is so important that we need to continue it here.

In 1865 he published his pathbreaking paper titled "A Dynamical theory of the Electromagnetic Field". Although that title may seem a little simple, it was a paper that would blow the minds of physicists all across the globe.

In the paper he mathematically derived the speed of light, which he calculated to be just under 3,000,000 km/s ($3x10^8$ m/s), and also calculated that the speed of "magnetism" to be the same. He then commented:

*"The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an*

*electromagnetic disturbance propagated through the field according to electromagnetic laws."*

And this is how the theory of electromagnetism was born, and light and all radiation firmly covered under it forever.

Not to say that Maxwell wasn't wrong about a few things, because he also believed that light needed a "medium" to travel in, and since it could travel in vacuum, there was probably a medium that was undetectable to us. Many scientists at the time also believed in this "luminiferous aether", because light behaved like a wave, and traditional science taught us that waves were just disturbances in a medium of some sort.

In 1887, Albert Michelson and Edward Morley would conduct an experiment that would begin the downfall of the aether theory. This was ironic because their experiment was trying to prove its existence, and it's the reason why the Michelson-Morley experiment is known as the most successful failure in science.

To over-simplify the experiment they conducted, imagine you travelling in a train, at, say, 10 m/s, and your friend is standing still on a platform that you're passing. Now, you throw a ball at the front of your train compartment at a speed of 10 m/s and the ball travels 10 m. Thus, it takes 1 second for the ball to hit the front of the compartment. Imagine the same scene as seen by your friend. He sees you throw a ball just when you are both lined up, but 1 second later, you are 10 m away and the front of the compartment is 20 m away (from your friend) because of the speed of the train. Thus, your friend saw the ball travel 20 m in 1 second, and feels the speed of the ball is 20 m/s.

Known as Galilean Relativity, it was thought that you could not conduct an experiment that would know your speed, if you were in a frame of reference that was moving at a smooth, steady speed – this is why on a very smooth road it almost feels like your car isn't moving at all, and if you threw a ball up in the air, it would behave in exactly the same way it would if you were standing stationary on solid ground.

Michelson and Morley thought they could conduct an experiment to show this difference in the speed of light depending on the direction it was viewed at. They placed a semi transparent mirror at a 45 degree angle to the source of light, which would split a beam by reflecting some light and allowing some to pass straight through. The same light was then reflected back to the mirror, which would then focus the two beams on a screen. The idea was that if, there was a change in velocities, the waves would interfere and form a ring of light, and if there was no change, a bright spot would form.

This is because if the Earth itself was moving through the aether (it isn't, but it's what they thought in the 1880s), and the light beams were also moving through the aether as waves, there would be interference at some angles, and none at others, and thus you could just move the experimental apparatus around at various angles and get a ring pattern of light sometimes and a bright spot at others – in theory.

Of course, that didn't happen, and all they saw was the bright spot. This seemed to indicate that no matter what frame of reference was used, light always travels at C. This was in conflict with the aether theory, and eventually led to its death when Einstein came along with special relativity, and was laid to rest permanently when quantum mechanics was invented some time after that.

## EM

Based on what we know today, electromagnetic (EM) radiation are waves (or photons, if considering it as a beam of particles, because EM is both wave and particle at the same time) that travel through the medium we now call space-time, and carry energy. All EM radiation travels at the speed of light, and even "light" (visible light) is a form of EM radiation. Everything from radio waves, microwaves, infrared light, ultraviolet light, X-rays and gamma rays are all EM radiation as well.

EM waves have energy, momentum and also angular momentum, and when they interact (or collide if considered a particle) with matter, they impart those tiny amounts of energy and momentum to the object. Interestingly, although we think of only visible light being made up of photons, actually all EM radiation (EMR) have photons that are their "quanta" of energy – smallest packet of energy possible. The rest mass of a photon is zero, which means exactly what it seems to say… that if you were to somehow stop a photon from travelling at the speed of light and weighed it, it would have a mass of exactly zero.

Typically, we think of a photon as being the quanta of energy that's given off when an electron in an atom jumps from a higher state orbit to a lower state orbit. Since we consider the energy difference between successive electron orbits to be pretty standard, we might mistakenly think that all photons have the same energy. This isn't so, because energy depends on frequency.

EMR is also further broken up into ionising radiation and non-ionising radiation. This basically means that light, infrared, microwaves and radio waves (non-ionising radiation) is unable to break down living tissue into its component chemicals because the frequency of the wave (and as a result energy of the photon) is lower. Radio waves with low frequencies also have the lowest energy photons, while very high frequency gamma rays are made of very high energy photons.

Most living cells are able to handle the energy levels contained in visible light. It's starting at the ultraviolet spectrum, up to gamma rays that cause complex compounds to break up, and thus affect life. It's why X-ray technicians run and hide behind a lead wall when taking your X-ray, because although not much damage is done to you in one burst of x-rays once a year or so, there would be significant


X-rays go straight through soft tissue, and can damage them if exposed for too long damage to their tissues if they were exposed to the rays from all the hundreds of scans they perform a day.

Ultraviolet rays are harmful to us, and it's why we're told to wear sunscreen to reflect them away, and prevent absorption by our skins, and why it's important to pay attention to the UV index rating for the day when we go out into the sun. Although not a very common practice in India, it should be, given that we often have UV indexes in the highest category – highest category means high risk of sunburn and also of developing various cancers, most commonly skin cancer.

## Wave or Particle?

We keep talking about wave-particle duality, so we figured we should give you a very quick run through, just in case you're not familiar with the concept. If you are, just skip to the next headline.

Ever since quantum mechanics was introduced, the argument between whether light (or EMR, rather) was a wave or a particle was laid to rest. Before that however, it was very confusing in physics, because there were times it was impossible to treat light as a wave, and at other times impossible to treat it as a particle. The double-slit experiment is the perfect example. Instead of photons, which are zero mass particles (or waves, or both!), if you took electrons and did the double slit experiment, it was a lot easier to control. For example, it's very hard to isolate a photon and shoot them one at a time, but this is easier for a relatively larger particle like an electron.

Now let's run through a hypothetical double slit experiment that you are doing in a lab. The setup is simple, you have an electron gun, you have a barrier with two narrow slits in it, and a screen beyond that which registers an electron's impact. Obviously, if an electron impacts the screen, it has gone through one of the slits in the barrier. Now you shoot a steady stream of electrons, and notice the banding caused, which is identical to the banding caused by interference of waves, and is exactly the same as when you do the experiment with light... you get lines where many electrons are hitting the screen, and lines where few, or almost none of the electrons hit the screen. Dark and light bands, essentially.

Now you repeat the experiment, but you shoot one electron at a time. Ignoring the ones that hit the barrier and do not get through, and only counting the ones that make it to the screen, we find that although they hit one at a time, they still end up showing the same interference pattern, which is weird. Why weird? Because what are they *interfering with* if they're being shot out one at a time? Think of it this way... a steady stream of, say, a trillion electrons shot during the experiment causing the banding is one thing, because there are a trillion electrons interfering with one another that makes it kind of understandable why the banding forms. But how can you explain the exact same banding pattern forming when shooting a trillion electrons at the screen *one at a time*?

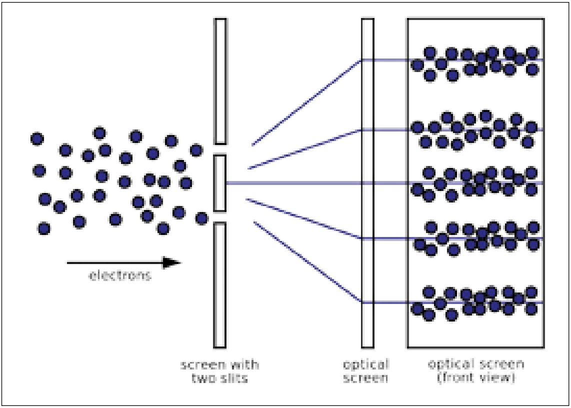
Essentially, even the individual particles seem to be going through *both* slits at the same time, and *interfering with themselves* to form the wave-like pattern on the screen. So what's the best way to test this? Add a way of measuring which slit the single electron passes through, right? Now we'd expect the act of observing to show that the electron passes through any one of the slits, but it shouldn't change the outcome, right? Turns out, adding the observer does exactly that, and the pattern formed on the screen when you shoot the trillion particles one at a time is totally random, and not the banded lines we expect from a wave. It's almost as if observing the electrons forced them to stop behaving like waves and start behaving like particles. Crazy!

So crazy was the effect that Albert Einstein once wrote:

*It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do.*

## Speed of Light?

We've covered the experimental and theoretical derivation of speed




**How electrons behave when no one is looking**

of light by Maxwell and others, so here we're going to look at the way it changes in different mediums.

Nothing can ever travel faster than the speed of light in empty space, which is why c is considered the speed limit of our universe. However, in various other mediums, light actually travels slower than that, and it depends on various factors. In glass, for example, visible light slows down. Glass has a refractive index of 1.5, so the speed of visible light in glass is c/1.5, or basically about $3 \times 10^8 / 1.5$ m/s = 2 x $10^8$ m/s. Now our atmosphere has a much lower refractive index of 1.0003 = 3/1.0003 = 2.9991 x $10^8$ m/s.

*Note: The above speeds are actually incorrect because the speed of light is actually 2.99792458 x $10^8$ m/s, and if you want accurate answers, you need to use that instead. So speed of light in glass is actually 1.99861639 x $10^8$ m/s, and speed of light in air is actually 2.99702547 x $10^8$ m/s.*

Now it's one thing to mathematically derive the speed of light, but how is it actually measured by experiments?

One of the first actual measurements of the speed of light was done after we knew the diameter of Earth's orbit. This was done by using trigonometry and using another planet, such as Venus, as the third point. The distance to the sun was calculated as was the distance to Venus and the other planets. Jupiter is especially important, because it was what was used to calculate the speed of light by experimentation.

Ole Rømer (1644 to 1710), was a Danish astronomer who was working in Paris at the French Royal Observatory (Observatoire de Paris). He was the first to calculate the speed of light using Io, Jupiter's closest moon. Because it is so close to Jupiter, and has a plane of rotation around Jupiter in the same plane of rotation as Jupiter going around the sun, Io experiences eclipses like clockwork, and this had been studied for many decades, even before Galileo.

When seen from Earth, thanks to using the telescopes that Galileo had popularised, eclipse events of Io were easy to see. Io orbits Jupiter once every 42.5 hours (42 hours 30 minutes). These events are two types – an immersion event where Io disappears from our view as it enters Jupiter's shadow, and an emergence event, where Io emerges from Jupiter's shadow.

It so happened that the time between two events also depended on whether the Earth was moving towards Jupiter or away from it, as the Earth orbited the sun. Rømer contended that this was because light had a finite speed, and used it to calculate (incorrectly) the time taken for light from the sun to reach us on Earth as 11 minutes (it's actually 8 minutes and 19 seconds). This is because Rømer made the mistake of considering Io's orbit to be a perfect circle, and didn't know about the tugs that Ganymede and Europa also exert on Io, which affects its orbit and orbital speed around Jupiter. Over a century later when all this was understood well, you could input those numbers into Rømer's method and arrive at a much more accurate speed of light.

It's important to note that because of the way the orbits work and the time taken, we can never observe an immersion and a successive emergence eclipse of Io in one night. So we're talking about data collected over years, and then tabulated and approximations being arrived at, because the Sun always plays spoilsport when it comes to astronomy. Considering that, and also considering it was 1676 when Rømer announced his findings, it's still a remarkable achievement. It was also so against conventional wisdom that Rømer's theory wasn't accepted at first, and it actually took ages for it to catch on. More experimentation would eventually prove him right – even if not in value, but in principle, that light indeed had a finite speed, and was not instantaneous as everyone thought – but sadly, it happened after his death.

Today, we can just bounce radar beams off Venus and calculate the actual distance from us to Venus, and then use that in trigonometry with the sun to arrive at ratios of distances and orbits of the planets around the sun. Calculating the speed of light today is far simpler, with lasers and mirrors being used on land to create very long paths of light, and being able to measure the time at origin and the time at arrival of the reflection of the laser. Once you know both distance and time, you automatically know the speed of light.

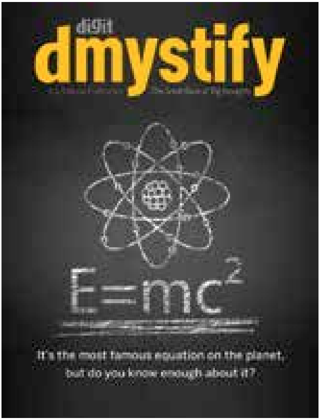
## Relativity

We're just giving you this headline but not going to delve into it because we have dedicated our very first dmystify to Einstein's special theory of relativity. We urge you to read that to understand why it was so important.

What's important in this context is what we've mentioned before, which was that Einstein's special theory of relativity killed off the need for the luminiferous aether, and instead made space-time the accepted reality.

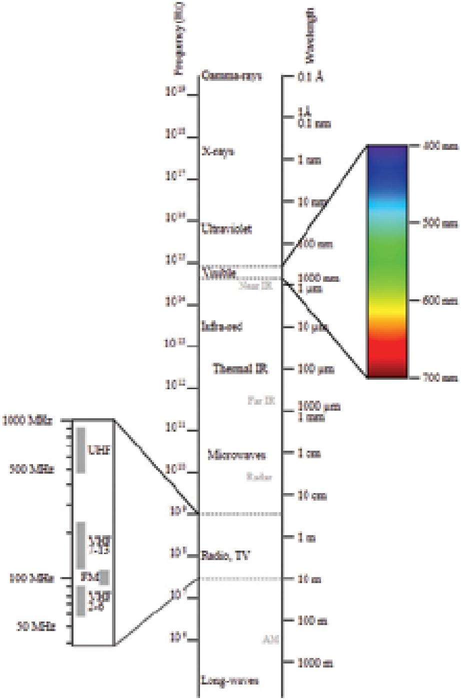
## Spectrum

We've mentioned the spectrum of EMR a few times, but this is where we give you a quick explanation. As we've said before, "light" is merely a small band of the overall EMR spectrum, and how small is best understood by looking at the image we've provided.




**If you want an introduction to special relativity, you should read this dmystify**

As you can see in the image, visible light is more towards the higher frequency of waves, but is a tiny band in which we see. Of course, other animals have the ability to see lower or higher frequencies than us, but we can't show them all here.




The entire EMR spectrum

You will also see that the radio and TV broadcast frequencies are quite low down in the frequency scale, and this is why they're harmless to us. Cellular phones usually operate on frequencies as low as 800 MHz and as high as 15 GHz (for upcoming 5G networks). Mostly, with 4G, you're looking at frequencies of about 2.6 GHz. Now, as you can tell, this is far, far lower than the terahertz to petahertz range of visible light, but with 5G we have properly entered the microwave range. While higher frequencies give you higher bandwidth, and 5G is promising speeds in the 5 gigabit region, but you also get much lower coverage for a given amount of energy input. This means that for a 5G network to be successful, there have to be many more cell sites covering the same area as far fewer 4G antennae. It's still the best solution for high speed mobile networks around, and it's ideally suited for our crowded Indian cities. ■

# Vision

## All about the light we see

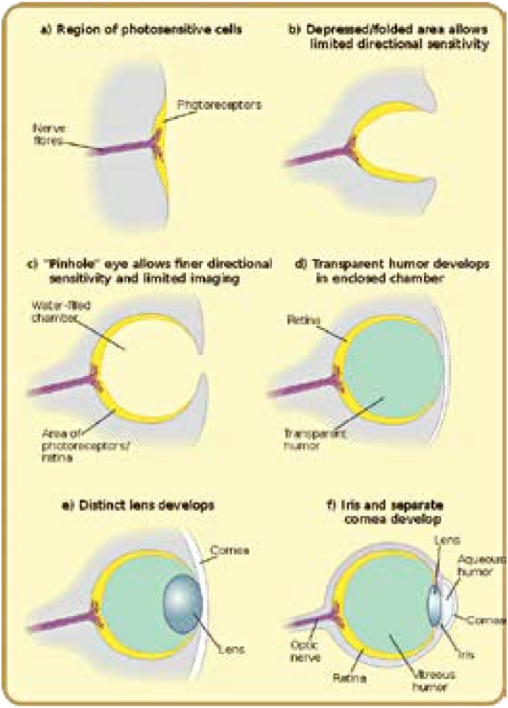
In India we're a very visual bunch of humans. Our festivals are all about lighting everything up, and we love colours, especially when celebrating something. The human eye responds to EMR with frequency range of about 430 to 770 terahertz. You can rest assured that we Indians use every last hertz of that visible spectrum in our daily lives!

But how did our eyes form? We touched upon this briefly earlier in the book, and now it's time to answer that question.

### Evolution

Extensive study of the eye by evolutionary biologists has arrived at the conclusion that the eye has evolved independently between 50 to 100 times in the history of life on Earth, and each with varying degrees of complexity.

The absolute basic level of an eye is what are found in many single-celled eukaryotes even today, which is essentially a light sensing

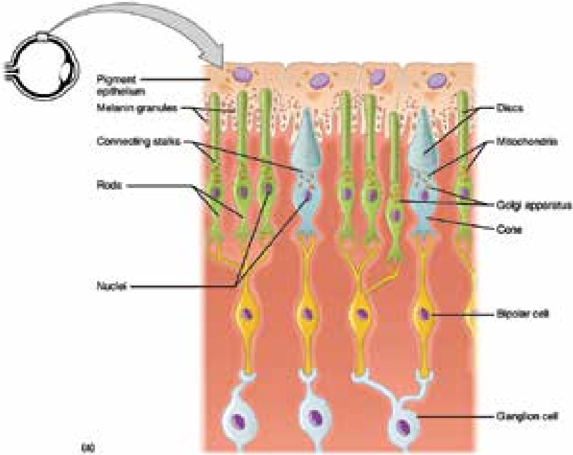



**Six steps in the evolution of the eye in vertebrates**

spot, that senses the difference between light and dark. Very slightly further up are single-celled organisms like Euglena gracilis, which have flagellum (a tail like structure), that they can use to locomote, and the eyespot they have helps them orient themselves in a way so as to approach the light. It's still debated whether this can be called an eye, or if this can be considered sight, but it doesn't change the fact that it is probably how eyes got started.

Another interesting thing of note is that most animals today have a very similar range of light perception (what we call visible light), and that is thought to be because of two reasons. For one thing, the sun's light has the highest intensity in this spectrum (400 to 750 nanometre wavelength), which means that it's kind of obvious why life would evolve to use that spectrum. A second, and much more important discovery in terms of this spectrum is that it's the spectrum of light that water does not absorb, and thus is the spectrum most ancient sea creatures would have been exposed to, and thus developed sight for. Because natural selection wouldn't offer any benefit to any populations that could develop vision outside of this spectrum, there just seemed no need to evolve beyond that.

What happened when we left the water all those millions of years ago though? Well, birds and bees and the like can see well into the UV spectrum, which we cannot, though we evolved the ability to resolve colours more than most life on Earth. Of course by no means are




**How eyes work using rods and cones**

we the best at anything natural in that sense, and it's a well known fact that, for example, birds of prey have far superior vision to us.

While bees have developed UV vision, flowers have patterns only visible to bees (and not us, for example), in order to exploit their vision. Then there's night animals, such as owls or snakes who have developed infrared vision, because at night, where light in the visible spectrum is low, infrared allows them to identify prey using body heat – something we humans have achieved by developing the night vision goggles used by militaries.

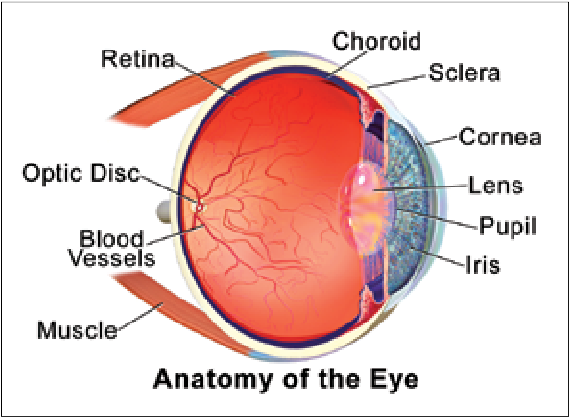
## Human eyes

We could probably write a dmystify on just the human eye itself, so we're not going to go into great depth about the eye, and encourage you to read more about it online if it interests you. In this book, we want to look at the physics of the eye, and not so much the biology.

The human eye is capable of quite a wide field of view, and when both eyes are used together, humans can see about 135 degrees vertically and 200 degrees horizontally. This means that if you're looking straight ahead (0 degrees vertically and horizontally), you can see up to 67.5 degrees above the center and the same amount below, and 100 degrees to the left and right of the center. Now we may not be focussing on all of that, but this peripheral vision is what allowed our ancestors to stay alert when hunting, and more importantly, when being hunted.

Our eyes are very sensitive to both low and bright light scenarios. We can still "see" when the light is as low as 0.000001 candela per sq. metre. That's one millionth the light of a standard wax candle in an area of one square metre – or pretty darn dark. Of course, we're no match for, say, an owl, who has night vision capable of seeing about 100 times better than humans. Owls don't even have eyes that can rotate and move about in the socket like our eyes, in fact their eyes are stationary, which means owls can only see straight ahead. They make up for this seeming limitation by being able to turn their necks 270 degrees.

Human eyes also have stereo vision (two eyes = stereo vision) and also binocular vision (areas that both eyes see) because our eyes are located in the front of the head, both facing the same direction. This enables us to focus more clearly and perceive depth




**The human eye**

and distance to a great degree of accuracy. Those of us who have played cricket and ever caught a ball that's been hit very high into the air can testify to how our brain accurately perceives moving objects that are far away. To do this, you need two eyes facing the same way. It's why dogs are able to catch frisbees and cats are so sure footed, for example.

We can see about 10 million colours, thanks to having three types of photoreceptors.

## Photoreceptors

A photoreceptor cell is a very special kind of cell indeed. It's a cell that can catch a photon, and then proteins in the cell absorb the photon and emit an electrical signal. This signal is then passed to the brain which knows what colour it sees. In essence, a photoreceptor converts the energy of a photon into data!

In mammals, there are three different types of photoreceptor cells: rods, cones and ganglion cells. Each of these three types are responsible for different functions and not all mammals have all three. Humans do, but for example, dogs don't. More on this later.

**Rods:** These are cells that actually look like rods, and are responsible for how well we see at night, or our peripheral vision, depending on the circumstances. Rod cells are not able to pick up colours very well though, which is why we aren't able to make out colours in the dark, or why everything at night looks monochromatic. Creatures who see well at night have many more rod cells than humans. As it is, the typical human eye contains about 90 million rod cells, and almost all of them are located on the outer edges of the retina. They're about 100 times more sensitive to light as a cone cell.

**Cones:** Cone cells look like cones, and that's where they get their name from. They're not as sensitive to light as the rod cells, which is why they work best in sunlight or bright lights. They are responsible for picking up colours though, and are far more sensitive to photon energies (i.e. frequencies and colours). We don't have as many cone cells as we do rod cells, and the ratio is about 1:15 – a mere 6 million cone cells to about 90 million rod cells in the human eye. Almost all of these cones (about 4.5 million) are located in a small central pit in the retina called the fovea centralis, which is just 0.3 mm in diameter! Humans have three different types of cone cells and they're conveniently titled S, M and L cones – Short Medium and Long cones. They're called this because of the wavelength of light they respond to, with L cones responding to wavelengths up to 560 nm (red, orange and yellow), M cones up to 530 nm (green), and S cones seeing up to about 420 nm (violet, indigo and blue – these have now been corrected to violet/purple, blue and cyan). Some of us can see wavelengths as low as 390 nm and as high as 700 nm. There doesn't appear to be a fixed ratio of S, M and L cones in humans, as vastly varying numbers have been found, but as a thumb rule, we all seem to have many more M and L cones than S cones.

**Ganglion cells:** More accurately, Intrinsically photosensitive retinal ganglion cells (ipRGCs), are cells that are also involved with sight, though not directly with colour or night vision. ipRGCs actually are responsible for a number of things – synchronising our circadian rhythm, so that we wake up and sleep on time, and they also control the size of the pupil – to open or close it to let more or less light in, depending on the conditions. ipRGCs have been shown to play an even bigger role in rat vision, and are used to even recognise familiar spaces. In fact, it was when experimenting on rats that ipRGCs were found. When rats had both rods and cones destroyed by scientists, they were still able to perceive light, and their pupils dilated and constricted appropriately – surprising because researchers were sure they were "blinded" when all rods and cones in their eyes were destroyed.

## Animal vision

Humans are far from the species with the best eyesight, if such a thing is indeed possible to test for. This is because eyes are adapted to the surroundings that species live in, and for example, while the shark's eyes are useless in air when compared to ours, our eyes are useless in the water without aids such as goggles and the like. A bat doesn't even need eyes, while snakes have heat vision by seeing in the infrared spectrum. Here we'll look at the different spectrums of light that animals can see, starting from infrared and ending with ultraviolet.

It's an old myth that all animals see in black and white, and that humans are the only ones who see colour. As we've seen above, it's the cone cells that are responsible for viewing colour, and many animals have two or more different types of cone cells. Dogs and cats, for instance have two, so though they don't see as many colours as we do, they don't see in black and white either.

When animals have only one type of cone cell, they're able to see about 100 distinct colours (or shades). Examples of monochromatic vision include whales and seals.

Dichromatic vision (two types of cone cells) allows animals to see up to about 10,000 colours, and this group includes dogs, cats, some primates and most mammals such as such as cows, pigs sheep, etc.

Humans are trichromatic, as are our closest relatives, such as chimps and bonobos, gorillas and orangutans, etc. Having three types of cones gives us the ability to discern between 10 million colours ranging from red to violet, however, some insects are also trichromatic, but instead see from green to the ultraviolet spectrum, and can't discern reds at all. Honey bees are examples of this type of insect, and it makes you wonder why so many flowers have red in them if bees can't even see red!

Most reptiles, amphibians insects and birds have the ability to see about 100 million colours, as they are tetrachromatic and have four types of cone cells.

A small group of animals have pentachromatic vision, and it's thought that they might be able to see up to a billion different colours! Some species of butterflies (now the red flowers make sense again!), and certain birds such as pigeons are pentachromatic. Who thought the humble pigeon was capable of seeing so many colours... but then it makes sense, because although pigeons all look the same to us, they have markings and subtle differences in colour that we might not be able to discern, but to them it might be as obvious as the difference between red and green...

It doesn't stop there either because certain animals have a ridiculous amount of different photoreceptors (not just more types of cone cells). A species called the mantis shrimp have a visual system that puts everything else to shame. They have a whopping 16 different types of cone cells, and they can also "tune" their vision on purpose! Called spectral tuning, the shrimp are able to adapt the sensitivity of their L cones (in the red colour range) to adapt to the environment. So if they need to see better in the red spectrum, they do, and if there's too much red in the surroundings, they just lower the sensitivity and see the other colours more clearly!

If you thought that was cool, we have stereoscopic vision with a binocular effect because of two eyes, these shrimps have trinocular vision in each eye, which gives them far, far superior depth perception than humans even by using one of their eyes. Add to that the fact

**A peacock mantis shrimp in the Andaman Sea**

that their eyes are mounted on stalks and move about independently, and you can see why their vision is so flexible.

Recent studies have suggested that although the shrimp has many different photoreceptors, its brain is not complex enough to distinguish between the colours. Researchers tried training the shrimp to respond to one particular colour in order to get food, and then kept varying the other colour choice that was shown to closer and closer wavelengths to the reward colour. The shrimps were able to respond correctly with a difference of between 50 to 100 nm, but when this was dropped to 25 nm, the shrimps acted like they were randomly guessing the colour, not actually choosing correctly. This has led researchers to suggest that the shrimp are like that 75-year old granny in Sweden who had the fastest home internet connection in 2007 – 40 Gbps (yes, G not M) – but was using the equipment (her router) to dry clothes on! ■

# Optics

## Playing with light

Finally, we get to optics, and a journey through understanding how we humans have played with light for centuries. No doubt, playing with glass would have started as fun. Who knows how many cavemen would have played with or worshipped the glass that's formed when lightning strikes a beach. The interesting shapes and patterns that are formed, and the possibility that it might have acted like a prism might have freaked out early humans.

Even in ancient Egypt, gemstones and crystals were used as lenses, perhaps for entertainment purposes. Then, the Greeks and Romans would later start using glass jars filled with water as refractive lenses. Over the centuries optics was toyed with by many, and it grew into an increasingly important field, especially when it was learnt that lenses could enhance poor vision. Rich people especially wanted to be able to see clearly, and poor vision has probably plagued mankind ever since we lived in caves and could live past the age of young adults.

It was in the late 1200s (thirteenth century) that eyeglasses were invented in Italy, and soon caught on across the world. An entire new industry was established once people realised that they need not suffer bad eyesight any longer.

It wasn't just myopic people who benefited, with the increased interest in optics, it became cheaper to produce lenses, and eventually led to experiments in lenses. In fact, while Italy might have invented the lenses, it was in the Netherlands that the first crude microscopes and telescopes started appearing. Of course people perfected those designs, and made much better versions later.

If you're one of the people like us who are afflicted with poor vision and need to wear spectacles... the next time someone tries to poke fun of your poor vision, remind them that it was because of people like us that the telescope and microscope were invented, and that led to the enormous discoveries of the vastness of our universe, as well as the discovery of the miniature worlds of bacteria and viruses. Call us four-eyes all you want, we literally changed the world!

## Optics

Before we had a modern understanding of optics, we dealt with everything in what we call a classical optics methodology. To be honest, this worked pretty well for quite a long time, and was basically subdivided based on the wave or particle theory of light.

### Geometrical Optics

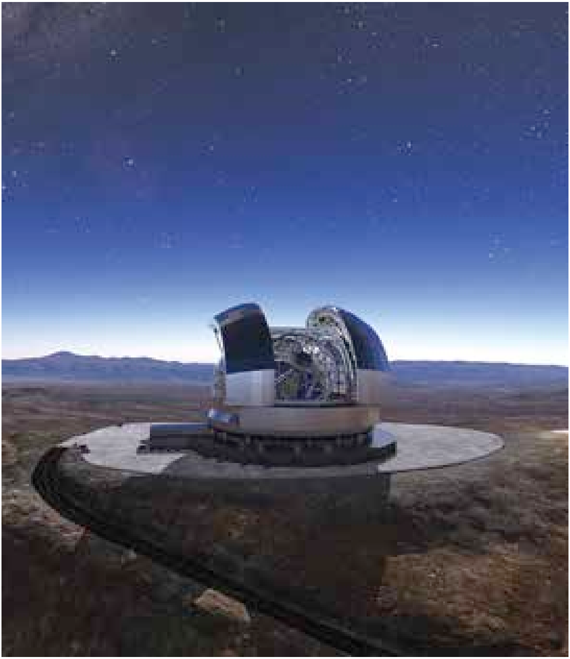
This is essentially a field of optics that treats light as particles, or rather rays of photons. This method usually worked fine so long as the wavelengths of the light being used was much smaller than the lenses being used. It's essentially the physics that goes into making spectacles and microscopes and hobby telescopes. It's a field where slight approximations are not a deal breaker, and yes, your eyesight is corrected using approximations.

### Physical Optics

This is a branch of classical optics that assumes light is a wave, and takes into account all the complexities that come with light being a wave. It's used to design more serious optics for engineering purposes, and accounts for things such as interference, diffraction and polarisation of light. Camera design and the like need physical optics or a more modern branch of optics.

### Modern Optics

This is the study of optics based on what we know about quantum mechanics. There's a subset of modern optics known as Quantum Optics, which is pretty much the only type used for all serious optics work anymore. So whether its fibre optics, producing lasers, manufacturing lenses and mirrors for experiments, or doing anything that



The Extremely Large Telescope (ELT) being built in Chile will be the largest ever needs the kind of accuracy we're used to these days, it all comes under quantum optics. Even the latest cameras and their sensors are a result of quantum optics, as we look for higher and higher fidelity, but in smaller and smaller packages. More on this later.

## Lenses

The field of study of correcting human sight is the field of optics that we're most exposed to on a daily basis. It's not just corrective though, and can include other fields such as virtual reality headsets, which also use lenses and our stereoscopic vision to immerse you in a 3D world.

We will focus on corrective lenses though, for the purposes of this dmystify. There are three basic maladies that affect human sight – myopia, hyperopia and presbyopia. Let's run you through them quickly.

### Myopia

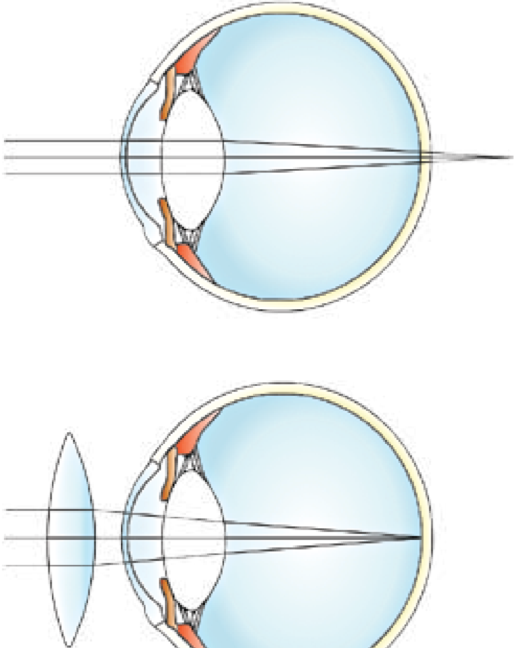
By far the most common eye condition, it affects people of all ages and is also known by the term nearsightedness or short-sightedness. It essentially means that you cannot see objects that are far away clearly, and it happens because of a fault in your eye muscles that are supposed to control the amount of refraction that occurs via your eye's lens. It happens when the eye is focussing light in front of the retina instead of on it. Causes include genetics, too much time spent focussing on things close to you and not enough time spent outdoors looking at distant objects. It's estimated that over 20 per cent of the world suffers from myopia, and that works out to over 1.5 billion people!

### Hyperopia

The exact opposite of myopia, hyperopia results in people not being able to clearly bring into focus objects that are close to them, whilst being able to properly focus on objects far away. This happens because the eye ends up focussing the light that enters the eye behind the retina, instead of at it. It's something that can affect both young and old people. Sadly, some people have to suffer both hyperopia and myopia at the same time, so consider their plight before you complain about your own eyesight!

### Presbyopia

The difference between presbyopia and hyperopia are very hard to judge. Like hyperopia, presbyopia also results in a difficulty seeing things close up, and especially at an arm's length... which means it's hard to read. Presbyopia is exclusively an old people problem, and is caused by the lens itself becoming less flexible with age. This results in improper focussing of light, and also finding it hard to look



Hyperopia and a corrective lens being used at something far away and then quickly look at something close up, or vice versa. All of these are fixed using lenses.

### Lenses

Coming back to lenses, the type of lens used is dependent on the condition you have, as listed before. So, for example, if you have hyperopia or presbyopia you will have a lens that has a spherical number that's positive. If you suffer from myopia, you will have a spherical number that's negative. Think of this as a lens whose inner edge either curves towards you or away from you. This is because convex lenses make light converge (for farsighted people) while concave lenses make light diverge (for nearsighted people). The spherical number you see on your prescription merely informs the people making the lens of the power of lens you need. The power of the lens is merely 1/f (where f is the focal point of the lens). A lower focal point means a higher spherical power of lens. Power is measured in diopters.

The next number that you will probably see on a prescription is a Cyl number, which stands for cylindrical, and an axis number. These are basically corrections that have to be made because your eye is not a perfect sphere, and your cornea is not a smooth curve. The positive or negative numbers for cylindrical values here don't mean much, and in various parts of the world you get either positive or negative numbers based on the customary usage of the region.

## Telescopes

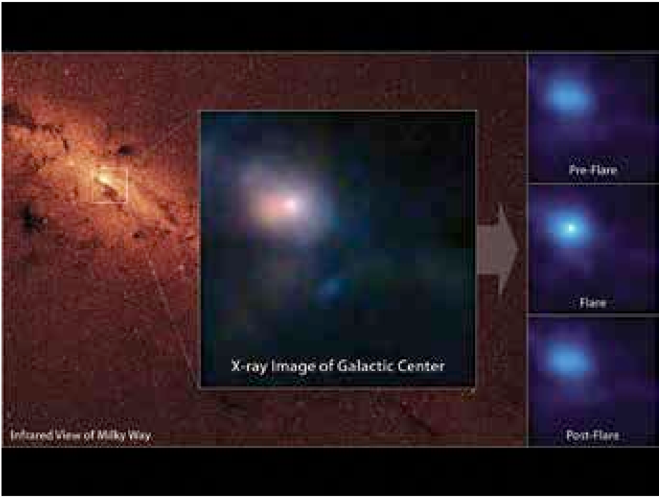
The simple optical telescope is very easy to understand, because it uses two lenses to magnify an image and make it appear a lot closer than it is. Ever since Galileo perfected it, the optical telescope is the cheapest choice for observing the heavens. Most amateur astronomers use these, but the professionals have long since moved beyond this.

### Radio Telescopes

A radio telescope is basically a large dish antenna that's used to "listen" to radio waves from space. Whether to search for signs of alien life, or to search for distant stars and pulsars. Most astronomical objects emit EMR across the band, and radio telescopes are able to pick up longer wavelength waves that help build images of entire galaxies, or even individual stars of our galaxy.

### X-ray Telescopes

These are used to image distant objects that are emitting EMR in the X-ray frequency, and are usually useless on the ground. Since our atmosphere absorbs X-rays, they are usually used at very high




**An X-ray telescope looking at the supermassive black hole at the center of our galaxy caught a flare event**

altitudes by being sent up in high altitude balloons, or be launched into space for the least amount of interference possible. They're used to image things such as supermassive black holes at the centers of galaxies, and supernovas.

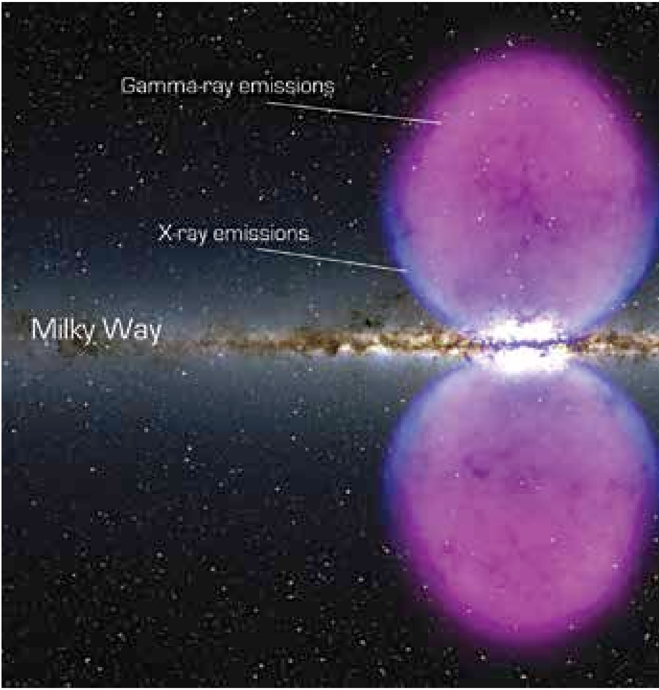
### Gamma ray Telescopes

Just like X-ray telescopes, gamma ray telescopes are useless on the surface of the Earth. They also study things like pulsars, black holes and the like, and also have to be launched into space to be used, because our atmosphere blocks most gamma radiation from the sun and the rest of the universe.

## The future

The future of optics and light seems to be in computing, with everyone trying to crack the problem of light computing. If we were able to get processors and perhaps even whole computers to run off photons and not electrons, we could solve the energy crisis and prevent CPUs and GPUs from heating up under load. There's only one problem... light is too darn fast, and we haven't built a CPU that can compute at the speed of light just yet.

Except, we very well might have... It's early days still, but a team from the University of Sydney has developed what they claim is a way to slow light down a bit so as to be able to get a CPU to respond. Typically, a pulse of light (just photons carrying data) would shoot through a light based CPU in a matter of a few nanoseconds, which didn't leave the CPU any time to read the data. The research team has fixed this by shooting out another pulse to interact with the data entering the CPU, and this interaction produces a sound wave,




**The Gamma ray bubble thought to exist at the center**


of the Milky Way

which is then hit by another control signal, which then releases the original signal and allows it to pass through the rest of the CPU. This technique has allowed them to be able to slow things down to a more respectable 10 nanosecond time scale! Who knows, your laptop might just be 20 times faster and at least as half as light!

There is tonnes of research like this happening all over the world, and it bodes well for us as a society that we're focussing more on the science and less on other distractions. Remember to write in and tell us about any cutting edge breakthroughs you have come across when reading about light!

As always, remember to send us feedback, positive or negative, we love hearing from you. ■


**Your biology might be over, but your physics will live on forever!**