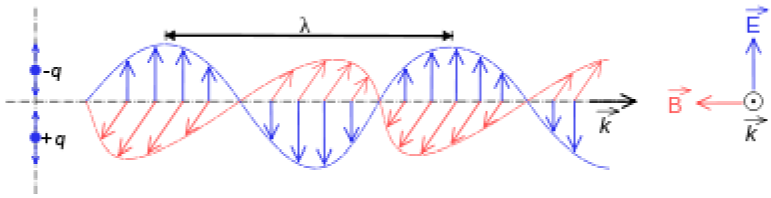
Quantum Mechanics_Electromagnetic radiation



The electromagnetic waves that compose electromagnetic radiation can be imagined as a self-propagating transverse oscillating wave of electric and magnetic fields. This diagram shows a plane linearly polarized EMR wave propagating from left to right. The electric field is in a vertical plane and the magnetic field in a horizontal plane. The two types of fields in EMR waves are always in phase with each other with a fixed ratio of electric to magnetic field intensity.

Electromagnetic radiation (**EM radiation** or**EMR**) is a fundamental phenomenon ofElectromagnetism, behaving as waves propagating through space, and also as photon particles traveling through space, carrying radiant energy. In avacuum, it propagates at a characteristic speed, thespeed of light, normally in straight lines. EMR is emitted and absorbed by charged particles. As an electromagnetic wave, it has both electric andMagnetic field components, which oscillate in a fixed relationship to one another, perpendicular to each other and perpendicular to the direction of energy and wave propagation.

In classical physics, EMR is considered to be produced when charged particles are accelerated byforces acting on them. Electrons are responsible for emission of most EMR because they have low mass, and therefore are easily accelerated by a variety of mechanisms. Quantum processes can also produce EMR, such as when atomic nuclei undergo gamma decay, and processes such as neutral pion decay.

EMR carries energy—sometimes called radiant energy—through space continuously away from the source (this is not true of the near-field part of the EM field). EMR also carries both momentum andangular momentum. These properties may all be imparted to matter with which it interacts. EMR is produced from other types of energy when created, and it is converted to other types of energy when it is destroyed.

The electromagnetic spectrum, in order of increasing frequency and decreasing wavelength, can be divided, for practical engineering purposes, into radio waves, microwaves, infrared radiation,visible light, ultraviolet radiation, X-rays and gamma rays. The eyes of various organisms sense a relatively small range of frequencies of EMR called the visible spectrum or light; what is visible depends somewhat on which species of organism is under consideration. Higher frequencies (shorter wavelengths) correspond to proportionately more energy carried by each photon, according to the well-known law $E=h\nu$, where E is the energy per photon, ν is the frequency carried by the photon, and h is Planck's constant. For instance, a single gamma ray photon carries far more energy than a single photon of visible light.

The photon is the quantum of the electromagnetic interaction, and is the basic "unit" or constituent of all forms of EMR. The quantum nature of light becomes more apparent at high frequencies (thus high photon energy). Such photons behave more like particles than lower-frequency photons do.

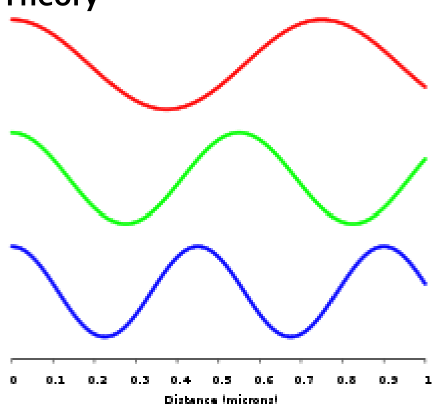
Electromagnetic waves in free space must be solutions of Maxwell's electromagnetic wave equation. Two main classes of solutions are known, namely plane waves and spherical waves. The plane waves may be viewed as the limiting case of spherical waves at a very large (ideally infinite) distance from the source. Both types of waves can have a waveform which is an arbitrary time function (so long as it is sufficiently differentiable to conform to the wave equation). As with any time function, this can be decomposed by means of Fourier analysisinto its frequency spectrum, or individual sinusoidal components, each of which contains a single frequency, amplitude, and phase. Such a component wave is said to be *monochromatic*. A monochromatic electromagnetic wave can be characterized by itsfrequency or wavelength, its peak amplitude, its phase relative to some reference phase, its direction of propagation, and its polarization.

Electromagnetic radiation is associated with EM fields that are free to propagate themselves without the continuing influence of the moving charges that produced them, because they have achieved sufficient distance from those charges. Thus, EMR is sometimes referred to as the far field. In this language, the *near field* refers to EM fields near the charges and current that directly produced them, as for example with simple magnets and Static electricity phenomena. In EMR, the magnetic and electric fields are each induced by changes in the other type of field, thus propagating itself as a wave. This close relationship assures that both types of fields in EMR stand in phase and in a fixed ratio of intensity to each other, with maxima and nodes in each found at the same places in space.

The effects of EMR upon biological systems (and also to many other chemical systems, under standard conditions) depend both upon the radiation's power and frequency. For lower frequencies of EMR up to those of visible light (i.e., radio, microwave, infrared), the damage done to cells and also to many ordinary materials under such conditions is determined mainly by heating effects, and thus by the radiation power. By contrast, for higher frequency radiations at ultraviolet frequencies and above (i.e., X-rays and gamma rays) the damage to chemical materials and living cells by EMR is far larger than that done by simple heating, due to the ability of single photons in such high frequency EMR to damage individual molecules chemically.

Physics

Theory



Shows the relative wavelengths of the electromagnetic waves of three different colors of light (blue, green, and red) with a distance scale in micrometers along the x-axis.

Main articles: Maxwell's equations and Near and far field

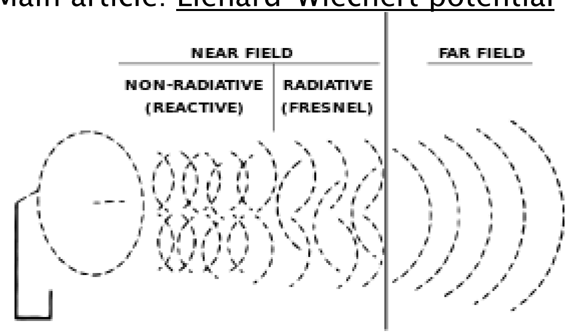
Maxwell's equations for EM fields far from sources

James Clerk Maxwell first formally postulated *electromagnetic waves*. These were subsequently confirmed by Heinrich Hertz. Maxwell derived a wave form of the electric and magnetic equations, thus uncovering the wave-like nature of electric and magnetic fields, and their symmetry. Because the speed of EM waves predicted by the wave equation coincided with the measured speed of light, Maxwell concluded that light itself is an EM wave.

According to Maxwell's equations, a spatially varying Electric field is always associated with a Magnetic field that changes over time. Likewise, a spatially varying magnetic field is associated with specific changes over time in the electric field. In an electromagnetic wave, the changes in the electric field are always accompanied by a wave in the magnetic field in one direction, and vice versa. This relationship between the two occurs without either type field causing the other; rather, they occur together in the same way that time and space changes occur together and are interlinked in special relativity. In fact, magnetic fields may be viewed as relativistic distortions of electric fields, so the close relationship between space and time changes here is more than an analogy. Together, these fields form a propagating electromagnetic wave, which moves out into space and need never again affect the source. The distant EM field formed in this way by the acceleration of a charge carries energy with it that "radiates" away through space, hence the term for it.

Near and far fields

Main article: Liénard–Wiechert potential



In electromagnetic radiation (such as microwaves from an antenna, shown here) the term applies only to the parts of theElectromagnetic field that radiate into infinite space and decrease in intensity by an inverse-square law of power, so that the total radiation energy that crosses through an imaginary spherical surface is the same, no matter how far away from the antenna the spherical surface is drawn. Electromagnetic radiation thus includes the far field part of the electromagnetic field around a transmitter. A part of the "near-field" close to the transmitter, forms part of the changing Electromagnetic field, but does not count as electromagnetic radiation.

Maxwell's equations established that some charges and currents ("sources") produce a local type of Electromagnetic field near them that does *not* have the behavior of EMR. In particular, according to Maxwell, currents directly produce a magnetic field, but it is of a magnetic dipole type which dies out rapidly with distance from the current. In a similar manner, moving charges being separated from each other in a conductor by a changing electrical potential (such as in an antenna) produce an electric dipole type electrical field, but this also dies away very quickly with distance. Both of these fields make up the near-field near the EMR source. Neither of these behaviors are responsible for EM radiation. Instead, they cause electromagnetic field behavior that only efficiently transfers power to a receiver very close to the source, such as the magnetic induction inside atransformer, or the feedback behavior that happens close to the coil of a metal detector. Typically, near-fields have a powerful effect on their own sources, causing an increased “load” (decreased electrical reactance) in the source or transmitter, whenever energy is withdrawn from the EM field by a receiver. Otherwise, these fields do not “propagate,” freely out into space, carrying their energy away without distance-limit, but rather oscillate back and forth, returning their energy to the transmitter if it is not received by a receiver.[*citation needed*]

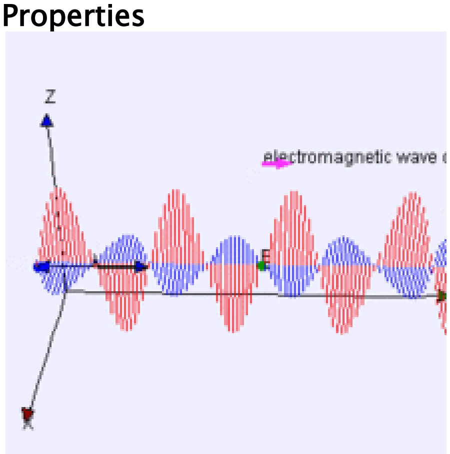
By contrast, the EM far-field is composed of radiation that is free of the transmitter in the sense that (unlike the case in an electrical transformer) the transmitter requires the same power to send these changes in the fields out, whether the signal is immediately picked up, or not. This distant part of the electromagnetic field *is* "electromagnetic radiation" (also called the far-field). The far-fields propagate without ability for the transmitter to affect them, and this causes them to be independent in the sense that their existence and their energy, after they have left the transmitter, is completely independent of both transmitter and receiver. Because such waves conserve the amount of energy they transmit through any spherical boundary surface drawn around their source, and because such surfaces have an area that is defined by the square of the distance from the source, the power of EM radiation always varies according to an inverse-square law. This is in contrast to dipole parts of the EM field close to the source (the near-field), which varies in power according to an inverse cube power law, and thus does *not* transport a conserved amount of energy over distances, but instead dies away rapidly with distance, with its energy (as noted) either rapidly returning to the transmitter, or else absorbed by a nearby receiver (such as a transformer secondary coil).[*citation needed*]

The far-field (EMR) depends on a different mechanism for its production than the near-field, and upon different terms in Maxwell’s equations. Whereas the magnetic part of the near-field is due to currents in the source, the magnetic field in EMR is due only to the local change in the electric field. In a similar way, while the electric field in the near-field is due directly to the charges and charge-separation in the source, the electric field in EMR is due to a change in the local magnetic field. Both of these processes for producing electric and magnetic EMR fields have a different dependence on distance than do near-field dipole electric and magnetic fields, and that is why the EMR type of EM field becomes dominant in power “far” from sources. The term “far from sources” refers to how far from the source (moving at the speed of light) any portion of the outward-moving EM field is located, by the time that source currents are changed by the varying source potential, and the source has therefore begun to generate an outwardly moving EM field of a different phase.[*citation needed*]

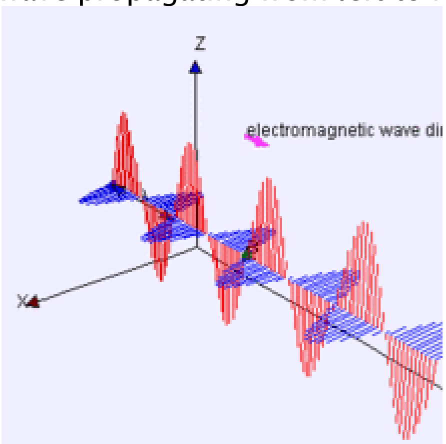
A more compact view of EMR is that the far-field that composes EMR is generally that part of the EM field that has traveled sufficient distance from the source, that it has become completely disconnected from any feedback to the charges and currents that were originally responsible for it. Now independent of the source charges, the EM field, as it moves farther away, is dependent only upon the accelerations of the charges that produced it. It no longer has a strong connection to the direct fields of the charges, or to the velocity of the charges (currents).[*citation needed*]

In the Liénard–Wiechert potential formulation of the electric and magnetic fields due to motion of a single particle (according to Maxwell's equations), the terms associated with acceleration of the particle are those that are responsible for the part of the field that is regarded as electromagnetic radiation. By contrast, the term associated with the changing static electric field of the particle and the magnetic term that results from the particle's uniform velocity, are both seen to be associated with the electromagnetic near-field, and do not comprise EM radiation.[*citation needed*]

Properties



Electromagnetic waves can be imagined as a self-propagating transverse oscillating wave of electric and magnetic fields. This 3D diagram shows a plane linearly polarized wave propagating from left to right



This 3D diagram shows a plane linearly polarized wave propagating from left to right. Note that the electric and magnetic fields in such a wave are in-phase with each other, reaching minima and maxima together

The physics of electromagnetic radiation is electrodynamics. Electromagnetism is the physical phenomenon associated with the theory of electrodynamics. Electric and magnetic fields obey the properties of superposition. Thus, a field due to any particular particle or time-varying electric or magnetic field contributes to the fields present in the same space due to other causes. Further, as they are vectorfields, all magnetic and electric field vectors add together according to vector addition. For example, in optics two or more coherent lightwaves may interact and by constructive or destructive interference yield a resultant irradiance deviating from the sum of the component irradiances of the individual lightwaves.[*citation needed*]

Since light is an oscillation it is not affected by travelling through static electric or magnetic fields in a linear medium such as a vacuum. However, in nonlinear media, such as some crystals, interactions can occur between light and static electric and magnetic fields — these interactions include the Faraday effect and the Kerr effect.[*citation needed*]

In refraction, a wave crossing from one medium to another of different densityalters its speed and direction upon entering the new medium. The ratio of the refractive indices of the media determines the degree of refraction, and is summarized by Snell's law. Light of composite wavelengths (natural sunlight) disperses into a visible spectrum passing through a prism, because of the wavelength dependent refractive index of the prism material (dispersion); that is, each component wave within the composite light is bent a different amount.[*citation needed*]

EM radiation exhibits both wave properties and particle properties at the same time (see wave–particle duality). Both wave and particle characteristics have been confirmed in a large number of experiments. Wave characteristics are more apparent when EM radiation is measured over relatively large timescales and over large distances while particle characteristics are more evident when measuring small timescales and distances. For example, when electromagnetic radiation is absorbed by matter, particle-like properties will be more obvious when the average number of photons in the cube of the relevant wavelength is much smaller than 1. It is not too difficult to experimentally observe non-uniform deposition of energy when light is absorbed, however this alone is not evidence of "particulate" behavior of light. Rather, it reflects the quantum nature of *matter*.[1]Demonstrating that the light itself is quantized, not merely its interaction with matter, is a more subtle problem.

There are experiments in which the wave and particle natures of electromagnetic waves appear in the same experiment, such as the self-interference of a singlephoton. *True* single-photon experiments (in a quantum optical sense) can be done today in undergraduate-level labs.[2] When a single photon is sent through aninterferometer, it passes through both paths, interfering with itself, as waves do, yet is detected by a photomultiplier or other sensitive detector only once.

A quantum theory of the interaction between electromagnetic radiation and matter such as electrons is described by the theory of quantum electrodynamics.[*citation needed*]

Wave model

Electromagnetic radiation is a transverse wave, meaning that the oscillations of the waves are perpendicular to the direction of energy transfer and travel. The electric and magnetic parts of the field stand in a fixed ratio of strengths in order to satisfy the two Maxwell equations that specify how one is produced from the other. These **E** and **B** fields are also in phase, with both reaching maxima and minima at the same points in space (see illustrations). A common misconception is that the **E** and **B** fields in electromagnetic radiation are out of phase because a change in one produces the other, and this would produce a phase difference between them as sinusoidal functions (as indeed happens in Electromagnetic induction, and in the near-field close to antennas). However, in the far-field EM radiation which is described by the two source-free Maxwell curl operatorequations, a more correct description is that a time-change in one type of field is proportional to a space-change in the other. These derivatives require that the **E**and **B** fields in EMR are in-phase (see math section below).[*citation needed*]

An important aspect of the nature of light is frequency. The frequency of a wave is its rate of oscillation and is measured in hertz, the SI unit of frequency, where one hertz is equal to one oscillation per second. Light usually has a spectrum of frequencies that sum to form the resultant wave. Different frequencies undergo different angles of refraction, a phenomenon known as dispersion.

A wave consists of successive troughs and crests, and the distance between two adjacent crests or troughs is called the wavelength. Waves of the electromagnetic spectrum vary in size, from very long radio waves the size of buildings to very short gamma rays smaller than atom nuclei. Frequency is inversely proportional to wavelength, according to the equation:[*citation needed*]

$$v = f\lambda$$

where *v* is the speed of the wave (*c* in a vacuum, or less in other media), *f* is the frequency and λ is the wavelength. As waves cross boundaries between different media, their speeds change but their frequencies remain constant.

Interference is the superposition of two or more waves resulting in a new wave pattern. If the fields have components in the same direction, they constructively interfere, while opposite directions cause destructive interference. An example of interference caused by EMR is electromagnetic interference (EMI) or as it is more commonly known as, radio-frequency interference (RFI).[*citation needed*]

The energy in electromagnetic waves is sometimes called radiant energy.[*citation needed*]

Particle model and quantum theory

See also: Quantization (physics) and Quantum optics

An anomaly arose in the late 19th century involving a contradiction between the wave theory of light on the one hand, and on the other, observers' actual measurements of the electromagnetic spectra that were being emitted by thermal radiators known as black bodies. Physicists struggled with this problem, which later became known as the ultraviolet catastrophe, unsuccessfully for many years. In 1900, Max

Planck developed a new theory of black-body radiation that explained the observed spectrum. Planck's theory was based on the idea that black bodies emit light (and other electromagnetic radiation) only as discrete bundles or packets of energy. These packets were called quanta. Later, Albert Einsteinproposed that the quanta of light might be regarded as real particles, and (still later) the particle of light was given the name photon, to correspond with other particles being described around this time, such as the electron and proton. A photon has an energy, *E*, proportional to its frequency, *f*, by

$$E = hf = \frac{hc}{\lambda}$$

where *h* is Planck's constant, λ is the wavelength and *c* is the speed of light. This is sometimes known as the Planck–Einstein equation.[3] In quantum theory (seefirst quantization) the energy of the photons is thus directly proportional to the frequency of the EMR wave.[4]

Likewise, the momentum *p* of a photon is also proportional to its frequency and inversely proportional to its wavelength:

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}.$$

The source of Einstein's proposal that light was composed of particles (or could act as particles in some circumstances) was an experimental anomaly not explained by the wave theory: the photoelectric effect, in which light striking a metal surface ejected electrons from the surface, causing an Electric current to flow across an applied Voltage. Experimental measurements demonstrated that the energy of individual ejected electrons was proportional to the *frequency*, rather than the *intensity*, of the light. Furthermore, below a certain minimum frequency, which depended on the particular metal, no current would flow regardless of the intensity. These observations appeared to contradict the wave theory, and for years physicists tried in vain to find an explanation. In 1905, Einstein explained this puzzle by resurrecting the particle theory of light to explain the observed effect. Because of the preponderance of evidence in favor of the wave theory, however, Einstein's ideas were met initially with great skepticism among established physicists. Eventually Einstein's explanation was accepted as new particle-like behavior of light was observed, such as the Compton effect.[*citation needed*]

As a photon is absorbed by an atom, it excites the atom, elevating an electron to a higher energy level (on average, one that is farther from the nucleus). When an electron in an excited molecule or atom descends to a lower energy level, it emits a photon of light equal to the energy difference. Since the energy levels of electrons in atoms are discrete, each element and each molecule emits and absorbs its own characteristic frequencies. When the emission of the photon is immediate, this phenomenon is called fluorescence, a type of photoluminescence. An example is visible light emitted from fluorescent paints, in response to ultraviolet (blacklight). Many other fluorescent emissions are known in spectral bands other than visible light. When the emission of the photon is delayed, the phenomenon is called phosphorescence.[*citation needed*]

Wave–particle duality

The modern theory that explains the nature of light includes the notion of wave–particle duality. More generally, the theory states that everything has both a particle nature and a wave nature, and various experiments can be done to bring out one or the other. The particle nature is more easily discerned if an object has a large mass, and it was not until a bold proposition by Louis de Broglie in 1924 that the scientific community realised that electrons also exhibited wave–particle duality.[*citation needed*]

Wave and particle effects of electromagnetic radiation

Together, wave and particle effects explain the emission and absorption spectra of EM radiation, wherever it is seen. The matter-composition of the medium through which the light travels determines the nature of the absorption and emission spectrum. These bands correspond to the allowed energy levels in the atoms. Dark bands in the absorption spectrum are due to the atoms in an intervening medium between source and observer, absorbing certain frequencies of the light between emitter and detector/eye, then emitting them in all directions, so that a dark band appears to the detector, due to the radiation scattered out of the beam. For instance, dark bands in the light emitted by a distant star are due to the atoms in the star's atmosphere. A similar phenomenon occurs for emission, which is seen when the emitting gas is glowing due to excitation of the atoms from any mechanism, including heat. As electrons descend to lower energy levels, a spectrum is emitted that represents the jumps between the energy levels of the electrons, but lines are seen because again emission happens only at particular energies after excitation. An example is theemission spectrum of nebulae.[*citation needed*] Rapidly moving electrons are most sharply accelerated when they encounter a region of force, so they are responsible for producing much of the highest frequency electromagnetic radiation observed in nature.

Today, scientists use these phenomena to perform various chemical determinations for the composition of gases lit from behind (absorption spectra) and for glowing gases (emission spectra). Spectroscopy (for example) determines what chemical elements a star is composed of. Spectroscopy is also used in the determination of the distance of a star, using the red shift.[*citation needed*]

Speed of propagation

Main article: speed of light

Any electric charge that accelerates, or any changing magnetic field, produces electromagnetic radiation. Electromagnetic information about the charge travels at the speed of light. Accurate treatment thus incorporates a concept known asretarded time (as opposed to advanced time, which is not physically possible in light of causality), which adds to the expressions for the electrodynamic Electric field and Magnetic field. These extra terms are responsible for electromagnetic radiation.[*citation needed*]

When any wire (or other conducting object such as an antenna) conductsAlternating current, electromagnetic radiation is propagated at the same frequency as the electric current. In many such situations it is possible to identify an electrical dipole moment that arises from separation of charges due to the exciting electrical potential, and this dipole moment oscillates in time, as the charges move back and forth. This oscillation at a given frequency gives rise to changing electric and magnetic fields, which then set the electromagnetic radiation in motion.[*citation needed*]

At the quantum level, electromagnetic radiation is produced when the wavepacket of a charged particle oscillates or otherwise accelerates. Charged particles in a stationary state do not move, but a superposition of such states may result in transition state which has an Electric dipole moment that oscillates in time. This oscillating dipole moment is responsible for the phenomenon of radiative transition between quantum states of a charged particle. Such states occur (for example) in atoms when photons are radiated as the atom shifts from one stationary state to another.[*citation needed*]

Depending on the circumstances, electromagnetic radiation may behave as a waveor as particles. As a wave, it is characterized by a velocity (the speed of light),wavelength, and frequency. When considered as particles, they are known asphotons, and each has an energy related to the frequency of the wave given byPlanck's relation $E = h\nu$, where E is the energy of the photon, $h = 6.626 \times 10^{-34}$ J·s is Planck's constant, and ν is the frequency of the wave.[*citation needed*]

One rule is always obeyed regardless of the circumstances: EM radiation in a vacuum always travels at the speed of light, *relative to the observer*, regardless of the observer's velocity. (This observation led to Albert Einstein's development of the theory of special relativity.)[*citation needed*]

In a medium (other than vacuum), velocity factor or refractive index are considered, depending on frequency and application. Both of these are ratios of the speed in a medium to speed in a vacuum.[*citation needed*]

Special theory of relativity

Main article: Special theory of relativity

By the late nineteenth century, however, a handful of experimental anomalies remained that could not be explained by the simple wave theory. One of these anomalies involved a controversy over the speed of light. The speed of light and other EMR predicted by Maxwell's equations did not appear unless the equations were modified in a way first suggested by FitzGerald and Lorentz (see history of special relativity), or else otherwise it would depend on the speed of observer relative to the "medium" (called luminiferous aether) which supposedly "carried" the electromagnetic wave (in a manner analogous to the way air carries sound waves). Experiments failed to find any observer effect, however. In 1905, Albert Einstein proposed that space and time appeared to be velocity-changeable entities, not only for light propagation, but all other processes and laws as well. These changes then automatically accounted for the constancy of the speed of light and all electromagnetic radiation, from the viewpoints of all observers—even those in relative motion.

History of discovery

Electromagnetic radiation of wavelengths other than those of visible light were discovered in the early 19th century. The discovery of infrared radiation is ascribed to William Herschel, the astronomer. Herschel published his results in 1800 before the Royal Society of London.[5] Herschel used a glass prism to refractlight from the Sun and detected invisible rays that caused heating beyond the redpart of the spectrum, through an increase in the temperature recorded with athermometer. These "calorific rays" were later termed infrared.[*citation needed*]

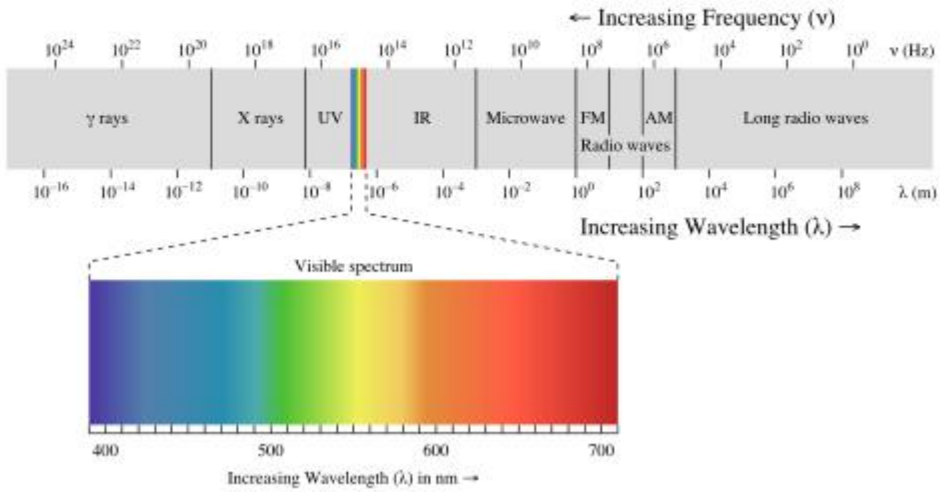
In 1801, the German physicist Johann Wilhelm Ritter made the discovery ofultraviolet in an experiment similar to Hershel's, using sunlight and a glass prism. Ritter noted that invisible rays near the violet edge of a solar spectrum dispersed by a triangular prism darkened silver chloride preparations more quickly than did the nearby violet light. Ritter's experiments were an early precursor to what would become photography. Ritter noted that the ultraviolet rays (which at first were called "chemical rays") were capable of causing chemical reactions.[*citation needed*]

In 1862-4 James Clerk Maxwell developed equations for the electromagnetic field which suggested that waves in the field would travel with a speed that was very close to the known speed of light. Maxwell therefore suggested that visible light (as well as invisible infrared and ultraviolet rays by inference) all consisted of propagating disturbances (or radiation) in the electromagnetic field. Radio waves were not first detected from a natural source, but were rather produced deliberately and artificially by the German scientist Heinrich Hertz in 1887, using electrical circuits calculated to produce oscillations at a much lower frequency than that of visible light, following recipes for producing oscillating charges and currents suggested by Maxwell's equations. Hertz also developed ways to detect these waves, and produced and characterized what were later termed radio wavesand microwaves.[*citation needed*]

Wilhelm Röntgen discovered and named X-rays. After experimenting with high voltages applied to an evaccuated tube on 8 November 1895, he noticed a fluorescence on a nearby plate of coated glass. In one month, he discovered the main properties of X-rays that we understand to this day.[*citation needed*]

The last portion of the EM spectrum was discovered associated with radioactivity.Henri Becquerel found that uranium salts caused fogging of an unexposed photographic plate through a covering paper in a manner similar to X-rays, andMarie Curie discovered that only certain elements gave off these rays of energy, soon discovering the intense radiation of radium. The radiation from pitchblende was differentiated into alpha rays (alpha particles) and beta rays (beta particles) byErnest Rutherford through simple experimentation in 1899, but these proved to be charged particulate types of radiation. However, in 1900 the French scientistPaul Villard discovered a third neutrally charged and especially penetrating type of radiation from radium, and after he described it, Rutherford realized it must be yet a third type of radiation, which in 1903 Rutherford named gamma rays. In 1910 British physicist William Henry Bragg demonstrated that gamma rays are electromagnetic radiation, not particles, and in 1914 Rutherford and Edward Andrade measured their wavelengths, and found that they were similar to X-rays but with shorter wavelengths and higher frequency.[citation needed]

Electromagnetic spectrum



electromagnetic spectrum with visible light highlighted

Main article: electromagnetic spectrum

CLASS	FREQUENCY	WAVELENGTH	ENERGY
γ	300 EHz	1 pm	1.24 MeV
HX	30 EHz	10 pm	124 keV
	3 EHz	100 pm	12.4 keV
SX	300 PHz	1 nm	1.24 keV
EUV	30 PHz	10 nm	124 eV
NUV	3 PHz	100 nm	12.4 eV
NIR	300 THz	1 μm	1.24 eV
MIR	30 THz	10 μm	124 meV
FIR	3 THz	100 μm	12.4 meV
EHF	300 GHz	1 mm	1.24 meV
SHF	30 GHz	1 cm	124 μeV
UHF	3 GHz	1 dm	12.4 μeV
VHF	300 MHz	1 m	1.24 μeV
HF	30 MHz	10 m	124 neV
MF	3 MHz	100 m	12.4 neV
LF	300 kHz	1 km	1.24 neV
VLF	30 kHz	10 km	124 peV
VF/ULF	3 kHz	100 km	12.4 peV
SLF	300 Hz	1 Mm	1.24 peV
ELF	30 Hz	10 Mm	124 feV
	3 Hz	100 Mm	12.4 feV

Legend:

γ = gamma rays

HX = Hard X-rays

SX = Soft X-Rays

EUV = Extreme-ultraviolet

NUV = Near-ultraviolet

Visible light (colored bands)

NIR = Near-infrared

MIR = Moderate-infrared

FIR = Far-infrared

EHF = Extremely high frequency (microwaves)

SHF = Super-high frequency (microwaves)

UHF = Ultrahigh frequency (radio waves)
VHF = Very high frequency (radio)
HF = High frequency (radio)
MF = Medium frequency (radio)
LF = Low frequency (radio)
VLF = Very low frequency (radio)
VF = Voice frequency
ULF = Ultra-low frequency (radio)
SLF = Super-low frequency (radio)
ELF = Extremely low frequency(radio)

In general, EM radiation (the designation 'radiation' excludes static electric and magnetic and near fields) is classified by wavelength into radio, microwave,infrared, the visible spectrum we perceive as visible light, ultraviolet, X-rays, andgamma rays. Arbitrary electromagnetic waves can always be expressed by Fourier analysis in terms of sinusoidal monochromatic waves, which in turn can each be classified into these regions of the EMR spectrum.

For certain classes of EM waves, the waveform is most usefully treated as *random*, and then spectral analysis must be done by slightly different mathematical techniques appropriate to random or stochastic processes. In such cases, the individual frequency components are represented in terms of their *power*content, and the phase information is not preserved. Such a representation is called the power spectral density of the random process. Random electromagnetic radiation requiring this kind of analysis is, for example, encountered in the interior of stars, and in certain other very wideband forms of radiation such as the Zero-Point wave field of the electromagnetic vacuum.

The behavior of EM radiation depends on its frequency. Lower frequencies have longer wavelengths, and higher frequencies have shorter wavelengths, and are associated with photons of higher energy. There is no fundamental limit known to these wavelengths or energies, at either end of the spectrum, although photons with energies near the Planck energy or exceeding it (far too high to have ever been observed) will require new physical theories to describe.

Soundwaves are not electromagnetic radiation. At the lower end of the electromagnetic spectrum, about 20 Hz to about 20 kHz, are frequencies that might be considered in the audio range. However, electromagnetic waves cannot be directly perceived by human ears. Sound waves are the oscillating compression of molecules. To be heard, electromagnetic radiation must be converted to pressure waves of the fluid in which the ear is located (whether the fluid is air, water or something else).

Radio and microwave heating and currents, and infrared heating

When EM radiation interacts with matter, its behavior changes qualitatively as its frequency changes. At radio and microwave frequencies, EMR interacts with matter largely as a bulk collection of charges which are spread out over large numbers of affected atoms. In electrical conductors, such induced bulk movement of charges (electric currents) results in absorption of the EMR, or else separations of charges that cause generation of new EMR (effective reflection of the EMR). An example is absorption or emission of radio waves by antennas, or absorption of microwaves by water or other molecules with an electric dipole moment, as for example inside a microwave oven. These interactions produce either electric currents or heat, or both. Infrared EMR interacts with dipoles present in single molecules, which change as atoms vibrate at the ends of a single chemical bond. For this reason, infrared is reflected by metals (as is most EMR into the ultraviolet) but is absorbed by a wide range of substances, causing them to increase in temperature as the vibrations dissipate as heat. In the same process, bulk substances radiate in the infrared spontaneously (see thermal radiationsection below).

Reversible and nonreversible molecular changes from visible light

As frequency increases into the visible range, photons of EMR have enough energy to change the bond structure of some individual molecules. It is not a coincidence that this happens in the "visible range," as the mechanism of visioninvolves the change in bonding of a single molecule (retinal) which absorbs light in the rhodopsin the retina of the human eye. Photosynthesis becomes possible in this range as well, for similar reasons, as a single molecule of chlorophyll is excited by a single photon. Animals which detect infrared do not use such single molecule processes, but are forced to make use of small packets of water which change temperature, in an essentially thermal process that involves many photons (see infrared sensing in snakes). For this reason, infrared, microwaves, and radio waves are thought to damage molecules and biological tissue only by bulk heating, not excitation from single photons of the radiation (however, there does remain controversy about possible non-thermal biological damage from low frequency EM radiation, see below).

Visible light is able to affect a few molecules with single photons, but usually not in a permanent or damaging way, in the absence of power high enough to increase temperature to damaging levels. However, in plant tissues that carry on photosynthesis, carotenoids act to quench electronically excited chlorophyll produced by visible light in a process called non-photochemical quenching, in order to prevent reactions which would otherwise interfere with photosynthesis at high light levels. There is also some limited evidence that some reactive oxygen species are created by visible light in skin, and that these may have some role in photoaging, in the same manner as ultraviolet A does.[6]

Molecular damage from ultraviolet

As a photon interacts with single atoms and molecules, the effect depends on the amount of energy the photon carries. As frequency increases beyond visible into the ultraviolet, photons now carry enough energy (about three electron volts or more) to excite certain doubly bonded molecules into permanent chemical rearrangement. If these molecules are biological molecules in DNA, this causes lasting damage. DNA is also indirectly damaged by reactive oxygen species produced by ultraviolet A (UVA), which has energy too low to damage DNA directly. This is why ultraviolet at all wavelengths can damage DNA, and is capable of causing cancer, and (for UVB) skin burns (sunburn) which are far worse than would be produced by simple heating (temperature increase) effects. This property of causing molecular damage that is far out of proportion to all temperature-changing (i.e., heating) effects, is characteristic of all EMR with frequencies at the visible light range and above. These properties of high-frequency EMR are due to quantum effects which cause permanent damage to materials and tissues at the single molecular level.[*citation needed*]

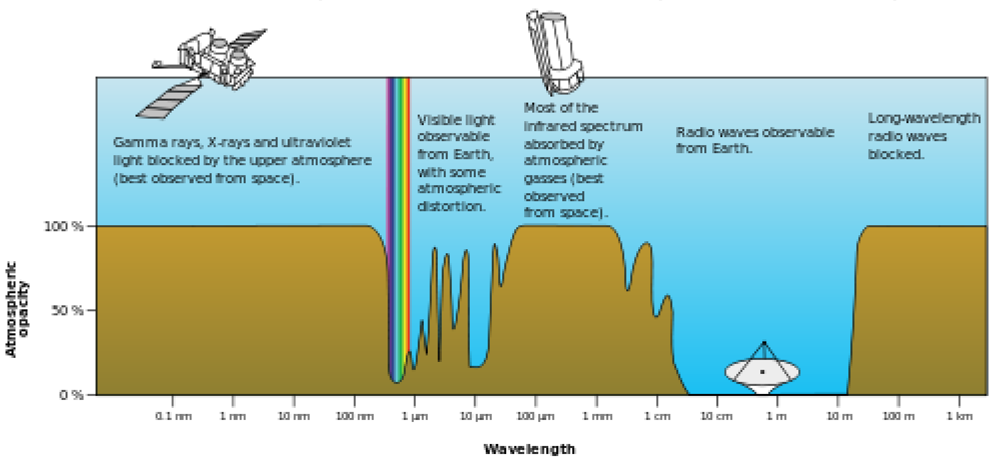
Ionization and extreme types of molecular damage from X-rays and gamma rays

At the higher end of the ultraviolet range, the energy of photons becomes large enough to impart enough energy to electrons to cause them to be liberated from the atom, in a process called photoionisation. The energy required for this is always larger than about 10 electron volts (eV) corresponding with wavelengths smaller than 124 nm (some sources suggest a more realistic cutoff of 33 eV, which is the energy required to ionize water). This high end of the ultraviolet spectrum with energies in the approximate ionization range, is sometimes called "extreme UV." (Most of this is filtered by the Earth's atmosphere).[*citation needed*]

Electromagnetic radiation composed of photons that carry minimum-ionization energy, or more, (which includes the entire spectrum with shorter wavelengths), is therefore termed ionizing radiation. (There are also many other kinds of ionizing radiation made of non-EM particles). Electromagnetic-type ionizing radiation extends from the extreme ultraviolet to all higher frequencies and shorter wavelengths, which means that all X-rays and gamma rays are ionizing radiation. These are capable of the most severe types of molecular damage, which can happen in biology to any type of biomolecule, including mutation and cancer, and often at great depths from the skin, since the higher end of the X-ray spectrum, and all of the gamma ray spectrum, are penetrating to matter. It is this type of damage which causes these types of radiation to be especially carefully monitored, due to their hazard, even at comparatively low-energies, to all living organisms.[citation needed]

Propagation and absorption in the Earth's atmosphere and magnetosphere

Main articles: ozone layer, shortwave radio, skywave and ionosphere



Rough plot of Earth's atmospheric absorption and scattering (or opacity) of various wavelengths of electromagnetic radiation

Most electromagnetic waves of higher frequency than visible light (UV and X-rays) are blocked by absorption first from the magnetosphere and then from the electronic excitation in ozone and dioxygen (for UV), and by ionization of air for energies in the extreme UV and above. Visible light is well transmitted in air, as it is not energetic enough to excite oxygen, but too energetic to excite molecular vibrational frequencies of molecules in air.[citation needed]

Below visible light, a number of absorption bands in the infrared are due to modes of vibrational excitation in water vapor. However, at energies too low to excite water vapor the atmosphere becomes transparent again, allowing free transmission of most microwave and radio waves.[*citation needed*]

Finally, at radio wavelengths longer than 10 meters or so (about 30 MHz), the air in the lower atmosphere remains transparent to radio, but plasma in certain layers of the ionosphere of upper Earth atmosphere begins to interact with radio waves (see skywave). This property allows some longer wavelengths (100 meters or 3 MHz) to be reflected and results in farther shortwave radio than can be obtained by line-of-sight. However, certain ionospheric effects begin to block incoming radiowaves from space, when their frequency is less than about 10 MHz (wavelength longer than about 30 meters).[*citation needed*]

Types and sources, classed by spectral band (frequency)

See electromagnetic spectrum for detail

Radio waves

Main article: radio waves

When EM radiation at the frequencies for which it is referred to as "radio waves" impinges upon a Conductor, it couples to the conductor, travels along it, andinduces an electric current on the surface of the conductor by moving the electrons of the conducting material in correlated bunches of charge. Such effects can cover macroscopic distances in conductors (including as radio antennas), since the wavelength of radiowaves is long, by human scales. Radio waves thus have the most overtly "wave-like" characteristics of all the types of EMR, since their waves are so long.[*citation needed*]

Microwaves

Main article: Microwaves

Infrared

Main article: infrared

Visible light

Main article: light

Natural sources produce EM radiation across the spectrum. EM radiation with awavelength between approximately 400 nm and 700 nm is directly detected by the human eye and perceived as visible light. Other wavelengths, especially nearby infrared (longer than 700 nm) and ultraviolet (shorter than 400 nm) are also sometimes referred to as light, especially when visibility to humans is not relevant.

Ultraviolet

Main article: ultraviolet

X-rays

Main article: X-rays

Gamma rays

Main article: gamma rays

Thermal radiation and electromagnetic radiation as a form of heat

Main articles: thermal radiation and Planck's law

The basic structure of matter involves charged particles bound together in many different ways. When electromagnetic radiation is incident on matter, it causes the charged particles to oscillate and gain energy. The ultimate fate of this energy depends on the situation. It could be immediately re-radiated and appear as scattered, reflected, or transmitted radiation. It may also get dissipated into other microscopic motions within the matter, coming to thermal equilibrium and manifesting itself as thermal energy in the material. With a few exceptions related to high-energy photons (such as fluorescence, harmonic generation,photochemical reactions, the photovoltaic effect for ionizing radiations at far ultraviolet, X-ray, and gamma radiation), absorbed electromagnetic radiation simply deposits its energy by heating the material. This happens both for infrared, microwave, and radio wave radiation. Intense radio waves can thermally burn living tissue and can cook food. In addition to infrared lasers, sufficiently intense visible and ultraviolet lasers can also easily set paper afire.[*citation needed*]

Ionizing electromagnetic radiation creates high-speed electrons in a material and breaks chemical bonds, but after these electrons collide many times with other atoms in the material eventually most of the energy is downgraded to thermal energy; this whole process happens in a tiny fraction of a second. This process makes ionizing radiation far more dangerous per unit of energy than non-ionizing radiation. This caveat also applies to the ultraviolet (UV) spectrum, even though almost all of it is not ionizing, because UV can damage molecules due to electronic excitation which is far greater per unit energy than heating effects produce.[*citation needed*]

Infrared radiation in the spectral distribution of a black body is usually considered a form of heat, since it has an equivalent temperature, and is associated with an entropy change per unit of thermal energy. However, the word "heat" is a highly technical term in physics and thermodynamics, and is often confused with thermal energy. Any type of electromagnetic energy can be transformed into thermal energy in interaction with matter. Thus, *any* electromagnetic radiation can "heat" (in the sense of increase the thermal energy termperature of) a material, when it is absorbed.[*citation needed*]

The inverse or time-reversed process of absorption is responsible for thermal radiation. Much of the thermal energy in matter consists of random motion of charged particles, and this energy can be radiated away from the matter. The resulting radiation may subsequently be absorbed by another piece of matter, with the deposited energy heating the material. thermal radiation is an important mechanism of heat transfer.[*citation needed*]

The electromagnetic radiation in an opaque cavity at thermal equilibrium is effectively a form of thermal energy, having maximum radiation entropy.[*citation needed*]

Biological effects

Main articles: Electromagnetic radiation and health and Mobile phone radiation and health

The effects of electromagnetic radiation upon living cells, including those in humans, depends upon the power and the frequency of the radiation. For low-frequency radiation (radio waves to visible light) the best-understood effects are those due to radiation power alone, acting through the effect of simple heating when the radiation is absorbed by the cell. For these thermal effects, the frequency of the radiation is important only as it affects radiation penetration into the organism (for example microwaves penetrate better than infrared). Initially, it was believed that low frequency fields that were too weak to cause significant heating could not possibly have any biological effect.[7]

Despite this opinion among researchers, evidence has accumulated that supports the existence of complex biological effects of weaker *non-thermal* electromagnetic fields, (including weak ELF magnetic fields, although the latter does not strictly qualify as EM radiation[7][8][9]), and modulated RF and microwave fields.[10][11][12] Fundamental mechanisms of the interaction between biological material and electromagnetic fields at non-thermal levels are not fully understood.[7] Bioelectromagnetics is the study of these interactions and effects.

The World Health Organization has classified radiofrequency electromagnetic radiation as a possible group 2b carcinogen.[13][14] This group contains possible carcinogens with weaker evidence, at the same level as coffee and automobile exhaust. For example, there have been a number of epidemiological studies of looking for a relationship between cell phone use and brain cancer development, which have been largely inconclusive, save to demonstrate that the effect, if it exists, cannot be a large one. See the main article referenced above.

At higher frequencies (visible and beyond), the effects of individual photons of the radiation begin to become important, as these now have enough energy individually directly or indirectly to damage biological molecules.[15] All frequences of UV radiation have been classed as Group 1 carcinogens by the World Health Organization. Ultraviolet radiation from sun exposure is the primary cause of skin cancer.[16][17]

Thus, at UV frequencies and higher (and probably somewhat also in the visible range),[6] electromagnetic radiation does far more damage to biological systems than simple heating predicts. This is most obvious in the "far" (or "extreme") ultraviolet, and also X-ray and gamma radiation, are referred to as ionizing radiation due to the ability of photons of this radiation to produce ions and free radicals in materials (including living tissue). Since such radiation can produce severe damage to life at powers that produce very little heating, it is considered far more dangerous (in terms of damage-produced per unit of energy, or power) than the rest of the electromagnetic spectrum.

Derivation from electromagnetic theory

Main article: electromagnetic wave equation

Electromagnetic waves as a general phenomenon were predicted by the classical laws of Electricity and magnetism, known as Maxwell's equations. Inspection of Maxwell's equations without sources (charges or currents) results in, along with the possibility of nothing happening, nontrivial solutions of changing electric and magnetic fields. Beginning with Maxwell's equations in free space:

$$\nabla \cdot \mathbf{E} = 0 \qquad (1)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad (2)$$

$$\nabla \cdot \mathbf{B} = 0 \qquad (3)$$

$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \qquad (4)$$

where

∇ is a vector differential operator (see Del).

One solution,

$$\mathbf{E} = \mathbf{B} = \mathbf{0},$$

is trivial.

For a more useful solution, we utilize vector identities, which work for any vector, as follows:

$$\nabla \times (\nabla \times \mathbf{A}) = \nabla (\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A}$$

To see how we can use this, take the curl of equation (2):

$$\nabla \times (\nabla \times \mathbf{E}) = \nabla \times \left(-\frac{\partial \mathbf{B}}{\partial t}\right) \qquad (5)$$

Evaluating the left hand side:

$$\nabla \times (\nabla \times \mathbf{E}) = \nabla (\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} = -\nabla^2 \mathbf{E} \qquad (6)$$

where we simplified the above by using equation (1).

Evaluate the right hand side:

$$\nabla \times \left(-\frac{\partial \mathbf{B}}{\partial t}\right) = -\frac{\partial}{\partial t} (\nabla \times \mathbf{B}) = -\mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad (7)$$

Equations (6) and (7) are equal, so this results in a vector-valued differential equation for the electric field, namely

$$\nabla^2 \mathbf{E} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

Applying a similar pattern results in similar differential equation for the magnetic field:

$$\nabla^2 \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2}.$$

These differential equations are equivalent to the wave equation:

$$\nabla^2 f = \frac{1}{{c_0}^2} \frac{\partial^2 f}{\partial t^2}$$

where

c_0 is the speed of the wave in free space and

f describes a displacement

Or more simply:

$$\Box f = 0$$

where $\Box$ is d'Alembertian:

$$\Box = \nabla^2 - \frac{1}{{c_0}^2} \frac{\partial^2}{\partial t^2} = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} - \frac{1}{{c_0}^2} \frac{\partial^2}{\partial t^2}$$

Notice that, in the case of the electric and magnetic fields, the speed is:

$$c_0 = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

This is the speed of light in vacuum. Maxwell's equations unified the vacuum permittivity ϵ_0, the vacuum permeability μ_0, and the speed of light itself, c_0. This relationship had been discovered by Wilhelm Eduard Weber and Rudolf Kohlrausch prior to the development of Maxwell's electrodynamics, however Maxwell was the first to produce a field theory consistent with waves traveling at the speed of light.

But these are only two equations and we started with four, so there is still more information pertaining to these waves hidden within Maxwell's equations. Let's consider a generic vector wave for the electric field.

$$\mathbf{E} = \mathbf{E}_0 f\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right)$$

Here, $\mathbf{E}_0$ is the constant amplitude, f is any second differentiable function, $\hat{\mathbf{k}}$is a unit vector in the direction of propagation, and $\mathbf{x}$is a position vector. We observe that $f\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right)$ is a generic solution to the wave equation. In other words

$$\nabla^2 f\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right) = \frac{1}{{c_0}^2}\frac{\partial^2}{\partial t^2} f\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right),$$

for a generic wave traveling in the $\hat{\mathbf{k}}$ direction.

This form will satisfy the wave equation, but will it satisfy all of Maxwell's equations, and with what corresponding magnetic field?

$$\nabla \cdot \mathbf{E} = \hat{\mathbf{k}} \cdot \mathbf{E}_0 f'\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right) = 0$$

$$\mathbf{E} \cdot \hat{\mathbf{k}} = 0$$

The first of Maxwell's equations implies that electric field is orthogonal to the direction the wave propagates.

$$\nabla \times \mathbf{E} = \hat{\mathbf{k}} \times \mathbf{E}_0 f'\left(\hat{\mathbf{k}} \cdot \mathbf{x} - c_0 t\right) = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{B} = \frac{1}{c_0}\hat{\mathbf{k}} \times \mathbf{E}$$

The second of Maxwell's equations yields the magnetic field. The remaining equations will be satisfied by this choice of $\mathbf{E}, \mathbf{B}$.

Not only are the electric and magnetic field waves in the far-field traveling at the speed of light, but they always have a special restricted orientation and proportional magnitudes, $E_0 = c_0 B_0$, which can be seen immediately from thePoynting vector. The electric field, magnetic field, and direction of wave propagation are all orthogonal, and the wave propagates in the same direction as $\mathbf{E} \times \mathbf{B}$. Also, **E** and **B** far-fields in free space, which as wave solutions depend primarily on these two Maxwell equations, are always in-phase with each other. This is guaranteed since the generic wave solution is first order in both space and time, and the curl operator on one side of these equations results in first-order spacial derivatives of the wave solution, while the time-derivative on the other side of the equations, which gives the other field, is first order in time, resulting in the same phase shift for both fields in each mathematical operation.

From the viewpoint of an electromagnetic wave traveling forward, the electric field might be oscillating up and down, while the magnetic field oscillates right and left; but this picture can be rotated with the electric field oscillating right and left and the magnetic field oscillating down and up. This is a different solution that is traveling in the same direction. This arbitrariness in the orientation with respect to propagation direction is known as polarization. On a quantum level, it is described as photon polarization. The direction of the polarization is defined as the direction of the electric field.

More general forms of the second-order wave equations given above are available, allowing for both non-vacuum propagation media and sources. A great many competing derivations exist, all with varying levels of approximation and intended applications. One very general example is a form of the electric field equation,[18] which was factorized into a pair of explicitly directional wave equations, and then efficiently reduced into a single uni-directional wave equation by means of a simple slow-evolution approximation.

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