TECHNICAL UNIVERSITY
OF CLUJ-NAPOCA
ROMANIA

Faculty of Electronics, Telecom and Info Technology

Lecture 1

Optoelectronic Systems for Telecom (SOT)

Associate prof eng Ramona Galatus, PhD
Basis of Electronics Department

Outlines

- Course overview
- Economic Impact (Real World)
- Introduction to
  - Photonics and
  - Optical communication
- Photonic applications

Examination rules: **SYLLABUS**

Activity type	10.1	Assessment criteria	10.2	Assessment methods	10.3	Weight in the final grade
Course		The level of acquired theoretical knowledge and practical skills		- after 7 courses, preliminary exam (oral examination) -optional - Summative evaluation written exam (theory and problems) – 14 subjects, one from each lecture (for the students with preliminary exam – 8 subjects)		- T, max 10 pts. 20% - E, max 10 pts. 60%
Applications		The level of acquired abilities		- Continuous formative evaluation - practical lab test		- L, max. 10 pts. 20%
10.4 Minimum standard of performance						
The presence of the course is considered activity and chronic absenteeism requires further verification of material lost. Presence in all laboratories, obtaining a minimum of 4.5 notes in laboratory activities, and partly written exam. **Lab (L) ≥ 4.5 and Essay (E) ≥ 4.5 and Exam (T) ≥ 4.5 : 0,6E+0,20L+0,20T ≥ 4.5**						

Written score=
10% lecture attending
+90% written exam

Optical Communication= communication with light signal

Duality of Light

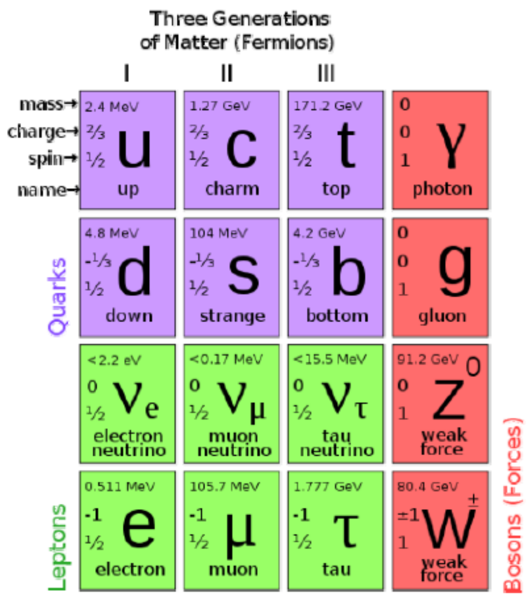
- Wave
- Particle (photons)

Photonics is the science and technology of harnessing light

Photonics and Electronics => OPTO-ELECTRONICS

Photonics bears the same relationship to light and photons as

Electronics does to electricity and electrons



Three Generations of Matter (Fermions)

	I	II	III	
mass→ charge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon
Quarks	4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon
	<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
Leptons	0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force

Bosons (Forces)

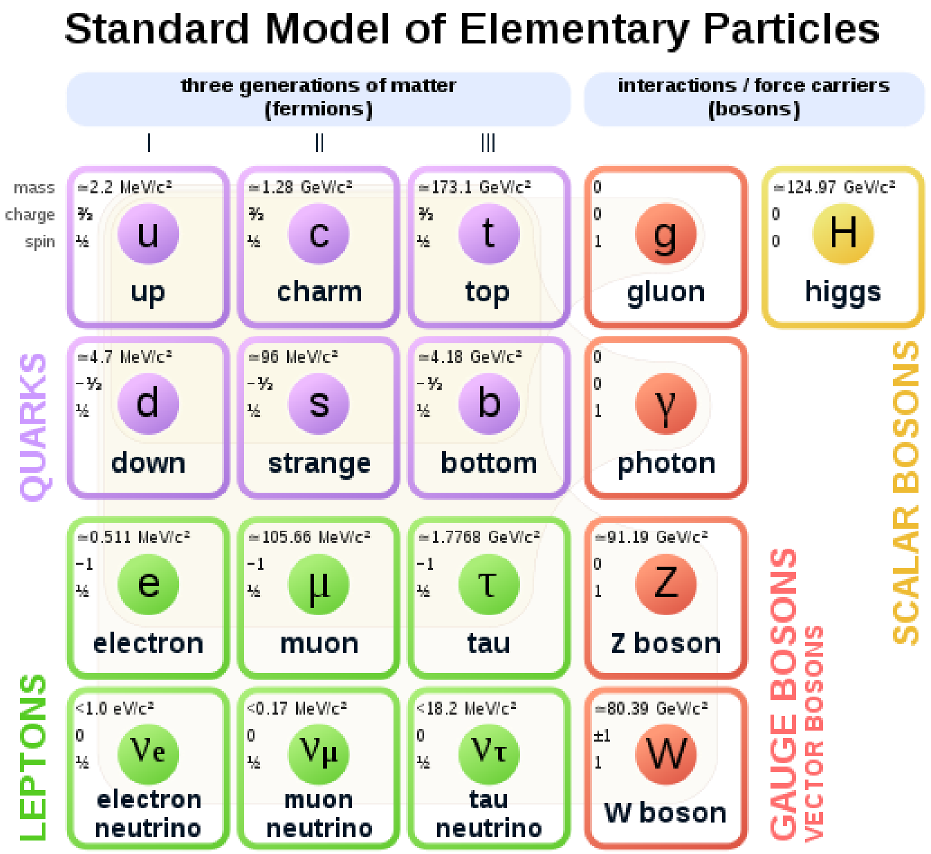
Standard Model of elementary particles.
The electron is at lower left.
The photon is at upper right.

Heath Salter- Quantum Electronics, English Press, New Delphi, 2011, ISBN 978-93-81157-29-9

Standard Model of elementary particles

Electron

- In the Standard Model of particle physics, cap 4: **electrons** belong to the group of subatomic particles called **leptons**, which are believed to be fundamental or elementary particles.
- Electrons have the lowest mass of any charged lepton (or electrically charged particle of any type) and belong to the first-generation of fundamental particles.
- The second and third generation contain charged leptons, the muon and the tau, which are identical to the electron in charge, spin and interactions, but are more massive. Leptons differ from the other basic constituent of matter, the quarks, by their lack of strong interaction.
- All members of the lepton group are fermions, because they all have half-odd integer spin;
- the electron has spin 1⁄2.
- The positron is symbolized by e+ because it has the same properties as the electron but with a positive rather than negative charge.



Modelul standard – Fizica

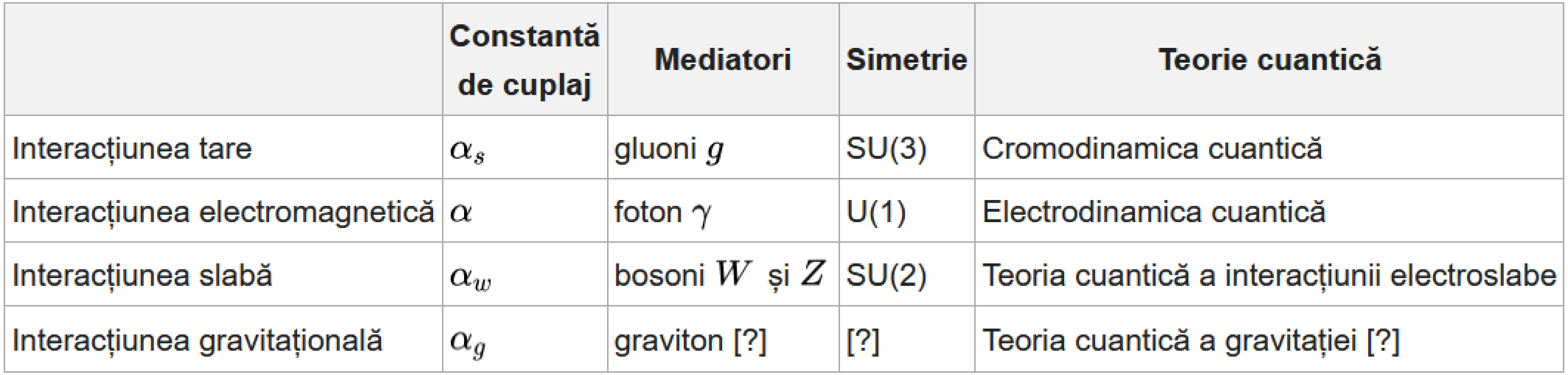
- Inițial (aproximativ între anii 1950–1975) s-a crezut că particulele din modelul standard stau la baza întregii materii din univers. La ora actuală se știe însă că ele formează numai cca 4,6 % din univers, restul fiind desemnat drept materie întunecată (cca 23 %) și energie întunecată (cca 72 %).

- Modelul standard nu este o teorie completă a interacțiunilor fundamentale, deoarece în prezent el nu reușește să integreze a patra forță fundamentală, gravitația, și de asemenea pentru că este incompatibil cu recentele observații ale oscilațiilor neutrinilor.

Modelul standard

- În prezent modelul standard înglobează un total de 61 de particule considerate fundamentale (fără structură internă), și 3 din cele 4 tipuri de interacțiuni de bază (forțe).
- Particulele fundamentale sunt împărțite în două mari categorii după o proprietate numită **spin**, și anume
  - fermioni fundamentali (a căror valoare a spinului e un număr fracționar) și
  - bosoni fundamentali (a căror valoare a spinului e un număr întreg).
- Fermionii fundamentali sunt împărțiți în quarkuri și leptoni.
  - Există 6 quarkuri și 6 leptoni, cu tot atâtea antiparticule corespondente; fiecare quark există în trei subtipuri, denumite culori.
- Interacțiunile dintre fermioni sunt mediate prin schimbul unor particule de calibrare (etalonare), bosonii intermediari(en), asociați celor 4 forțe fundamentale.
- Bosonii intermediari sunt:
  - fotonul (corespondent forței electromagnetice),
  - 3 bosoni W+, W- și Z (corespondenți forței nucleare slabe) și
  - 8 gluoni (corespondenți forței nucleare tari).
  - Acestora li se adaugă bosonul Higgs, detectat experimental în anul 2013.

Cele 4 forte fundamentale



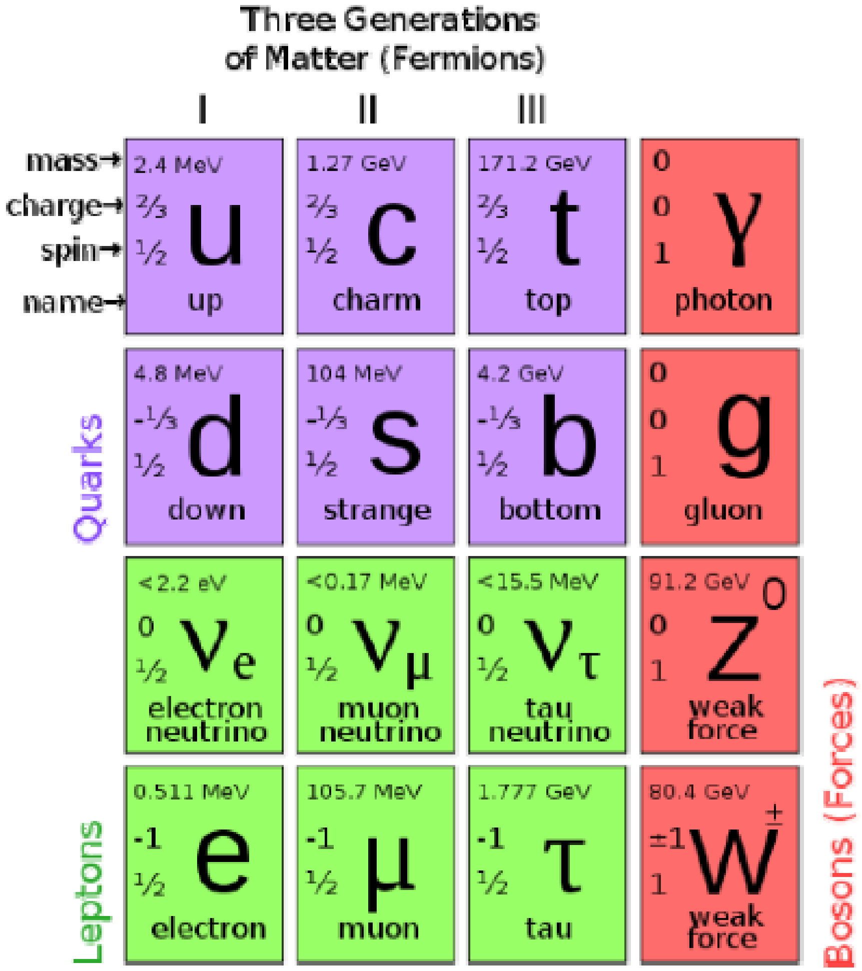
	Constantă de cuplaj	**Mediatori**	**Simetrie**	**Teorie cuantică**
Interacțiunea tare	α_s	gluoni g	SU(3)	Cromodinamica cuantică
Interacțiunea electromagnetică	α	foton γ	U(1)	Electrodinamica cuantică
Interacțiunea slabă	α_w	bosoni W și Z	SU(2)	Teoria cuantică a interacțiunii electroslabe
Interacțiunea gravitațională	α_g	graviton [?]	[?]	Teoria cuantică a gravitației [?]

Heath Salter- Quantum Electronics, English Press, New Delphi, 2011, ISBN 978-93-81157-29-9

Standard Model of elementary particles

Photon

- In the Standard Model of particle physics, cap 5: **Cap 5: a photon is an elementary particle, the quantum of the electromagnetic** interaction and the basic unit of light
- The modern concept of the photon was developed gradually by Albert Einstein
- In 1900, Max Planck was working on black-body radiation and suggested that the energy in electromagnetic waves could only be released in "packets" of energy. In his 1901 article in Annalen der Physik he called these packets "energy elements".
- The word *quanta* (singular *quantum*) was used even before 1900 to mean particles or amounts of different quantities, including electricity .
- Later, in 1905 Albert Einstein went further by suggesting that electromagnetic waves could only exist in these discrete wave-packets. He called such a wave-packet *the light quantum* (German: *das Lichtquant*).
- The name *photon* derives from the Greek word for light, *φως* (transliterated *phôs*), and was coined in 1926 by the physical chemist Gilbert Lewis, who published a speculative theory in which photons were "uncreatable and indestructible". Although Lewis' theory was never accepted as it was contradicted by many experiments, his new name, *photon*, was adopted immediately by most physicists.
- Isaac Asimov credits **Arthur Compton with defining quanta of energy as photons in 1927.**
- for the explanation of the photoelectric effect, Einstein received the 1921 Nobel Prize in physics.



Three Generations of Matter (Fermions)

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PREREQUIREMENTS → SOT Course – 4th year

Optoelectronics – 3rd year of study -> basic concepts

- Optic properties
- LEDs
- Lasers
- Waveguides
- Optical fibers

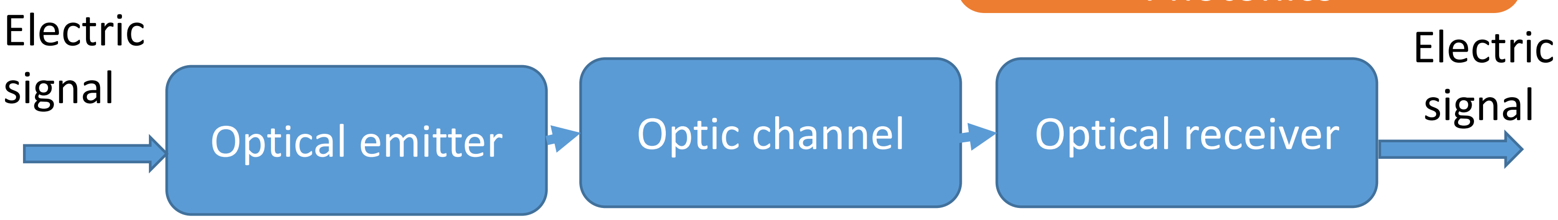
etc

That will be used for the SOT course = Optoelectronic Systems for Telecommunication:

Advanced Optoelectronics concepts: Optical waveguides and Optical components, Special optical fibers

Introduction to Optical Communication: Design, Linear and Nonlinear Phenomena etc

Applications: Photonics for 5G, Quantum computing, Microwave Photonics, Artificial Intelligence in Photonics



A generic optical communication system

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www.Photonics21.org

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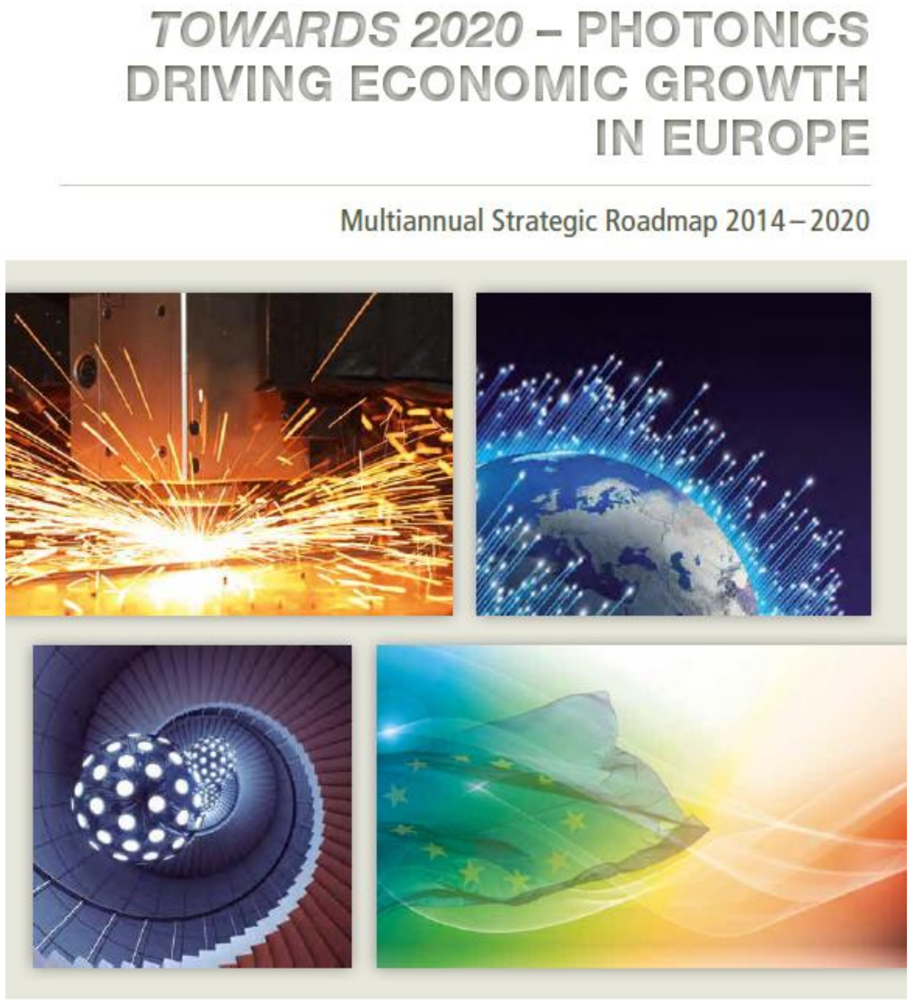
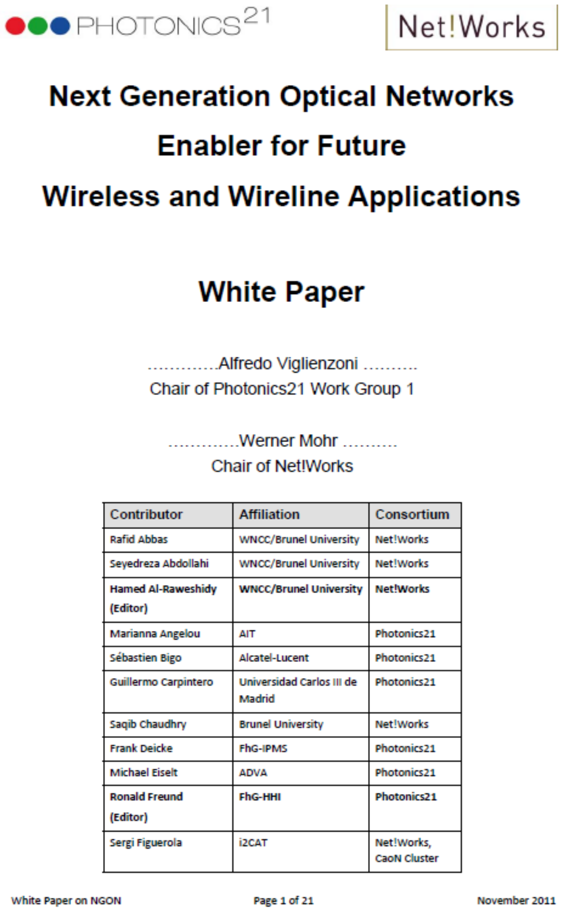


TOWARDS 2020 – PHOTONICS
DRIVING ECONOMIC GROWTH
IN EUROPE

Multiannual Strategic Roadmap 2014 – 2020

PHOTONICS21



PHOTONICS21 Net!Works

Next Generation Optical Networks
Enabler for Future
Wireless and Wireline Applications

White Paper

………….Alfredo Viglienzoni ………
Chair of Photonics21 Work Group 1

………….Werner Mohr ……….
Chair of Net!Works

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White Paper on NGON Page 1 of 21 November 2011

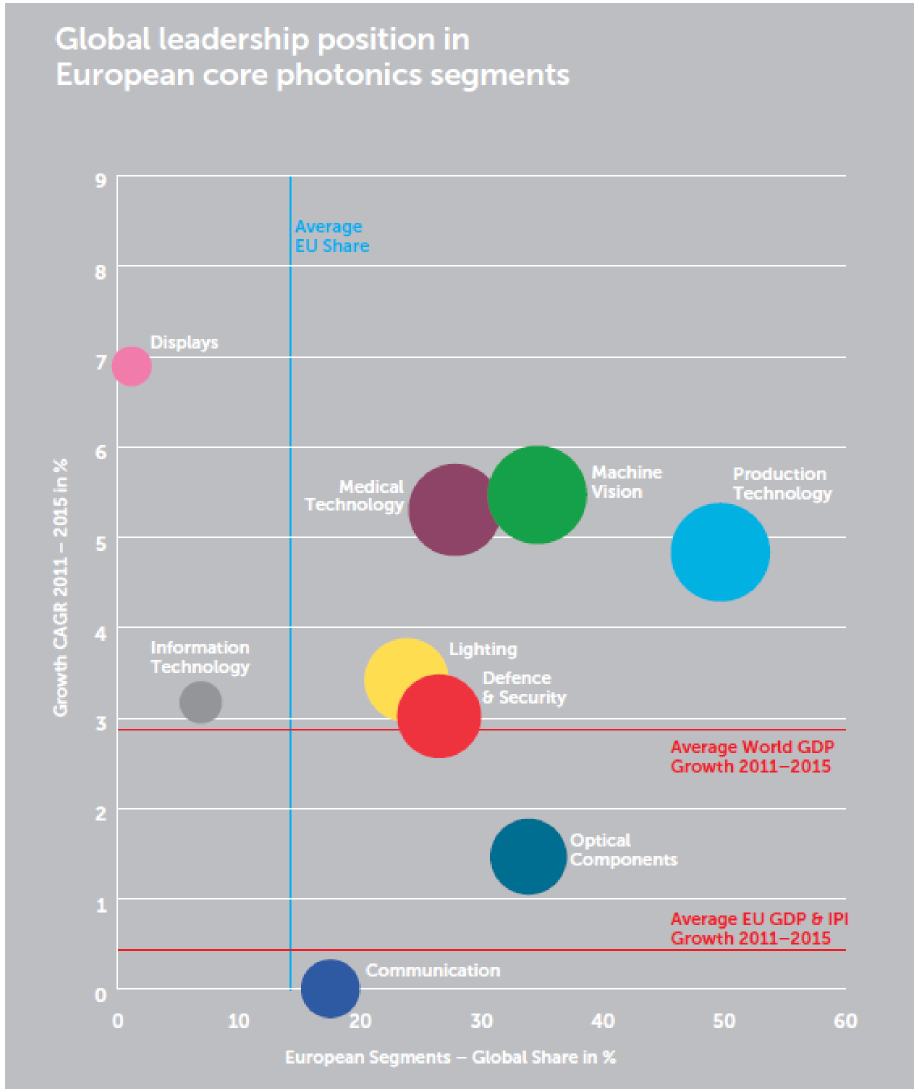
"Each person will soon have at least a mobile smart phone with the capability of accessing extremely high data rates. This will require more power generation which will have a severe impact on the environment. Therefore the future network is required to be fast, cheap, clean and cognitive (FCCC). To achieve an FCCC network, the wired and wireless networks need to be fully merged to have a transparent and widely seamless network with as much optical fibre close to the end user as possible to reduce power consumption, increase the data rate and reduce the cost of the transmitted and routed bit. "

………….Alfredo Viglienzoni, Ericsson ……….
Chair of Photonics21 Work Group 1 –
Optical Communication

Optech Consulting Market Research Study 24.1.2017

Europe's age of light!

How photonics will power growth and innovation



"access network by exploiting the vast bandwidth, low loss and dispersion of new types of fibres currently being developed to set up a massive pool of WDM channels at aggregate rates "

2 Research Priorities.................. 6
2.1 Making optical networks more transparent and secure............. 6
2.2 Making optical networks more dynamic and cognitive 9
2.3 Making optical networks faster .. 12
2.4 Making optical networks greener ...15
2.5 Bringing optical networks closer to the customer 16

Next Generation Optical Networks
Enabler for Future
Wireless and Wireline Applications

ICT

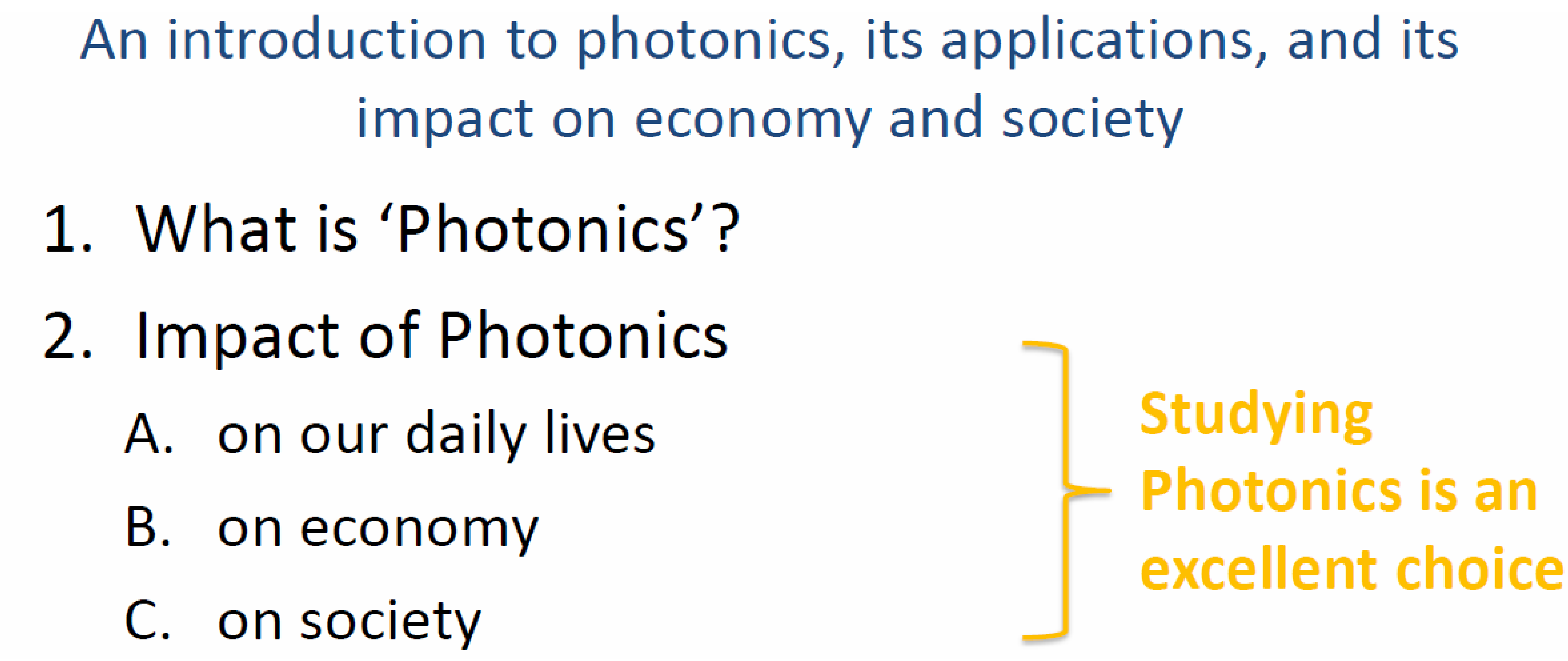
………….Alfredo Viglienzoni, Ericsson ………
Chair of
Photonics21 Work Group 1 –
Optical Communication

BRUSSELS, EU

- Information and Communication Technologies (ICT) will continue to be a key driver for the future economy of Europe as evidenced by the national infrastructure of broadband Internet, mobile communications and web services.
- The ICT infrastructure is now considered in most countries to be part of a Critical National Infrastructure and is the key to future economic growth.
- The ICT sector is directly responsible for 5 % of Europe's gross domestic product, with an annual market value of €660 Billion [1]. However, ICT contributes considerably more to overall productivity growth (20 % directly from the ICT sector and 30 % from ICT investments). As an enabler, ICT plays a vital role in enhancing other sectors' business growth.
- According to the Information Technology and Innovation Foundation, a $10 Billion investment in broadband networks, in one year, would create almost 500,000 jobs in the US [2]. Europe is home to the world's largest and most successful telecom industry, with 7 out of the 10 largest telecom operators (Telefonica, Deutsche Telekom, Vodafone, Orange, BT, Telecom Italia, Telenor Group) alongside major world telecom manufacturers (Alcatel-Lucent, ADVA Optical Networking, Ericsson, Nokia Siemens Networks and Intune Networks), leading manufacturers of optical components (e.g. Oclaro, u2t, Leoni, and ULM Photonics) and manufacturers of network test equipment (e.g. JDS Uniphase and Agilent).
- Maintaining the strong European leadership in communications is essential for its economy, employment and innovation. Europe's communications industry has the strength to remain competitive and to establish leadership in a new wave of broadband networking technologies and business innovations.
- All this is motivated by the end users' demand for higher bandwidth: Better quality video on smart phones, IP-based television, smart homes with networked appliances, data-hungry business applications and 3D-video conferencing - all of these need data rates which require efficient network infrastructure based on photonic technologies.

[1] Photonics21, "Second Strategic Research Agenda in Photonics, Lighting the way ahead."
[2] R. Atkinson, D. Castro and S. Ezell, "The Digital Road to Recovery: A Stimulus Plan to Create Jobs, Boost Productivity and Revitalize America", Report by the Information Technology and Innovation Foundation, 7 January 2009.

I. Introduction to photonics

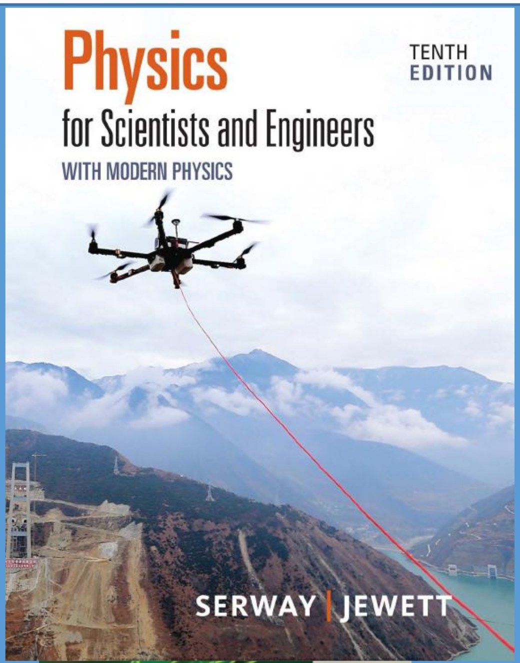


An introduction to photonics, its applications, and its impact on economy and society

1. What is ‘Photonics’?
2. Impact of Photonics
    - A. on our daily lives
    - B. on economy
    - C. on society

Studying Photonics is an excellent choice

References

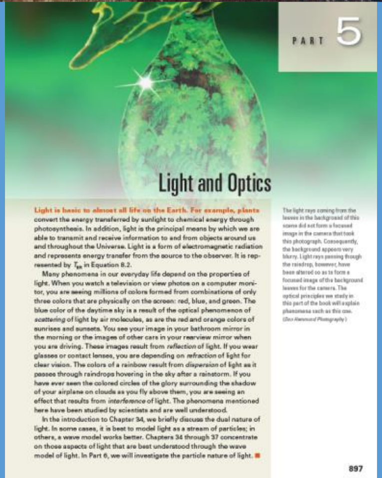


Physics for Scientists and Engineers

WITH MODERN PHYSICS

TENTH EDITION

SERWAY | JEWETT



PART 5

Light and Optics

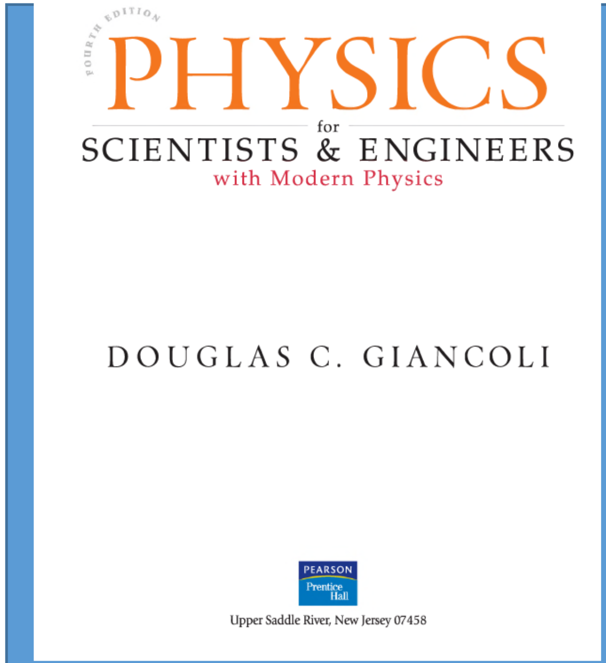
Light is basic to almost all life on the Earth. For example, plants convert the energy transferred by sunlight to chemical energy through photosynthesis. In addition, light is the principal means by which we are able to transmit and receive information to and from objects around us and throughout the Universe. Light is a form of electromagnetic radiation and represents energy transfer from the source to the observer. It is represented by T_{ER} in Equation 8.2.

Many phenomena in our everyday life depend on the properties of light. When you watch a television or view photos on a computer monitor, you are seeing millions of colors formed from combinations of only three colors that are physically on the screen: red, blue, and green. The blue color of the daytime sky is a result of the optical phenomenon of *scattering* of light by air molecules, as are the red and orange colors of sunrises and sunsets. You see your image in your bathroom mirror in the morning or the images of other cars in your rearview mirror when you are driving. These images result from *reflection* of light. If you wear glasses or contact lenses, you are depending on *refraction* of light for clear vision. The colors of a rainbow result from *dispersion* of light as it passes through raindrops hovering in the sky after a rainstorm. If you have ever seen the colored circles of the glory surrounding the shadow of your airplane on clouds as you fly above them, you are seeing an effect that results from *interference* of light. The phenomena mentioned here have been studied by scientists and are well understood.

In the introduction to Chapter 34, we briefly discuss the dual nature of light. In some cases, it is best to model light as a stream of particles; in others, a wave model works better. Chapters 34 through 37 concentrate on those aspects of light that are best understood through the wave model of light. In Part 6, we will investigate the particle nature of light. ■

The light rays coming from the leaves in the background of this scene did not form a focused image in the camera that took this photograph. Consequently, the background appears very blurry. Light rays passing through the raindrop, however, have been altered so as to form a focused image of the background leaves for the camera. The optical principles we study in this part of the book will explain phenomena such as this one. *(Don Hammond Photography)*

897



FOURTH EDITION

PHYSICS

for

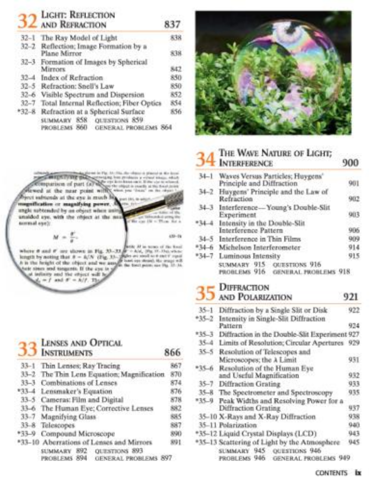
SCIENTISTS & ENGINEERS

with Modern Physics

DOUGLAS C. GIANCOLI

PEARSON
Prentice Hall

Upper Saddle River, New Jersey 07458



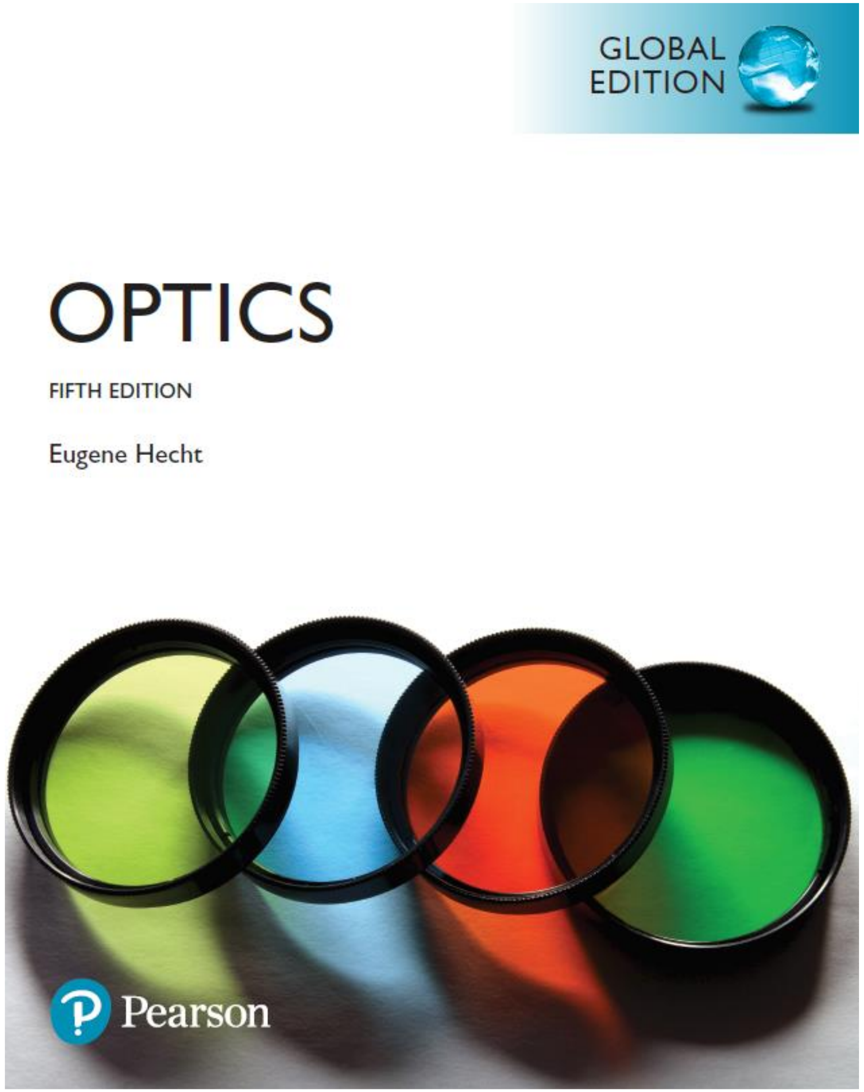
32 LIGHT: REFLECTION AND REFRACTION 837
32–1 The Ray Model of Light 838
32–2 Reflection; Image Formation by a Plane Mirror 838
32–3 Formation of Images by Spherical Mirrors 842
32–4 Index of Refraction 850
32–5 Refraction: Snell's Law 850
32–6 Visible Spectrum and Dispersion 852
32–7 Total Internal Reflection; Fiber Optics 854
*32–8 Refraction at a Spherical Surface 856
SUMMARY 858 QUESTIONS 859
PROBLEMS 860 GENERAL PROBLEMS 864

33 LENSES AND OPTICAL INSTRUMENTS 866
33–1 Thin Lenses; Ray Tracing 867
33–2 The Thin Lens Equation; Magnification 870
33–3 Combinations of Lenses 874
*33–4 Lensmaker's Equation 876
33–5 Cameras: Film and Digital 878
33–6 The Human Eye; Corrective Lenses 882
33–7 Magnifying Glass 885
33–8 Telescopes 887
*33–9 Compound Microscope 890
*33–10 Aberrations of Lenses and Mirrors 891
SUMMARY 892 QUESTIONS 893
PROBLEMS 894 GENERAL PROBLEMS 897

34 THE WAVE NATURE OF LIGHT; INTERFERENCE 900
34–1 Waves Versus Particles; Huygens' Principle and Diffraction 901
34–2 Huygens' Principle and the Law of Refraction 902
34–3 Interference—Young's Double-Slit Experiment 903
*34–4 Intensity in the Double-Slit Interference Pattern 906
34–5 Interference in Thin Films 909
*34–6 Michelson Interferometer 914
*34–7 Luminous Intensity 915
SUMMARY 915 QUESTIONS 916
PROBLEMS 916 GENERAL PROBLEMS 918

35 DIFFRACTION AND POLARIZATION 921
35–1 Diffraction by a Single Slit or Disk 922
*35–2 Intensity in Single-Slit Diffraction Pattern 924
*35–3 Diffraction in the Double-Slit Experiment 927
35–4 Limits of Resolution; Circular Apertures 929
35–5 Resolution of Telescopes and Microscopes; the λ Limit 931
*35–6 Resolution of the Human Eye and Useful Magnification 932
35–7 Diffraction Grating 933
35–8 The Spectrometer and Spectroscopy 935
*35–9 Peak Widths and Resolving Power for a Diffraction Grating 937
35–10 X-Rays and X-Ray Diffraction 938
35–11 Polarization 940
*35–12 Liquid Crystal Displays (LCD) 943
*35–13 Scattering of Light by the Atmosphere 945
SUMMARY 945 QUESTIONS 946
PROBLEMS 946 GENERAL PROBLEMS 949

CONTENTS ix



GLOBAL EDITION

OPTICS

FIFTH EDITION

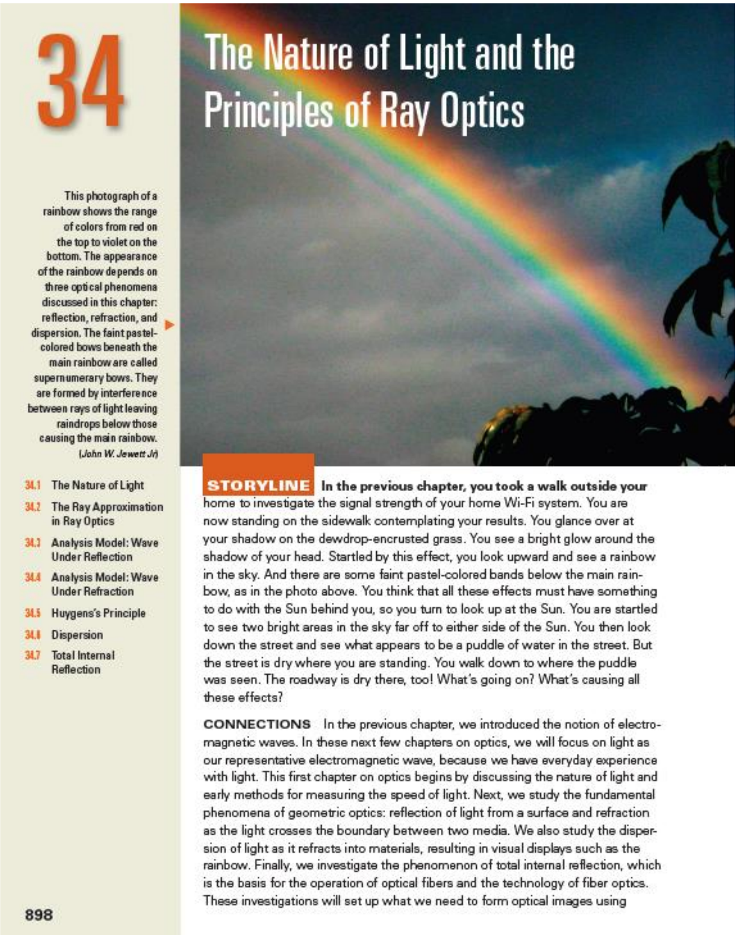
Eugene Hecht

Pearson

Serway-
Optics
-Ray optics
-Wave optics

Material	$n = \frac{c}{v}$
Vacuum	1.0000
Air (at STP)	1.0003
Water	1.33
Ethyl alcohol	1.36
Glass	
Fused quartz	1.46
Crown glass	1.52
Light flint	1.58
Lucite or Plexiglas	1.51
Sodium chloride	1.53
Diamond	2.42

† λ = 589 nm.



34 The Nature of Light and the Principles of Ray Optics

This photograph of a rainbow shows the range of colors from red on the top to violet on the bottom. The appearance of the rainbow depends on three optical phenomena discussed in this chapter: reflection, refraction, and dispersion. The faint pastel-colored bows beneath the main rainbow are called supernumerary bows. They are formed by interference between rays of light leaving raindrops below those causing the main rainbow. *(John W. Jewett Jr)*

34.1 The Nature of Light
34.2 The Ray Approximation in Ray Optics
34.3 Analysis Model: Wave Under Reflection
34.4 Analysis Model: Wave Under Refraction
34.5 Huygens's Principle
34.6 Dispersion
34.7 Total Internal Reflection

STORYLINE **In the previous chapter, you took a walk outside your** home to investigate the signal strength of your home Wi-Fi system. You are now standing on the sidewalk contemplating your results. You glance over at your shadow on the dewdrop-encrusted grass. You see a bright glow around the shadow of your head. Startled by this effect, you look upward and see a rainbow in the sky. And there are some faint pastel-colored bands below the main rainbow, as in the photo above. You think that all these effects must have something to do with the Sun behind you, so you turn to look up at the Sun. You are startled to see two bright areas in the sky far off to either side of the Sun. You then look down the street and see what appears to be a puddle of water in the street. But the street is dry where you are standing. You walk down to where the puddle was seen. The roadway is dry there, too! What's going on? What's causing all these effects?

CONNECTIONS In the previous chapter, we introduced the notion of electromagnetic waves. In these next few chapters on optics, we will focus on light as our representative electromagnetic wave, because we have everyday experience with light. This first chapter on optics begins by discussing the nature of light and early methods for measuring the speed of light. Next, we study the fundamental phenomena of geometric optics: reflection of light from a surface and refraction as the light crosses the boundary between two media. We also study the dispersion of light as it refracts into materials, resulting in visual displays such as the rainbow. Finally, we investigate the phenomenon of total internal reflection, which is the basis for the operation of optical fibers and the technology of fiber optics. These investigations will set up what we need to form optical images using

36 Wave Optics

The colors in many of a hummingbird's feathers are not due to pigment. What do you think is the origin of these colors? *(Dec Hogan/Shutterstock)*

36.1 Young's Double-Slit Experiment
36.2 Analysis Model: Waves in Interference
36.3 Intensity Distribution of the Double-Slit Interference Pattern
36.4 Change of Phase Due to Reflection
36.5 Interference in Thin Films
36.6 The Michelson Interferometer

STORYLINE **Time to take a break from studying physics and just** chill out on your back patio! You are lying in your chaise lounge and enjoying the nice spring day. Suddenly, a hummingbird flies in, doesn't notice you, and lands just a few feet away. You hold still and watch quietly, amazed at the beautiful colors on the feathers of the bird, which seem to glisten. Then you notice, as the bird turns a bit, that the colors shift in their intensity and hue. You think, "Wait a minute! Why would that happen?" And then, in direct contradiction to your efforts to take a break from physics, you think, "Could there be some physics behind the appearance of the colors in this bird's feathers?" The startled bird flies away in fear as you reach for your smartphone and fire up the Internet.

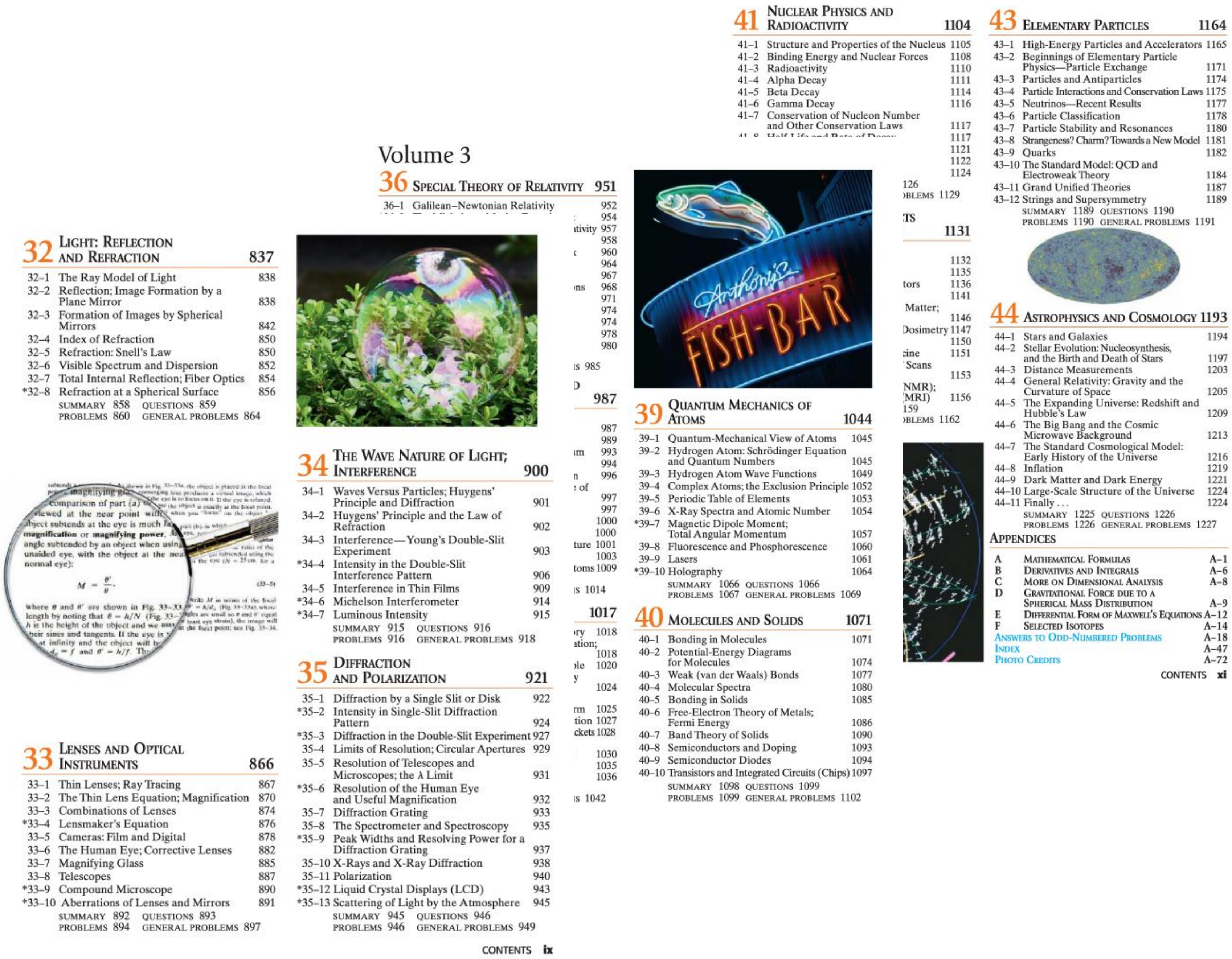
CONNECTIONS In Chapter 35, we studied light rays passing through a lens or reflecting from a mirror to describe the formation of images. This discussion completed our study of *ray optics*. In this chapter and in Chapter 37, we are concerned with *wave optics*, sometimes called *physical optics*, the study of interference, diffraction, and polarization of light. We studied *interference* of sound waves in Chapter 17 and will look at the comparable effect for light in this chapter. We introduced the phenomenon of *diffraction* for light waves in Section 34.2. We did not discuss *polarization* in Chapter 17 because sound waves cannot be polarized. Light waves can be polarized, however, and we shall study that phenomenon in Chapter 37. These three phenomena cannot be adequately explained with the ray optics used in Chapters 34 and 35 because they depend on the fact that light is wavelike in nature. The discussion of interference leads to the historical development of the *Michelson interferometer*, one of the tools used to investigate relativity, leading in turn to the development of modern physics, which begins in Chapter 38.

c=3x10^8m/s

$h=6.62607015\times10^{-34}$

Giancoli

-Light: Reflection and Refraction (Ray Optics)
-The Wave Nature of Light; Interference (Wave Optics)
-Diffraction and Polarization
-Quantum mechanics of atoms: Lasers and Holography
-Relativity: Doppler effect of light



32 LIGHT: REFLECTION AND REFRACTION 837
32–1 The Ray Model of Light 838
32–2 Reflection; Image Formation by a Plane Mirror 838
32–3 Formation of Images by Spherical Mirrors 842
32–4 Index of Refraction 850
32–5 Refraction: Snell's Law 850
32–6 Visible Spectrum and Dispersion 852
32–7 Total Internal Reflection; Fiber Optics 854
*32–8 Refraction at a Spherical Surface 856
SUMMARY 858 QUESTIONS 859
PROBLEMS 860 GENERAL PROBLEMS 864

33 LENSES AND OPTICAL INSTRUMENTS 866
33–1 Thin Lenses; Ray Tracing 867
33–2 The Thin Lens Equation; Magnification 870
33–3 Combinations of Lenses 874
*33–4 Lensmaker's Equation 876
33–5 Cameras: Film and Digital 878
33–6 The Human Eye; Corrective Lenses 882
33–7 Magnifying Glass 885
33–8 Telescopes 887
*33–9 Compound Microscope 890
*33–10 Aberrations of Lenses and Mirrors 891
SUMMARY 892 QUESTIONS 893
PROBLEMS 894 GENERAL PROBLEMS 897

34 THE WAVE NATURE OF LIGHT; INTERFERENCE 900
34–1 Waves Versus Particles; Huygens' Principle and Diffraction 901
34–2 Huygens' Principle and the Law of Refraction 902
34–3 Interference—Young's Double-Slit Experiment 903
*34–4 Intensity in the Double-Slit Interference Pattern 906
34–5 Interference in Thin Films 909
*34–6 Michelson Interferometer 914
*34–7 Luminous Intensity 915
SUMMARY 915 QUESTIONS 916
PROBLEMS 916 GENERAL PROBLEMS 918

35 DIFFRACTION AND POLARIZATION 921
35–1 Diffraction by a Single Slit or Disk 922
*35–2 Intensity in Single-Slit Diffraction Pattern 924
*35–3 Diffraction in the Double-Slit Experiment 927
35–4 Limits of Resolution; Circular Apertures 929
35–5 Resolution of Telescopes and Microscopes; the λ Limit 931
*35–6 Resolution of the Human Eye and Useful Magnification 932
35–7 Diffraction Grating 933
35–8 The Spectrometer and Spectroscopy 935
*35–9 Peak Widths and Resolving Power for a Diffraction Grating 937
35–10 X-Rays and X-Ray Diffraction 938
35–11 Polarization 940
*35–12 Liquid Crystal Displays (LCD) 943
*35–13 Scattering of Light by the Atmosphere 945
SUMMARY 945 QUESTIONS 946
PROBLEMS 946 GENERAL PROBLEMS 949

CONTENTS ix

Volume 3

36 SPECIAL THEORY OF RELATIVITY 951
36–1 Galilean–Newtonian Relativity 952

39 QUANTUM MECHANICS OF ATOMS 1044
39–1 Quantum-Mechanical View of Atoms 1045
39–2 Hydrogen Atom: Schrödinger Equation and Quantum Numbers 1045
39–3 Hydrogen Atom Wave Functions 1049
39–4 Complex Atoms; the Exclusion Principle 1052
39–5 Periodic Table of Elements 1053
39–6 X-Ray Spectra and Atomic Number 1054
*39–7 Magnetic Dipole Moment; Total Angular Momentum 1057
39–8 Fluorescence and Phosphorescence 1060
39–9 Lasers 1061
*39–10 Holography 1064
SUMMARY 1066 QUESTIONS 1066
PROBLEMS 1067 GENERAL PROBLEMS 1069

40 MOLECULES AND SOLIDS 1071
40–1 Bonding in Molecules 1071
40–2 Potential-Energy Diagrams for Molecules 1074
40–3 Weak (van der Waals) Bonds 1077
40–4 Molecular Spectra 1080
40–5 Bonding in Solids 1085
40–6 Free-Electron Theory of Metals; Fermi Energy 1086
40–7 Band Theory of Solids 1090
40–8 Semiconductors and Doping 1093
40–9 Semiconductor Diodes 1094
40–10 Transistors and Integrated Circuits (Chips) 1097
SUMMARY 1098 QUESTIONS 1099
PROBLEMS 1099 GENERAL PROBLEMS 1102

41 NUCLEAR PHYSICS AND RADIOACTIVITY 1104
41–1 Structure and Properties of the Nucleus 1105
41–2 Binding Energy and Nuclear Forces 1108
41–3 Radioactivity 1110
41–4 Alpha Decay 1111
41–5 Beta Decay 1114
41–6 Gamma Decay 1116
41–7 Conservation of Nucleon Number and Other Conservation Laws 1117

43 ELEMENTARY PARTICLES 1164
43–1 High-Energy Particles and Accelerators 1165
43–2 Beginnings of Elementary Particle Physics—Particle Exchange 1171
43–3 Particles and Antiparticles 1174
43–4 Particle Interactions and Conservation Laws 1175
43–5 Neutrinos—Recent Results 1177
43–6 Particle Classification 1178
43–7 Particle Stability and Resonances 1180
43–8 Strangeness? Charm? Towards a New Model 1181
43–9 Quarks 1182
43–10 The Standard Model: QCD and Electroweak Theory 1184
43–11 Grand Unified Theories 1187
43–12 Strings and Supersymmetry 1189
SUMMARY 1189 QUESTIONS 1190
PROBLEMS 1190 GENERAL PROBLEMS 1191

44 ASTROPHYSICS AND COSMOLOGY 1193
44–1 Stars and Galaxies 1194
44–2 Stellar Evolution: Nucleosynthesis, and the Birth and Death of Stars 1197
44–3 Distance Measurements 1203
44–4 General Relativity: Gravity and the Curvature of Space 1205
44–5 The Expanding Universe: Redshift and Hubble's Law 1209
44–6 The Big Bang and the Cosmic Microwave Background 1213
44–7 The Standard Cosmological Model: Early History of the Universe 1216
44–8 Inflation 1219
44–9 Dark Matter and Dark Energy 1221
44–10 Large-Scale Structure of the Universe 1224
44–11 Finally . . . 1224
SUMMARY 1225 QUESTIONS 1226
PROBLEMS 1226 GENERAL PROBLEMS 1227

APPENDICES
A MATHEMATICAL FORMULAS A–1
B DERIVATIVES AND INTEGRALS A–6
C MORE ON DIMENSIONAL ANALYSIS A–8
D GRAVITATIONAL FORCE DUE TO A SPHERICAL MASS DISTRIBUTION A–9
E DIFFERENTIAL FORM OF MAXWELL'S EQUATIONS A–12
F SELECTED ISOTOPES A–14
ANSWERS TO ODD-NUMBERED PROBLEMS A–18
INDEX A–47
PHOTO CREDITS A–72

CONTENTS xi

Photonics

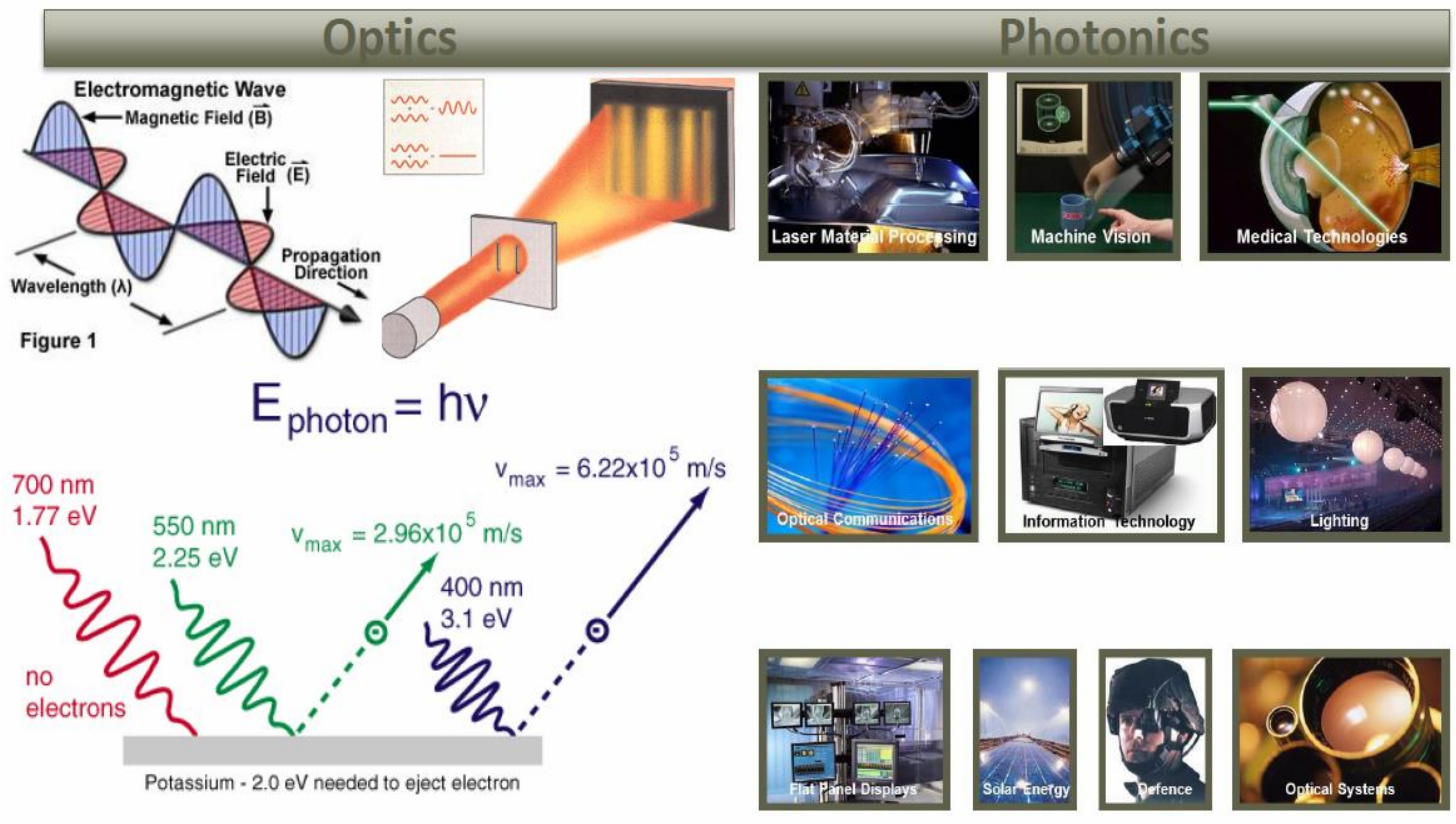
Ref: Giancoli - Physics for Scientists and Engineers
https://www.youtube.com/watch?v=knRDHwzQ9fY

Electromagnetic theory (Maxwell)

plane waves
transverse waves

$$\vec{\mathbf{S}} = \frac{1}{\mu_0}(\vec{\mathbf{E}} \times \vec{\mathbf{B}}).$$

Corpuscular theory (quantum mechanics)



Duality wave-corpuscle of light

Is the theory that *light* is a series of spherical *waves* progressing from the source with velocity c (three hundred thousand km/s), and the theory that *light* is a group of *corpuscles* moving in straight lines from the source with velocity c

Simulators

https://ricktu288.github.io/ray-optics/

https://aapt.scitation.org/doi/10.1119/1.3677652

Lasers: https://phet.colorado.edu/sims/cheerpj/lasers/latest/lasers.html?simulation=lasers
Optical quantum control with gratings: https://phet.colorado.edu/sims/cheerpj/optical-quantum-control/latest/optical-quantum-control.html?simulation=optical-quantum-control
Interference: https://phet.colorado.edu/sims/cheerpj/quantum-wave-interference/latest/quantum-wave-interference.html?simulation=quantum-wave-interference

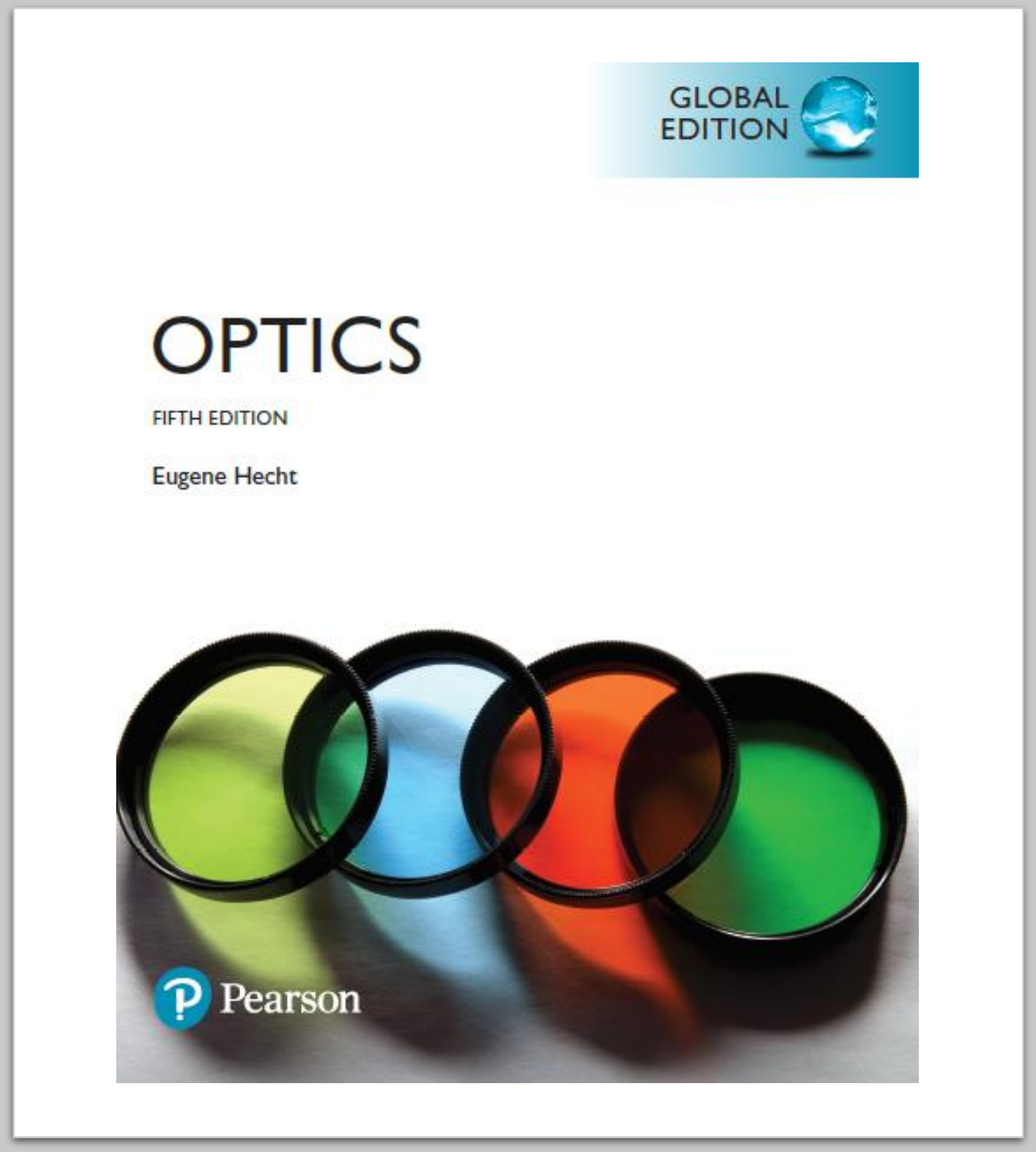
https://www.physicsclassroom.com/Physics-Interactives/Refraction-and-Lenses/Optics-Bench/Optics-Bench-Refraction-Interactive
https://github.com/aasim74/Wave-Optics-Simulations
https://www.codeseeder.com/examples/rib-waveguide-modes/

Optics

- Propagation: *transmission, reflection, refraction*
- Scattering, diffraction and Interference
- **Ray Optics**: A ray is a line drawn in space corresponding to the direction of flow of radiant energy. Is valid as long as the light waves propagate through and around objects whose dimensions are much greater than the light's wavelength. Ray theory (geometrical optics) does not describe phenomena such as diffraction, which require wave theory
- **Wave theory** -

$$\vec{E}_r = \vec{E}_{0r} \cos(\vec{k}_r \cdot \vec{r} - \omega_r t + \varepsilon_r)$$

$$\vec{E}_t = \vec{E}_{0t} \cos(\vec{k}_t \cdot \vec{r} - \omega_t t + \varepsilon_t)$$



GLOBAL EDITION

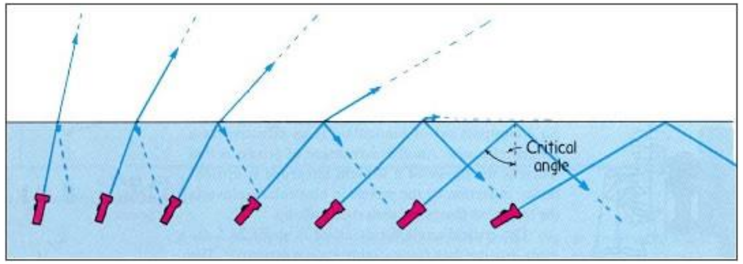
OPTICS

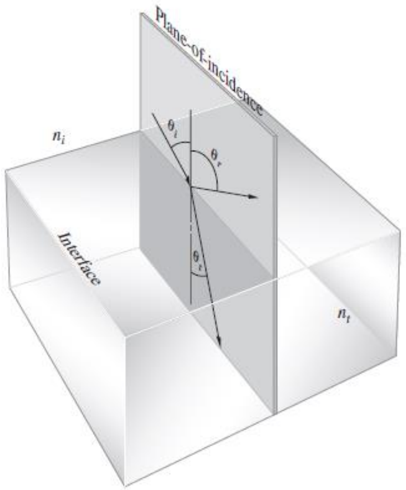
FIFTH EDITION

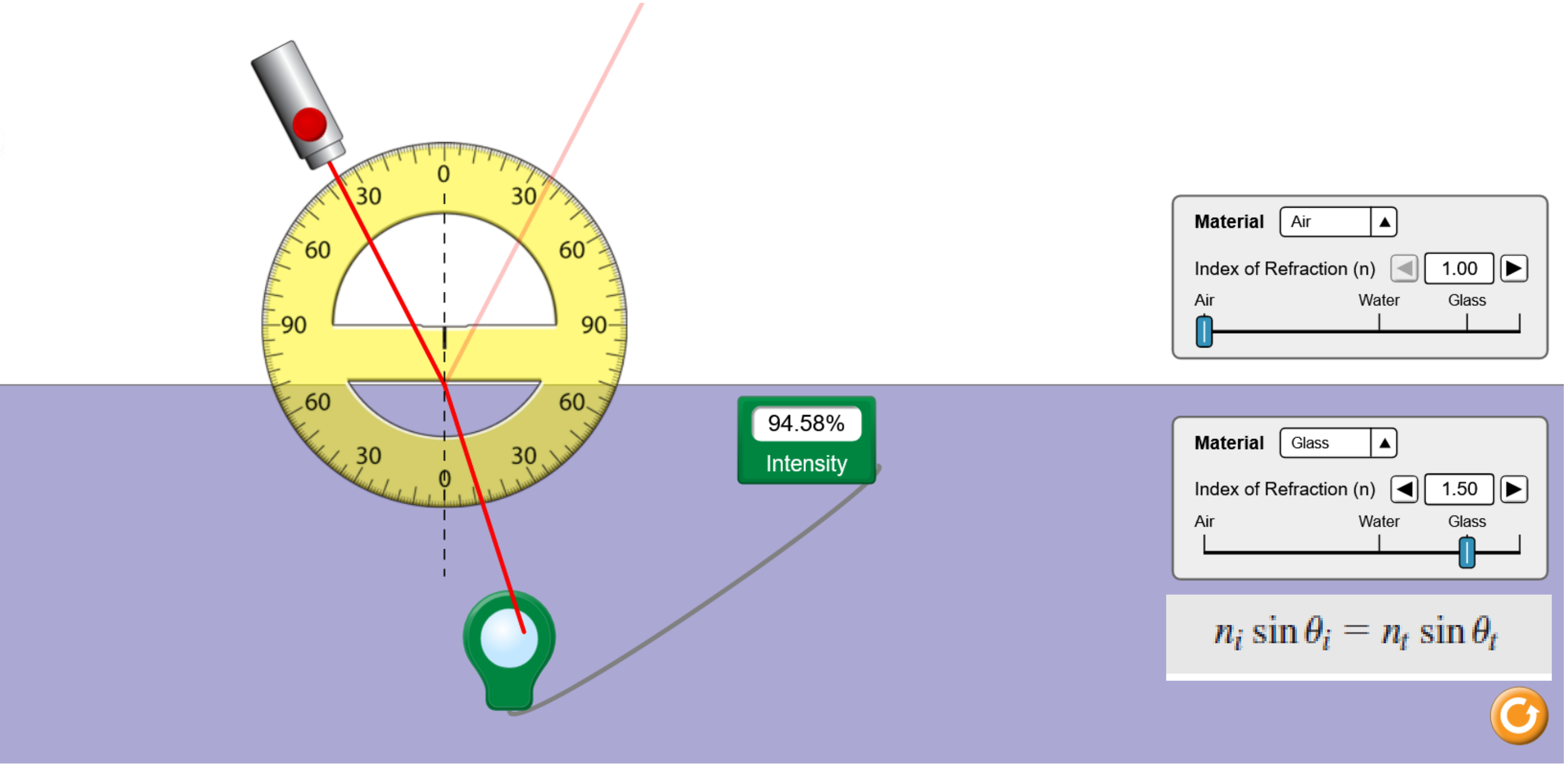
Eugene Hecht

Pearson

Reflection and Refraction (Ray Optics)







Material: Air

Index of Refraction (n): 1.00

Material: Glass

Index of Refraction (n): 1.50

94.58% Intensity

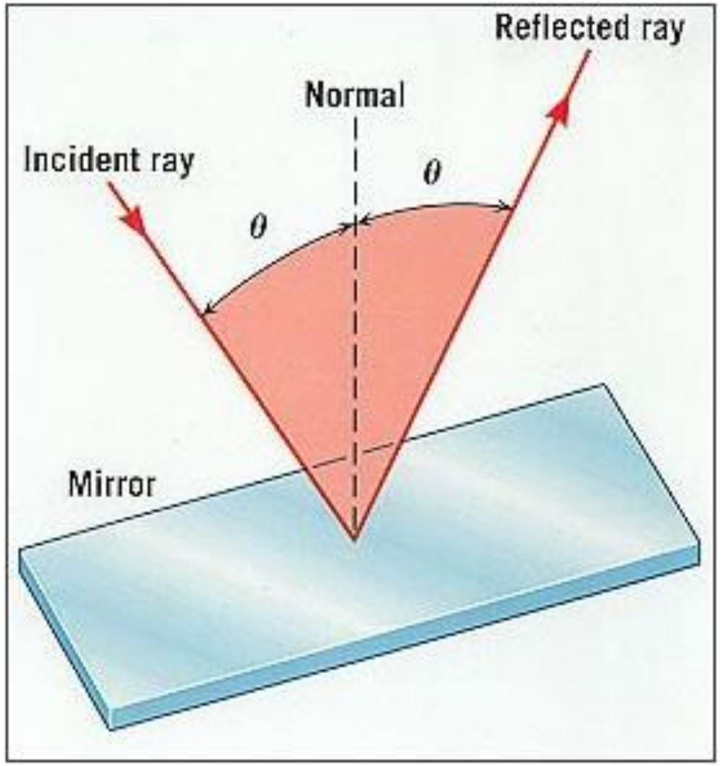
☑ Normal

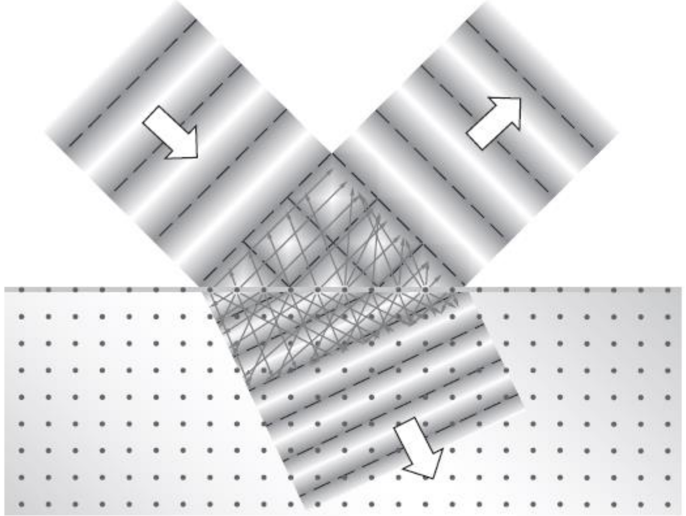
$$n_i \sin\theta_i = n_t \sin\theta_t$$

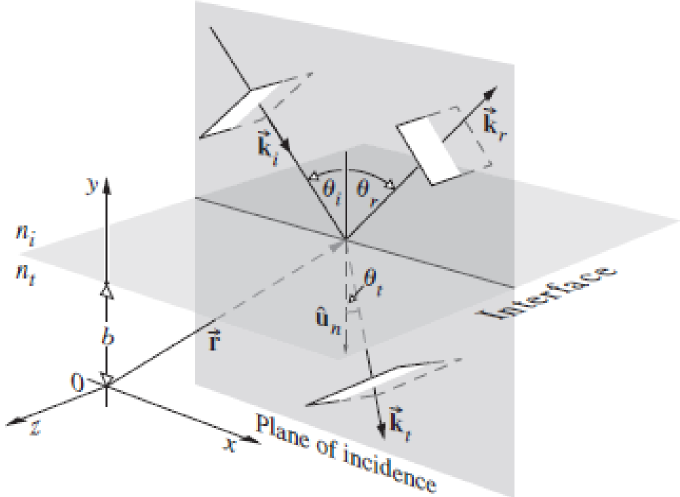
https://phet.colorado.edu/sims/html/bending-light/latest/bending-light_en.html

Ray optics and wave optics

https://ricktu288.github.io/ray-optics/





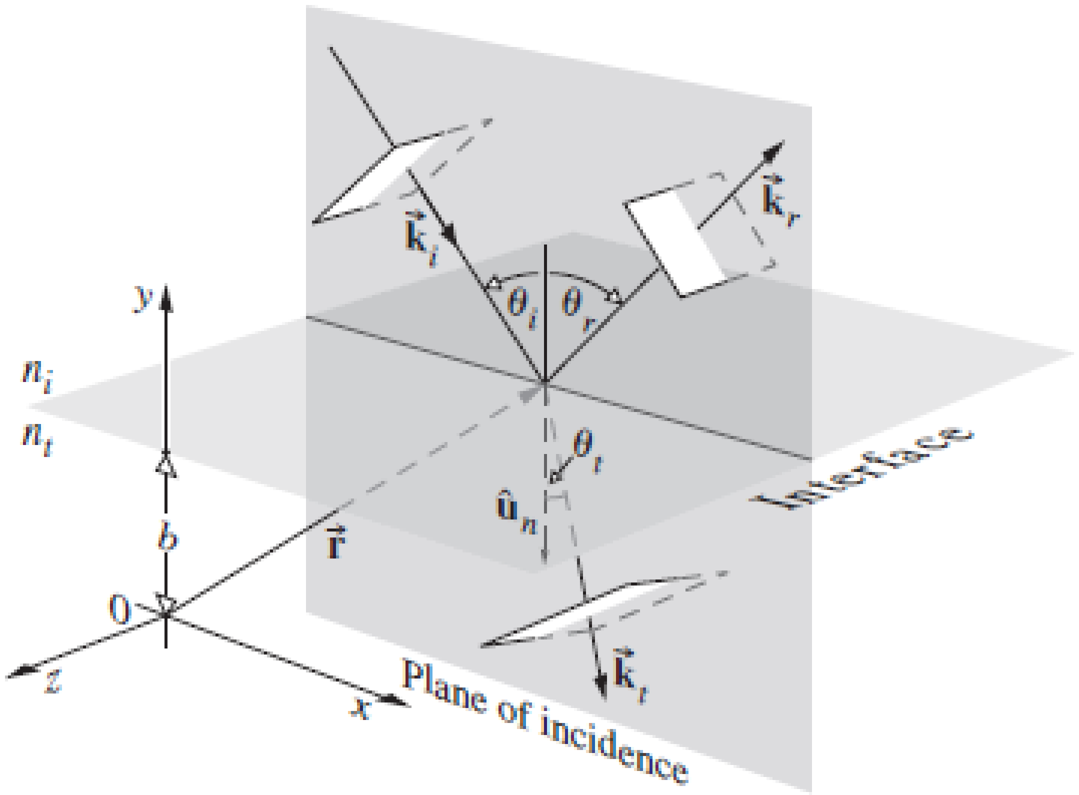


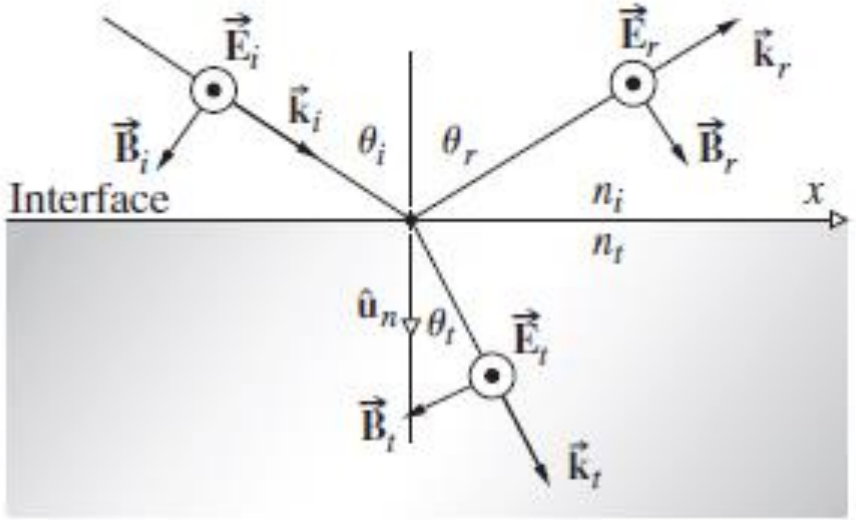
Wave optics

$$\vec{\mathbf{E}}_r = \vec{\mathbf{E}}_{0r} \cos(\vec{\mathbf{k}}_r \cdot \vec{\mathbf{r}} - \omega_r t + \varepsilon_r)$$

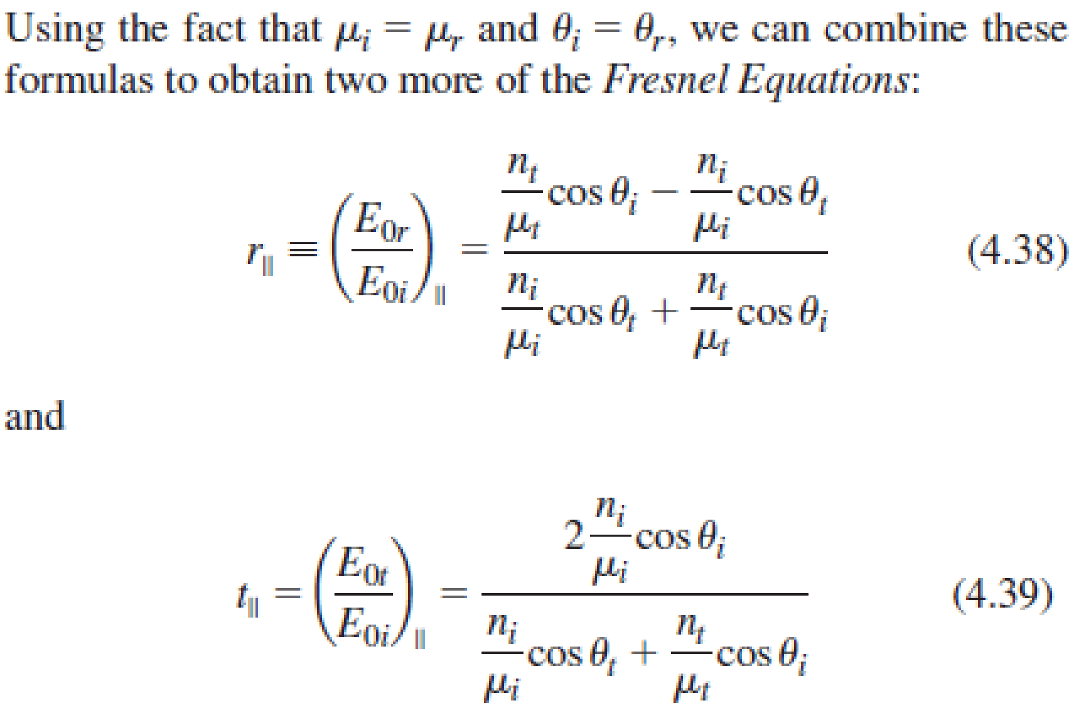
$$\vec{\mathbf{E}}_t = \vec{\mathbf{E}}_{0t} \cos(\vec{\mathbf{k}}_t \cdot \vec{\mathbf{r}} - \omega_t t + \varepsilon_t)$$

$$\hat{\mathbf{u}}_n \times \vec{\mathbf{E}}_i + \hat{\mathbf{u}}_n \times \vec{\mathbf{E}}_r = \hat{\mathbf{u}}_n \times \vec{\mathbf{E}}_t$$





Fresnel equations



Using the fact that $\mu_i = \mu_r$ and $\theta_i = \theta_r$, we can combine these formulas to obtain two more of the *Fresnel Equations*:

$$r_\parallel \equiv \left(\frac{E_{0r}}{E_{0i}}\right)_\parallel = \frac{\dfrac{n_t}{\mu_t}\cos\theta_i - \dfrac{n_i}{\mu_i}\cos\theta_t}{\dfrac{n_i}{\mu_i}\cos\theta_t + \dfrac{n_t}{\mu_t}\cos\theta_i} \tag{4.38}$$

and

$$t_\parallel = \left(\frac{E_{0t}}{E_{0i}}\right)_\parallel = \frac{2\dfrac{n_i}{\mu_i}\cos\theta_i}{\dfrac{n_i}{\mu_i}\cos\theta_t + \dfrac{n_t}{\mu_t}\cos\theta_i} \tag{4.39}$$

$$r_\parallel = \frac{n_t\cos\theta_i - n_i\cos\theta_t}{n_i\cos\theta_t + n_t\cos\theta_i}$$

$$t_\parallel = \frac{2n_i\cos\theta_i}{n_i\cos\theta_t + n_t\cos\theta_i}$$

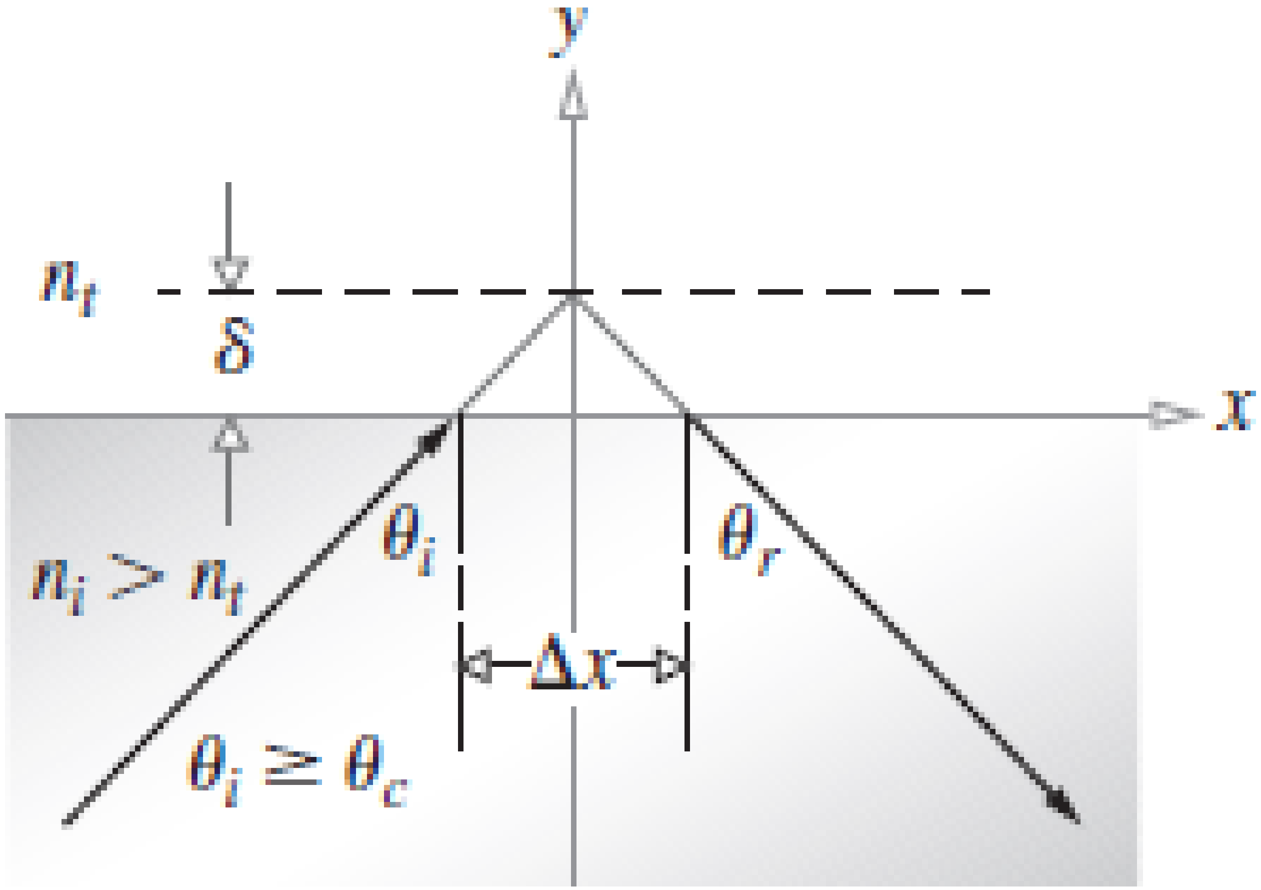
$$r_\perp = -\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)}$$

$$r_\parallel = +\frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)}$$

$$t_\perp = +\frac{2\sin\theta_t\cos\theta_i}{\sin(\theta_i + \theta_t)}$$

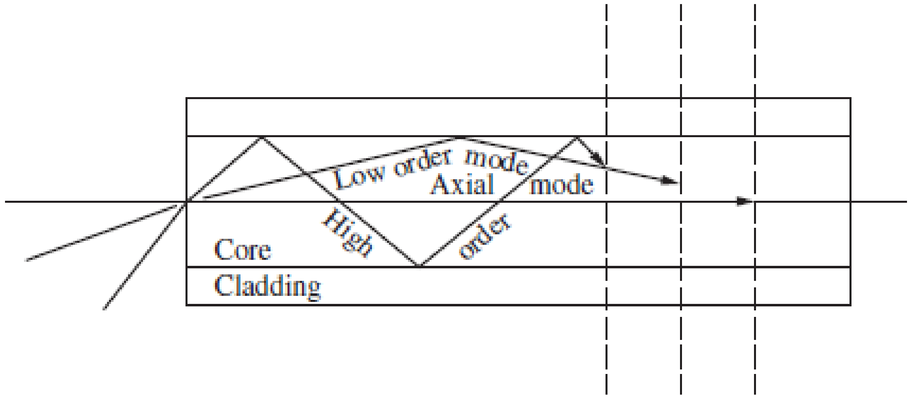
$$t_\parallel = +\frac{2\sin\theta_t\cos\theta_i}{\sin(\theta_i + \theta_t)\cos(\theta_i - \theta_t)}$$

Goose Hanchen Shift



a light beam, which is totally internally reflected, undergoes a minute lateral shift from the position where the beam strikes the interface

! Very important for optical fibers



Waves

First, ***the electric and magnetic fields are perpendicular to each other at any point and to the direction of wave travel -> plane waves***

Second, we can see that the fields alternate in the propagation direction

The electric and magnetic fields are “ in phase” : that is, they each are zero at the same points and reach their maxima at the same points in space

$$E = E_y = E_0 \sin(kx - \omega t)$$
$$B = B_z = B_0 \sin(kx - \omega t)$$

$$k = \frac{2\pi}{\lambda}, \qquad \omega = 2\pi f, \qquad \text{and} \qquad f\lambda = \frac{\omega}{k} = v,$$

Polarization

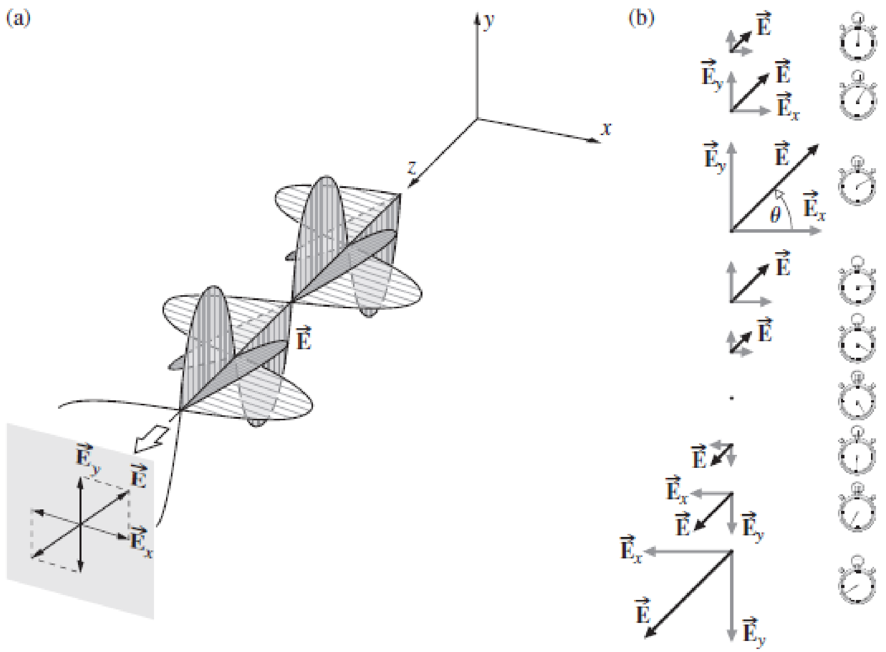
It has already been established that light may be treated as a

transverse electromagnetic wave. Thus far we have considered

only **linearly polarized** or **plane-polarized** light, that is, light

for which the orientation of the electric field is constant, although

its magnitude and sign vary in time



Polarization and phasor

- Phasor addition provides a highly useful technique for dealing with the superposition of orthogonal waves
- Axis projections

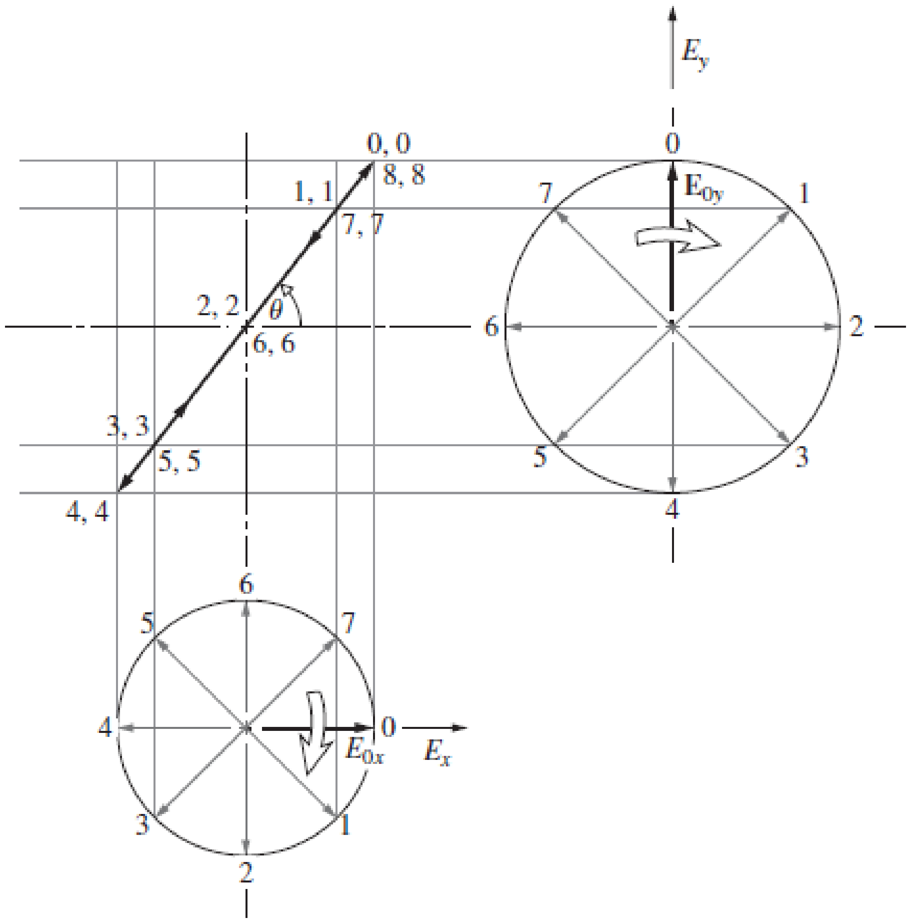
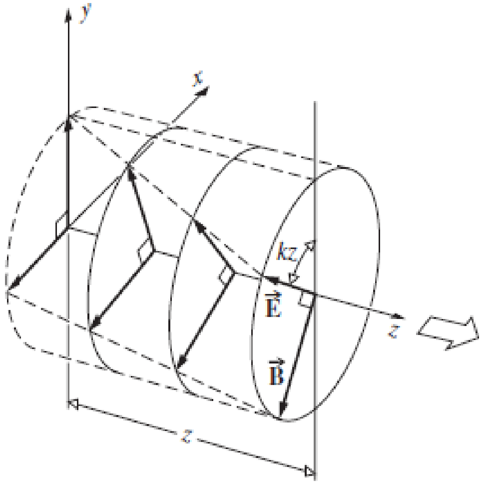


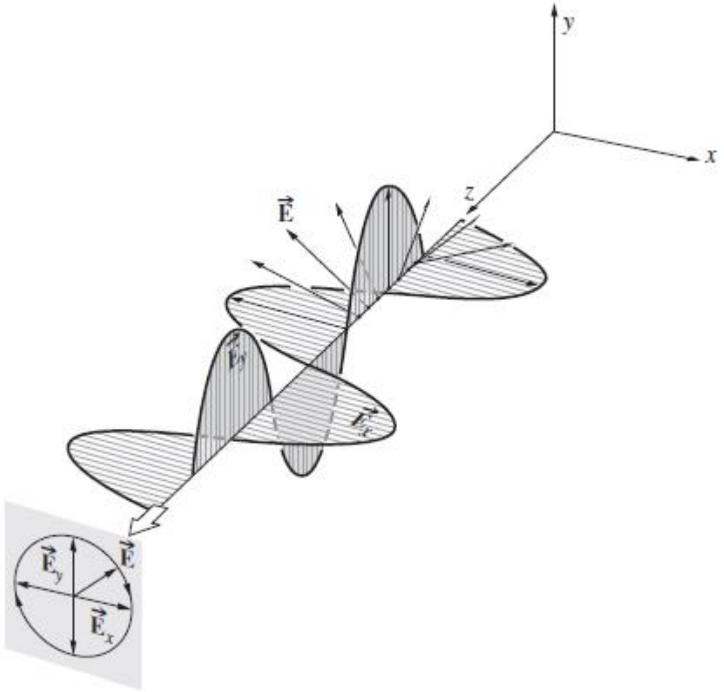
Figure 8.3 Phasor addition of two orthogonal electromagnetic waves in-phase and of amplitudes E_{0x} and E_{0y}. Both rotate clockwise at a rate ω.

Circular polarization

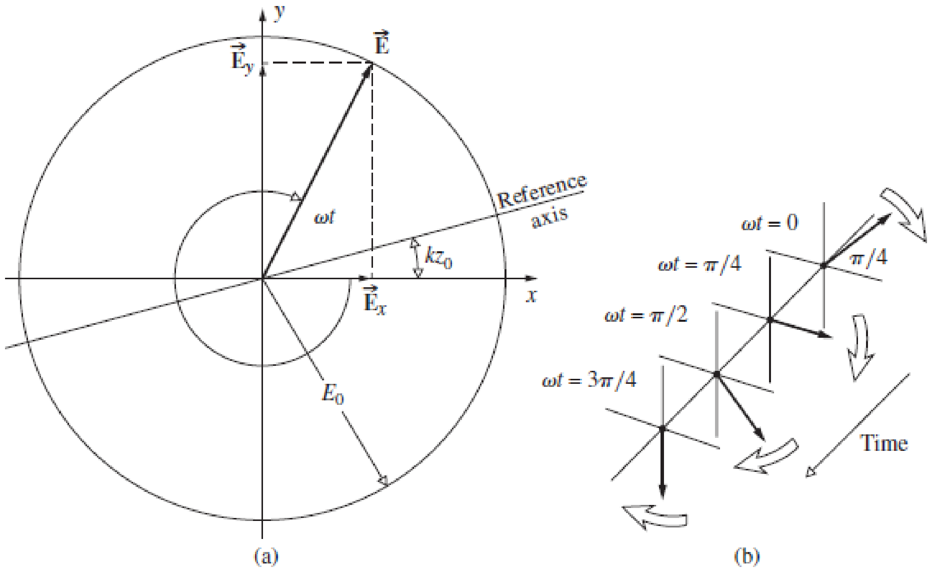


Optical fiber –

acts like a sequential polarizer



Wave propagation



Circular vector rotation (right)- clockwise

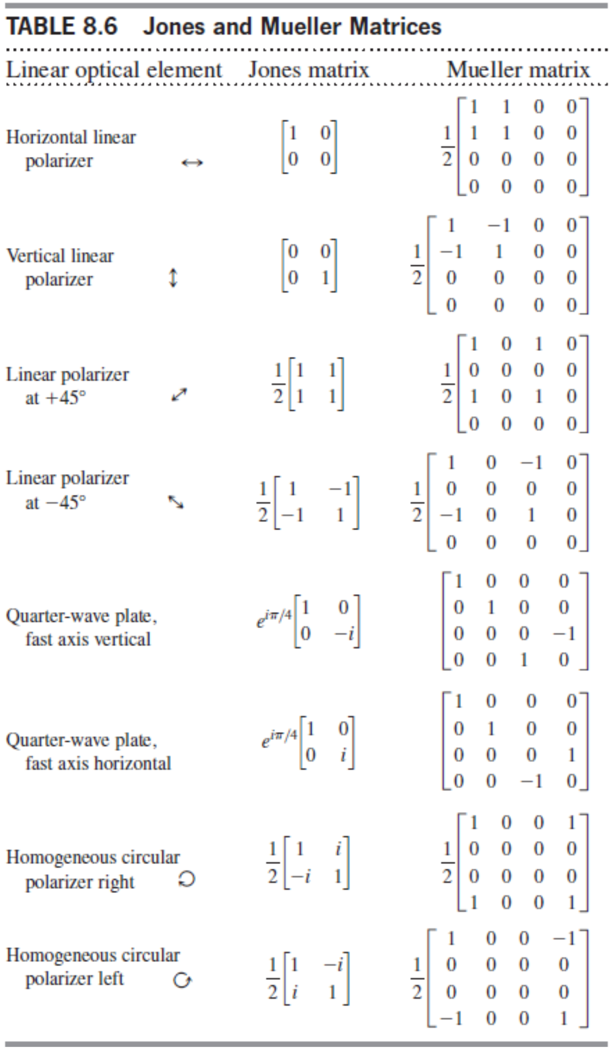
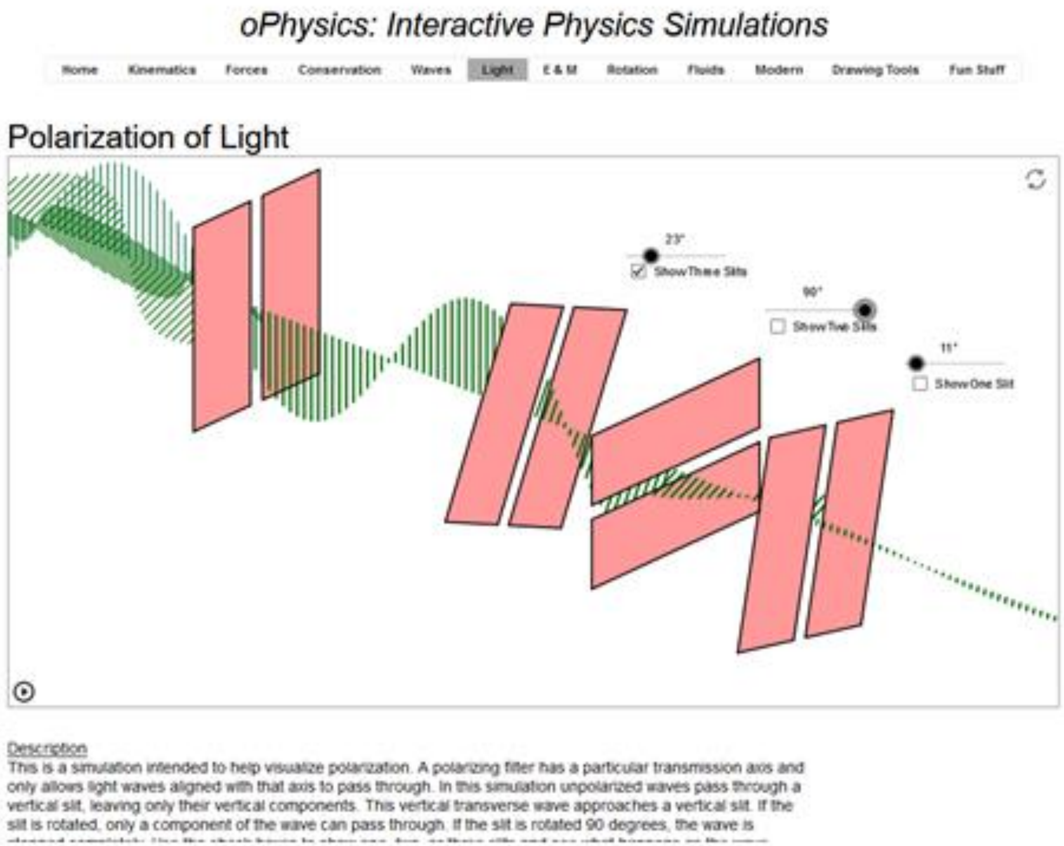


TABLE 8.6 Jones and Mueller Matrices

Linear optical element		Jones matrix	Mueller matrix
Horizontal linear polarizer	↔	$\begin{bmatrix}1 & 0\\0 & 0\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1 & 0 & 0\\1 & 1 & 0 & 0\\0 & 0 & 0 & 0\\0 & 0 & 0 & 0\end{bmatrix}$
Vertical linear polarizer	↕	$\begin{bmatrix}0 & 0\\0 & 1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & -1 & 0 & 0\\-1 & 1 & 0 & 0\\0 & 0 & 0 & 0\\0 & 0 & 0 & 0\end{bmatrix}$
Linear polarizer at +45°	⤢	$\frac{1}{2}\begin{bmatrix}1 & 1\\1 & 1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 0 & 1 & 0\\0 & 0 & 0 & 0\\1 & 0 & 1 & 0\\0 & 0 & 0 & 0\end{bmatrix}$
Linear polarizer at −45°	⤡	$\frac{1}{2}\begin{bmatrix}1 & -1\\-1 & 1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 0 & -1 & 0\\0 & 0 & 0 & 0\\-1 & 0 & 1 & 0\\0 & 0 & 0 & 0\end{bmatrix}$
Quarter-wave plate, fast axis vertical		$e^{i\pi/4}\begin{bmatrix}1 & 0\\0 & -i\end{bmatrix}$	$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & -1\\0 & 0 & 1 & 0\end{bmatrix}$
Quarter-wave plate, fast axis horizontal		$e^{i\pi/4}\begin{bmatrix}1 & 0\\0 & i\end{bmatrix}$	$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & -1 & 0\end{bmatrix}$
Homogeneous circular polarizer right	↻	$\frac{1}{2}\begin{bmatrix}1 & i\\-i & 1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 0 & 0 & 1\\0 & 0 & 0 & 0\\0 & 0 & 0 & 0\\1 & 0 & 0 & 1\end{bmatrix}$
Homogeneous circular polarizer left	↺	$\frac{1}{2}\begin{bmatrix}1 & -i\\i & 1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 0 & 0 & -1\\0 & 0 & 0 & 0\\0 & 0 & 0 & 0\\-1 & 0 & 0 & 1\end{bmatrix}$

Polarisation



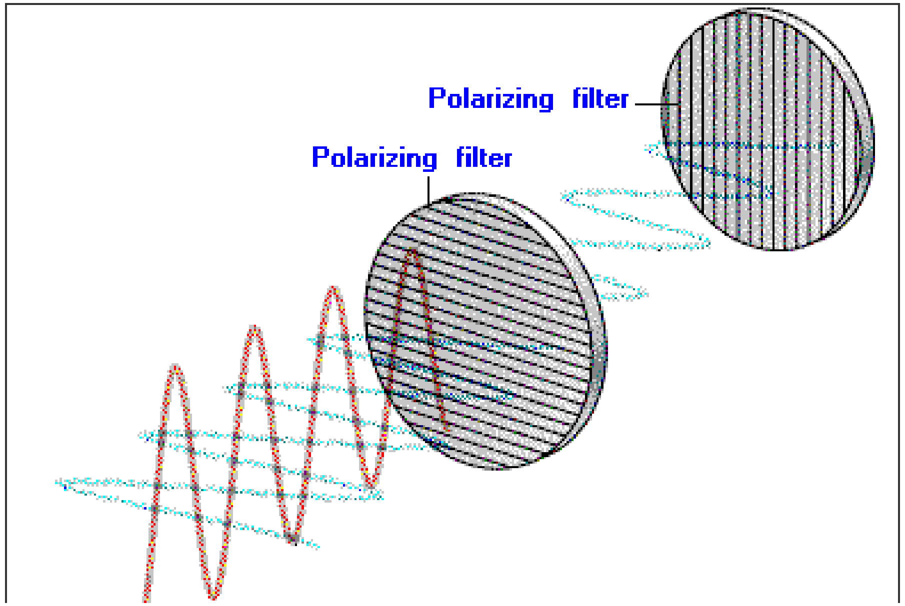
oPhysics: Interactive Physics Simulations

Polarization of Light

Description

This is a simulation intended to help visualize polarization. A polarizing filter has a particular transmission axis and only allows light waves aligned with that axis to pass through. In this simulation unpolarized waves pass through a vertical slit, leaving only their vertical components. This vertical transverse wave approaches a vertical slit. If the slit is rotated, only a component of the wave can pass through. If the slit is rotated 90 degrees, the wave is

https://ophysics.com/l.html



Malus Law

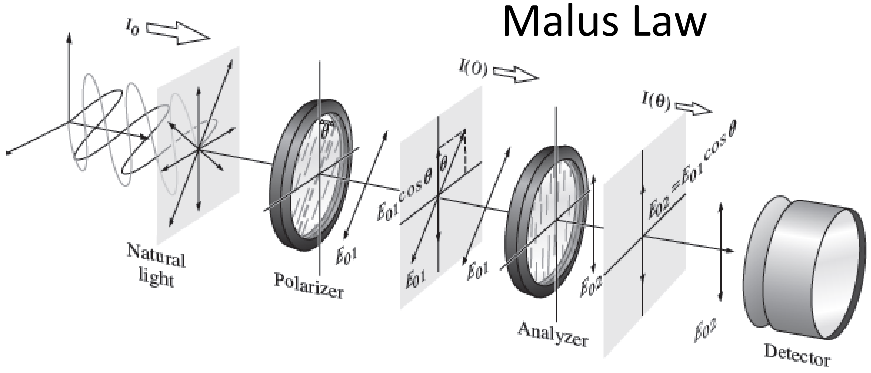


Figure 8.14 A linear polarizer and analyzer—Malus's Law. Natural light of irradiance I_0 is incident on a linear polarizer tilted at an angle θ with respect to the vertical. The irradiance leaving the first linear polarizer is $I_1 = I(0)$. The irradiance leaving the second linear polarizer (which makes an angle θ with the first) is $I(\theta)$.

you certainly can confirm Malus's Law with two ordinary Polaroids, you'll have to be careful to use light in the range from 450 nm to 650 nm.

Birefringence

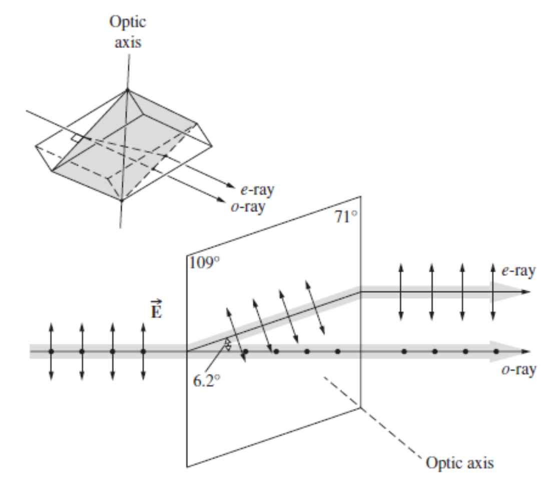
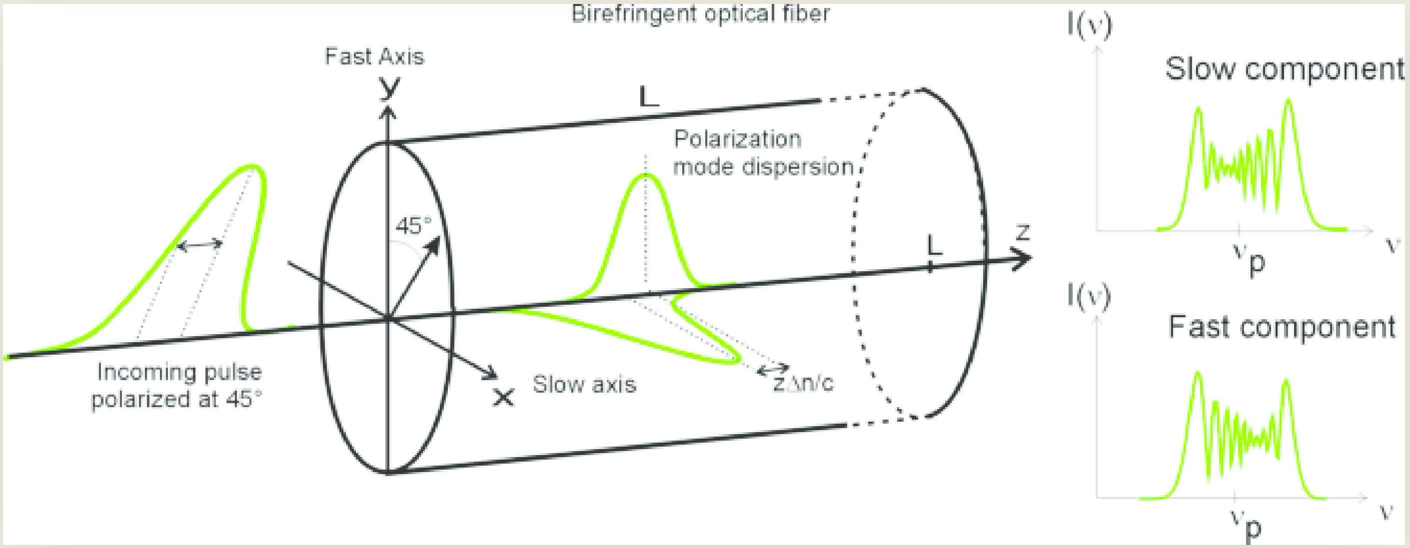


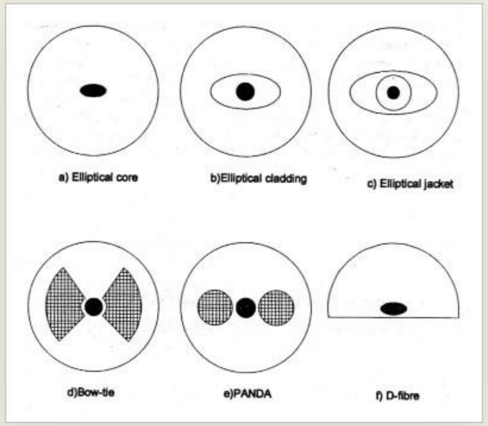
Figure 8.22 A lightbeam with two orthogonal field components traversing a calcite principal section.

Many crystalline substances (i.e., solids whose atoms are arranged in some sort of regular repetitive array) are *optically anisotropic.* Their optical properties are not the same in all directions within any given sample.

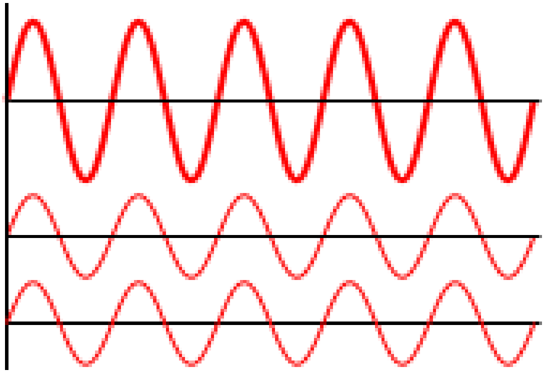
https://en.wikipedia.org/wiki/Birefringence



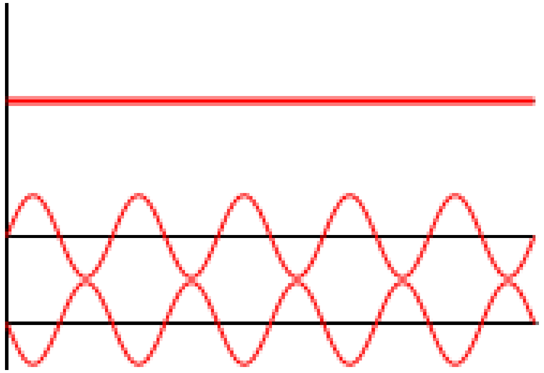
Optical fibers



Wave – Interference
INTERFEROMETER

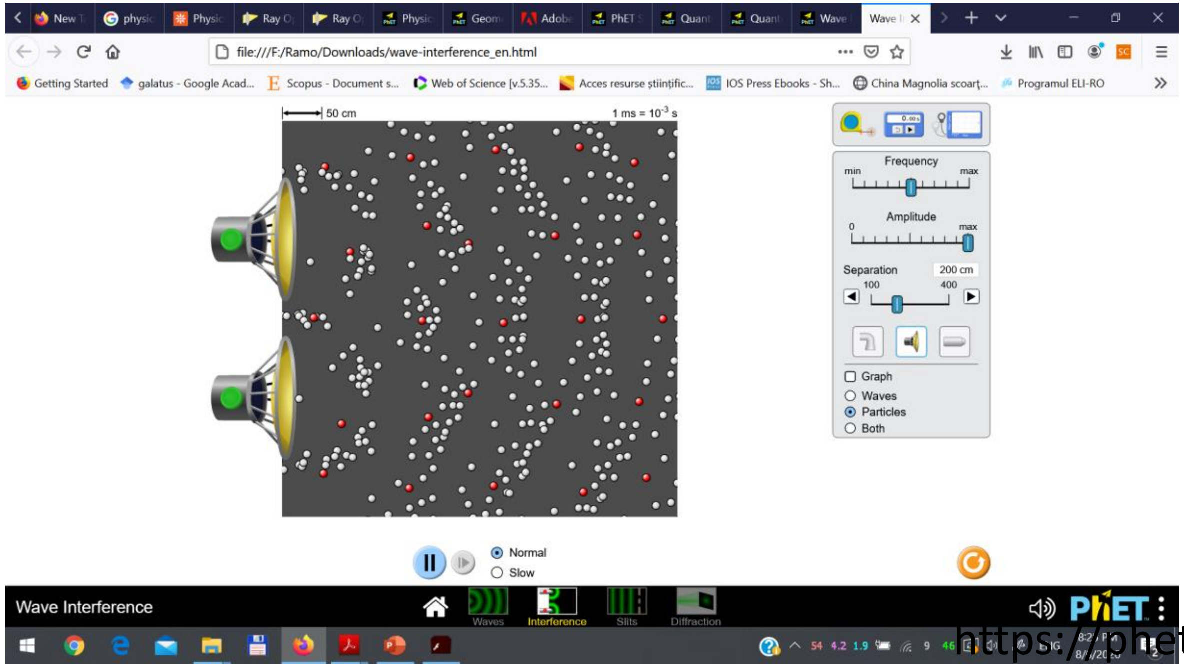


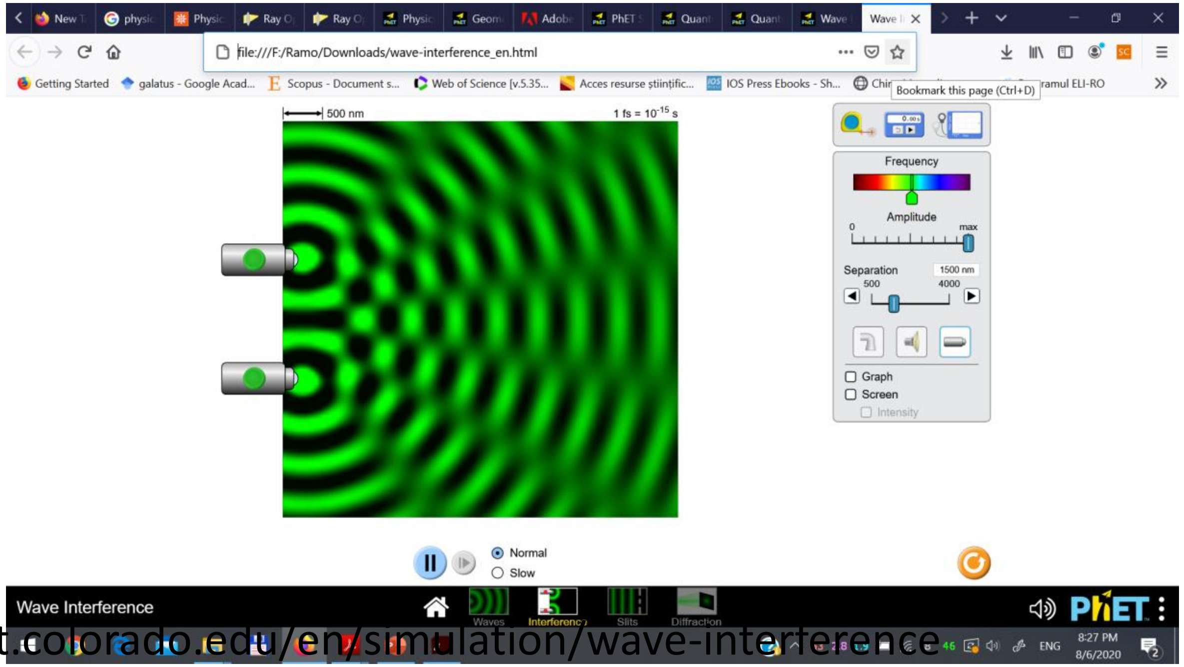
Constructive – in phase



Destructive

Simulators https://phet.colorado.edu/sims/html/wave-interference/latest/wave-interference_en.html





https://phet.colorado.edu/en/simulation/wave-interference

Interference

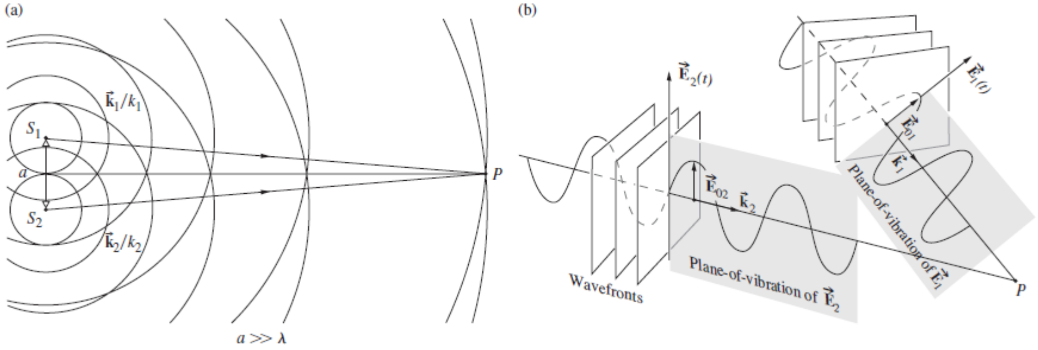


Figure 9.2 Waves from two point sources overlapping in space.

- ***optical interference corresponds to the interaction of two or more lightwaves yielding a resultant irradiance that deviates from the sum of the component irradiances***.

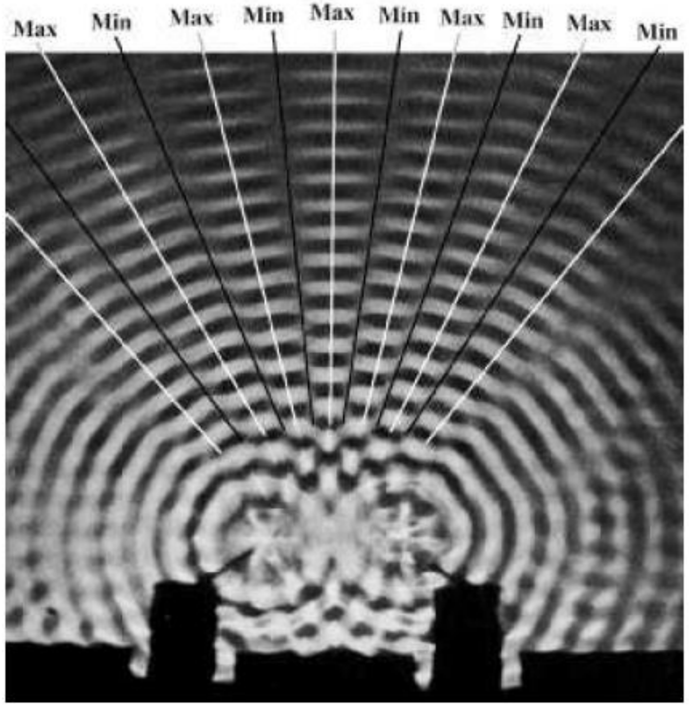


Figure 9.1 Water waves from two in-phase point sources in a ripple tank. In the middle of the pattern the wave peaks (thin bright bands), and troughs (thin black bands) lie within long wedge-shaped areas (maxima) separated by narrow dark regions of calm (minima). Although the superim-

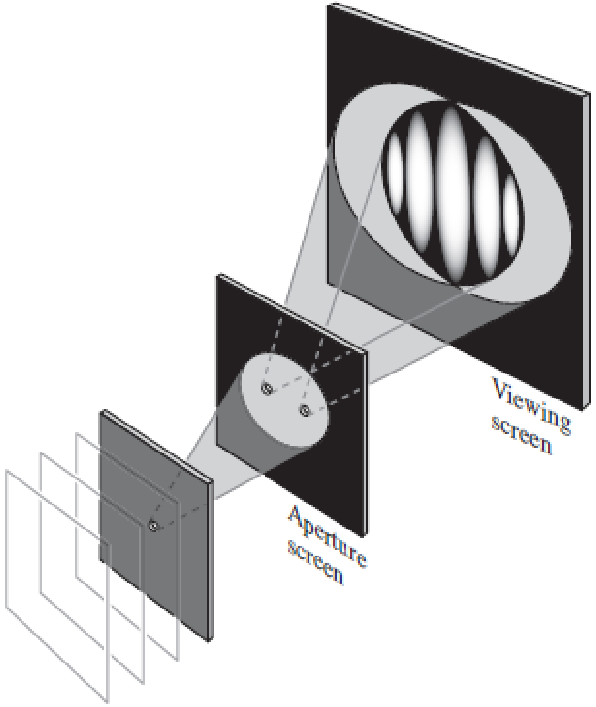
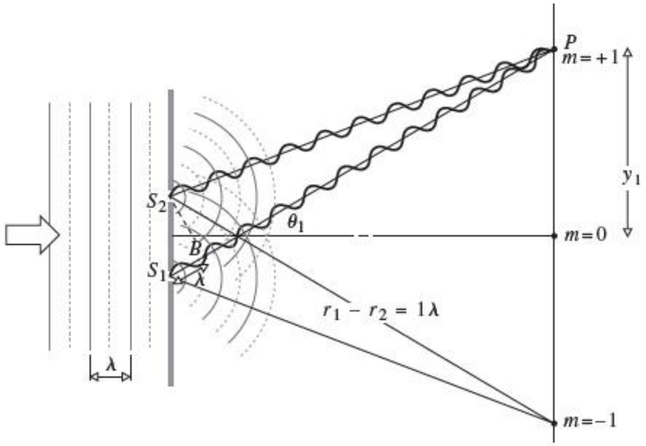
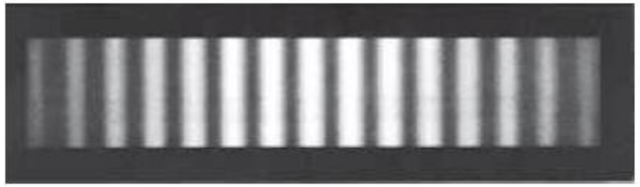


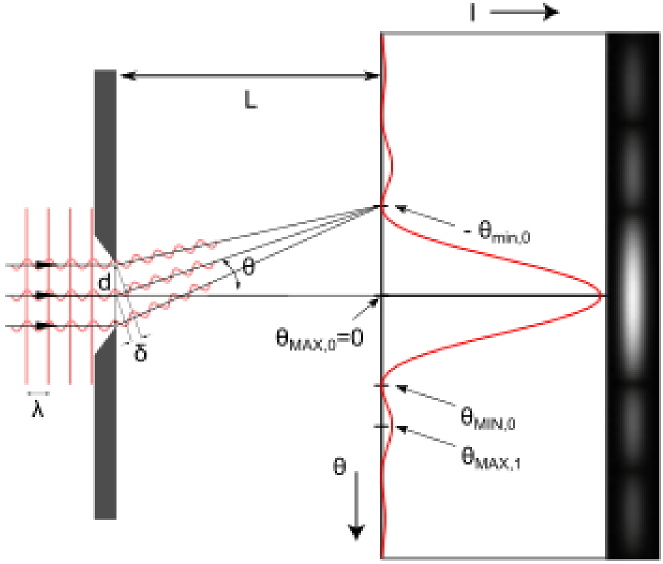
Figure 9.10 Young's Experiment employing cones of light from two small circular holes. Waves of illumination impinge from the left on a screen containing a single circular hole.

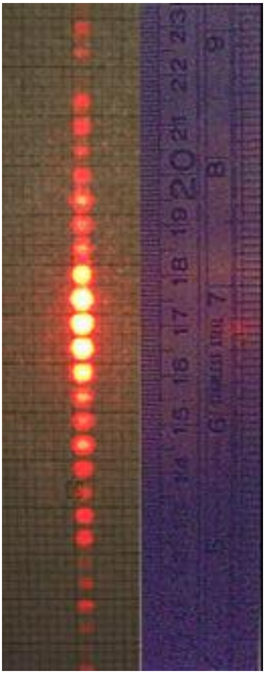


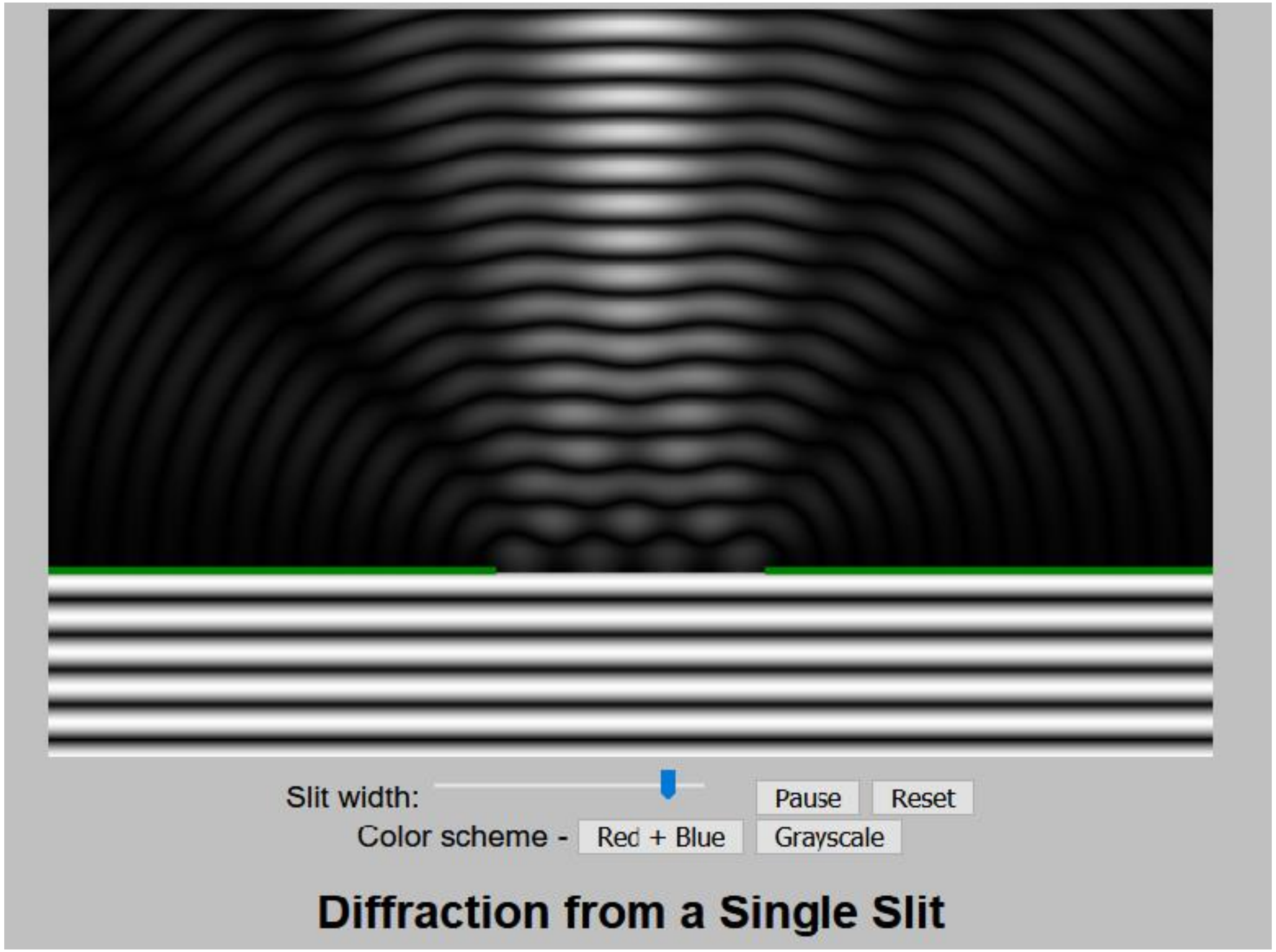


Max and min – young experiment

Diffraction
GRATINGS







Diffraction from a Single Slit

https://ophysics.com/l5b.html

https://ophysics.com/l4.html

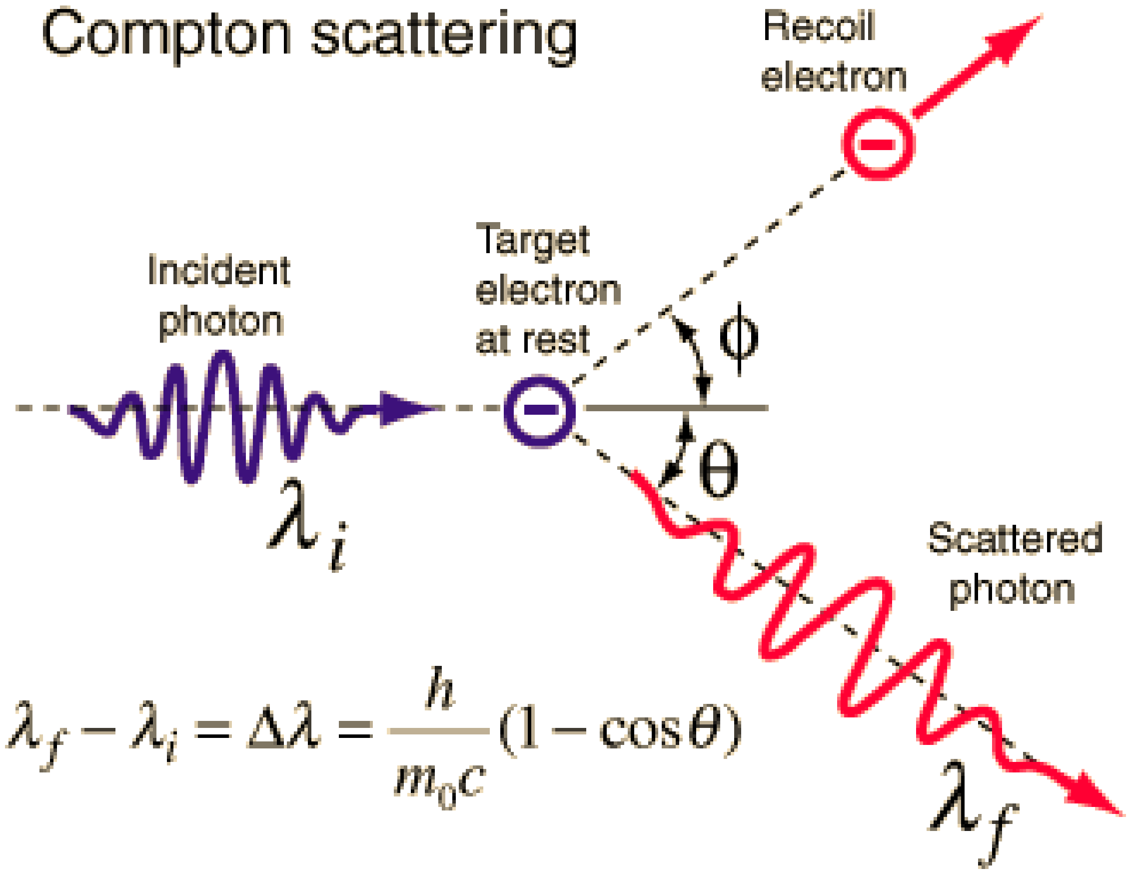
https://phet.colorado.edu/sims/html/wave-interference/latest/wave-interference_en.html

http://physics.bu.edu/~duffy/HTML5/diffraction.html

https://www.animations.physics.unsw.edu.au/light/diffraction/index.html

Quantum optics

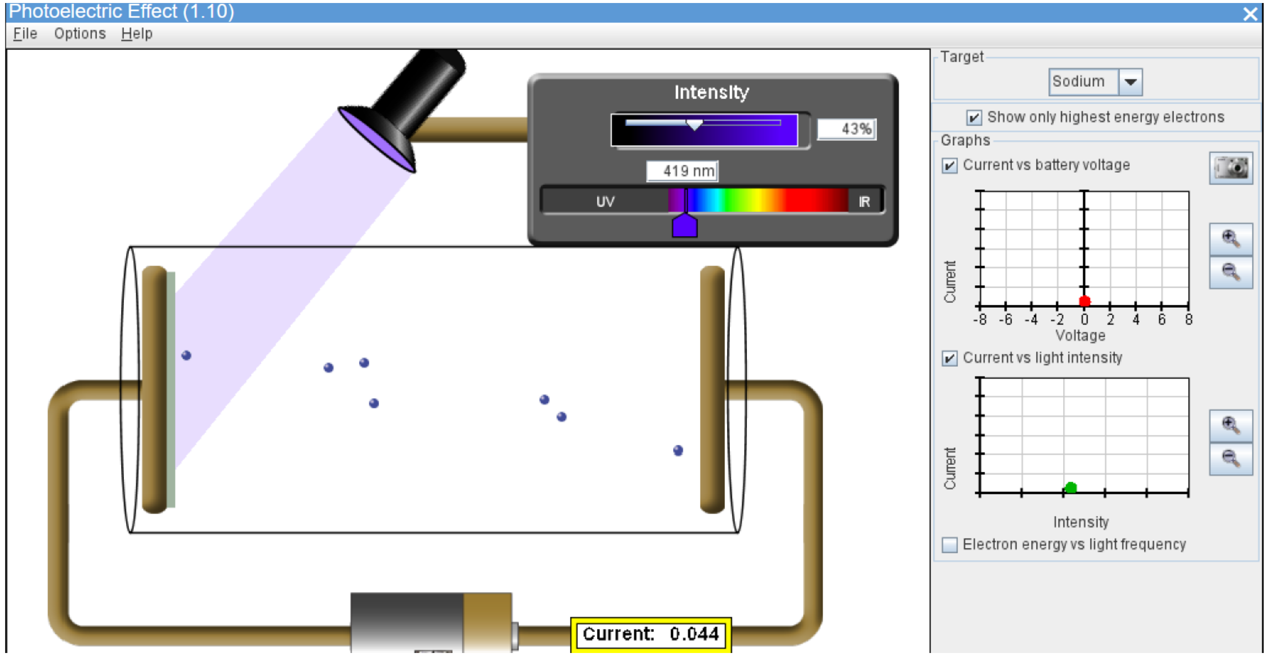
- Emission
- Adsorption
- Photoelectric effect
- Compton



$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1-\cos\theta)$$

https://ocw.mit.edu/courses/physics/8-04-quantum-physics-i-spring-2016/video-lectures/part-1/compton-scattering/

Photoelectric effect



Target: Sodium

☑ Show only highest energy electrons

Intensity: 43%

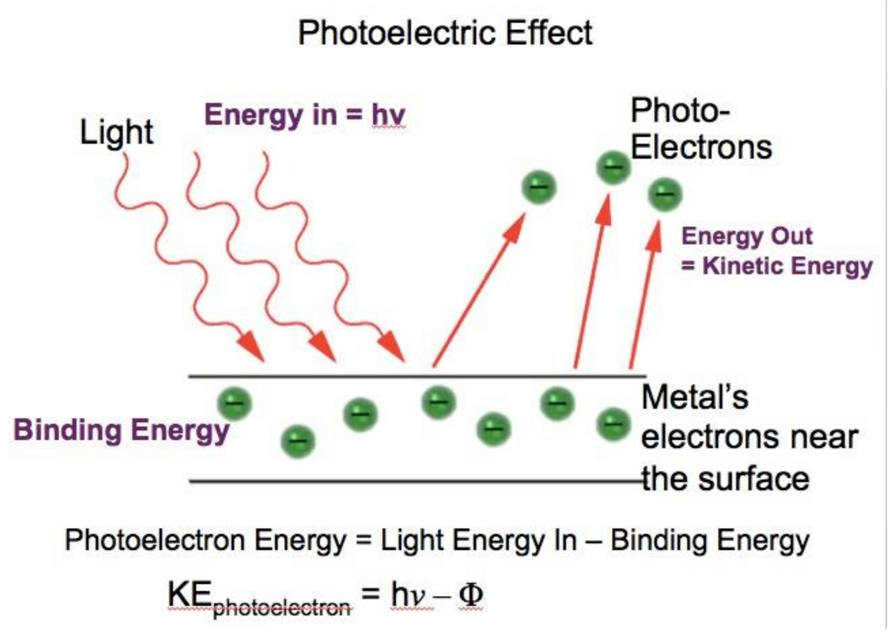
419 nm

☑ Current vs battery voltage

☑ Current vs light intensity

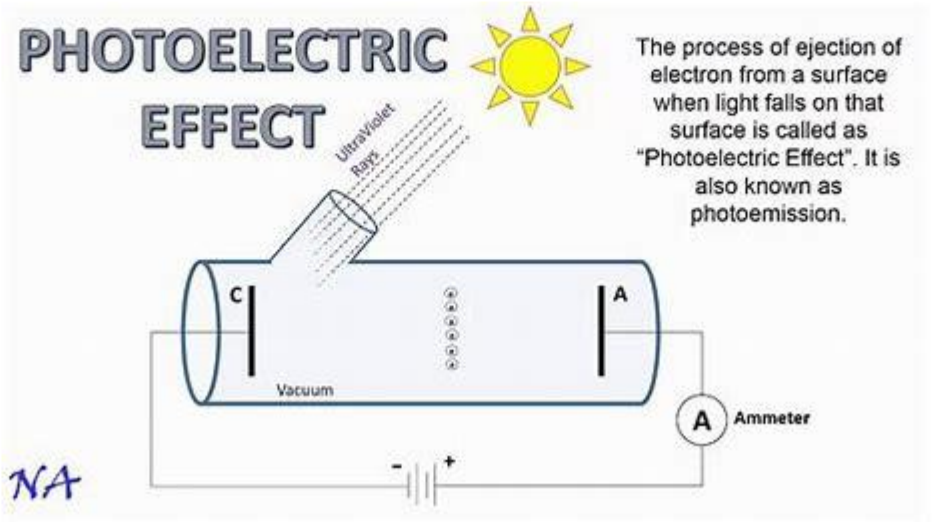
☐ Electron energy vs light frequency

Current: 0.044



Photoelectron Energy = Light Energy In – Binding Energy

$KE_{photoelectron} = h\nu - \Phi$

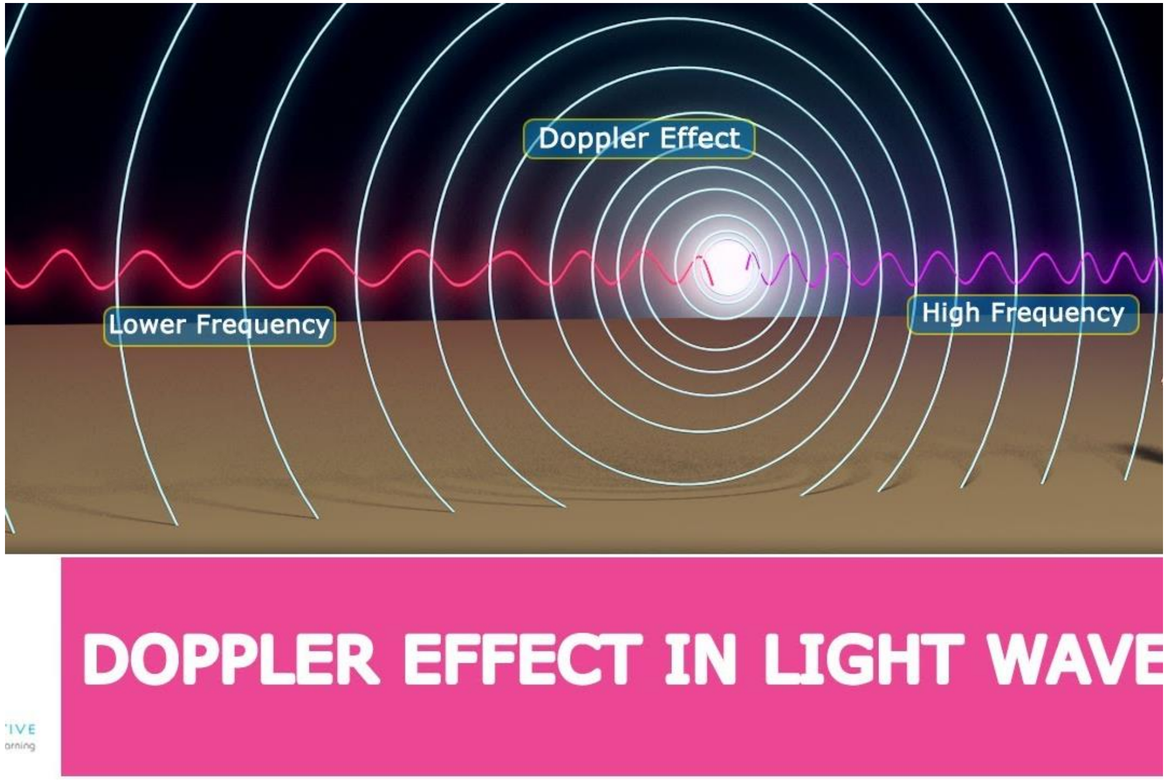


The process of ejection of electron from a surface when light falls on that surface is called as "Photoelectric Effect". It is also known as photoemission.

https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric

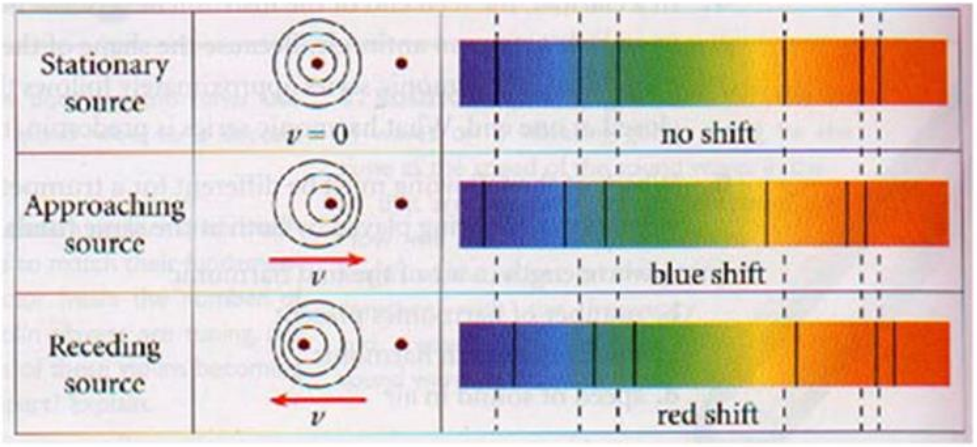
The Doppler effect is an effect observed in light and **sound waves as they move toward or away from an observer**

Doppler effect



And this is used to tell if the source is moving toward or away from us and at what speed.

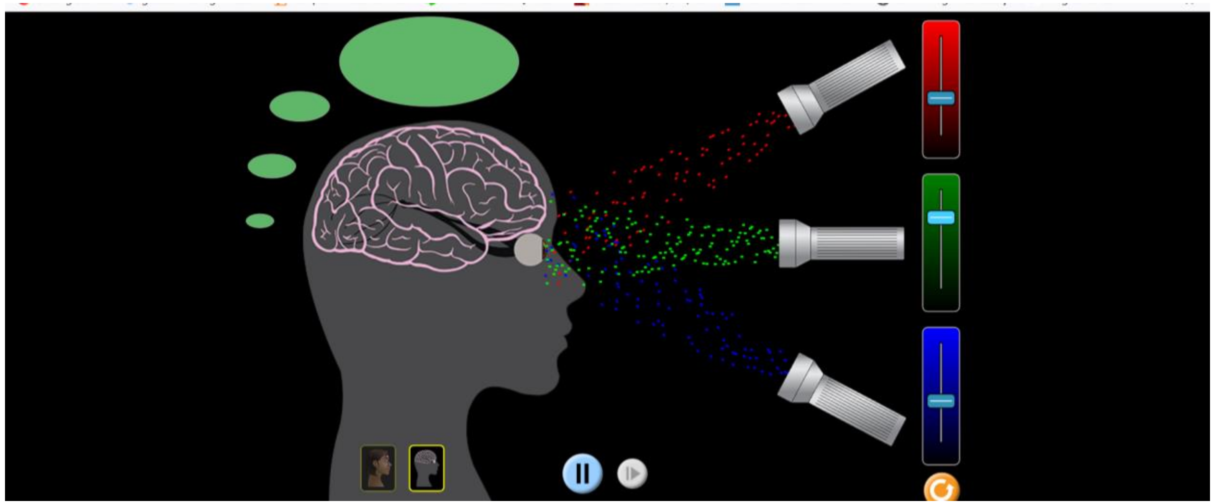
Doppler Effect

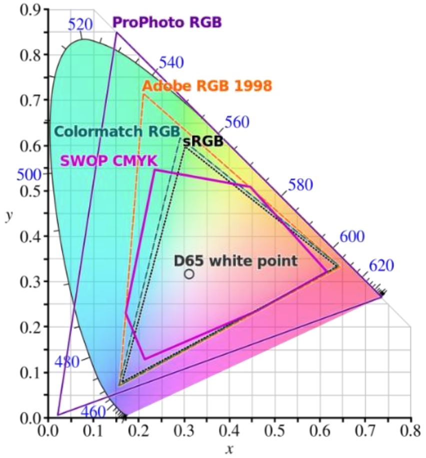


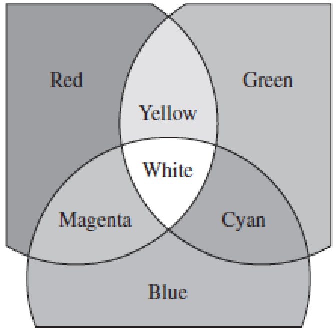
Measuring the relative velocities of stars by the Doppler shift.

https://www.youtube.com/watch?v=vDvIhiCnatE
https://phys.org/news/2016-03-nonlinear-rotational-doppler-effect.html

RGB colour vision (camera vision)







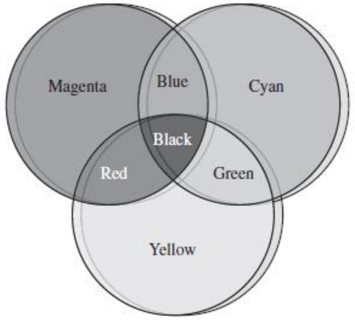
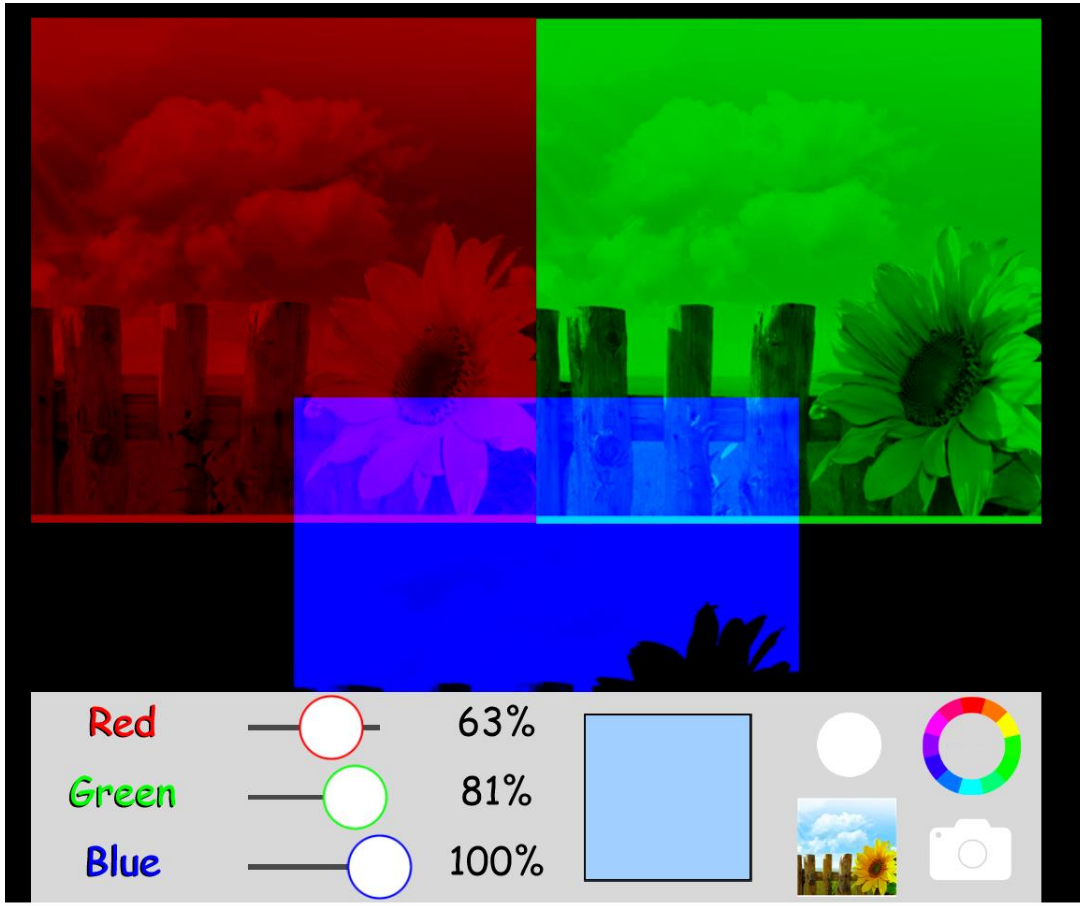


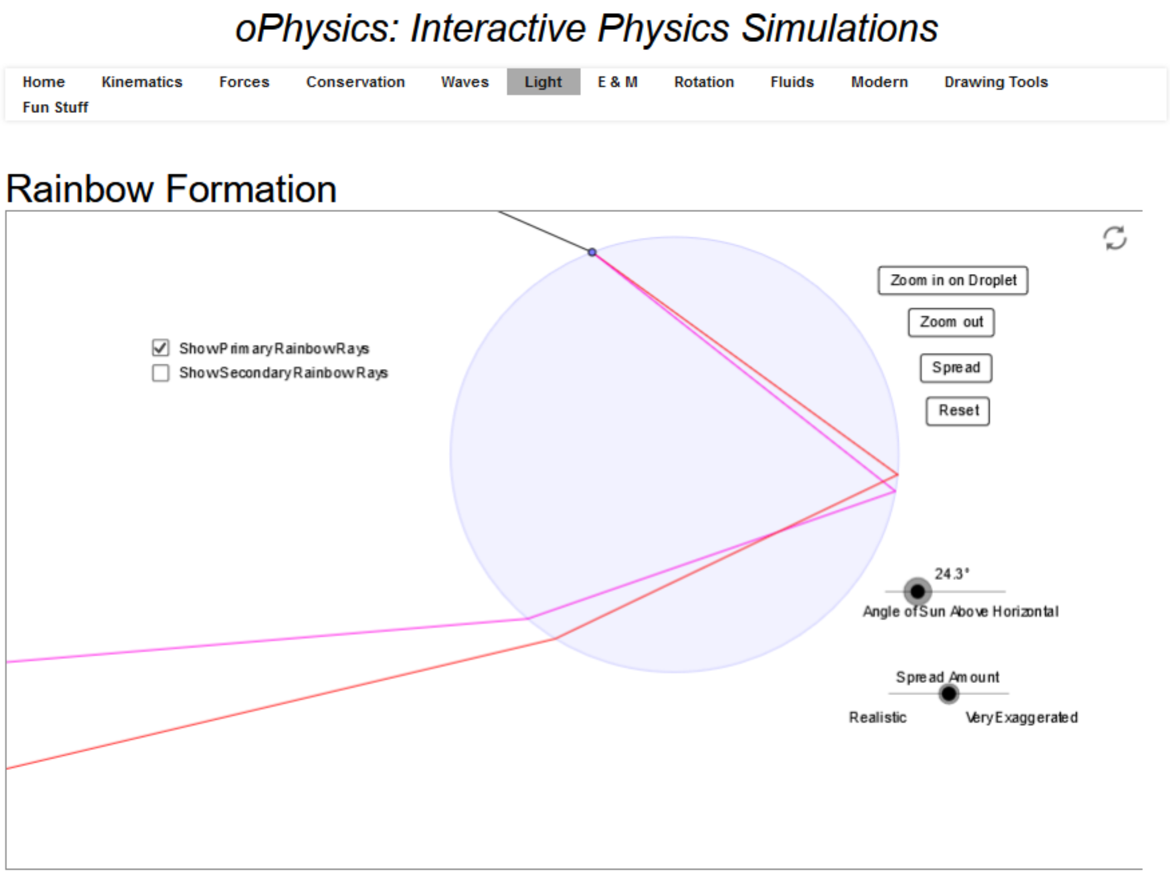
Figure 4.77 Overlapping magenta, cyan, and yellow filters illuminated from the rear with white light.



Red 63%
Green 81%
Blue 100%

https://phet.colorado.edu/sims/html/color-vision/latest/color-vision_en.html

Rainbow



oPhysics: Interactive Physics Simulations

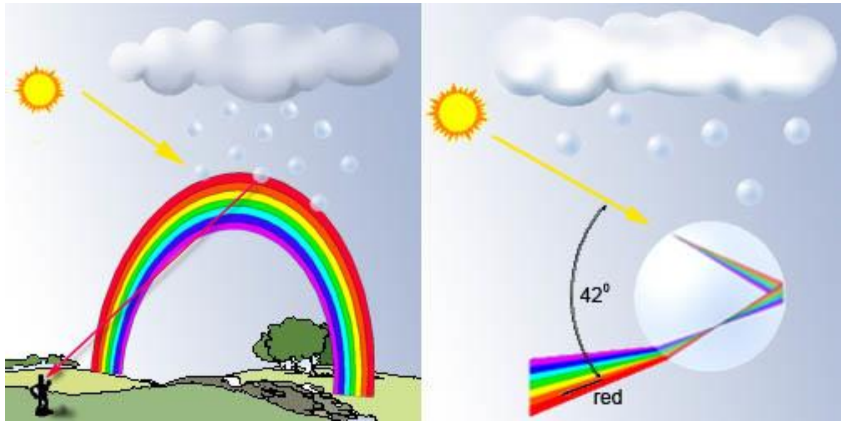
Rainbow Formation

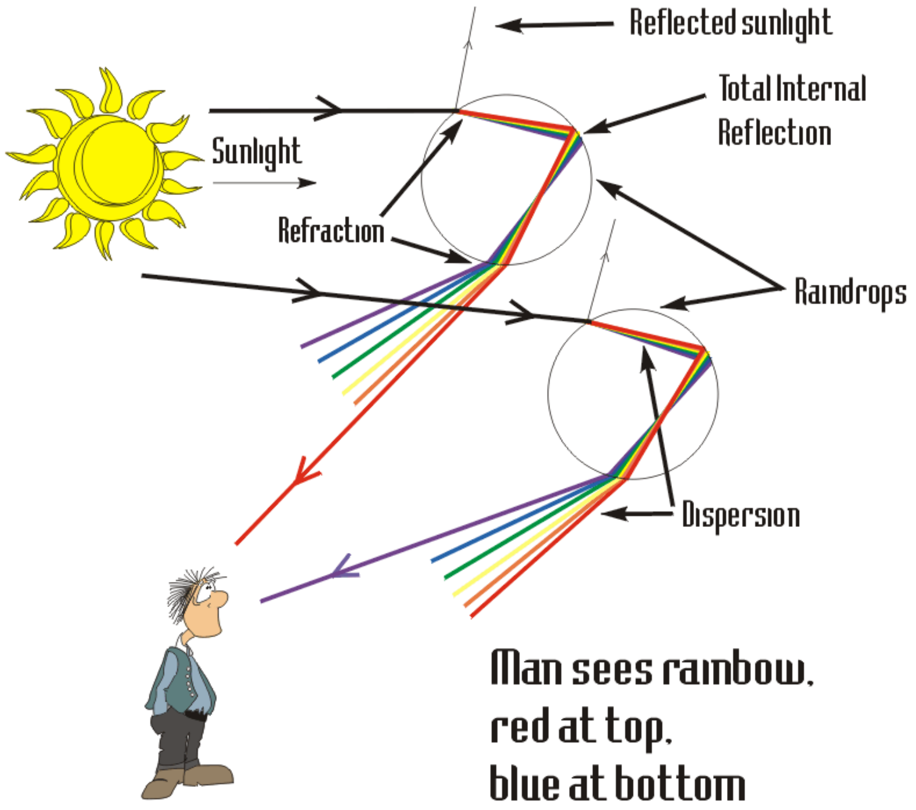
☑ Show Primary Rainbow Rays
☐ Show Secondary Rainbow Rays

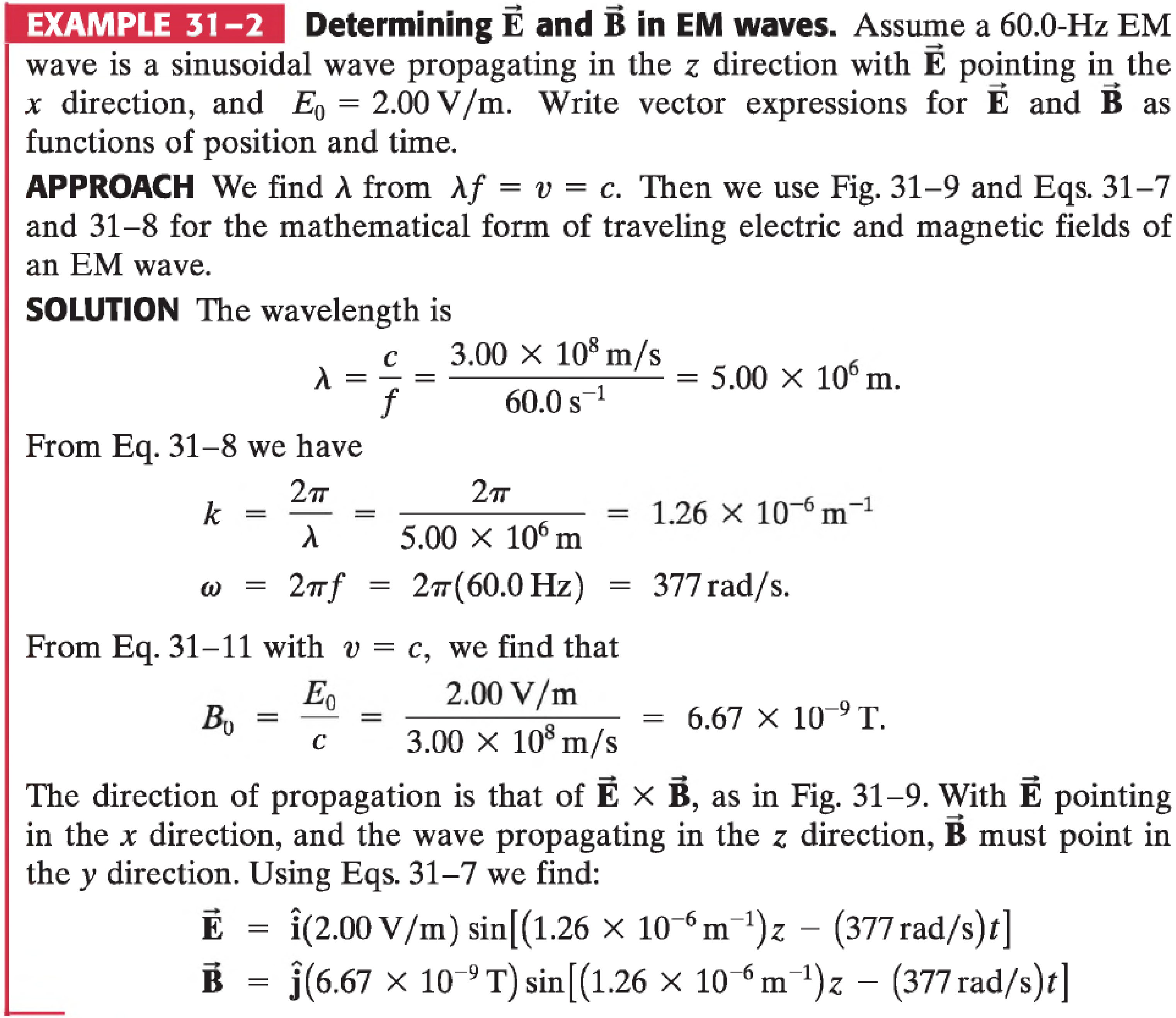
24.3° Angle of Sun Above Horizontal

Spread Amount: Realistic ● Very Exaggerated

https://ophysics.com/l17.html







EXAMPLE 31–2 **Determining $\vec{\mathbf{E}}$ and $\vec{\mathbf{B}}$ in EM waves.** Assume a 60.0-Hz EM wave is a sinusoidal wave propagating in the z direction with $\vec{\mathbf{E}}$ pointing in the x direction, and $E_0 = 2.00\ \mathrm{V/m}$. Write vector expressions for $\vec{\mathbf{E}}$ and $\vec{\mathbf{B}}$ as functions of position and time.

APPROACH We find λ from $\lambda f = v = c$. Then we use Fig. 31–9 and Eqs. 31–7 and 31–8 for the mathematical form of traveling electric and magnetic fields of an EM wave.

SOLUTION The wavelength is

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^8\ \mathrm{m/s}}{60.0\ \mathrm{s^{-1}}} = 5.00 \times 10^6\ \mathrm{m}.$$

From Eq. 31–8 we have

$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{5.00 \times 10^6\ \mathrm{m}} = 1.26 \times 10^{-6}\ \mathrm{m^{-1}}$$

$$\omega = 2\pi f = 2\pi(60.0\ \mathrm{Hz}) = 377\ \mathrm{rad/s}.$$

From Eq. 31–11 with $v = c$, we find that

$$B_0 = \frac{E_0}{c} = \frac{2.00\ \mathrm{V/m}}{3.00 \times 10^8\ \mathrm{m/s}} = 6.67 \times 10^{-9}\ \mathrm{T}.$$

The direction of propagation is that of $\vec{\mathbf{E}} \times \vec{\mathbf{B}}$, as in Fig. 31–9. With $\vec{\mathbf{E}}$ pointing in the x direction, and the wave propagating in the z direction, $\vec{\mathbf{B}}$ must point in the y direction. Using Eqs. 31–7 we find:

$$\vec{\mathbf{E}} = \hat{\mathbf{i}}(2.00\ \mathrm{V/m}) \sin\left[(1.26 \times 10^{-6}\ \mathrm{m^{-1}})z - (377\ \mathrm{rad/s})t\right]$$

$$\vec{\mathbf{B}} = \hat{\mathbf{j}}(6.67 \times 10^{-9}\ \mathrm{T}) \sin\left[(1.26 \times 10^{-6}\ \mathrm{m^{-1}})z - (377\ \mathrm{rad/s})t\right]$$

Speed of light

$$3.00 \times 10^8\ \mathrm{m/s}.$$

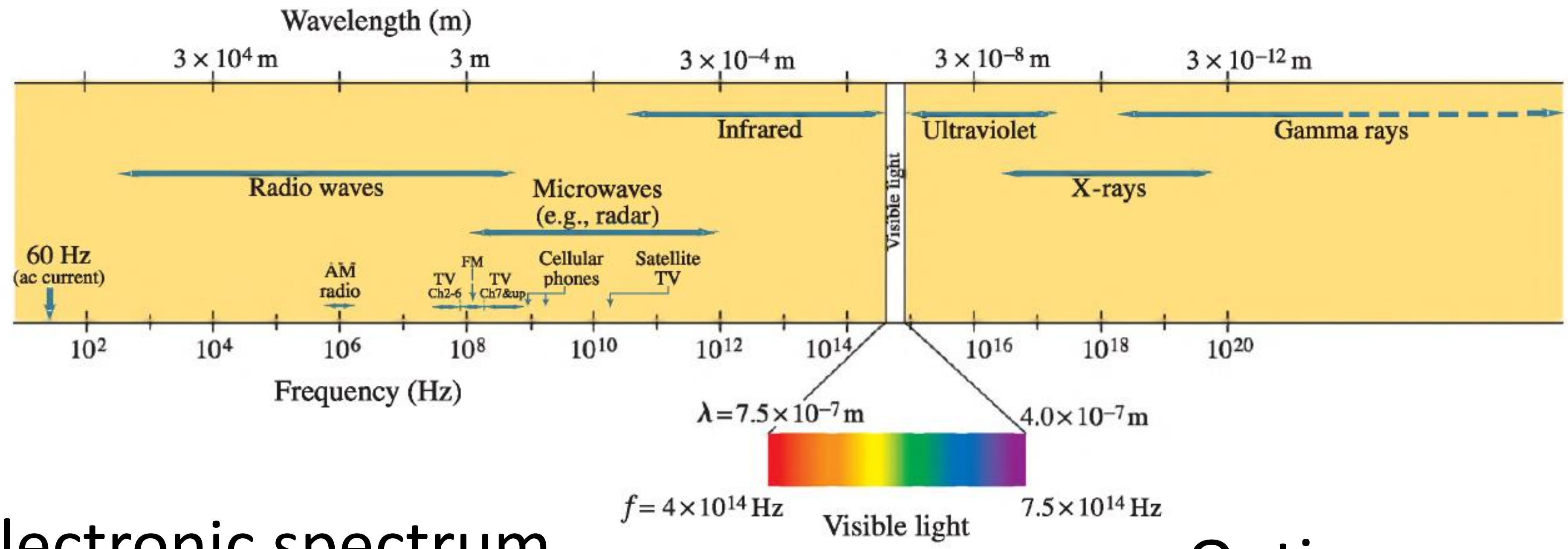
Attempts:

*Galileo attempted to measure the speed of light

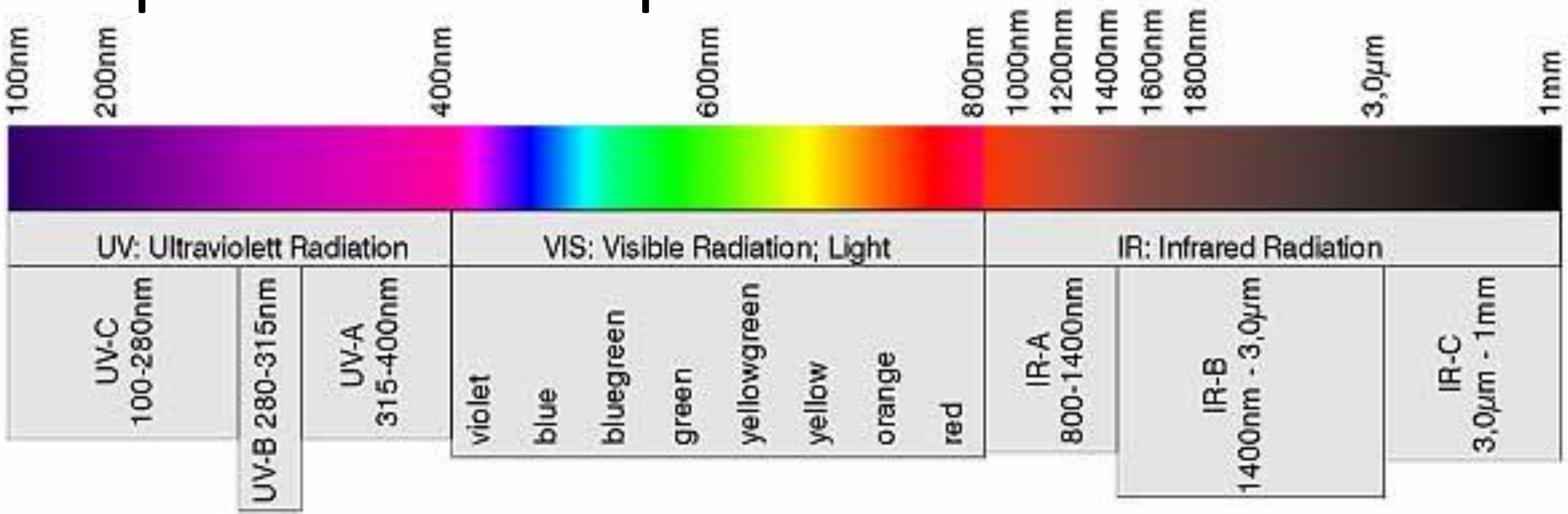
*Albert A. Michelson (1852-1931)

Electromagnetic spectrum

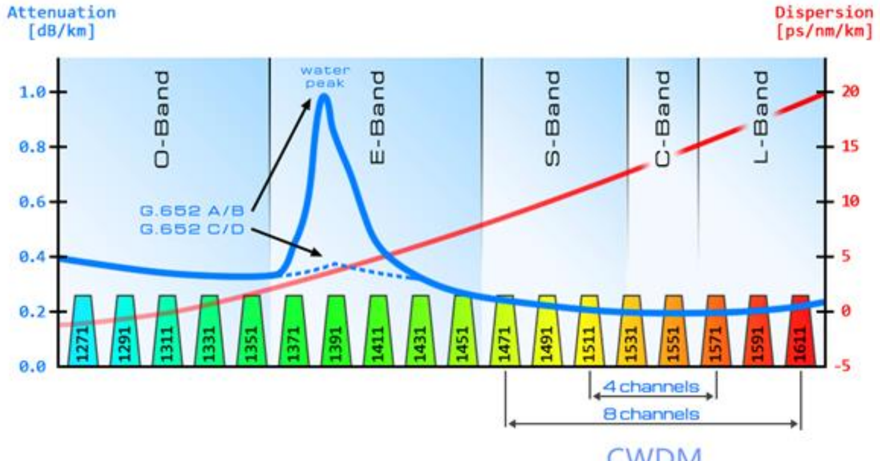
https://light-measurement.com/wavelength-range/


Electromagnetic spectrum.

Optoelectronic spectrum



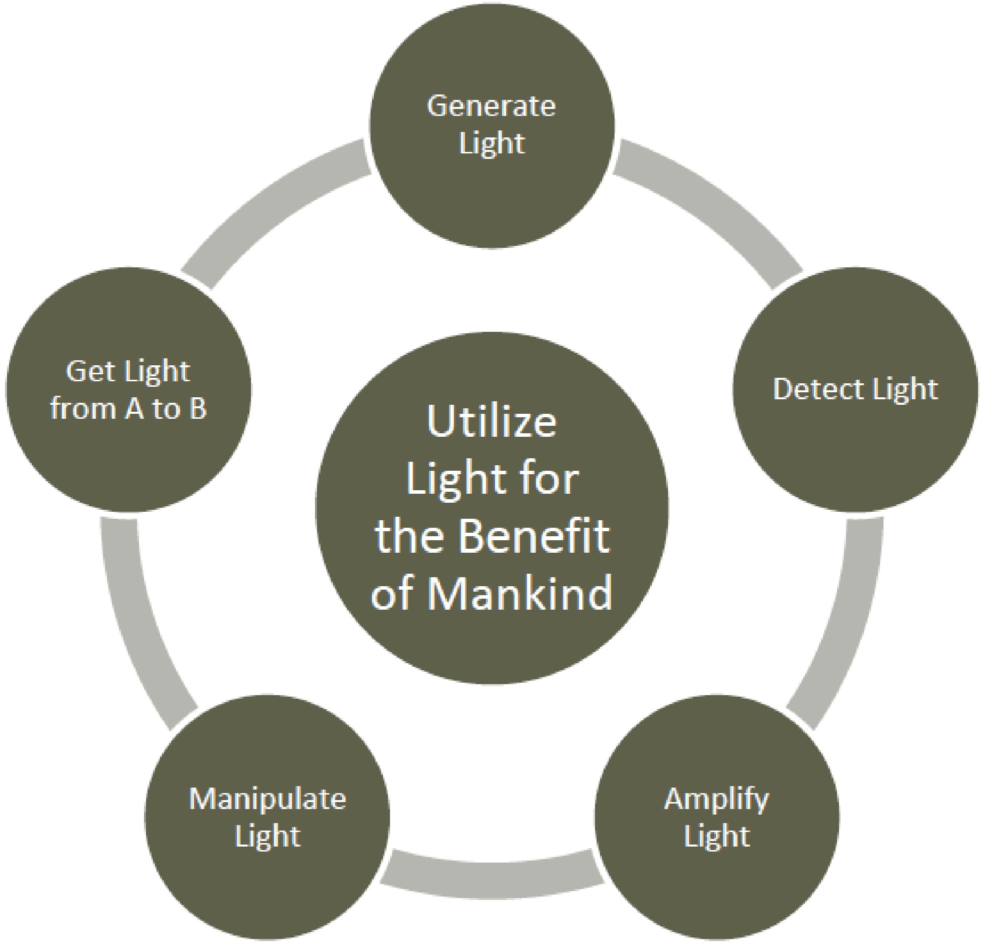
Optic communication



Conclusions

Optics	Photonics
Science – questions the nature of light – models light and its properties – predicts the behaviour and propagation of light – studies interaction of light with matter	**Science and technology** – puts light at work – exploits the unique features of light to develop new applications and functionalities
Etymology – οψ = ‘ops’ = the eye – ‘optikos’ = ‘pertaining to sight’	**Etymology** – Gilbert E. Lewis in a letter to the editor of Nature (Vol. 118, Part 2, December 18, 1926, p. 874-875) ➔ ‘Photon’ = ‘carrier of radiant energy’

II. Photonics applications


Generate Light

Detect Light

Amplify Light

Manipulate Light

Get Light from A to B

Utilize Light for the Benefit of Mankind

Photonics is a key engineering discipline

Photonics comprises the

- **generation**
- **amplification**
- **transmission**
- **modulation**
- **detection**

of light

Lighting
(LEDs, displays)

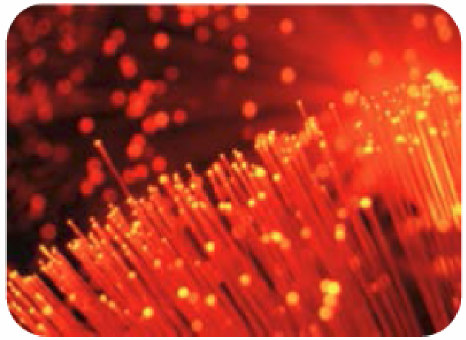
Manufacturing
(high power lasers)

Telecommunication
(fibers, components,
systems)

Medicine
(lasers, microscopes)

Sensor technology
(optical sensors)


LED light bulb


glass fibers

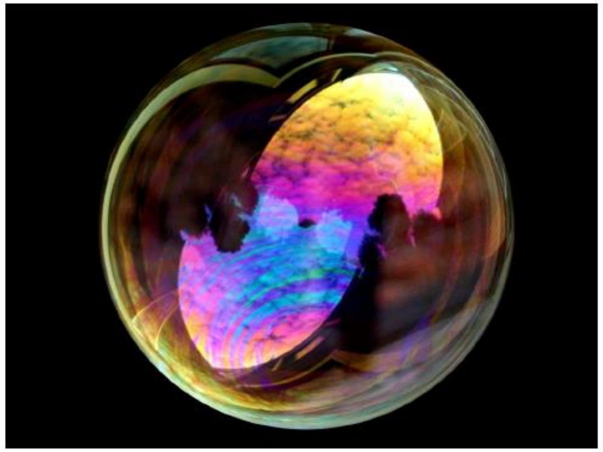
Photonics bears the same relationship to light and photons as electronics does to electricity and electrons.

First definition

Photonics is the science of the harnessing of light. Photonics encompasses the generation of light, the detection of light, the management of light through guidance, manipulation, and amplification, and most importantly, its utilisation for the benefit of mankind

Pierre Aigrain, 1967

Nature = a source of inspiration



- Lighting, displays & PV ➔ photonics for well-being & energy

www.light2015.org

UNESCO

United Nations
Educational, Scientific and
Cultural Organization

International
Year of Light
2015

Was declared

Key enable technology

Photonics is selected as a Key Enabling Technology

- Photonics
- Nanotechnology
- Nano- & micro-electronics
- Industrial biotechnology
- Advanced manufacturing
- Advanced materials

Information and Communication

Manufacturing and Quality

Healthcare and Life Sciences

Lighting and Displays

Cutting Edge Materials and Technologies

Safety and Security

Healthcare

- Early diagnosis through new detection methods
- Minimally invasive surgery

Energy Efficiency

- LEDs, OLEDs and intelligent networks can save 2/3 of electricity for lighting

Safety & Security

- Smart sensors for automotive safety; IR detection systems

Manufacturing

- Lasers enable new lightweight structures
- Laser drilling: 25,000 holes per second for efficient solar cells

Inclusion

- High speed fibre networks with multi-terabit capacity are backbone for web 2.0 & 3.0 products & internet of things

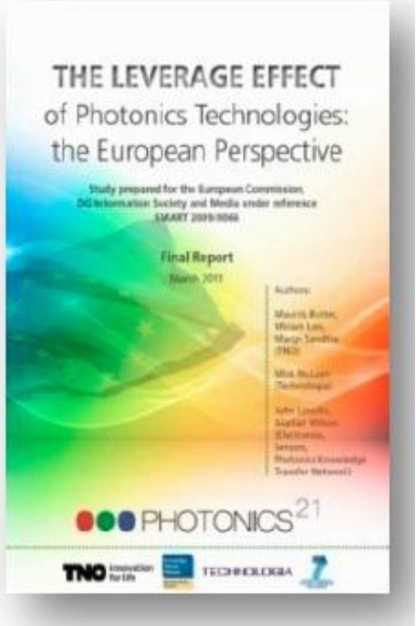


- Total Photonics market € 350 bn (in 2011)
- Average yearly growth rate of 6,5% compared to 2011
- Estimated market size in 2020 ~ € 615 bn
- **European Photonics market ~ € 64 bn**
- **European market share 18%** (in 2011)
- Many market-leading industrial players
- Market shares of European companies

Production technology	55%
Optical components & systems	40%
Measurement & automated vision	35%
Medical technology & life sciences	30%

- **More than 5000 SMEs in Europe**
- **~ 300,000 employees**


High-Level Expert Group on
Key Enabling Technologies
Final Report
EUROPEAN COMMISSION


THE LEVERAGE EFFECT
of Photonics Technologies:
the European Perspective
Final Report
PHOTONICS21
TNO
TECHNOLOGIA

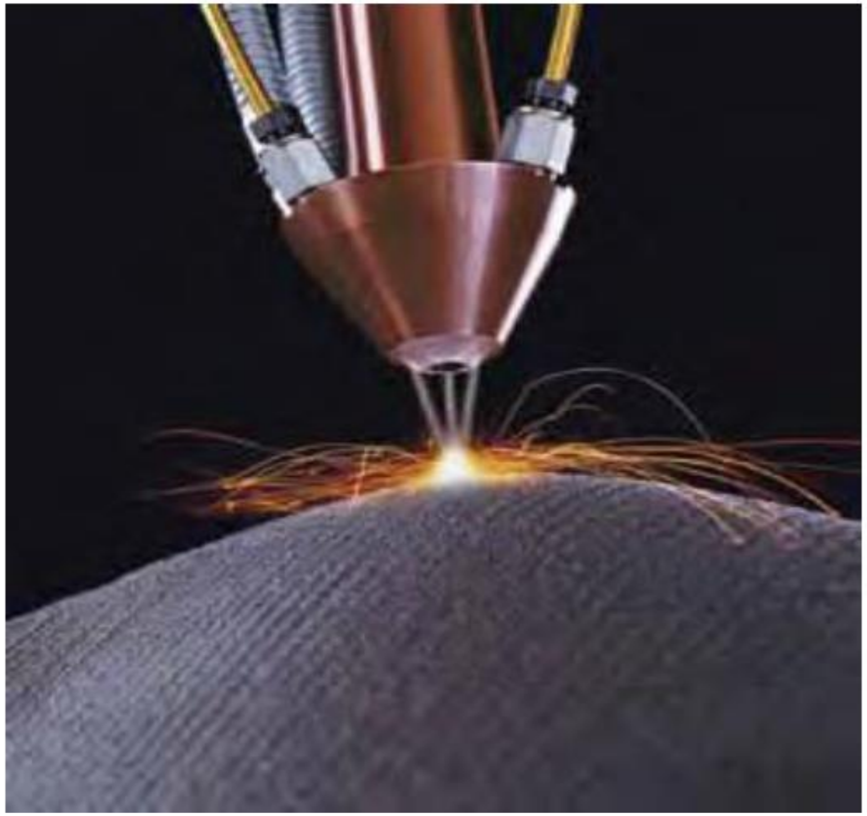

KEY DATA
PHOTONICS
INDUSTRY REPORT 2013

- Self driving cars

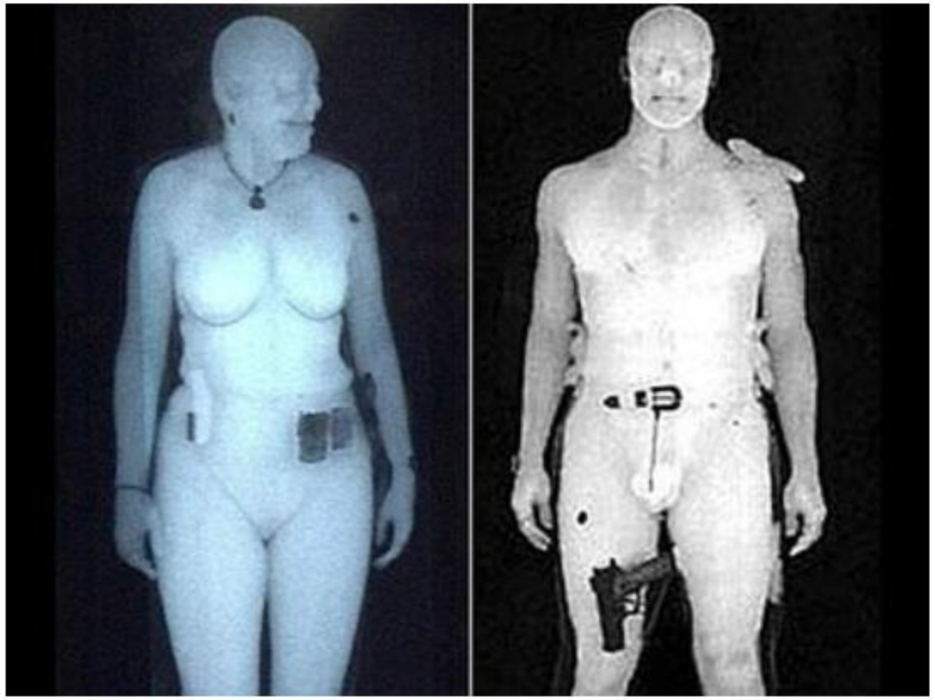
- Precision agriculture

- ICT ➔ photonics enabling all wired and wireless communications

- Industrial manufacturing ➔ laser light tools allow for unprecedented quality



- More secure airports

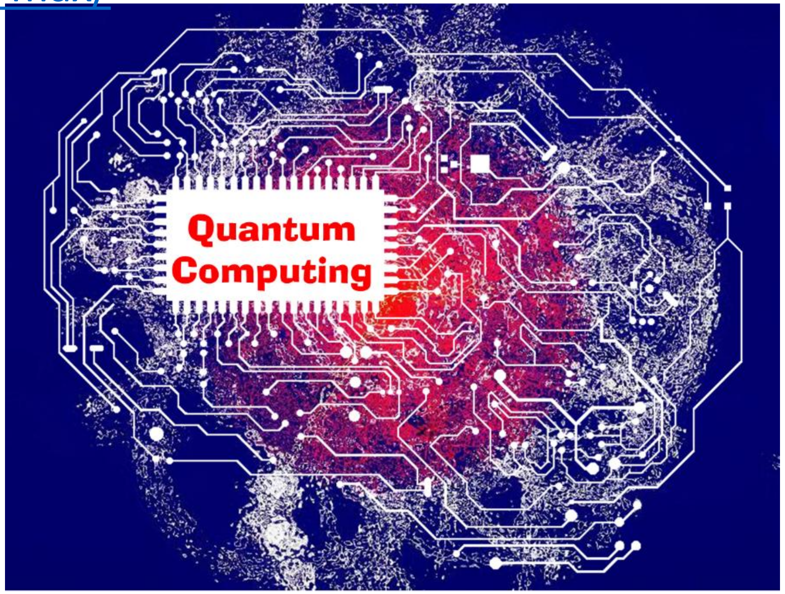


- Better headlights

https://phys.org/news/2019-09-scientists-quantum-milestone.html
https://phys.org/news/2019-09-quantum.html
http://news.mit.edu/2011/quantum-light-0909
https://www.oledcomm.net/lifi-max/

- Faster internet

Light Fidelity (LiFi) Internet Service Provider ...



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TOMRA
SORTING SOLUTIONS
ODENBERG *BEST

ICOS

FBGS
DRAW TOWER GRATINGS

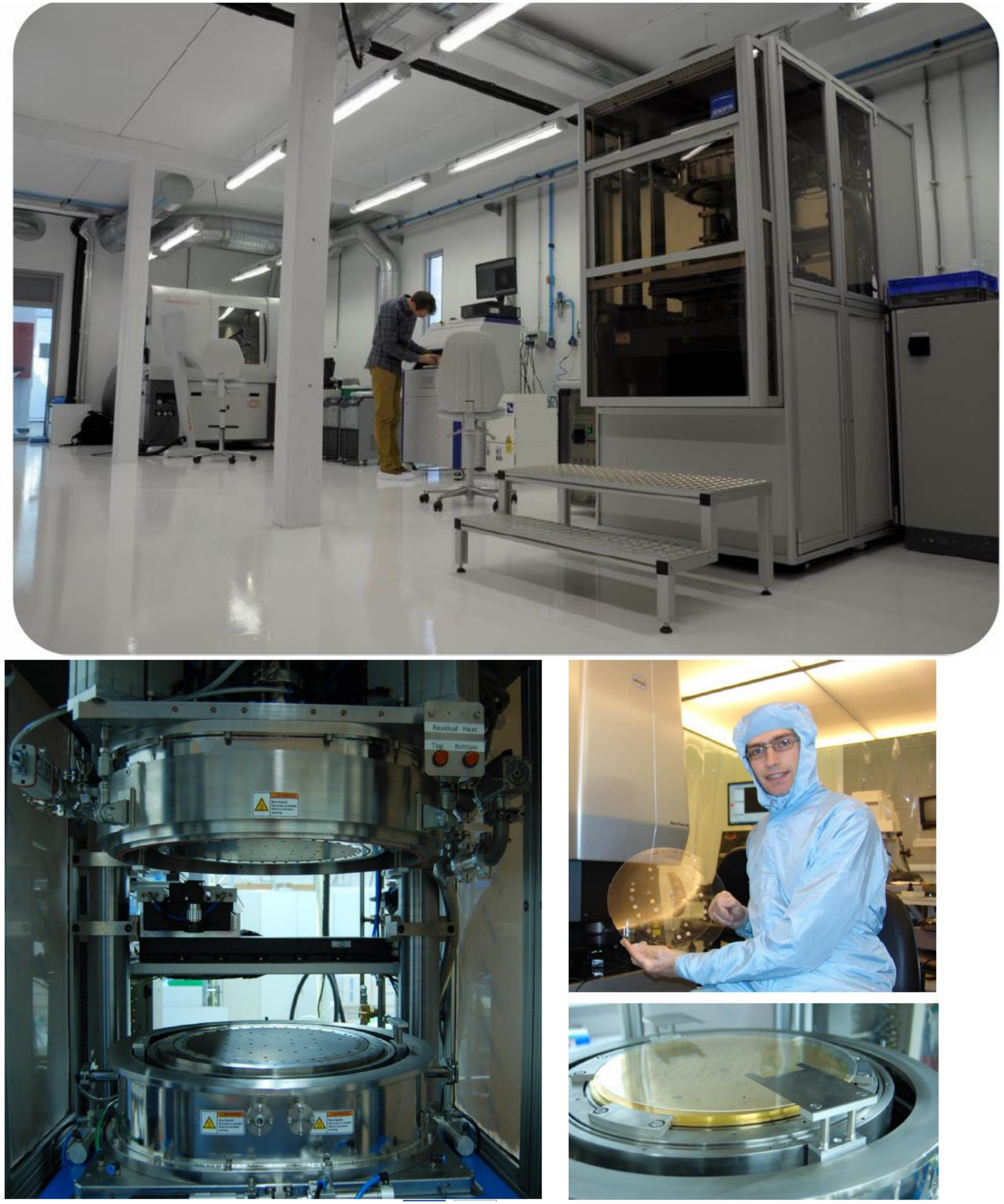
umicore

Melexis
Microelectronic Integrated Systems

PHILIPS
sense and simplicity

PUNCH | graphix

anteryon
LEADERS IN OPTICAL INTERFACE TECHNOLOGY



Infrared nightvision
for safety and security

umicore Autoliv

Optical fiber sensors for
smart structures

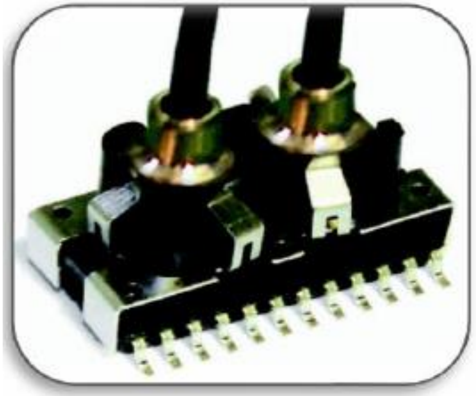
FBGS
DRAW TOWER GRATINGS

3-Dimensional
displays and projectors

BARCO

Freeform micro-optics
for solar energy

umicore



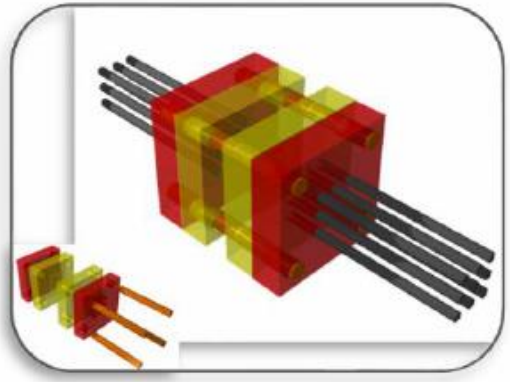
Opto-electronic chips
for automotive

Melexis
Microelectronic Integrated Systems

Optical engines for
food-sorting

TOMRA
SORTING SOLUTIONS

ODENBERG BEST

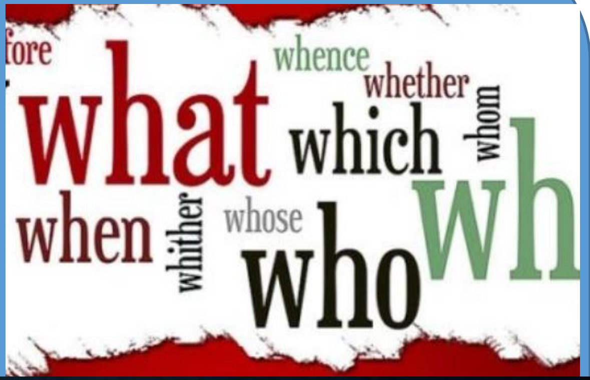


Optical interconnects
for Local Area Networks

COMMSCOPE®

High-efficiency
lighting applications

PHILIPS



Have you ever gotten super lost?
What happened?