Nonlinear Optical Engineering

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Text book and references

B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics*, 2nd ed., John Wiley & Sons, New York, USA, 2007.

References:

R. W. Boyd, *Nonlinear Optics*, 3rd ed., Academic Press, Burlington, MA, USA, 2008.

A. Yariv and P. Yeh, *Photonics - Optical Electronics in Modern Communications*, 6th ed., Oxford University Press, New York, USA, 2007.

What Do We Learn?

Week 1 (9/2, 9/4): Electromagnetic Optics (Ch. 5)
Week 2 (9/9, 9/11): Electromagnetic Optics (Ch. 5)
Week 3 (9/16, 9/18): Polarization optics (Ch. 6)
Week 4 (9/23, 9/25): Photonic-Crystal Optics (Ch. 7)
Week 5 (9/30, 10/2): Photonic-Crystal Optics (Ch. 7), Midterm Exam 1
Week 6 (10/7, 10/9): Fiber Optics (Ch. 9)
Week 7 (10/14, 10/16): Photon Optics (Ch. 12)
Week 8 (10/21, 10/23): Photons and Atoms (Ch. 13)
Week 9 (10/28, 10/30): Photons and Atoms (Ch. 13)
Week 10 (11/4, 11/6): Acousto-Optics (Ch. 19), Midterm Exam 2
Week 11 (11/11, 11/13): Nonlinear Optics (Ch. 21)
Week 12 (11/18, 11/20): Nonlinear Optics (Ch. 21)
Week 13 (11/25, 11/27): Nonlinear Optics (Boyd, Chs. 1-3)
Week 14 (12/2, 12/4): Ultrafast Optics (Ch. 22)
Week 15 (12/9, 12/11): Ultrafast Optics (Ch. 22), Final Exam

Light

And God said, “Let there be light,” and there was light.

God saw that the light was good, and he separated the light from the darkness.

(Genesis 1:3-4)

Light

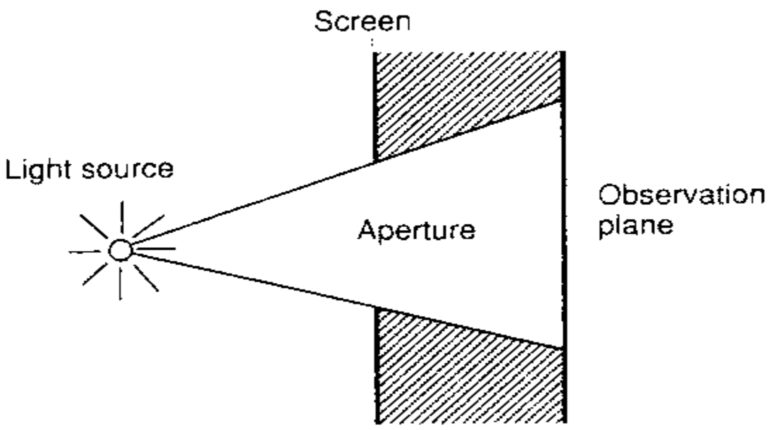
- We all *know* what light is; but it is not easy to *tell* what it is.

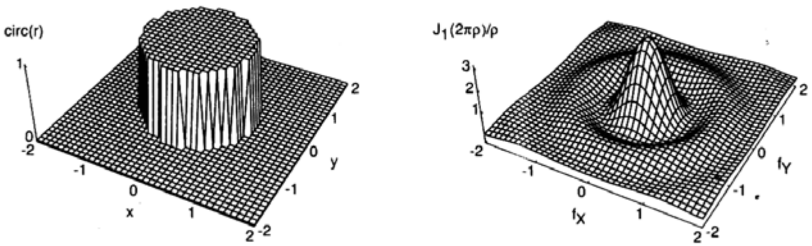
  - Samuel Johnson

- Wave property: Electromagnetic Wave
- Particle property: Photon

History

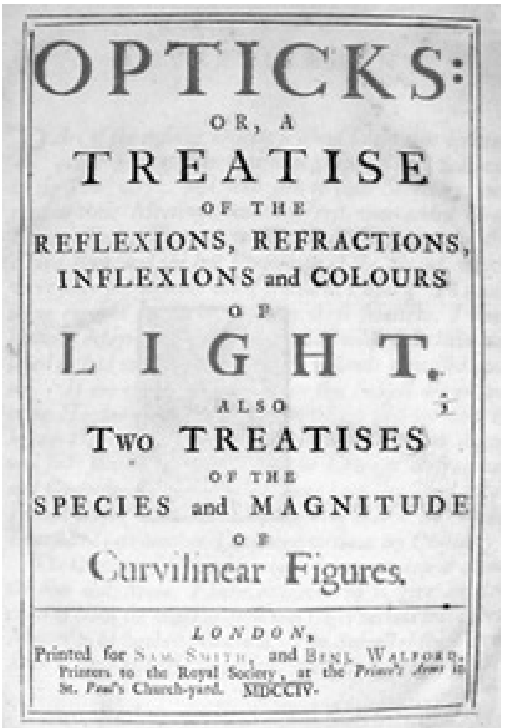
- 1665 Grimaldi
- 1678 Huygens
- 1704 Newton
- 1804 Young
- 1818 Fresnel
- 1860 Maxwell
- 1882 Kirchhoff
- 1905 Einstein





(a) (b)

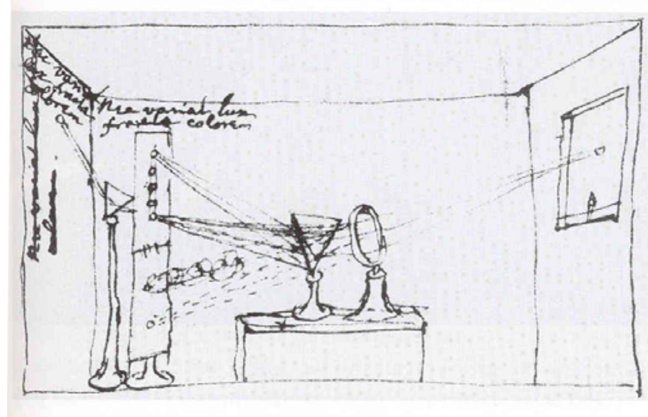
Newton



OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD,
Printers to the Royal Society, at the Prince's Arms in
St. Paul's Church-yard. MDCCIV.

- Isaac Newton
- (1642-1727)

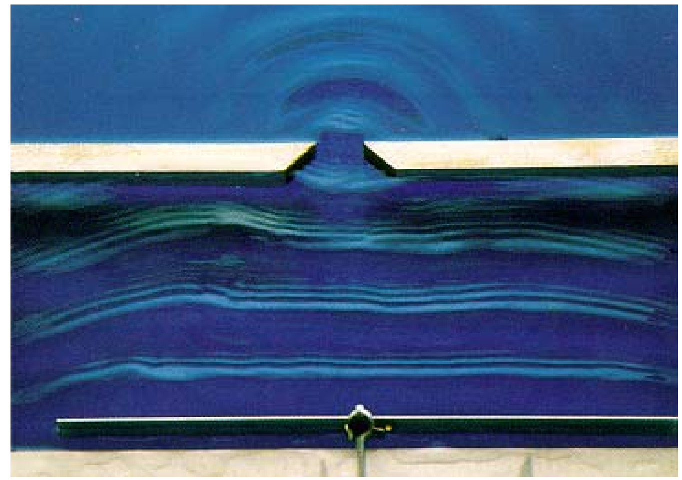


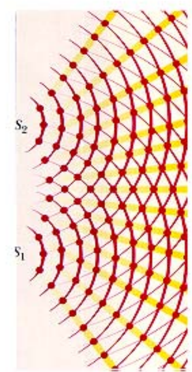
A sketch (left) from Newton's 1672 notebook shows sunlight entering through the window at right, passing through a triangular prism, and splitting into a spectrum of colors. One of the earliest known studies of optics (the science of light and vision) was done by Islamic mathematician Ibn al-Haytham (965–1040), also known as Alhazen. His sketch of lenses is below.

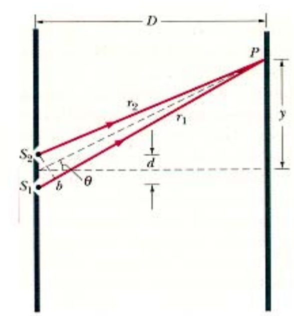
J. Hakim, The Story of Science – Newton at the Center, Smithsonian Books, Washington DC, USA, 2005

Young

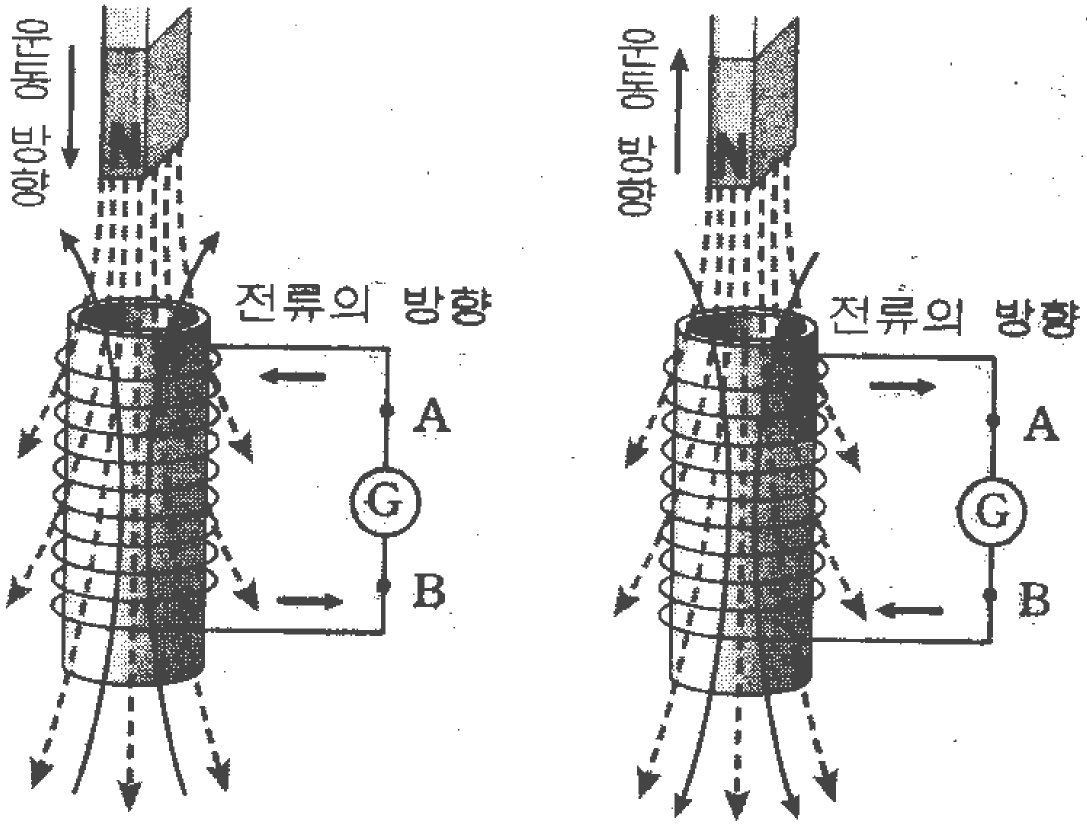
Thomas Young (1773-1829)







Faraday의 법칙

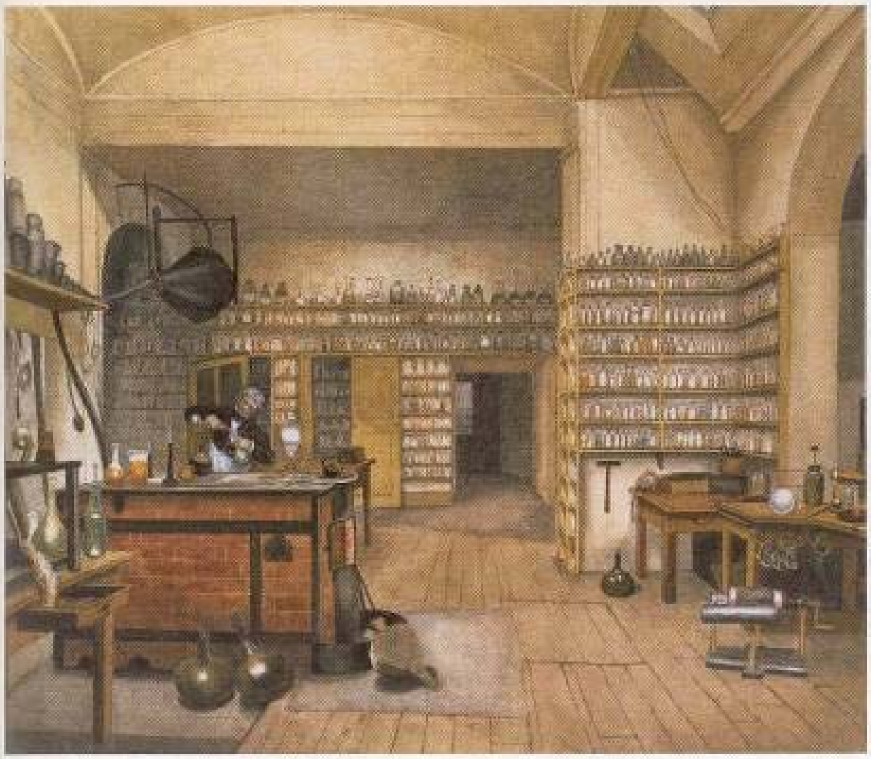


자계(자기장)의 변화 ⇒ 전류 유도

변압기

발전기

Faraday and Maxwell



In 1860, 29-year-old James Clerk Maxwell became a professor at King's College in London. He was able to go to lectures and discussions at the Royal Society and the Royal Institution. He especially enjoyed walks with his hero, Michael Faraday. Faraday, in his 70s, was suffering from failing memory (perhaps due to exposure to dangerous chemicals). The two modest, gracious men shared a passion for science, and Maxwell understood Faraday's genius in a way that few others did. Too bad we can't know what they said to each other.
A watercolor painting from 1852 (left) shows Faraday experimenting in his lab.

J. Hakim, The Story of Science – Newton at the Center, Smithsonian Books, Washington DC, USA, 2005

Maxwell

James Clerk Maxwell (1831-1879)

전자기에 관한 방정식 정립 **(**맥스웰 방정식**)**

전자파의 존재 예측

빛 또한 전자기파의 일종

전자파의 속력**(**빛의 속력**)**은 초당 **30**만 **km**

$$\vec{\nabla}\cdot\vec{D}=\rho \qquad \vec{\nabla}\cdot\vec{B}=0 \qquad \vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t} \qquad \vec{\nabla}\times\vec{H}=\vec{J}+\frac{\partial\vec{D}}{\partial t}$$

Hertz

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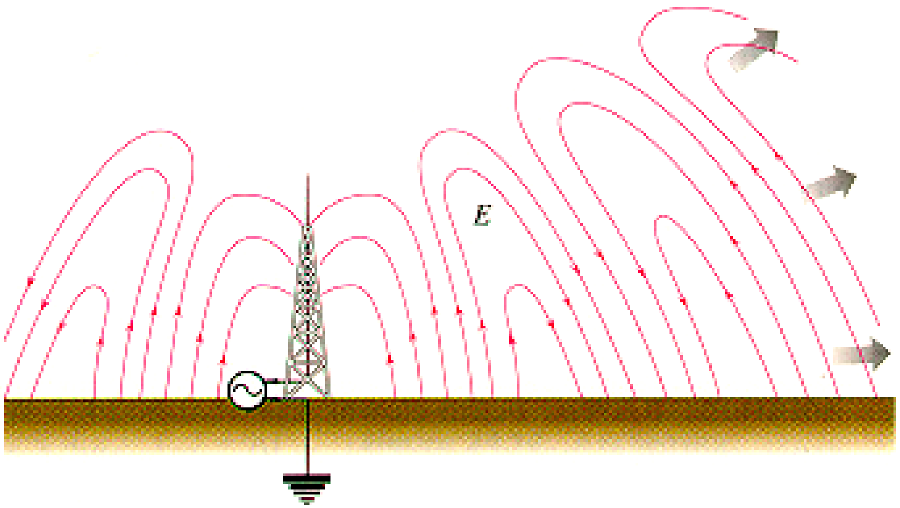
Heinrich Hertz (1857-1894)

Tragically, Hertz was as unfortunate with his health as he was fortunate with his talent. The first sign of trouble was a series of toothaches in 1888, which led to removal of all his teeth in 1889. By 1892, he was suffering from pains in his nose and throat, and was often depressed. His doctors could give him no satisfactory diagnosis. Several operations failed to provide permanent relief. By December 1893, he knew he would not recover, and in a letter he asked his parents *"not to mourn... rather you must be a little proud and consider that I am among the especially elect destined to live for only a short while and yet to live enough. I did not choose this fate, but since it has overtaken me, I must be content; and if the choice had been left to me, perhaps I should have chosen it myself."*

Hertz died of blood poisoning on New Year's Day, 1894; he was thirty-six years old.

--- From 'Great Physicists' by W. H. Cropper

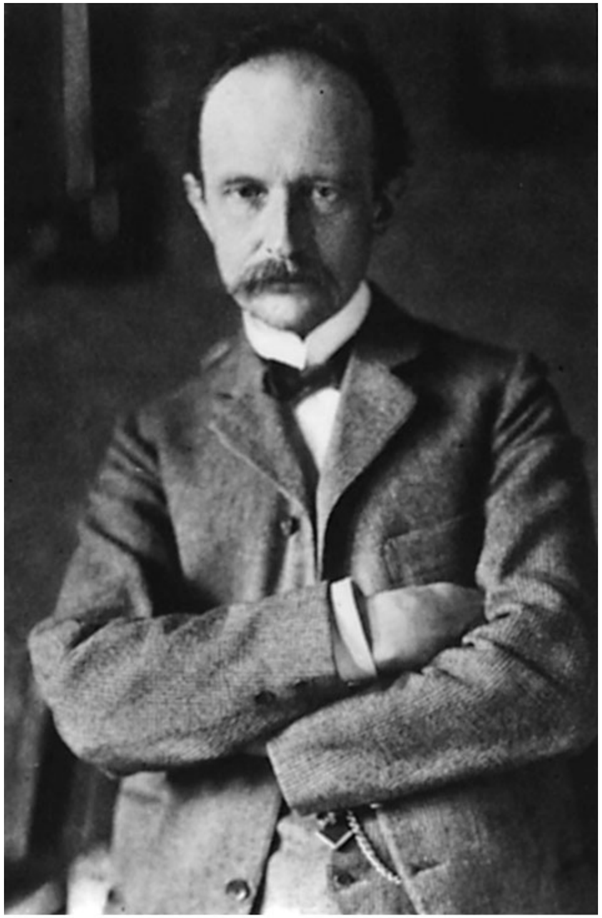
전자파의 발생 예 (안테나)



Marconi

Guglielmo Marconi (1874–1937)

Planck



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In 1900

"After some weeks of the most intense work of my life, light began to appear to me and unexpected views revealed themselves in the distance."

Max Planck (1858-1947)

1905

Young Einstein at the Swiss Patent Office in Berne

Annalen der Physik, vol. 17 (1905)

"one of the most remarkable volumes in the whole scientific literature. It contains three papers by Einstein, each dealing with a different subject and each today acknowledged to be a masterpiece." – Max Born

Einstein

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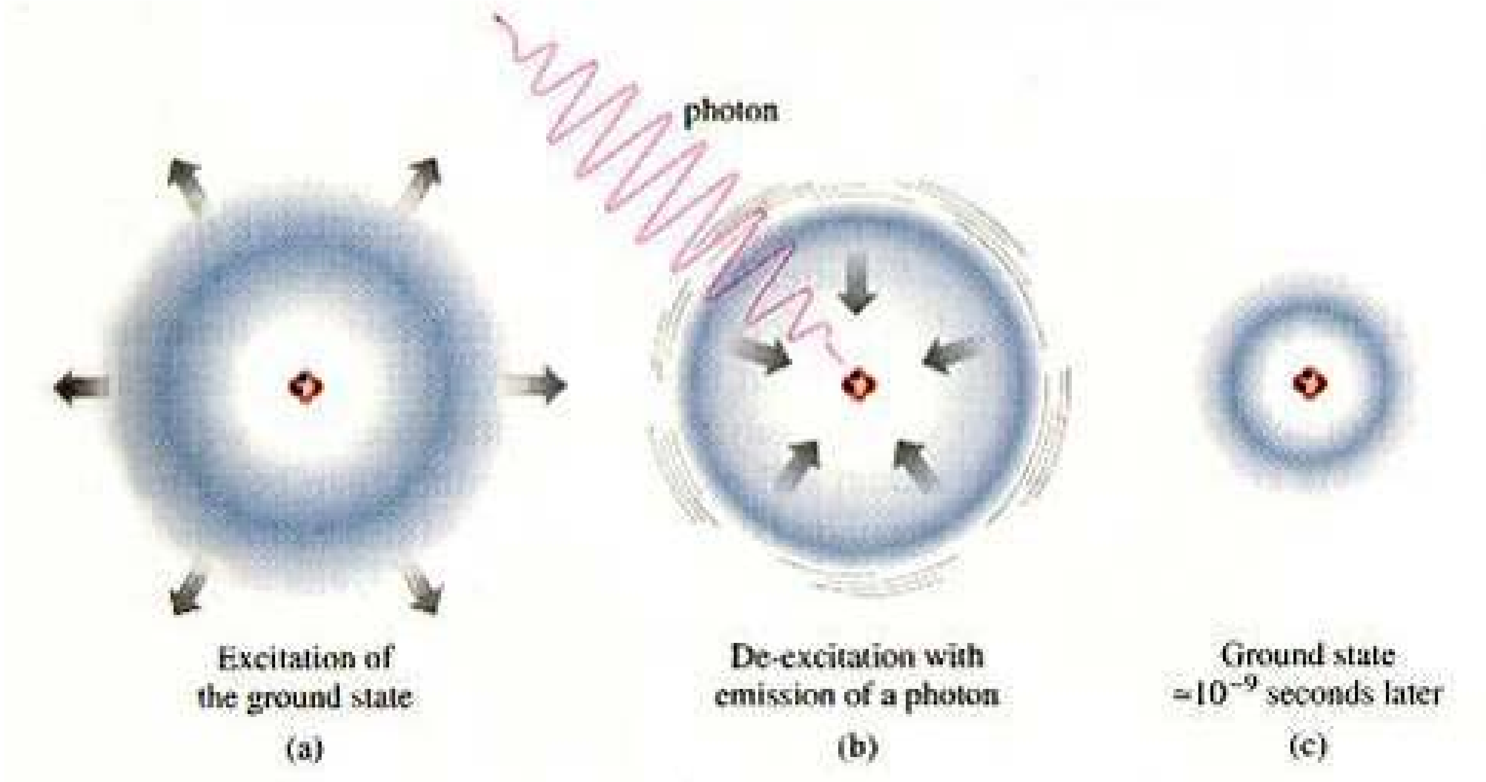
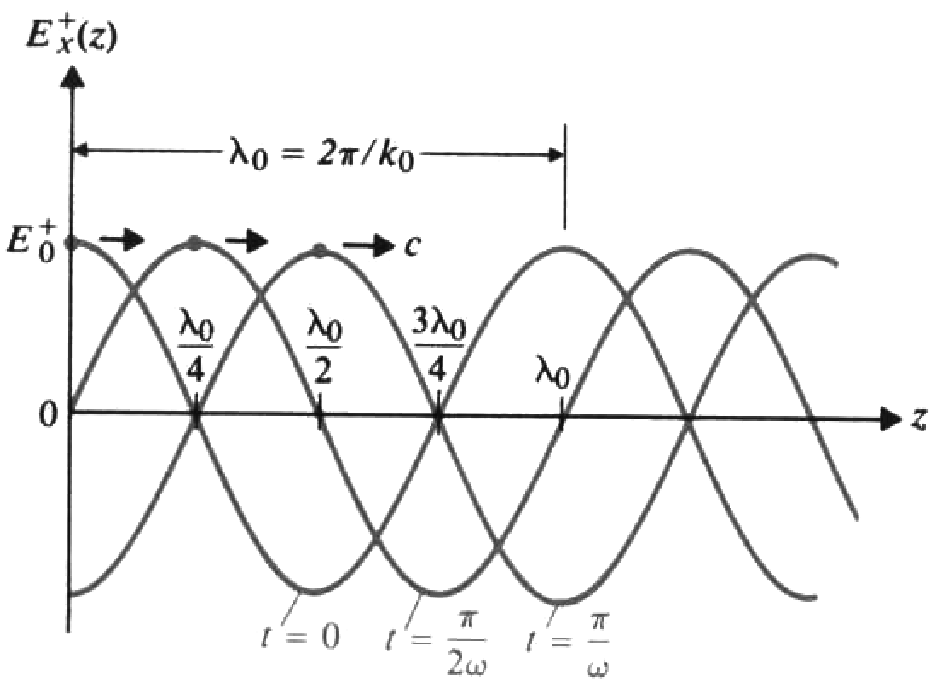
Nobel Prize in Physics 1921

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

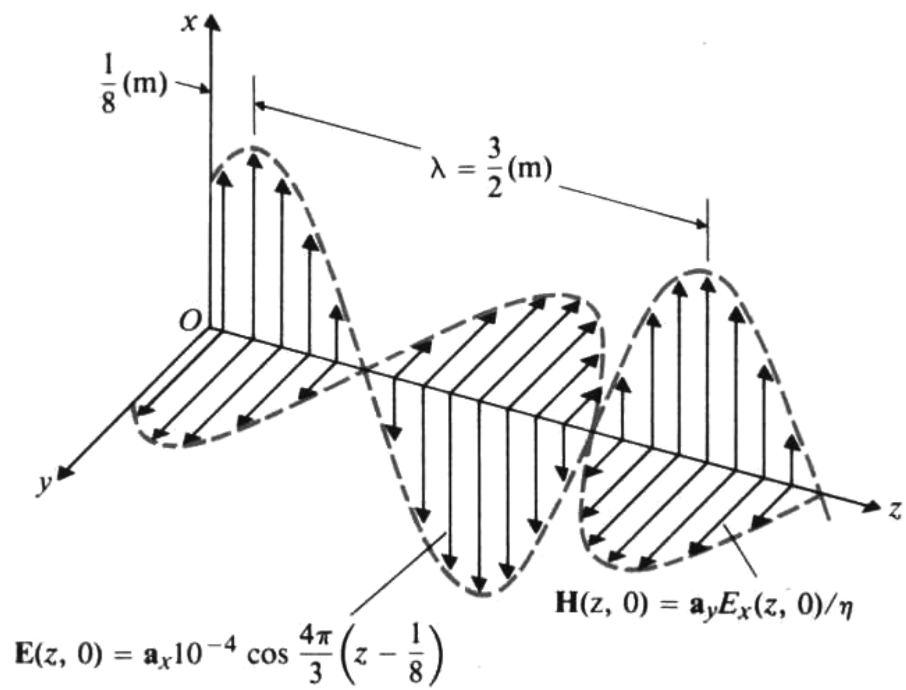
빛의 발생의 예


photon
Excitation of
the ground state
(a)
De-excitation with
emission of a photon
(b)
Ground state
≈10^−9 seconds later
(c)



Wave traveling in positive *z* direction

$E_x^+ = E_0^+ \cos(wt-k_0z)$, for several values of *t*.



E and H fields

of a uniform plane wave at a fixed *t*.

파장과 주파수

주기 T

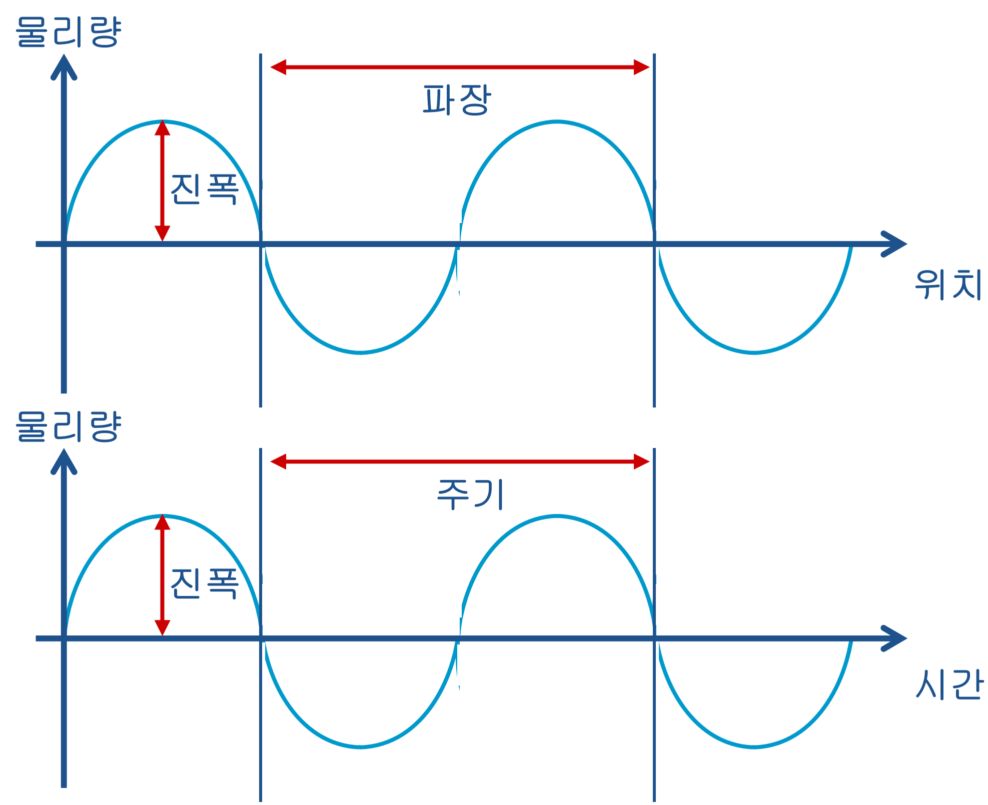
주파수 $f \quad (\nu)$

파장 λ

진공에서의 빛의 속력 c

$$f = \frac{1}{T}$$

$$c = \frac{\lambda}{T} = \lambda f$$



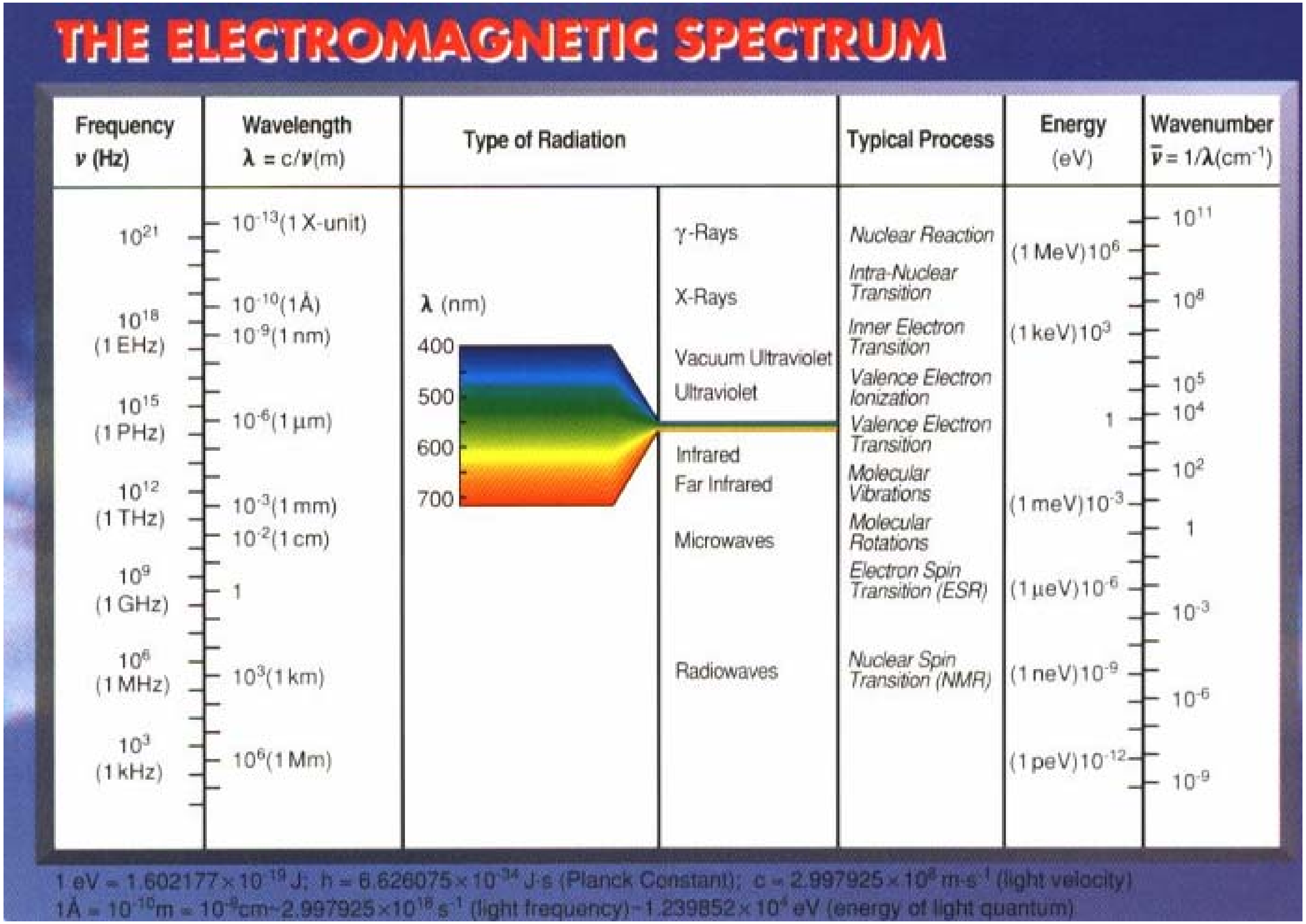
Photon

Energy $$E = hf = \frac{h}{T} = \frac{hc}{\lambda}$$

Momentum $$p = \frac{h}{\lambda}$$

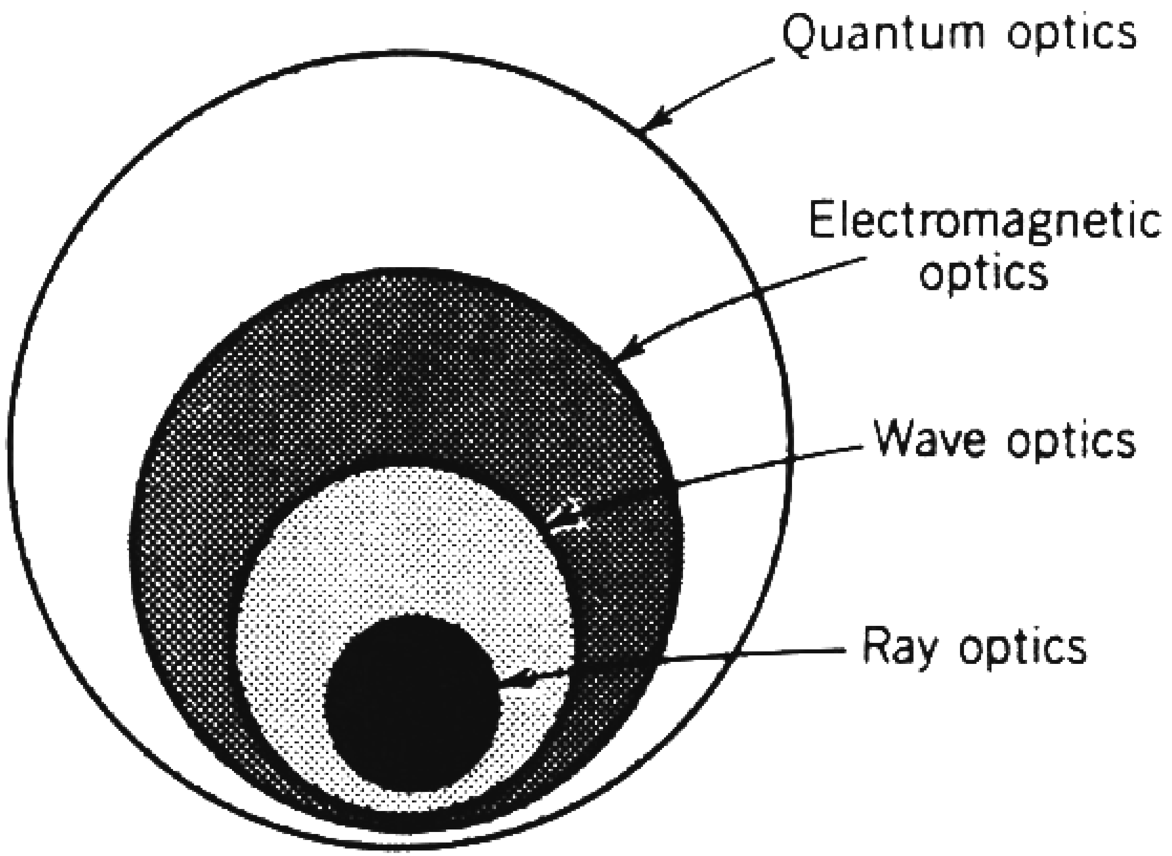
Einstein

전자파의 스펙트럼



THE ELECTROMAGNETIC SPECTRUM
Frequency ν (Hz)
Wavelength λ = c/ν(m)
Type of Radiation
Typical Process
Energy (eV)
Wavenumber ν̄ = 1/λ(cm⁻¹)
10²¹
10¹⁸ (1 EHz)
10¹⁵ (1 PHz)
10¹² (1 THz)
10⁹ (1 GHz)
10⁶ (1 MHz)
10³ (1 kHz)
10⁻¹³(1 X-unit)
10⁻¹⁰(1 Å)
10⁻⁹(1 nm)
10⁻⁶(1 μm)
10⁻³(1 mm)
10⁻²(1 cm)
1
10³(1 km)
10⁶(1 Mm)
λ (nm)
400
500
600
700
γ-Rays
X-Rays
Vacuum Ultraviolet
Ultraviolet
Infrared
Far Infrared
Microwaves
Radiowaves
Nuclear Reaction
Intra-Nuclear Transition
Inner Electron Transition
Valence Electron Ionization
Valence Electron Transition
Molecular Vibrations
Molecular Rotations
Electron Spin Transition (ESR)
Nuclear Spin Transition (NMR)
(1 MeV)10⁶
(1 keV)10³
1
(1 meV)10⁻³
(1 μeV)10⁻⁶
(1 neV)10⁻⁹
(1 peV)10⁻¹²
10¹¹
10⁸
10⁵
10⁴
10²
1
10⁻³
10⁻⁶
10⁻⁹
1 eV = 1.602177×10⁻¹⁹ J; h = 6.626075×10⁻³⁴ J·s (Planck Constant); c = 2.997925×10⁸ m·s⁻¹ (light velocity)
1Å = 10⁻¹⁰m = 10⁻⁸cm~2.997925×10¹⁸ s⁻¹ (light frequency)~1.239852×10⁴ eV (energy of light quantum)

Category of Optics



Photon - nomenclature

The photon was originally called a **"light quantum"** (*das Lichtquant*) by Albert Einstein. The modern name "photon" derives from the Greek word for light, *φῶς*, (transliterated *phos*), and was coined in 1926 by the physical chemist Gilbert N. Lewis, who published a speculative theory in which photons were "uncreatable and indestructible". Although Lewis' theory was never accepted — being contradicted by many experiments — his new name, *photon*, was adopted immediately by most physicists.

(http://en.wikipedia.org/wiki/Photon)

Unit systems

System	ε_0	μ_0	D, H	Microscopic Maxwell Equations	Lorentz Force per Unit charge
Electrostatic (esu)	1	c^{-2} $(t^2 l^{-2})$	$\mathbf{D}=\mathbf{E}+4\pi\mathbf{P}$ $\mathbf{H}=c^2\mathbf{B}-4\pi\mathbf{M}$	$\nabla\cdot\mathbf{D}=4\pi\rho$ $\nabla\times\mathbf{H}=4\pi\mathbf{J}+\frac{\partial\mathbf{D}}{\partial t}$ $\nabla\times\mathbf{E}+\frac{\partial\mathbf{B}}{\partial t}=0$ $\nabla\cdot\mathbf{B}=0$	$\mathbf{E}+\mathbf{v}\times\mathbf{B}$
Electromagnetic (emu)	c^{-2} $(t^2 l^{-2})$	1	$\mathbf{D}=\frac{1}{c^2}\mathbf{E}+4\pi\mathbf{P}$ $\mathbf{H}=\mathbf{B}-4\pi\mathbf{M}$	$\nabla\cdot\mathbf{D}=4\pi\rho$ $\nabla\times\mathbf{H}=4\pi\mathbf{J}+\frac{\partial\mathbf{D}}{\partial t}$ $\nabla\times\mathbf{E}+\frac{\partial\mathbf{B}}{\partial t}=0$ $\nabla\cdot\mathbf{B}=0$	$\mathbf{E}+\mathbf{v}\times\mathbf{B}$
Gaussian	1	1	$\mathbf{D}=\mathbf{E}+4\pi\mathbf{P}$ $\mathbf{H}=\mathbf{B}-4\pi\mathbf{M}$	$\nabla\cdot\mathbf{D}=4\pi\rho$ $\nabla\times\mathbf{H}=\frac{4\pi}{c}\mathbf{J}+\frac{1}{c}\frac{\partial\mathbf{D}}{\partial t}$ $\nabla\times\mathbf{E}+\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t}=0$ $\nabla\cdot\mathbf{B}=0$	$\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}$
Heaviside-Lorentz	1	1	$\mathbf{D}=\mathbf{E}+\mathbf{P}$ $\mathbf{H}=\mathbf{B}-\mathbf{M}$	$\nabla\cdot\mathbf{D}=\rho$ $\nabla\times\mathbf{H}=\frac{1}{c}\left(\mathbf{J}+\frac{\partial\mathbf{D}}{\partial t}\right)$ $\nabla\times\mathbf{E}+\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t}=0$ $\nabla\cdot\mathbf{B}=0$	$\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}$
Rationalized MKSA	$\frac{10^7}{4\pi c^2}$ $(I^2 t^4 m^{-1} l^{-3})$	$4\pi\times10^{-7}$ $(m l I^{-2} t^{-2})$	$\mathbf{D}=\epsilon_0\mathbf{E}+\mathbf{P}$ $\mathbf{H}=\frac{1}{\mu_0}\mathbf{B}-\mathbf{M}$	$\nabla\cdot\mathbf{D}=\rho$ $\nabla\times\mathbf{H}=\mathbf{J}+\frac{\partial\mathbf{D}}{\partial t}$ $\nabla\times\mathbf{E}+\frac{\partial\mathbf{B}}{\partial t}=0$ $\nabla\cdot\mathbf{B}=0$	$\mathbf{E}+\mathbf{v}\times\mathbf{B}$