Outline of Electromagnetism
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Note: To look up references, see the Consciousness Bibliography, listing 10,000 books and articles, with full journal and author names, available in text and PDF file formats at http://www.outline-of-knowledge.info/Consciousness_Bibliography/index.html.

PHYS>Physics>Electromagnetism

electromagnetism

Electric force is attraction or repulsion between electric charges. Magnetism is moving-charge relativistic effects and so is apparent electric force {electromagnetism}|. If electric fields cancel, because positive and electric charges are equal, magnetic fields do not necessarily cancel, because both positive and electric charges can move relativistically.

PHYS>Physics>Electromagnetism>Charge

charge of electricity

Particle properties {charge, electricity}| can cause electric force. Electron charge {negative charge} is one negative unit. Proton charge {positive charge} is one positive unit. Total electric charge is sum of particle electric charges.

static electricity

Rubbing glass with cloth keeps protons on glass and puts electrons on cloth. Rubbing rubber with cloth puts electrons on rubber and keeps protons on cloth. Rubbing energy frees electrons from rubbed material surface. Quickly pulling the materials apart leaves net charge on both materials. Sliding on rugs rubs electrons off rug, and touching metal doorknobs makes electrons jump to metal.

static electricity: lightning

High winds, when hot air rises, rub higher cold air, separate electrons from air molecules, and take electrons away before they can recombine. Lightning carries electrons back to positive-charge regions or to ground.

strong nuclear force

Only strong nuclear force can change particle electric charge.

charge coupling

Surface voltages can move charges around semiconductors {charge coupling}|. Semiconductors have capacitance. Charge moves between capacitors at each clock pulse. Solid-state TV cameras and memory circuits use charge coupling. Semiconductors {charge coupled device} (CCD) can move free electric charges from one storage element to another, by externally changing voltage. Charge can vary by varying voltage and capacitance. Image sensors and computer memories use CCDs.

charge induction

Electric forces on materials can pull electrons in one direction and protons in opposite direction {induction, charge} {charge induction}|.

dielectric

Conductors have free charges, so charges move to counter outside electric force, with no net charge. Dielectrics have no free charges, so induction pulls electrons and protons apart to make induced charge and dipoles.

factors

If electric field is more, electric force is more, and system has more dipoles. If atoms are small, smaller mass moves easier, and system has more dipoles.

factors: temperature

In polar materials, if temperature is lower, material has fewer random motions, and material has more dipoles. In non-polar materials, temperature has little effect.

factors: frequency

If electric-field frequency is more than 10^10 Hz, dipole moments cancel, because dipole moments change slower than field changes. If electric-field frequency is above 10^11 Hz, bending and stretching dipole moments cancel, because vibrations are slower than frequency, and only electrons affect polarization.

examples

Sifting sugar or streaming water through electric fields illustrates charge induction.

dipole

Outside electric force on dielectrics can pull electrons one way and protons opposite way, to separate charges {dipole}|. Negative charges are at one end, and positive charges are at other end, along outside-electric-field direction.

electroscope

Instruments {electroscope}| can detect static electricity.

St. Elmo's fire

Friction can cause glow {St. Elmo's fire}| around objects in storms.

static electricity

Objects can have stationary extra surface charges {static electricity}|. Electric charge is on material surface, because electrons repel each other to farthest points. More charges are at higher-curvature surface points, because repulsions are less where average distances are more. Sparks, van de Graaf generators, pith balls, cloths and rods, and electroscopes demonstrate static electricity.

valence of ion

Ions can have charge {valence, ion}, of -7 to +7.

PHYS>Physics>Electromagnetism>Force

Coulomb law

Electric force depends on charge and distance {Coulomb's law} {Coulomb law}. Electric force F between two charges varies directly with charge q and varies inversely with square of distance r between charges: F = k * q1 * q2 / r^2 = (1 / (4 * pi * e)) * q1 * q2 / r^2.

permittivity

Electric-force constant k depends on medium electric permittivity e: k = 1 / (4 * pi * e).

distance

Force varies with distance squared, because space is isotropic in all directions, time has no effect, and field-line number stays constant as surface area increases. Sphere surface area = 4 * pi * r^2.

charge

Force depends on both charges, because force is interaction. Electric force depends on charge linearly, because charge directly causes force. Because charges can be positive or negative, electric force can be attractive positive or repulsive negative. If both charges are positive or negative, electric force is positive. If one charge is positive and one charge is negative, electric force is negative.

comparison

Electric force is very strong compared to gravity. Gravitational force and electric force equations are similar, because interactions cause both forces and both forces radiate in all directions.

voltage

dW = F * ds = q * dV. F = q * dV / ds = q * E.

d'Alembert equation

In potential equations {d'Alembert equation, electromagnetism} for electric and magnetic fields, source-charge density and three current-density components make four potentials for each field.

Faraday law of induction

For stationary magnet and moving wire in a circuit, electric force F makes electric current, and force varies directly with magnetic-flux (phi, depending on magnetic field B and surface area A) change over time {Faraday law of induction} {Faraday's law of induction}: F ~ d(phi)/dt, and phi = sum over A of B. Induced electric current makes magnetic field opposed to stationary magnetic field. For moving magnet and stationary wire, electric field E makes electric current in wire, and electromotive force on charges varies directly with magnetic-flux change over time. Faraday law of induction applies to both Maxwell-Faraday equation, for changing magnetic field and stationary charge, and Lorentz force law, for stationary magnet and moving wire in a circuit.

fine-structure constant

A constant {fine-structure constant} {coupling constant} measures electromagnetism force strength (Sommerfield) [1916]. It has no dimensions. It equals 7.297 * 10^-3 ~ 1/137. The fine-structure constant depends on electron charge, Planck constant, light speed, and permittivity or permeability or Coulomb constant. The coupling constant measures photon-electron force.

Maxwell-Faraday equation

For changing magnetic field and stationary charge, changing magnetic field B makes electric field E {Maxwell-Faraday equation} {Faraday's law}: curl of E = partial derivative over time of B. This has an integral form {Kelvin-Stokes theorem}: line integral of E = integral over surface area of partial derivative of B with time.

Lorentz force law

For stationary magnet and moving wire in a circuit, Lorentz force F on charges makes electric current and electric force varies directly with electric charge q and with wire velocity v and magnetic field B cross product {Lorentz force law}: F ~ q * (v x B). Induced electric current makes magnetic field opposed to stationary magnetic field.

Gauss law

Flux equals integral of electric field E over area A, which equals sum of charges q divided by electric permittivity e {Gauss' law} {Gauss law}: integral of E * dA = (sum of q) / e. Gauss' law can find electric field and voltage.

Gauss law of magnetism

Divergence of magnetic field B equals zero {Gauss law of magnetism} {Gauss's law of magnetism} {transversality requirement} {absence of free magnetic poles}: divergence of B = 0, or line integral over a surface of B = 0. Magnetic fields are solenoids. Magnetic "charges" are dipoles, and there are no magnetic monopoles.

PHYS>Physics>Electromagnetism>Force>Lines

lines of force

Electric fields are like force lines {force lines} {lines of force}| radiating from center outward in all directions. Force lines per area equal electric field. Force lines have direction, from positive to negative, because test charges are positive. Force lines entering closed surfaces are negative. Force lines leaving closed surfaces are positive. For large charged objects, electric-field lines are perpendicular to surfaces, because force lines are symmetric around surface perpendiculars.

flux of field

Electric-force lines pass through areas in directions {flux, electric} {electric flux}. Positive and negative fluxes from different sources add together. Does infinite flux exist? Perhaps, field lines cannot come closer than Planck length. Then flux has maximum density, and field has no infinities.

PHYS>Physics>Electromagnetism>Energy

electric energy

For electricity, energy W {electric energy}| is charge q times voltage V: W = q*V. Electric energy is in joules: W = F*s = (k * q * Q / s^2) * s = q * (k * Q / s) = q * (E / s) = q*V, where F is electric force, k is electric-force constant, Q is charge, E is electric field, and s is distance.

electric field

Electric charge causes potential energy {electric field}| that radiates in all directions. Electric fields can cancel each other, because charges can be positive or negative.

potential

Electric charges q Q make electric force F, which decreases with distance r squared: F = k * q * Q / r^2, where k is electric force constant. Electric-field strength intensity H changes with distance r from charge Q: H = F/q = k * Q / r^2, where k is electric-force constant. Electric field depends on material electric permittivity.

Different distances have different potential energies. Charge can move between two electric-field points, causing potential-energy-change potential difference. Electric-field energy change E is potential difference V times charge q: E = F*s = (k * q * Q / s^2) * s = q * (k * Q / s) = q*V. Potential-energy difference is work done by electric force as charge moves through distance.

examples: surface

Potential is equal all over large charged-object surfaces. Otherwise, electrons flow to lowest-potential location to equalize potential.

examples: plate

Electric field H above charged plates equals charge q divided by electric permittivity k: H = q/k.

examples: rod

Electric field H above long rods varies as reciprocal of distance d from rod: H = C * (1/d).

examples: point

Electric field H around point charges or spheres varies as reciprocal of square of distance r from center: H = k * Q / r^2.

examples: dipole

Electric field H around dipole varies as reciprocal of cube of distance d from dipole center: H = C * (1 / d^3).

electric power

For electricity, power P {electric power}| is current I times voltage V: P = dE / dt = V * dq / dt = V*I.

piezoelectricity

Pressure on crystals can cause voltage {piezoelectricity}|. Pressure polarizes crystals, such as quartz, mica, or lead zirconate titanate (PZT). Pressure changes polarized-material charge separation to make voltage. In reverse, applying electric field contracts crystals in field direction.

voltage

Tendency for charges to flow depends on electric energy per charge {voltage}| {potential difference}. Higher potential is positive and attracts negative charge. If two points have potential difference and path exists, charge flows from one point to the other.

energy

Because field is electric force F divided by charge q, voltage V is electric field H times distance ds moved in field direction: V = H * ds = (F/q) * ds = (F * ds) / q = W/q, where W is electric energy. Voltage is electric energy divided by charge.

field

Separating charges using work creates electric field, with voltage between charges. Batteries separate charges to create voltage. Electromagnetic induction creates voltage by separating charges. Voltage V equals area A times negative of field change dH divided by time change dt: V = A * -dH / dt. Voltage V equals negative of inductance I times current change di divided by time change dt: V = -I * di / dt.

wakefield

Electric fields {wakefield} can pulse and so force electrons to accelerate.

PHYS>Physics>Electromagnetism>Conductivity

resistance of electricity

Moving-electron and stationary-molecule interactions oppose electric current flow {resistance}| and turn electric energy into heat. Electrical resistance depends on path length, cross-sectional area, and material resistivity.

voltage

Resistance makes heat from electrical kinetic energy and, as potential energy decreases, drops potential across resistor.

current

For same voltage, more resistance makes less current, because flow slows.

factors

Resistance is more for poor conductors with few electrons that can move, for longer conductor length, or for less cross-sectional area. If cross-sectional area is more, conductor perimeter is more, fewer electron collisions happen, and resistance is less. If conductor length is more, distance is longer, and total resistance is more. If material resistivity is more, conductor has fewer free charges, and resistance is more.

factors: temperature

In conductors at higher temperature, resistance is more, because random motions are more. In insulators or semiconductors at higher temperature, resistance is less, because more electrons are free to move. Alloys have smaller resistance change when temperature changes, because alloys have fewer free electrons than pure metals.

resistor

Electrical devices {resistor} can have resistance. Conductor resistance R equals material resistivity r, which differs at different temperatures, times conductor length l divided by conductor cross-sectional area A: R = r * l / A.

resistivity

Resistivity is 10^-6 to 10^-1 ohm-cm for conductors, 10^-1 to 10^8 ohm-cm for semiconductors, and 10^8 to 10^21 ohm-cm for insulators.

examples

Resistance in incandescent light bulbs creates light. Resistance in electric heaters creates heat. Fuses, circuit breakers, voltmeters, ammeters, tube resistors, rod resistors, and coil resistors demonstrate electrical resistance. Lie detectors detect skin electrical resistance, which varies with sweat amount.

conductance

Resistance reciprocal {conductance}| measures current-flow ease.

Wiedemann and Franz

At same temperature, electrical-conductivity to heat-conductivity ratio is the same for all metals {law of Wiedemann and Franz} {Wiedemann and Franz law}.

PHYS>Physics>Electromagnetism>Conductivity>Conductor

conductor

Materials {conductor}|, such as metals, can allow electrons to move almost freely.

dipoles

Because electrons are free to move, no dipoles form. Conductor dielectric strength is zero, and dielectric constant is infinite, because charges can move freely. Rubbing metal with cloth cannot rub off charges, because electrons move freely and quickly in conductors.

spark

If charge touches conductors, electrons flow to neutralize charge, typically making sparks.

spread

Potential difference between conductor points is zero, because all electrons already repel each other equally. No electrons flow.

compression

Compressing metal increases conductivity, because crystals have fewer imperfections.

conduction of electricity

Materials can allow electrons to move almost freely {conduction, electricity}|. Semiconductors allow electrons to move with high resistance. Insulators do not conduct electricity. Circuit loads are either conductors or semiconductors.

charge mobility

Electric force causes average drift velocity per unit force {mobility, charge} {charge mobility, conductor}|.

free electron

Metallic bonds are electron deficient and leave electrons free {free electron}. Metal has electrons that can move among atoms around metal surface. Outside electric force can pull electrons completely away from atoms.

mean free time

In conductors, moving electrons have average time between collisions {mean free time}| and have average distance, mean free path, between collisions. Collisions tend to reduce charge velocities.

Ohm law

In conductors, voltage V equals resistance R times current I {Ohm's law} {Ohm law}: V = R*I.

PHYS>Physics>Electromagnetism>Conductivity>Insulator

insulator

Most materials {insulator}| {dielectric} allow no free electron movement. Air, vacuum, paper, and glass are insulators.

dipoles

Outside electric field separates electrons and protons, to make induced charge. Inducing charge can be easy or hard. Dielectric strength is ratio between material capacitance and vacuum capacitance. For vacuum, dielectric constant is 1. For insulators, dielectric constant is 1 to 8. For water, dielectric constant is 81, because water has high polarization and free dipole rotation. For conductors, dielectric constant is infinite. Lustrous metals have negative dielectric constant.

permittivity

Materials have ease by which electric fields can go through {permittivity}|. Metals have free electrons and cannot have electric fields inside. Insulators have charges that move relative to electric field and oppose electric field. Empty space has no charges and allows electric field. Electric-force constant k inversely depends on permittivity.

polarizability

Insulators have different abilities to make dipoles {polarizability}| {polarization, electricity}. If polarization is more, refraction index is more. Polarization K is refractive index n squared: K = n^2. Metal has free electrons and cannot make dipoles. Empty space has no charges and cannot make dipoles.

PHYS>Physics>Electromagnetism>Conductivity>Semiconductor

semiconductor

Materials {semiconductor}| can have electrons that can move from atom to atom in atomic-orbital conducting bands. Silicon and germanium are semiconductors. Semiconductor compounds include indium gallium arsenide and indium antimonide.

impurities

Semiconductors can be silicon with added gallium {P-type semiconductor} or arsenic {N-type semiconductor}. P-type semiconductors transfer electron vacancies. N-type semiconductors transfer electrons. Holes and electrons must move in opposite directions to complete circuit.

electric charge

If charge touches semiconductor, no change happens, because semiconductor electrons are not free to move.

doping of semiconductor

Impurities {doping}| added to silicon or germanium supply more negative or positive charges, to make more conduction.

donor

Adding material with five electrons in highest orbital {donor impurity} adds extra electron. Antimony, arsenic, and phosphorus are donors {n-type semiconductor}.

acceptor

Adding material that has three electrons in highest orbital {acceptor impurity} results in extra proton {electron deficiency}. Gallium, indium, aluminum, and boron are acceptors {p-type semiconductor}.

junction

If p-type semiconductor touches n-type semiconductor, electrons in n-type semiconductor flow into holes in p-type semiconductor until reaching balance, with voltage across junction. p-type semiconductor has become slightly negative. n-type semiconductor has become slightly positive. No more free charges exist. Junction width is 50 atoms.

diode

If voltage across np junction makes p side positive, current flows greatly, because p side attracts electrons. If voltage across np junction makes p side negative, no current flows, because p side repels electrons. np junctions allow current in only one direction and allow current to be ON or zero OFF, like diodes.

electroluminescence

Semiconductors can emit light {electroluminescence}| across pn junctions when current flows. Phosphors can glow if AC current passes through. Machine sprays glass panel with thin transparent metal layer, adds a phosphor layer, and adds thin metal foil. Electroluminescence is efficient and cool but allows only low light levels.

exciton

One electron and one hole {exciton} can bind electrostatically for 4 to 40 microseconds, 1150 nanometers apart. Electric forces cause free electrons and holes to drift in opposite directions, at same velocity. Electric force causes average drift velocity per unit force {charge mobility, exciton}. When electron meets hole, they merge. At constant force, ejections and recombinations are in equilibrium.

fractional quantum Hall effect

A thin layer of electrons is between two semiconductors. Near 0 K in high magnetic field [1982], pairs {quasiparticle, pair} of excited superposition of electron states have fractional charges {fractional quantum Hall effect}, with edge effects {edge state}. Fractional quantum Hall effect can extend to four dimensions, as on five-dimensional-sphere surfaces, which have three-dimensional edge states that emerge with relativity. Excitations can carry magnetic-flux units.

hole in semiconductor

Adding electron-deficient materials, with three electrons in highest orbital, results in extra protons, because of electron vacancies {hole}|.

Josephson junction

Two semiconductors can have insulator between them {Josephson junction}. Microwaves can supply energy to electron pairs. Voltage V is n = 1/2, 1, 3/3, or 2 times Planck's constant h times frequency f divided by electron charge e: V = (n*h*f) / (2*e). Third semiconductor can supply control current. Control current sets voltage at zero or one, using quantum-mechanical tunneling.

junction of semiconductors

Two semiconductors, or semiconductor and conductor, can meet in region {junction}| 50 molecules thick. Contact point between metal and semiconductor has resistance that does not follow Ohm's law, because current depends on surface properties.

metal oxide semiconductor

Semiconductors {metal oxide semiconductor} (MOS) can be metal oxides, which can be unipolar, rather than just bipolar.

PHYS>Physics>Electromagnetism>Conductivity>Semiconductor>Transistor

transistor

Solid-state semiconductor circuit elements {transistor, electronic}| amplify current.

types

N-type semiconductor, P-type semiconductor, and N-type semiconductor can join in sandwich {NPN transistor}. P-type semiconductor, N-type semiconductor, and P-type semiconductor can join in sandwich {PNP transistor}. NPN or PNP transistors are bipolar transistors {junction transistor}, with two junctions. Weak signals control current flow. Junction transistors are current operated.

parts

Transistors have cathode emitter, anode collector, and base controller. Collector is between emitter and base. In PNP transistors, electrons flow from emitter to middle collector and from base to middle. In NPN transistors, electrons flow from middle collector to emitter and from middle to base.

process

Holes and electron diffusion across semiconductor np junction continues until electric force equilibrium, preventing further diffusing. Voltage is across emitter and base and across collector and emitter. Applying small positive charge to base attracts electrons and amplifies current 10^5 times. Electron flow from emitter to collector multiplies directly with voltage from base to emitter.

surface barrier

A depletion layer {space charge, transistor} between metal and semiconductor can control conductivity {point contact semiconductor} {surface barrier transistor}.

field effect

Electric field at right angles to silicon surface causes lateral conductance {field-effect transistor}. Insulated field plate can have field that induces conducting surface channel between two surface pn junctions {gate}, as in field-effect transistors, such as metal oxide semiconductors. Field-effect transistors have slow response and high impedance. They are voltage operated, rather than current operated.

electron tubes

Transistors can replace all electron tube types.

base of transistor

In PNP transistors, electrons flow from emitter to collector, and from other sandwich side {base, transistor} to middle.

collector of transistor

In PNP transistors, electrons flow from emitter to middle {collector, transistor}, and from base to middle.

emitter of transistor

In PNP transistors, electrons flow from one sandwich side {emitter, transistor} to collector, and from base to middle.

PHYS>Physics>Electromagnetism>Conductivity>Superconductivity

superconductivity

At low temperatures, substances can be electrical conductors {superconductor} with no electrical resistance {superconductivity}|. Liquid oxygen, liquid nitrogen, and liquid hydrogen are superconductors. Organic crystals, metal oxides, and insulators can have superconductivity.

high temperature

Most high-temperature superconductors are copper oxide {cuprate} layers between other layers. Mercury-barium-calcium copper oxide superconducts at 164 K under 10,000 atm pressure and at 138 K at 1 atm.

Iron and arsenic layers between a lanthanum, cerium, samarium, neodymium, or praseodymium layer and an oxygen or fluoride layer can superconduct up to 52 K. Magnesium boride superconducts at 39 K. Bismuth, strontium, calcium, copper, and oxygen atoms can combine to make BSCCO high-temperature superconductor. Yttrium, barium, copper, and oxygen atoms can combine to make YBCO high-temperature superconductor.

cause

Large-scale quantum effects cause superconductivity, which happens when energies are small, such as at low temperature. Bosons in same quantum state can condense {Bose-Einstein condensation, superconductivity} (BEC) from gas to liquid. Repulsive bosons condense better. Materials can Bose-Einstein-condense at cold temperatures.

Fermions, such as electrons, form Cooper pairs at temperature lower than temperature at which material becomes degenerate Fermi gas. Both electrons have same spin. Making electron pairs makes positive metal ions. Cooper pairs have streamline flow through metal ions and travel with no resistance.

Fermions can pair more easily if attraction increases. Electrons can resonate {Feshbach resonance} in magnetic fields {magnetic resonance} and so pair better.

Magnetic flux has quanta in superconductors. Electric field has no quanta but quantizing it can make calculations easier.

magnetic field

Outside magnetic field can enter only short distance into superconductors with current, because photons acquire mass as electromagnetic gauge symmetry breaks spontaneously.

insulator

Forcing atoms {Mott insulator} in Bose-Einstein condensates to have definite positions changes quantum properties.

BCS theory

In superconducting materials, electrons distort positive-ion lattice to make phonons, which interact with other electrons, causing attraction and electron pairing {BCS theory}. Critical temperature is higher if more electrons can go to superconductive state, if lattice-vibration frequencies are higher, and if electrons and lattice interact stronger. Mercury-barium-calcium copper oxide does not follow BCS theory. Magnesium boride follows BCS theory. Liquid oxygen, liquid nitrogen, and liquid hydrogen follow BCS theory.

Cooper pair

Fermions can pair {Cooper pair} at temperatures much lower than temperature at which system is degenerate Fermi gas.

degenerate Fermi gas

Systems {degenerate Fermi gas} can have one fermion in each low-energy quantum state.

transition edge sensor

Devices {transition edge sensor} can detect photons at transition temperature to superconductivity.

PHYS>Physics>Electromagnetism>Current

current of electricity

Electric charges can flow past a point over time {current, electricity}| {electric current}. Flowing charge has one-tenth light speed.

current density

Current I per area A {current density}| equals conductivity K times electric field E: I/A = K*E. Current I equals current density j times cross-sectional area A: I = (I/A) * A = j*A.

skin effect

Current tends to stay on conducting-material surface {skin effect}, because electrons repel each other.

PHYS>Physics>Electromagnetism>Current>Kinds

alternating current

Charge flow can alternate directions over time {alternating current}| (AC). Alternating voltages cause electrons to oscillate. Commercial alternating current oscillates at 60 Hz in USA and 50 Hz in most other countries.

comparison

Direct current has less power loss and more average power than alternating current.

voltage

In alternating-current circuits, average or effective voltage equals maximum voltage divided by square root of two. In alternating-current circuits, average or effective current equals maximum current divided by square root of two.

transformer

Transformers change alternating-current voltage.

direct current

Charge flow can be in one direction only {direct current}| (DC). Direct current has less power loss and more average power than alternating current. Adding voltage sources alters direct-current voltage.

PHYS>Physics>Electromagnetism>Circuit

circuit

Charges must flow from source around loop back to source {circuit, electricity}| {electric circuit, flow}. At circuit points, current that goes in must equal current that comes out. Voltages around circuit loops must add to zero. Otherwise, electron density increases somewhere in circuit.

ground for electricity

Earth {ground, electricity}|, or conductor leading to Earth, is an electron sink. Earth has many molecules and can absorb or give any number of charges without changing potential.

Kirchoff laws

Circuit current and voltage follow laws {Kirchoff's laws} {Kirchoff laws}. Kirchoff's laws apply to circuit steady state. Transiently, Kirchoff's laws can break.

At circuit points, current coming in equals current going out. If current flowing in did not equal current flowing out, charge builds or falls at point and repels or attracts incoming charges, to make net charge return to zero.

Around circuit loops, voltages add to zero. If voltages around loop do not add to zero, extra voltage sends more charges to low-voltage point and so makes sum of voltages become zero again.

modulation of wave

Wave-front amplitude or phase modifications {modulation, electricity}| can carry information on carrier waves. Information can vary amplitude {amplitude modulation, circuit} (AM) or frequency {frequency modulation, circuit} (FM). Frequency modulation carries temporal information along propagation line. Amplitude modulation carries spatial information perpendicular to propagation line.

short circuit

Circuits {short circuit}| can have almost no resistance, allowing very high current.

PHYS>Physics>Electromagnetism>Circuit>Impedance

impedance

RC, RL, and RLC circuits have reactance and resistance vector sum {impedance}|. Voltage equals impedance times current. Maximum power has equal source and circuit impedances.

reactance

Inductance and capacitance {reactance}| aid or impede current flow by storing and releasing energy, without heat loss.

comparison

Resistance opposes current and has heat loss.

phase

Reactance causes lag between voltage and current. In inductors, high frequency makes big current change and so large voltage. High inductance makes current changes make big voltage changes. Inductive reactance R equals two times pi times frequency f times inductance L: R = 2 * pi * f * L. In capacitors, high frequency makes voltage stay low, because little charge can build up. High capacitance requires large charge to make voltage, so voltage stays low. Capacitive reactance R equals reciprocal of two times pi times frequency f times capacitance C: R = 1 / (2 * pi * f * C).

capacitance electric

Electrical devices {capacitor} {capacitance}| can store electrical energy. Electric-energy storage ability C is charge Q divided by voltage V: C = Q / V. Capacitance C equals material dielectric strength d times length l divided by cross-sectional area A: C = d * l / A.

field

In capacitors, electric field stores energy E: E = 0.5 * Q * V = 0.5 * C * V^2.

current

Electric-field energy builds as current flows. Electric-field energy tends to push current out. Current I is capacitance C times voltage change dV over time change dt: I = (1 / C) * dV / dt. Current and voltage are out of phase.

parallel plates

In parallel-plate capacitors, capacitance C equals electric permittivity e times dielectric constant k times cross-sectional area A divided by distance d between plates: C = e * k * A / d. Electric field between plates is constant and perpendicular to plates. If plates are farther apart, charge separation is more, voltage is more, and capacitance is less. If plate area is larger, charges spread out more, voltage is less, and capacitance is more. If dielectric constant is greater, material between plates has more polarization, field is less, voltage is less, and capacitance is more.

examples

Disk capacitors and rod capacitors work like parallel-plate capacitors. Two aluminum pie plates can make capacitor. Leyden jars can store charge as capacitance. Electrolytic capacitors allow only one-way current.

inductance in magnetism

Circuits with current can store magnetic energy {inductance}|. Circuit devices {inductor} can store magnetic energy. Inductors are wire coils, so current makes strong magnetic field down coil middle. Soft iron bar can be in middle.

energy

Energy stored depends on current change compared to voltage. Inductance L is voltage V divided by current change dI with time change dt: $L = V / (dI/dt)$. $V = L * dI/dt$. Magnetic-field energy builds as current flows. Magnetic-field energy tends to push current to stop. Current and voltage are out of phase. Magnetic-field energy E equals half inductance L times current I squared: $E = 0.5 * L * I^2$.

factors

Inductance increases as coil area increases, current-change frequency decreases, space magnetic-permeability increases, current decreases, voltage increases, coil-turn number decreases, and inductor length increases.

mutual inductance

Two coils with current have mutual inductance.

PHYS>Physics>Electromagnetism>Circuit>Loads

parallel circuit

Circuit loads can be on separate wires {parallel circuit}|. Loads split currents. Voltages are equal. If circuit voltage sources are on separate wires, currents add, and voltages are equal. For resistances in parallel, resistance reciprocals add to equal total-resistance reciprocal, because cross-sectional area is more. Capacitances in parallel add, because area is more. For inductances in parallel, inductance reciprocals add to equal total-inductance reciprocal, because area is more.

series circuit

Circuit loads can be in same wire {series circuit}|. Currents through loads are equal. Loads split voltages. If circuit voltage sources are in same wire, currents through loads are equal and voltages add. Resistances in series add, because length is longer. For capacitances in series, capacitance reciprocals add to equal total-capacitance reciprocal, because distance is more. Inductances in series add, because length is more.

PHYS>Physics>Electromagnetism>Circuit>Kinds

coupled circuit

Two circuits {coupled circuit} can share impedance, allowing energy transfer.

filter circuit

Circuits {filter circuit} can transmit frequency range, while blocking other frequencies. Filter circuits can remove frequency range, while allowing other frequencies, by differentiating or averaging. Circuits can choose different frequencies {selectivity, filter}. Frequency filtering sharpens edges, because edges have high frequency, and blurs have low frequency.

LC circuit

Circuits {LC circuit} can have inductor and capacitor. Energy flows from inductance magnetic field to capacitance electric field and then from capacitance electric field to inductance magnetic field, at resonance frequency. In resonating circuits, capacitance and inductance reactances are equal, so total reactance equals zero.

RC circuit

Circuits {RC circuit} can have resistor and capacitor. Voltage V depends on time t: $V = Vo * e^{(-t / (R*C))}$. Switching on circuit makes voltage build up in capacitor as field builds. Current lags behind voltage. At voltage alternation frequency, circuit resonates.

RL circuit

Circuits {RL circuit} can have inductance and resistor. Current I depends on time t: $I = Io * e^{(-t * R / L)}$. At switching on, current changes fast, so voltage in coil is high. Then current becomes constant so voltage goes to zero, and current lags behind voltage. At current-alternation frequency, circuit resonates.

PHYS>Physics>Electromagnetism>Circuit>Kinds>Devices

cathode ray tube

Thermionically emitted electrons can travel in beams, under side-electromagnet control, to fluorescent screens, where they excite phosphor crystals to make light {cathode ray tube}|. Cathode ray tubes are in TVs and oscilloscopes.

detector device

Circuit devices {detector} can select one signal from several.

diode

Solid-state semiconductor circuit elements or vacuum tubes {diode}| can allow current to flow in only one direction. Diodes change alternating current to direct current. Tubes can have cathode emitter and anode plate. If plate is positive, emitted electrons flow toward plate. If plate is negative, no emitted electrons flow. For solid state, np junction allows charge to flow only in one direction, from P-type to N-type, with high resistance in other direction.

mixer in circuit

Circuit devices {mixer, signal} {electric circuit, mixer} can combine frequency signals.

oscillator device

Circuit devices {oscillator, circuit}| {electric oscillator} can change voltage waveform to other frequencies and amplitudes.

rectifier

Devices {rectifier}| can change alternating to direct current.

rheostat

Devices {rheostat}| can make variable resistance.

wave shaper

Circuit devices {wave shaper} can change voltage waveform.

PHYS>Physics>Electromagnetism>Circuit>Kinds>Devices>Photocell

photocell

Sunlight electric potential can make electric current in materials {photocell}|.

selenium cell

Shining light onto selenium {selenium cell} increases conductivity, because light increases electric field.

PHYS>Physics>Electromagnetism>Circuit>Kinds>Instruments

ammeter

Instruments {ammeter}| can measure currents.

galvanometer

Instruments {galvanometer}| can measure small currents and current direction.

ohmmeter

Instruments {ohmmeter}| can measure resistance.

potentiometer

Instruments {potentiometer}| can measure voltages at zero current, as ratio to exactly known voltage.

voltmeter

Instruments {voltmeter}| can measure electric potentials.

Wheatstone bridge

Devices {Wheatstone bridge}| can find resistance or capacitance in circuits using ratios. Wheatstone bridges eliminate voltage effects. AC current negates overall flow effects.

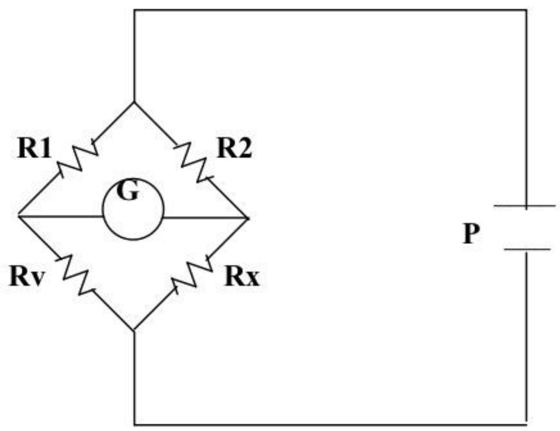
Current from a potential source P splits between two known resistances, R1 and R2, which have a galvanometer G across their endpoints to measure current and voltage (Figure 1). From one endpoint is an adjustable resistance Rv. From the other endpoint is an unknown resistance Rx. The resistances Rv and Rx meet at a point. If the ratio of the adjustable resistance Rv to the first known resistance R1 equals the ratio of the unknown resistance Rx to the second known resistance R2, the galvanometer has zero voltage and current.

For typical resistances, one can set R1 = R2, so Rv = Rx at galvanometer zero current and voltage.

If three resistances are known and one unknown, the measured voltage allows calculating the unknown resistance.

Wheatstone bridges can also find capacitance.

Figure 1
Wheatstone bridge



R1, R2, Rv, and Rx are resistances.
P is potential.
G is galvanometer.

PHYS>Physics>Electromagnetism>Magnetism

magnetism and electric force

Relativistic electric-charge motion can caused electric force {magnetism, force}|. Magnetic fields have no net charge to stationary observers.

special relativity

Atoms and molecules have equal numbers of protons and electrons and so no net electric charge. Protons are in nuclei. Electrons orbit nuclei at 10% light speed. At that speed, motions have relativistic effects, and observers see length contraction. Stationary protons observe moving electrons, and electrons observe moving protons. Length contraction makes charges appear closer together along motion-direction line. Moving-charge density appears higher than stationary-charge density, making net electric force. Electric-charge number does not change, but relative distance decreases.

materials: iron

If electron orbits do not align, relativistic effects have all directions, and net force is zero. If electron orbits align, as in ferromagnetic materials, net force is not zero, and material has magnetism.

materials: conductors

Conductors have fixed protons and easily transferable electrons, with no net charge. Electric current moves electrons in wires at 10% light speed. Relativistic length contraction makes apparent increase in relative electric-charge density and apparent electric force. Current makes magnetism.

non-magnetic materials

People and non-magnetic materials have random molecule orientations and so no net magnetic effects.

no dipoles

Apparent electric charge in magnetism is not induced charge. Magnetism has no dipoles.

strength

At 10% light speed, relative electric-charge density increases by 1%, so magnetism is approximately one-hundredth electric-force strength. Larger currents make stronger magnetic forces. Electric generators and motors use many wires with high currents, to make strong magnetism.

direction

Electric longitudinal force between charges is along line between charge centers. Because it has no net charge, magnetic apparent-electric force cannot be along line between apparent charge centers. Magnetic transverse force is across line between apparent charges, along motion line, because apparent charge density increases only along motion line.

attraction and repulsion

Like electric force, magnetic force depends on interactions between charges. Like electric force, magnetic force can be attractive or repulsive. If apparent moving charges and stationary charges are both positive or both negative, magnetism is repulsive, because charges observe like charges. If apparent moving charges and stationary charges have opposite charge, magnetism is attractive, because charges observe unlike charges.

Wires at Rest with No Current

Charges are equal on both wires, and there is no movement and so no relativistic effects, so net force is zero. See Figure 1.

Wires at Rest and One Wire with Current

Stationary protons on wire with current see stationary protons and stationary electrons on other wire and so see no relativistic effects. Stationary protons on wire with no current see stationary protons and moving electrons on other wire and so see relativistic negative charge, making attractive force. Stationary electrons on wire with no current see stationary protons moving electrons on other wire and so see relativistic negative charge on other wire, making repulsive force. Moving electrons on wire with current see moving protons and moving electrons on other wire and so see relativistic effects, but they cancel. One force is attractive and one is negative, so net force is zero. See Figure 2.

Wires at Rest and Opposite Currents

Protons in both wires see stationary protons and moving electrons in other wire and so see relativistic negative charge on other wire, making attractive force. Electrons in both wires see moving protons and moving-twice-as-fast electrons and so see net relativistic negative charge on other wire, making large repulsive force. Net force is repulsion. See Figure 3.

Wires at Rest and Same Currents

Protons in both wires see stationary protons and moving electrons in other wire and so see relativistic negative charge on other wire, making attractive force. Electrons in both wires see stationary electrons and moving protons in other wire and so see relativistic positive charge on other wire, making attractive force. Net force is attraction. See Figure 4.

Stationary Conductor and Stationary Test Charge

See Figure 5. Stationary conductors, with equal numbers of fixed protons and easily movable electrons, have no net charge. Electric field from protons is equal and opposite to electric field from electrons, so there is no net electric field. Conductor is not moving relative to anything, so there are no relativistic effects. Stationary single negative test charge has electric field but feels no net force from conductor, because conductor has no net charge. Test charge is not moving relative to anything, so there are no relativistic effects. Net force is zero.

Stationary Conductor and Moving Test Charge

See Figure 6. Stationary conductors have no net electric field. Negative charge moves downward at constant velocity. Constantly moving charge has constant concentric magnetic field, which represents magnetic-force direction and strength that it exerts if it observes apparent charges. Test charge feels no net electric force from conductor, because conductor has no net charge. Test charge moves relative to both electrons and protons in conductor, so there is no net relativistic effect. Net force is zero.

Moving Conductor and Stationary Test Charge

See Figure 7. Conductor moves downward at constant velocity. Electric field from protons is equal and opposite to electric field from electrons, so there is no net electric field. Magnetic field from moving protons is equal and opposite to magnetic field from moving electrons, so there is no net magnetic field. Negative charge is stationary. Test charge feels no net electric force from conductor, because conductor has no net charge. Test charge moves relative to both electrons and protons in conductor, so there is no net relativistic effect. Net force is zero.

Moving Conductor and Moving Test Charge

See Figure 8. Conductor moves downward at constant velocity. Net electric and magnetic fields are zero. Negative charge moves downward at constant velocity. Test charge feels no net electric force from conductor, because conductor has no net charge. Test charge is not moving relative to either electrons or protons in conductor, so there are no relativistic effects. Net force is zero.

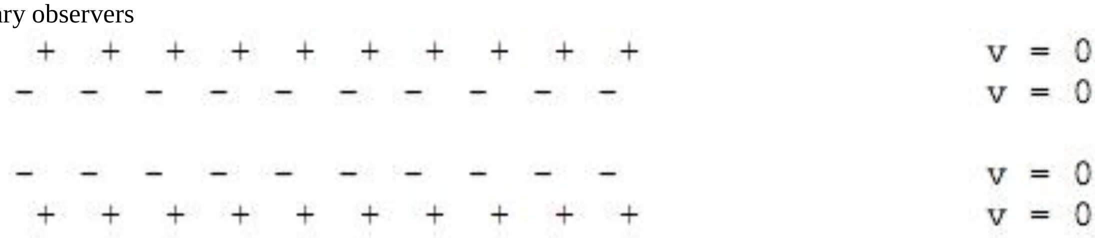
Moving Electrons in Stationary Conductor and Stationary Test Charge

See Figure 9. Conductor electrons move downward at constant velocity. Electric field from protons is equal and opposite to electric field from electrons, so there is no net electric field. Moving electrons make magnetic field. Negative charge is stationary. Test charge feels no net electric force from conductor, because conductor has no net charge. Test charge is not moving relative to protons in conductor, so there is no relativistic effect. Test charge moves relative to electrons in conductor and sees relativistic negative charge, making repulsive force.

Moving Electrons in Stationary Conductor and Moving Test Charge

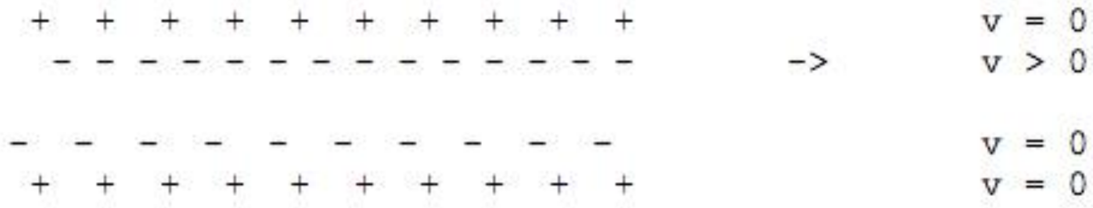
See Figure 10. Conductor electrons move downward at constant velocity. Electric field from protons is equal and opposite to electric field from electrons, so there is no net electric field. Moving electrons make magnetic field. Negative charge moves downward at constant velocity. Test charge feels no net electric force from conductor, because conductor has no net charge. Test charge is not moving relative to electrons in conductor, so there is no relativistic effect. Test charge moves relative to protons in conductor and so sees relativistic positive charge, making attractive force.

Figure 1
Wires at rest and current = 0.
Stationary observers

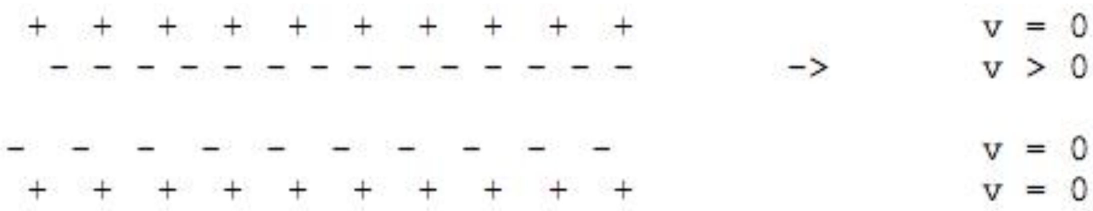


Both wires have equal charges, so no net charge or force occurs.

Figure 2
Wires at rest and one current > 0.
Stationary proton observers and electron observer

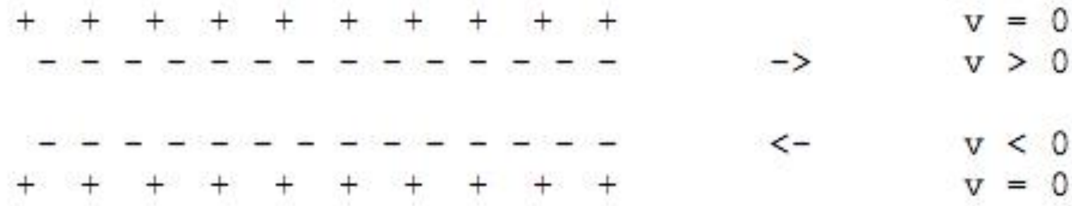


Stationary proton observers on wire with current see no net charge on the other wire.
Stationary proton observers on the wire with no current see relativistic net negative charge on the other wire.
Stationary electron observers on the wire with no current see relativistic net negative charge on the other wire.
Moving electron observer

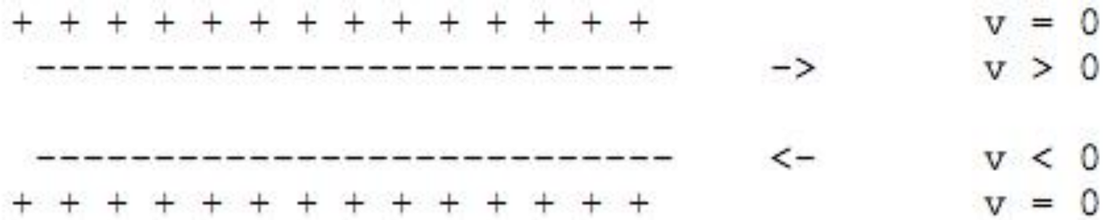


Moving electron observers on the wire with current see no net charge on the other wire.
The two forces cancel, so net force is zero.

Figure 3
Wires at rest and opposite currents.
Stationary proton observers

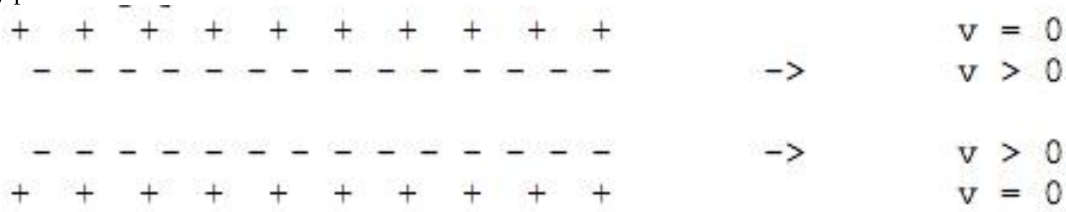


Protons in each wire see a smaller relativistic net negative charge on the other wire, so small attraction.
Moving electron observers, in opposite directions

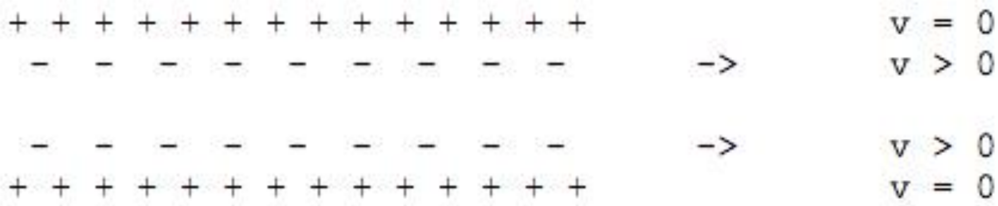


Electrons in each wire see a greater relativistic net negative charge on the other wire, so large repulsion.
Net force is repulsion.

Figure 4
Wires at rest and same currents.
Stationary proton observers



Protons in each wire see a relativistic net negative charge on the other wire.
Moving electron observers, in same direction



Electrons in each wire see a relativistic net positive charge on the other wire.
Net force is attraction.

Figure 5

+− −

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

PHYS>Physics>Electromagnetism>Magnetism>Force

magnetic force

Electric-charge relativistic motion causes weak electric force {magnetic force}| transverse to motion direction. Magnetic fields are electric fields caused by relativistic charge motions that make excess electrons or protons appear. Magnetic fields have no net charge to stationary observers.

examples

Wire in magnet field, tube and magnet, TV tube and magnet, two wires with current, and carpenter's bubble illustrate magnetic fields.

force

Magnetic force F equals moving charge q times velocity v times stationary-object magnetic field B times sine of angle A of approach to stationary object: F = q * v * B * sin(A). Magnetic force F equals wire current I times wire length L times stationary-object magnetic field B times sine of angle A between wire and stationary object: F = I * L * B * sin(A). Magnetic force F equals space magnetic permeability k' times wire current I1 times current I2 in other wire divided by distance r between wires: F = k' * I1 * I2 / r.

distance

Magnetic force depends on distance between wires, not distance squared, because relativistic effects are transverse to current motion.

magnetic moment

Torques require moments {magnetic moment}. Magnetic moment M equals current i times coil area A: M = i * A. Magnetic moment equals pole strength p times path length l: M = p * l.

right hand rule magnetism

If positive current points in right-hand finger direction {right hand rule, magnetism}|, magnetic-field direction {north magnetic pole} points in thumb direction. The opposite direction is the other pole {south magnetic pole}.

PHYS>Physics>Electromagnetism>Magnetism>Field

magnetic field

Magnetic dipoles have magnetic force lines {magnetic field}| {flux density} {magnetic intensity} {magnetic induction}, from south pole to north pole. Magnetic field H is magnetic force F divided by pole strength p: H = F/p.

wire

Around wires, magnetic field H is space magnetic permeability k' times current I divided by two times pi times distance d from wire: H = (k' * I) / (2 * pi * d). Around solenoids, magnetic field H is space magnetic permeability k' times wire-turn number n times current I: H = k' * n * I. Around toroids, magnetic field H is space magnetic permeability k' times wire-turn number n times current I divided by two times pi times toroid radius r: H = (k' * n * I) / (2 * pi * r).

direction

Positive current in thumb direction makes magnetic field that circles conductor in right-hand finger direction {right hand rule, magnetic field}.

magnetic flux

Numbers {magnetic flux}| of magnetic-field lines go through areas.

Ampere circuital law

Magnetic field B times distance ds charge moves in field equals field magnetic permeability µ times current I {Ampere's circuital law} {Ampere circuital law} {Ampere's law}: integral of B * ds = µ * I. Current flows inside path of distance.

Bohr magneton

Because relativistic effects have small energies, atoms have quantized electric and magnetic fields. Magnetism quantum {Bohr magneton} is small magnetic pole.

Biot-Savart law

Magnetic field relates to magnetic flux {Biot-Savart law}.

Lenz law

Energy conservation causes voltage from electromagnetic induction to make magnetic field opposed to original magnetic field {Lenz law}.

PHYS>Physics>Electromagnetism>Magnetism>Induction

electromagnetic induction

In dynamos or motors, electric and magnetic forces induce currents and voltages {electromagnetic induction}|.

outside force

If force moves conducting material through magnetic field or moves magnetic field near conducting material, protons and electrons in conductor move relative to protons and electrons that caused magnetic field. Moving protons and electrons make two electric currents that make two magnetic fields around conductor. Outside force provides energy to make magnetic fields.

However, no net charge moves, and test charges detect no electric current, because protons and electrons move together, so charges cancel.

induction

The original magnetic field interacts with both generated magnetic fields, setting up relativistic electric forces. Forces move electrons in conductor, but protons cannot move. Moving electrons make electric current opposite to movement and create magnetic field around current opposite in polarity to original magnetic field. Magnetic field created by moving electrons tends to resist relative movement between conductor and original magnetic field.

moving wire

For example, wire can moves through magnetic field. Moving wire moves wire protons and electrons, creating proton current and electron current, and currents make magnetic field around motion direction. Original magnetic field interacts with moving magnetic fields. Wire electrons are free and move down wire. Wire protons cannot move, though they feel magnetic force in opposite direction. Net current appears. Relativistic electric force separates electrons from protons, to make voltage that then makes current.

Energy for charge separation comes from outside mechanical energy used to move wire through magnetic field. Induced current makes net magnetic field that resists wire movement. Mechanical energy used to move wire makes electric field, induces current, and creates induced magnetic field.

energy transfers

In electromagnetic induction, potential energy in electric field causes voltage that makes current with kinetic energy, then current makes magnetic field with potential energy, then magnetic field slows current and builds voltage, which is potential energy in electric field. Cycle repeats.

Electric field and magnetic field, and voltage and current, are out of phase, because energy in one transfers to the other and then back again.

When electric-field change is zero and electric field maximizes, voltage maximizes and current is zero, and magnetic-field change maximizes and magnetic field is zero. As electric field decreases to zero, voltage decreases and current increases. As current increases, magnetic field increases and maximizes when current maximizes, electric-field change maximizes, and electric field is zero. As magnetic field decreases to zero, voltage increases and current decreases. As voltage increases, electric field increases and maximizes when voltage maximizes and electric field change is zero. Magnetic-field phase lags electric-field phase by 90 degrees.

examples

Electromagnetic induction happens in dollar bills in magnet, inductance coils, transformers, solenoids with iron bars, motors, and generators.

Hall effect

In conductors with current in magnetic fields, magnetic field pushes charges to conductor sides and makes electric field {Hall resistance, magnetism} opposed to magnetic field. Hall resistance varies with magnetic field and current.

semiconductor

In semiconductors, high magnetic field separates charges across width, not length, and so causes transverse current {Hall effect}.

quantum Hall effect

Quantum Hall resistance {quantum Hall effect} is inverse of small positive integer n times Planck's constant h divided by electron charge e squared: $(1/n) * (h/e^2)$.

spin

In semiconductor ribbons with electric current, magnetic field from spin-orbit coupling causes excess electrons with one spin on one edge and excess electrons with opposite spin on other edge {spin Hall effect}.

Hall resistance

In conductors with current in magnetic fields, magnetic field forces charge to conductor sides and makes electric field opposed to magnetic field {Hall resistance, current}, that varies with magnetic field and current.

magnetic dipole

Wire coil with current creates magnet with north and south poles {magnetic dipole}|.

field

Magnetic-field direction relates to current direction. By right hand rule, if positive current points in right-hand finger direction, magnetic-field direction points in thumb direction for north magnetic pole, and the opposite direction is south magnetic pole.

force

Like magnetic poles repel. Opposite magnetic poles attract. Force between magnetic poles equals space magnetic permeability k' times one magnetic-pole strength P times other magnetic-pole strength p, divided by distance r between poles: F = k' * P * p / r.

pole

Current i times path length L is pole strength p: p = i*L. Pole strength p equals charge q times velocity v: p = q*v.

infinitesimal

Infinitesimal wire loops can have unit current {elementary magnet}, to make idealized unit dipoles.

PHYS>Physics>Electromagnetism>Magnetism>Permeability

permeability of magnetism

Materials have ease {permeability, magnetism}| {magnetic permeability} {mu, permeability} {μ, permeability} by which magnetic fields can go through. Permeability depends on ease with which magnetic dipoles form. Magnetic force constant k' directly depends on permeability.

types

Ferromagnetic materials have molecular magnetic fields that can align with outside magnetic field to enhance it. Non-magnetic materials and empty space have no magnetic fields and allow magnetic field. Diamagnetic materials have magnetic fields that oppose outside magnetic field. Paramagnetic materials have magnetic fields that slightly enhance outside magnetic field.

Barkhausen effect

Crystals with impurities have greatly increased magnetization after crystal imperfections are overwhelmed by pressure {Barkhausen effect}.

Curie temperature

Magnets cannot hold magnetism at high temperature {Curie temperature}, because random motions become great enough to cancel net magnetism.

domain of magnetism

In materials, all molecules in microscopic regions {domain, magnetism}| can have same magnetic-field alignment.

magnetization

After removing magnetization, domains return to original orientations {magnetic memory, domain}.

anistropy

Crystals magnetize differently on different axes {magnetocrystalline energy} {magnetocrystalline anisotropy}.

energy

Unaligned domains minimize magnetic-field potential energy {magnetostatic energy}. Boundaries between domains add potential energy {domain wall energy}. Domain-wall width increases by exchange energy but decreases by magnetocrystalline energy.

length

Crystals change length when magnetized, because domains shift {magnetostrictive energy}. Iron gets longer. Nickel gets shorter.

extraordinary magnetoresistance

Electrical resistance can increase with increased magnetic field strength {extraordinary magnetoresistance} (EMR). Non-magnetic indium antimonide is a narrow gap semiconductor with high carrier mobility. Indium antimonide and gold lattice at room temperature has high EMR and so can be a magnetic-field sensor. Magnetic fields can change manganese oxide {manganite} from non-magnetic to ferromagnetic and metallic {colossal magnetoresistance} (CMR). Ferromagnetic layers with non-magnetic material between them {giant magnetoresistance} (GMR) are in disk-drive read heads.

hysteresis

External magnetic-field change changes material magnetization, after a time delay {hysteresis, magnetism}|. In motors and generators, external magnetic-field changes cycle, and material changes have time-delayed cycles {hysteresis loop}, with heat losses. Magnetic memory devices {twistor, memory} can use hysteresis loops.

saturation of magnetism

Magnets can align all domains and have maximum magnetization {saturation, magnetism}|.

spin-glass

Magnetic materials {spin-glass} can have disordered magnetic domains that couple and make long-range effects.

PHYS>Physics>Electromagnetism>Magnetism>Kinds

diamagnetism

Outside magnetic field causes weak, oppositely acting magnetism {diamagnetism}| in all materials. Outside magnetic field changes atom electron spins and electron orbits. Bismuth has the most diamagnetism. Two diamagnetic materials repel each other.

electromagnet

Solenoid coils can have large magnetic field that points down middle in one direction {electromagnet}|.

PHYS>Physics>Electromagnetism>Magnetism>Kinds>Paramagnetism

paramagnetism

Outside magnetic field can induce weak enhancing magnetism {paramagnetism}| in materials, by affecting permanent magnetic dipole moment caused by unpaired-electron spin. Manganese, palladium, and metallic salts are paramagnetic. Paramagnetism is slightly stronger than diamagnetism. Higher temperature increases paramagnetism, by making longer dipoles. Two paramagnetic materials attract each other, because they have magnetic dipoles.

ferrimagnetism

In materials, paramagnetism {ferrimagnetism}| can subtract from magnetic field. Manganese oxide is ferrimagnetic.

PHYS>Physics>Electromagnetism>Magnetism>Kinds>Ferromagnetism

ferromagnetism

Materials can have asymmetric electron distributions in molecule outer orbits {ferromagnetism}|. Odd number of electrons allows materials to have permanent magnetism.

examples

Iron, nickel, cobalt, alnico alloy, liquid oxygen, lodestone, iron particles, magnetite, and ferrite have ferromagnetism.

alignment

Atom spins can align in same direction in microscopic domains. Electrostatic forces {exchange energy} align magnetic dipoles in domain. Magnets can align all domains in same orientation to make net magnetic field.

permanent magnet

Hard ferromagnetic materials {permanent magnet}| holds magnetism even in another magnetic field. Soft-metal ferromagnets {soft magnet} lose or change magnetism in another magnetic field.

PHYS>Physics>Electromagnetism>Magnetism>Machine

magnetic brake

A metal disk {magnetic brake} rotating between two permanent magnets dissipates energy, because eddy currents make magnetic field opposed to permanent magnetic field and slow disk.

magnetic memory

After removing magnetization, magnetic domains return to original orientations {magnetic memory, computer}.

solenoid

Devices {solenoid}| can have wire coils. If current is in coils, magnetic field is sum of coil magnetic fields. Large magnetic field points down coil middle. Soft iron core in coil middle increases magnetic field by adding atom magnetic fields.

transformer

Devices {transformer}| can transfer voltage from circuit with alternating current to voltage from second circuit with alternating current. Transformers induce current in stationary-wire second coil using alternating current in first coil. Power in first coil equals power in second coil. Power is circuit voltage V times wire current I times wire-coil number n: $V1 * I1 * n1 = V2 * I2 * n2$.

spintronics

Electronics can use electron charge and spin {spintronics} {magneto-electronics}. Flowing-electron spins {spin current} can align {spin-polarized}.

resistance

Electrical resistance {magnetoresistance} can change in different-polarization magnetic layers. Electrons take curved paths, slow in current direction, and decrease current. Computer hard drives can use magnetoresistant read heads [1998].

spin

Quantum spintronics can control single-electron spin. When nitrogen atoms replace carbon atoms in diamond, adjacent locations can be empty {nitrogen-vacancy center} (N-V center). Doped diamonds can semiconduct. N-V centers make single fluorescing electrons with two energy levels, with no ionization.

generator of electricity

Mechanical energy can turn metal coil in magnetic field to generate electric current {generator, electricity} {electric generator}.

current

Electric current is in coil leading and trailing edges. Current changes direction with coil half turns, to make alternating current.

voltage

Voltage V equals magnetic field H times wire movement velocity v times wire-coil length l: $V = H*v*l$. Voltage V equals magnetic field H times area change dA divided by time change dt: $V = H * dA / dt$. Voltage V equals flux change dF divided by time change dt. $V = dF / dt$. Voltage V equals mutual inductance I times current change di divided by time change dt. $V = I * di / dt$.

example

Water from dams or steam from steam engines can turn wire coils around steel shafts {rotor, generator}, which are inside permanent magnets. Magnets and rotation cause electric current to flow in coils. Electric current changes direction as coil flips.

AC or DC

Rotor shaft {commutator, generator} can have separate conductors {brush, generator} on halves to allow current to leave rotor as direct current. Large-generator shafts {armature} collect alternating current directly.

PHYS>Physics>Electromagnetism>Magnetism>Machine>Motor

electric motor

Alternating current in coil has alternating magnetic field that can interact with outside magnetic field to make magnetic force on coil leading and trailing edges, and so turn coil {electric motor}|.

parts

Direct current or alternating current causes magnetic field in stationary wire coils {stator, motor} and in rotating wire coils {rotor, motor}. As rotor turns, current can go in forward or backward direction, changing magnetic field direction, because rotor shaft has separate conductors {brush, motor} on halves. Rotor magnetic field continually pulls into alignment with stator field, turning rotor by magnetic force. Rotation angular momentum starts cycle again.

torque

Magnetic force causes torque on coil and makes both magnetic fields tend to align. Coil torque T equals coil number n times magnetic field B times current i times coil area A: T = n * B * i * A. When magnetic fields align, force or torque is zero. Just before magnetic fields align, current reverses in coil. Current can reverse every half circle using commutators. Current can reverse using alternating current at needed frequency.

torque: direction

Right-hand palm points in magnetic-force direction, fingers point in magnetic-field direction, and thumb points in positive-current direction {right hand rule, torque}.

types

Series motors have low back emf, high field, and high current when starting and low current, high back emf, and low field when running. Shunt motors have constant field and lower current at high speed. Series and shunt motors can combine. Electric motors use direct current {induction motor}, alternating current {synchronous motor}, or either {universal motor}.

commutator

Current can reverse every half circle using devices {commutator, motor}|.

PHYS>Physics>Electromagnetism>Temperature

thermoelectric effect

Voltage is between two different touching metals at different temperatures, because metals have different electronegativities {thermoelectric effect}|. If metal rod has different temperatures at ends, voltage is between ends.

Seebeck effect

If two different metals have different temperatures and contact at two different places, circuit forms {Seebeck effect}.

thermocouple

Thermoelectric-effect voltage can measure temperature {thermocouple}|.

thermopile

Thermocouples can be in series {thermopile}|.

PHYS>Physics>Wave

wave in physics

Mass acceleration or deceleration causes collisions with nearby particles, which collide with farther away masses, and so on, and the disturbance {wave, physics} continues outward at speed that depends on medium particle-connection strength.

mechanical waves

Water-table waves illustrate transverse mechanical waves. Long springs, such as slinkys, illustrate longitudinal mechanical waves. Tuning forks, guitar strings, bongs, and glasses with water at different levels illustrate mechanical longitudinal sound waves. Mechanical waves are in media, which determine wave velocity by electric forces between molecules.

longitudinal wave

Disturbances, such as collisions, can be along line between two masses. Imparting force requires acceleration. Molecules move toward nearby masses, hit them, and bounce backward. Hit molecules accelerate, move toward next masses, hit them, and bounce backward, and so on. Bounce-backs return masses to where they were before, and only heat remains, so no net mass moves. Only disturbance and energy move outward. Wave velocity depends on material elasticity.

transverse wave

Disturbances, such as plucking strings, can be perpendicular to line between two masses. Molecules accelerate transverse to line between two masses. Nearby molecules feel transverse pull, because molecules attract. Attractions eventually stop transverse motion and reverse it. Cycle repeats until only heat remains. No net mass moves along, or transverse to, line between masses. Only disturbance and energy move down line, in both directions. Wave velocity depends on material elasticity.

movement

Waves have to travel, because they must pass from mass to mass. Waves involve acceleration and decelerations.

properties

Mechanical waves displace mass from equilibrium position. Waves have maximum displacement amplitude before they return to equilibrium point. Wave trains have frequency of disturbances passing space point per second. Wave trains have period between disturbances. Waves have wavelength between first and second equilibrium points and have wavelength inverse or wave number. Waves have phase angle of displacement to amplitude. Waves have speed of disturbance travel.

electromagnetic waves

Charge acceleration or deceleration causes force-field change {half-wave, charge acceleration}, which travels outward at light speed. Charge-acceleration moments make photons, because photons have spin. After first acceleration or deceleration, reverse deceleration or acceleration can add half-wave disturbance in opposite direction, to make one complete wave. Repeated acceleration and deceleration can make wave train. Electromagnetic waves do not have position displacement, only field displacement.

Electromagnetic induction requires changing electric and magnetic fields. Electromagnetic-induction rate determines light speed and depends on electric-force strength. Changing electric and magnetic fields move induction point away from accelerating charge. Therefore, light cannot be at rest. Behind moving point, fields cancel. Photons are only at one point, so light has no motion relative to other reference points, and in vacuum, light has same speed for stationary and moving observers.

Electromagnetic induction does not need or have medium. Because light does not move in medium, light speed is not relative to medium. Light speed is absolute maximum speed.

Photons have no mass, so light has no inertia and moves as fast as anything can move. Light speed is maximum physical speed.

Light electric and magnetic fields from several sources add, because electromagnetic inductions add. In media, atoms and molecules absorb and emit light, and this slows light speed but does not change frequency or intensity.

wave equation

Trigonometric functions {wave equation}| can describe waves. y = A * sin(2 * pi * f * t), where y is displacement, A is amplitude, f is frequency, and t is time. y = A * sin(2 * pi * x / l), where y is displacement, A is amplitude, x is position, and l is wavelength.

position and time

Wave equations are differential equations and include length and time. (D^2)H(x,t) / Dt^2 = (v^2) * (D^2)H(x,t) / Dx^2, where (D^2) indicates second partial derivative, H is function of displacement and time, v is wave velocity, x is position, and t is time. Solutions are waves. In springs, velocity depends on mass and material elasticity {spring constant, oscillation}. For strings, velocity depends on density, tension, and material. For solids, velocity depends on density and material elasticity {Young's modulus, oscillation}. For liquids, velocity depends on density and material elasticity {bulk modulus}. For gases, velocity depends on density, pressure, and molecule type: monatomic, diatomic, triatomic, and so on. For light, velocity depends on material magnetic permeability and electric permittivity.

distortion

Devices can reproduce input frequency with constant amplitude and/or phase (no distortion). Devices can reproduce input frequency with varying frequency, amplitude, and/or phase {distortion}. Devices can vary output with input frequency {linear distortion} or with voltage {nonlinear distortion} below or above linear-response range.

compression

Large voltages can have less relative gain than small voltages {compression, audio}. Compression creates lower harmonics.

clipping

Voltage can have limits {clipping}. Clipping creates higher harmonics.

overdriven harmonics

Non-linearly amplifying a tone and its fifth (ratio 3/2) can generate sum and difference frequencies of harmonic tones: higher and lower octaves, fifths, and fourths {overdriven harmonics}.

Doppler effect

Sound changes frequency with source or observer movement {Doppler effect}|.

stationary case

When stationary sources emit sounds or light waves with one wavelength and frequency, stationary observers hear one pitch or see one color. See Figure 1. Only wave moves, at constant velocity, because medium does not change.

Source x emits maximum positive amplitude, a line in the diagram, once each cycle. In the diagram, wave travels left two spaces for each cycle line. From one cycle line to the next, observer encounters one peak. There is no Doppler effect.

moving-toward case

When sound-wave or light-wave source moves toward stationary observer, or observer moves toward stationary wave source, observer hears pitch increase or sees shift toward blue color. This is Doppler effect. When frequency increases, wavelength decreases, because only sound medium or electromagnetic-induction speed determines constant wave velocity. See Figure 2.

In the diagram, observer travels right one space for each line, at half wave speed. Observer movement brings it closer to next wave peak. From one line to the next, observer encounters one and one-half wave peaks. Frequency has increased.

See Figure 3. In the diagram, source travels left one space for each line, at half wave speed. Source movement brings it closer to previous wave peak. From one line to the next, observer encounters two wave peaks. Frequency has increased.

moving-away case

When sound-wave or light-wave source moves away from stationary observer, or observer moves away from stationary wave source, observer hears pitch decrease or sees shift toward red color. When frequency decreases, wavelength increases, because wave speed is constant. See Figure 4.

In the diagram, observer travels left one space for each line, at half wave speed. Observer movement brings it farther from next wave peak. From one line to the next, observer encounters one-half wave peaks. Frequency has decreased.

See Figure 5. In the diagram, source travels right one space for each line, at half wave speed. Source movement brings it farther from previous wave peak. From one line to the next, observer encounters two-thirds wave peaks. Frequency has decreased.

examples

As sound-emitting vehicles move closer, sound has higher pitch. As they move away, sound has lower pitch.

As light-emitting stars and galaxies move away from Earth as universe expands, Doppler effect makes emitted light have decreased frequencies, so light becomes redder {red-shift}.

Figure 1

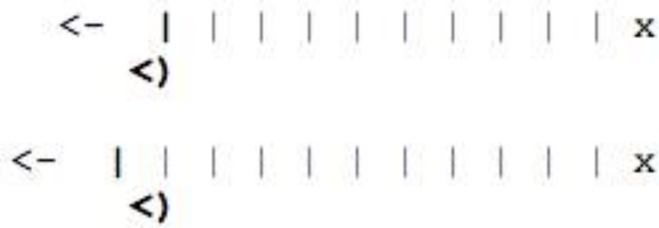


Figure 2

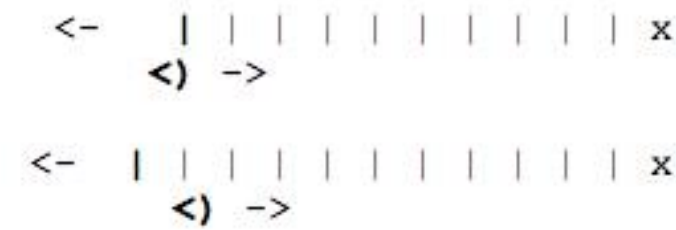


Figure 3

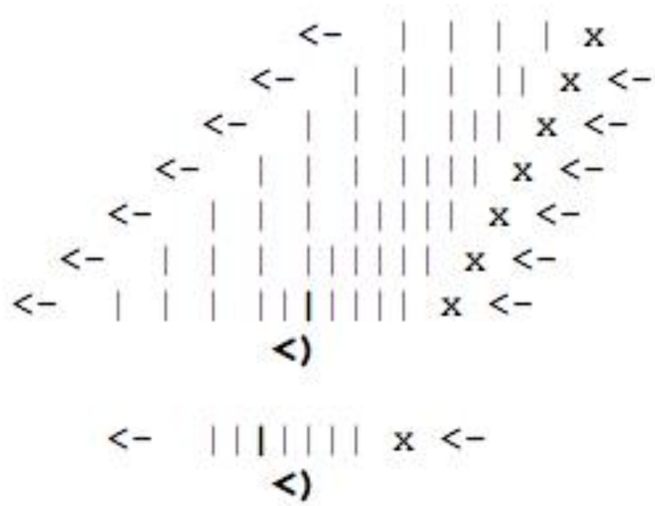


Figure 4

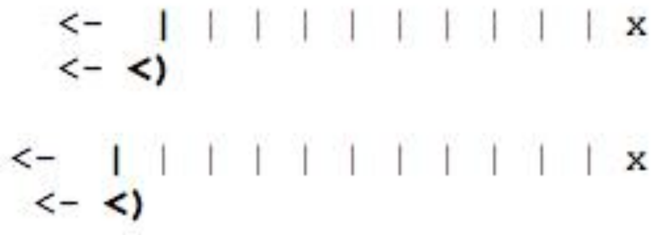
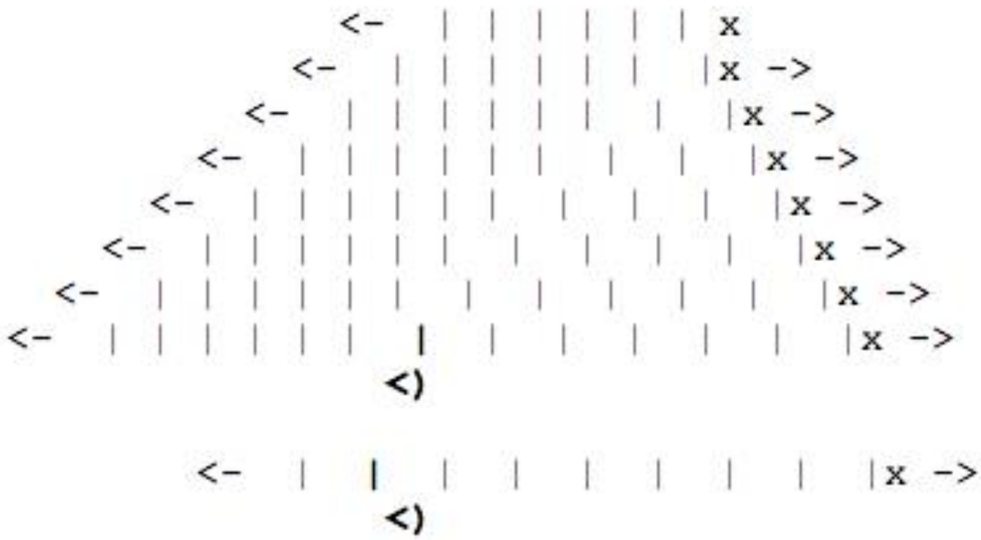


Figure 5



PHYS>Physics>Wave>Kinds

longitudinal wave

Vibration can be along motion direction {longitudinal wave}|. Sound waves are longitudinal waves.

transverse wave

Mechanical-wave vibrations can be across motion direction {transverse wave}|. Guitar or violin strings vibrate transversely. Molecular interactions are at right angles to direction that wave travels, which is down string and back. Longer strings make lower frequency. Tighter strings make higher frequency. Larger diameter strings decrease frequency. Electromagnetic waves have oscillating transverse electric and magnetic fields.

PHYS>Physics>Wave>Properties

amplitude of wave

Acceleration amount determines maximum displacement {amplitude, wave}. Mass displacement has distance oscillation. Zero-rest-mass displacement, as in electromagnetic waves, has field oscillation.

intensity of wave

Sound and light have energy flow per second per area {intensity, wave}|, which is power per area.

wave number

Wavelength has an inverse {wave number}|.

straight-line motion

Light rays travel in straight lines {straight-line motion}, because they follow least-action path.

PHYS>Physics>Wave>Superposition

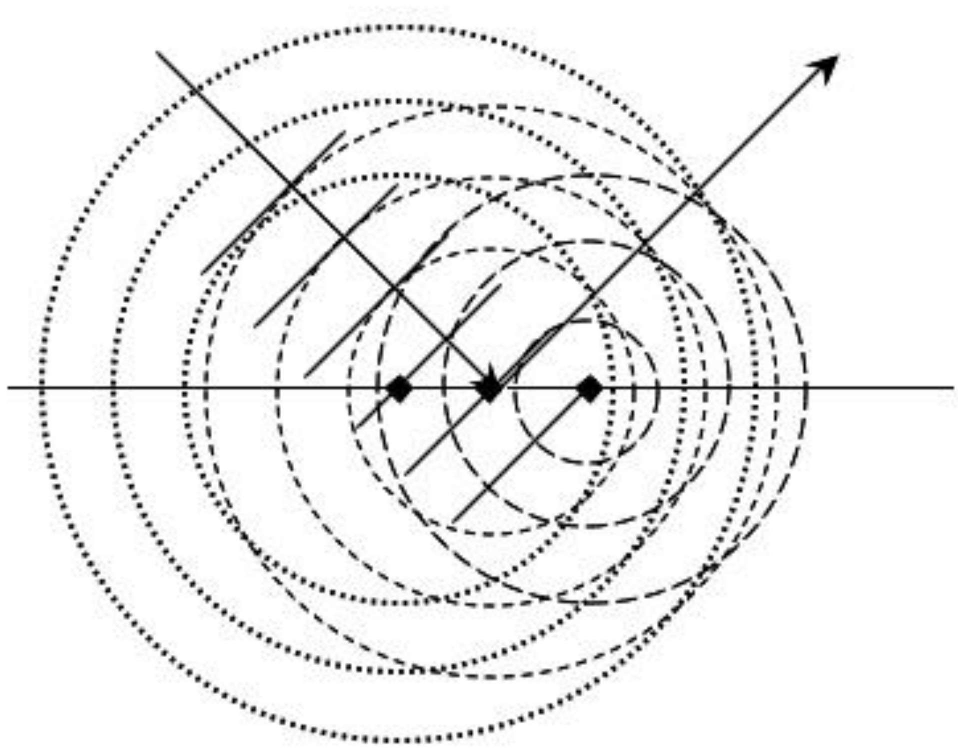
superposition of waves

At space points, wave trains can add {superposition, wave}|. Waves add without affecting each other. Waves are independent. Filtering other waves is subtracting and can leave one wave.

Huygen principle

Wavelets add by superposition to make a wavefront {Huygen's principle} {Huygen principle}. See Figure 1.

Figure 1



The parallel straight lines indicate maximum positive amplitudes of a wave.
The distances between the parallel lines are the wavelength.
If a source is far away, the wave front can be almost a straight line.

A wave front hits the surface first on the left, then continues along the surface.

At the instant of Figure 1, the third wave front from the right hits the surface at the left diamond, the second wave front from the right hits the surface at the middle diamond, and the first wave front from the right hits the surface at the right diamond.

The short-dash concentric circles show that surface has radiated the same-wavelength light from the left diamond. The medium-dash concentric circles show that surface has radiated the same-wavelength light from the middle diamond. The long-dash concentric circles show that surface has radiated the same-wavelength light from the right diamond.

The first long-dash circle intersects the first medium-dash circle and the first short-dash circle at the same point. The second long-dash circle intersects the second medium-dash circle and the second short-dash circle at the same point. The third long-dash circle intersects the third medium-dash circle and the third short-dash circle at the same point.

No other points show intersection.

The left arrow shows incoming light perpendicular to the wave front.
The right arrow shows outgoing light, perpendicular to the wave front made by the sum of the wavelets.

The incoming and outgoing light rays enter and leave at the same angle.

heterodyning

When two different-frequency waves start from same source, waves superpose {heterodyning}| to make net wave with frequency {beat frequency} equal to difference between the original frequencies. Two frequencies can mix to make lower difference frequency. For example, if frequency-2 wave superposes with frequency-3 wave, frequency-1 wave results.

orbital angular momentum

Light can have different wave-front shapes, such as plane, helix, or double helix {orbital angular momentum, light}. Diffraction gratings with fork or helical lens change plane-polarized light. After such transformation, light in phase makes circles with dark centers {cancellation by superposition}.

self-referencing

Spectrum low frequency can double in frequency {self-referencing}, to interfere with spectrum higher frequencies.

wavelet

When light waves hit surfaces, surface points re-radiate light {wavelet}|.

Young experiment

If plate has one vertical slit {slit experiment, wave}, light diffracts around edge and makes horizontal diffraction pattern. The most-intense light goes straight through. Lesser light amounts are farther from center. If plate has two vertical slits {double-slit experiment} {Young's experiment} {Young experiment}, light diffracts through both slits and makes horizontal interference pattern, because the diffraction patterns add.

Double-slit experiments can have ring pattern with no interference or striped pattern with interference. Detectors that detect only half the particles cause half-striped and half-ring pattern.

PHYS>Physics>Wave>Superposition>Reflection

reflection of wave

Light can bounce off surfaces {reflection, light}|, as surface molecules absorb and re-emit light. Reflections are like elastic collisions. Plane mirrors and wave tanks show reflections.

wavefront

Wavefronts are moving space disturbances. Behind wavefronts, all wavelets cancel each other, because wavelets have random phases. Beyond wavefronts, nothing has reached yet. Wavefronts are moving edges. Wavefront oscillation and movement carry energy. At surfaces, wavefronts re-radiate.

angles

Reflection angle equals incidence angle. Because light travels straight, light has no sideways motion components, and light plane stays the same. Angles are the same, because light effects are symmetric.

images

Images from flat mirrors appear to be behind mirror and so are virtual images. Images appear at same distance from mirror as distance that objects are from mirror. Images have same size and orientation as objects. Reflections from flat surfaces only reverse right and left.

surfaces

Dielectrics can be mirrors.

polarization

At incidence angle 45 degrees, if reflection from plane mirror has 90-degree angle between reflected and refracted beams, light polarizes.

angle of incidence

In reflection, incident light hits surface at angle {angle of incidence}| {incidence angle} to perpendicular.

angle of reflection

In reflection, reflected light leaves surface at angle {reflection angle} {angle of reflection}| to perpendicular, as superposed wavelets add to make wavefront. Reflection angle equals incidence angle and is in same plane.

PHYS>Physics>Wave>Superposition>Reflection>Mirror

curved mirror

Curved mirrors {curved mirror} focus incoming parallel light rays onto point {focus, mirror}.

types

Curved mirrors {spherical mirror} can have constant radius. Spherical mirrors {convex mirror} can curve out. Curvature radius is positive if curve is convex. For convex mirrors, image is always virtual and erect. For convex mirrors, if object is inside focal point, image is bigger. For convex mirrors, if object is outside focal point, image is smaller.

Spherical mirrors {concave mirror} can curve in. Curvature radius is negative if curve is concave. For concave mirrors, if object is outside focal point, image is real and inverted. For concave mirrors, if object is inside focal point, image is virtual, erect, and bigger.

Curved mirrors {parabolic mirror} can have changing radius.

magnification

Ratio of image size I to object size O equals ratio of distance q of image from mirror to distance p of object from mirror: I/O = q/p.

focal length

Focal length F is spherical-mirror curvature radius R divided by two: F = R/2.

lens equation for mirrors

Image distance I and object distance O relate to focal point distance F {lens equation, mirror}: 1/F = 1/I + 1/O.

method of rays

Find object image using incoming straight lines from object and outgoing straight lines to image {method of rays} {rays method}, which reflect from spherical mirror points.

PHYS>Physics>Wave>Superposition>Refraction

refraction

Light can go from one medium into another medium {refraction}|.

reflection

Some light enters second medium, and some light reflects from surface. For greater refraction-index difference, reflection is greater, because electric fields interact more.

refraction

As wavefront hits surface between media, surface re-radiates light waves, and wavelets add, to make new wavefront in second material.

planar

Incident light and refracted light have same plane, because light travels straight and so has no transverse motion component.

speed

If second medium has different refractive index, incident light and refracted light have different speeds.

frequency

Light frequency stays the same in both materials, because electromagnetic induction does not use medium.

wavelength

Because velocity changes and frequency stays constant, wavelength changes, and incident light and refracted light have different angles to perpendicular. If second medium has higher refractive index, light bends toward perpendicular, because wavelength becomes shorter. If second medium has lower refractive index, light bends away from perpendicular, because wavelength becomes longer.

examples

Glass with different refractive indices appears warped. Refraction from air to water causes coins in fish tanks to appear in different positions than they actually are. Prisms, water glasses, and camera lenses use refraction.

refractive index

Vacuums have no matter or electric or magnetic fields. Media have subatomic-particle electric and magnetic fields {refractive index}| {index of refraction}, which attract and repel light-wave electric and magnetic fields, decreasing light speed. Refractive index depends on electrical permittivity and magnetic permeability. Vacuum has refractive index 1. Glasses have refractive index near 1.5. Dense polar salts have refractive index 2.5. Teflon is transparent to microwaves but has high refractive index. Plasmas and metals have negative permittivity. No natural substances have negative permeability.

speed

In materials, velocity v equals light speed in vacuum c divided by refractive index n: v = c/n.

birefringence

In crystals {anisotropic crystal}, refractive index can vary with light-propagation direction {birefringence}|. In birefringence, incident light divides into two light rays that polarize in planes at right angles. Isotropic crystals, glasses, liquids, and gases have the same physical properties in all directions. Most crystals are isotropic.

chromatic aberration

Different-frequency light does not focus at same point, because refractive index differs for different frequencies {chromatic aberration}|.

dispersion in refraction

Higher frequencies refract more than lower frequencies {dispersion, refraction}. Higher frequencies travel slower than lower frequencies, because dielectric-dipole capacitance is higher, photon energy is higher, and electric forces are higher. Because wavelength is lower, percentage change is higher. Dispersion causes prism rainbows.

PHYS>Physics>Wave>Superposition>Refraction>Angle

Snell law

Incidence angle I and reflection angle R relate by media refractive indexes n {Snell's law} {Snell law}: nI * sin(I) = nR * sin(R).

critical angle

If incidence angle is more than angle {critical angle}|, all light reflects, in total reflection, because reflection angle is 90 degrees or more. Critical angle depends on media refractive indexes.

total reflection

If incidence angle is more than critical angle, all light reflects {total reflection}|, because refraction angle is 90 degrees or more.

PHYS>Physics>Wave>Superposition>Refraction>Transfer

opaque material

Materials {opaque material}| that have free electrons absorb all light.

translucent material

Materials {translucent material}| that have weakly bound electrons absorb some light and transmit some light, making blurry images.

transparent material

Materials {transparent material}| that have tightly bound electrons have no absorption and transmit light with clear images.

PHYS>Physics>Wave>Superposition>Refraction>Lens

lens in physics

Transparent curved surfaces {lens, physics}| can refract parallel light rays to point.

convex

For convex lenses, if object is inside focal point, image is virtual, erect, and smaller. For convex lenses, if object is outside focal point, image is real and inverted.

concave

For concave lenses, image is virtual and erect. For concave lenses, if object is inside focal point, image is bigger. For concave lenses, if object is outside focal point, image is smaller.

focus
Focal length F depends on lens refractive index n and radii R of sides: 1/F = (n - 1) * ((1 / Ri) - (1 / Ro)).
curvature radius
Curvature radius is positive if curve is convex. Curvature radius is negative if curve is concave.
size
Ratio of image size I to object size O equals ratio of distance q of image from lens to distance p of object from lens. I/O = q/p.
wavelets
Lenses perform spatial Fourier transforms.

aperture
Mirror or lens angular size {aperture}| is angle at focal point between two radii from ends of a spherical-mirror or spherical-lens diameter.

spherical aberration
Spherical mirrors or lenses with large aperture deviate from parabolic reflection {spherical aberration}| at edges. Edges do not refract to focal point.

PHYS>Physics>Wave>Superposition>Refraction>Lens>Focus

diopter
Units {diopter} can measure how much lenses converge or diverge light {dioptric power}. Zero diopters converges light from object at one meter to focus at one meter. Three diopters converges light from object at one meter to focus at one-third meter. Minus three diopters diverges light from object at one meter to focus at three meters.

focal point
Parallel light rays from one lens side go through lens to a point {focus, lens} {focal point}| on other lens side.

image
Images {real image} {image, object}| can form from actual light rays. Images {virtual image} can appear to be in locations where light rays cannot go. Images {erect image} can have same orientation as objects. Images {inverted image} can have opposite orientation as objects. Images can magnify or reduce objects.

lens equation lens
Image distance I and object distance O relate to focal point distance F {lens equation, lens}: 1/F = 1/I + 1/O.

PHYS>Physics>Wave>Superposition>Refraction>Lens>Shape

concave lens
Lens surface can curve in {concave lens}.

convex lens
Lens surface can curve out {convex lens}.

PHYS>Physics>Wave>Superposition>Refraction>Lens>Type

achromatic lens
Lens combinations {achromatic lens} can eliminate chromatic aberration.

aplanatic lens
Lenses {aplanatic lens} can correct spherical aberration.

microscope
Microscopes {microscope}| have large lens that collects light to focal point, and second small, high-curvature lens that focuses small but near image. Microscopes {phase contrast microscope} can look for different light phases.

PHYS>Physics>Wave>Superposition>Resonance

resonance of waves

Two waves {standing wave} can travel in opposite directions from point and then reflect back from end barriers, so they reinforce each other {resonance, wave}| when they meet again, because they are in phase.

node

Resonating waves are stationary. In stationary waves, some points {node, wave} always have zero displacement.

wavelength

Fundamental standing-wave wavelength is two times distance between endpoints. Closed tubes have resonant wavelength one-quarter tube length. Open tubes have resonant wavelength one-half tube length. String resonant frequency is lower if string length is longer.

fundamental wave

Systems can have standing waves {fundamental wave}| with lowest frequency.

harmonic wave

Waves {harmonic wave, physics}| {overtone} can have frequencies that are fundamental-frequency multiples.

octave of wave

Waves can have frequency fundamental frequency times two {octave, wave}|, three {twelfth}, four {fifteenth}, five {seventeenth}, six {nineteenth}, and so on. Higher frequencies must have more energy to have significant amplitude.

PHYS>Physics>Wave>Superposition>Soliton

soliton

Solitary, non-linear, stationary or moving waves {soliton}| can maintain size and shape. As wave components travel, solitons reinforce components by superposition. High-frequency components increase at same rate as they spread out, because they have different speeds. Solitons can be in plasma, crystal-lattice, elementary-particle, ocean, molecular-biology, and semiconductor boundary layers.

vacuum

Vacuum with periodic vacuum states can make soliton-antisoliton pairs.

quanta

Perhaps, massive elementary particles of 1000 GeV, or magnetic monopoles, are solitons. Solitons can allow bosons to make fermions and allow fermions to split.

Sine-Gordon theory

One-dimensional soliton-antisoliton pairs can be in two or three dimensions and require vector fields {Sine-Gordon theory}.

PHYS>Physics>Wave>Diffraction

diffraction of light

Light appears to bend {diffraction}| around corners and edges. If light rays meet corners, corner re-radiates light in all directions, so some light goes to region behind edge. Wavelets add to form wavefront there. At most wavefront points, wavelets cancel each other, so light intensity is zero. At some wavefront points, sum is positive, and light appears behind edge at regular intervals. Shadows have diffraction patterns at edges.

sound

Diffraction is how people can hear sound around corners.

size

If obstacle or edge is smaller than wavelength, wave goes farther around obstacle or edge. If obstacle or edge is larger than wavelength, diffraction has smaller angle.

frequency

Higher-frequency light and sound have smaller diffraction, because wavelengths are smaller. Lower-frequency light and sound bend more.

diffraction grating

Materials {diffraction grating}| can have regular repeating opening or ruling patterns, so surfaces are like many edges. Diffraction gratings can be for parallel rays {Fraunhofer grating} or spherical rays {Fresnel grating}. The many edges cause strong diffraction pattern, because more wavelets add together to make higher amplitude. If openings are small or rulings have close spacing, diffraction is more, because smaller edge can re-radiate more behind edge.

phase plate

Transparent plates {phase plate} with varying thickness can delay light slightly, to change phase. Phase plates are diffraction gratings. If only parallel light rays reach phase plate, diffraction is regular. Phase differences cause intensity differences at various points, by interference effects.

PHYS>Physics>Wave>Diffraction>Shadow

shadow light

Shadows {shadow}| have umbra and penumbra.

penumbra

Shadows have a lighter part {penumbra}|, where diffracted light enters.

umbra

Shadows have a dark part {umbra}|, where no diffracted light enters.

PHYS>Physics>Wave>Diffraction>Scattering

scattering of light

If light wavelength is less than object diameter, light bounces off object {scattering, light}|. If light wavelength is more than object diameter, light goes around object.

example

Sky is blue, because blue light has small enough wavelength to scatter from air molecules, but other colors have longer wavelengths. Air molecules are large enough to block blue and some green light from Sun, but longer wavelengths go around air molecules. Scattered blue light goes all over sky to make it blue instead of clear. Sun is red at horizon, because light goes through more atmosphere to eye, and air scatters blue, green, and yellow light.

Compton scattering

X-rays can have elastic scattering {Compton scattering} from stationary electrons in light elements. Scattered-radiation frequency decreases with increasing angle, so high frequencies are at narrow angles.

PHYS>Physics>Wave>Entrainment

entrainment

Two vibrators at similar frequency soon have same frequency and phase {entrainment}| {mode-locking}.

mutual entrainment

Two oscillators with similar frequencies soon have same frequency {virtual governor} {mutual entrainment}.

PHYS>Physics>Wave>Sound

sound in physics

Molecular-vibration waves {sound, physics} can move through materials.

process

Molecules from outside material can collide with material, causing material molecules to move. Molecular movement causes collision with adjacent molecules. First molecules bounce backward, and second molecules move, causing collision with adjacent molecules, and so on. Collisions send longitudinal wave down motion line.

Sound compresses {compression, sound} material in front of it, leaving slight vacuum {rarefaction} behind compression. Compression pushes next material bit forward. Original bit bounces back to original position, so material does not move. Compression wave travels through material. Only wave and energy move.

speed

Medium determines sound-wave speed. Sound-wave speed increases with stronger interactions between molecules. Wave frequency and amplitude do not affect speed.

amplitude

Sound has kinetic energy {loudness, sound}. Kinetic-energy increase increases sound-wave amplitude, by moving molecules farther. Frequency, wavelength, and speed do not affect wave amplitude.

pitch

Sound has number {frequency, sound} of vibrations per second. People can hear sounds of 20 to 20,000 Hz.

Sound has frequencies at two, three, four, and so on, times fundamental frequency {harmonics, physics}. Higher harmonics have lower amplitude.

Outside-material vibration frequency determines sound-wave frequency. Materials can have resonance frequencies.

Mach effect

Sound waves travel in a medium, and the medium can be moving, making net sound-wave velocity faster or slower {Mach effect}.

PHYS>Physics>Wave>Sound>Kinds

phonon

Vibration quanta {phonon}| are sound-wave packets. Crystal phonon vibrations cause temperature gradient sideways to phonon direction, analogous to Hall effect for electromagnetism.

Rayleigh wave

Surfaces can have acoustic waves {Rayleigh wave}. Earthquakes and radio waves can put Rayleigh waves in Earth or ionosphere. Ultrasonic surface acoustic waves can store, recognize, filter, and channel electronic signals in semiconductors, at 10^9 Hz.

shock wave

Moving objects make sound {sonic boom} as they push air aside {shock wave}|. If object speed becomes the same as sound speed, waves of pushed-aside air travel as fast as sound. Waves are in phase and grow to make large wave. If plane travels faster than sound speed, sound is behind pushed-aside air, waves do not build up, and no shock wave builds.

Objects can go through air faster than air sound speed. Sound from object contact with air cannot travel away faster than sound waves build up. Wave constructive interference creates shock wave, which carries extra energy away when object breaks sound barrier, causing sonic boom. After passing sound speed, acoustic waves at sound speed are slower than object speed, with no more constructive interference.

speech sound

Speech sounds {speech sound} have frequency range from 250 Hz to 2000 Hz and loudness range from 63 to 95 decibels.

ultrasonic sound

Sounds {ultrasonic sound}| can have frequency greater than 20,000 Hz. Ultrasonic sound can visualize body insides and clean dishware.

PHYS>Physics>Wave>Sound>Echo

echo of sound

Rooms {whispering gallery} can have focal points, where sound focuses {echo}|. Canyons and buildings can echo sound. Echoes work best with low amplitude and high frequency.

echolocation

High-frequency sound can locate objects by echo pattern {echolocation}| {sonar, location}.

PHYS>Physics>Wave>Electromagnetic

electromagnetic wave induction

Electric charges have virtual photons streaming outward as straight lines in all directions, making electric field. Electric fields begin at electron edge, which emits virtual photons. Electric-field lines indicate electric-force direction. Each line is one photon stream, so electric-field lines are not about electric-force strength or electric-field strength. Electric-field-line area density, photons per area, is electric-field strength. Because area varies directly with squared dimension, electric force decreases as distance squared: 1/r^2. Electric field has virtual kinetic energy, which can transfer to other charges at field positions to become potential energy.

moving charges

Maximum charge velocity is typically one-tenth light speed. For constant-velocity charge, electric field moves at same speed and direction as charge. Virtual photons stream outward as straight lines in all directions.

Constant-velocity fields have no transverse or longitudinal field changes, and so no waves.

moving charges: magnetic force

According to special relativity, constant-velocity charge causes observer transverse to charge-motion-direction to see length contraction and so increased charge-motion-direction charge density. Length contraction makes flattened-spheroid charge shape, with short axis in motion direction and long axes in transverse-direction plane. Because total charge is same for moving and stationary charge, total field strength stays the same. Relativistically increased charge density along vertical direction causes increased electric force along horizontal direction. Therefore, relativistic length contraction makes electric field appear to observer stronger horizontally. According to special relativity, observer in front or back of constant-velocity charge does not see length contraction, only that charge approaching or receding. Total electric field strength is same as for stationary electron, because total charge is same. Because total charge is same as before, charge density must be less as observed from vertical direction, so electric field appears to observer weaker vertically. Vertical electric field is foreshortened in motion direction, because electron catches up to virtual photons. Vertical electric field is lengthened opposite to motion direction, because electron moves away from virtual photons.

Electric force due to relativistic length contraction and charge-density change, and not due to total charge, is magnetic force. (Stationary charges have no relativistic motion and so no relativistic electric force.) Adjacent magnetic force is a torus around moving charge. Just as electric forces act only on electric forces, magnetic forces act only on magnetic forces, because magnetic is perpendicular to electric and so does not affect electric.

Electric force has electric field. Electric force and electric field have same direction and relative strength. Because magnetic force is relativistic electric force, magnetic force has magnetic field. Magnetic force and magnetic field have same relative strength but perpendicular direction, because force is due to transverse relativistic length contraction and so is perpendicular to motion and field. Therefore, magnetic forces have magnetic fields perpendicular to electric force/magnetic force and perpendicular to charge-motion orientation. Moving-charge magnetic field is a torus adjacent to and around charge, transverse to motion direction. See Figure 1.

For positive charge moving in right-hand thumb direction, magnetic field is in curling index-finger direction, in a circle around moving proton, and magnetic force is outward from palm (right-hand rule). For proton moving vertically downward, magnetic field is in on left and out on right. Electron has negative charge, so magnetic field is out on left and in on right.

Magnetic field has virtual photons and so has virtual kinetic energy, which can transfer to other charges at field positions to become potential energy. Stationary charge has no magnetic field, because it has no relativistic length contraction.

accelerating charge

Charge acceleration pushes electric-field line transversely and stretches it sideways, causing tension and restoring force. Charge acceleration causes transverse electric field, while keeping radial field. Because virtual photons continually leave charge, transverse component moves outward along field line, so spatial transverse waves travel outward. See Figure 2.

Charge acceleration pushes magnetic-field line transversely and stretches it sideways, causing tension and restoring force. Charge acceleration causes magnetic field in charge-motion direction, transverse to magnetic field.

When stationary charge accelerates to constant velocity, electric-field lines curve toward motion direction, because charge and adjacent photon have higher velocity. When constant-velocity charge decelerates to zero velocity, electric-field lines curve away from motion direction, because charge and adjacent photon have lower velocity.

See Figure 3. Force causing electron deceleration also puts transverse upward pushing force on field lines and distorts electric-field lines. As electron slows down, electric-field-lines beginning at electron edge slow down, so horizontal electric-field lines begin to have transverse component upward.

See Figure 3. As electron slows down, electric-field upward transverse component increases over time. Changing electric-field flux (changing electric force) through an area causes relativistic length contraction transverse to area (in same plane) and magnetic-force change in toward or out from area (in same plane), and so causes induced magnetic field around area. Magnetic force has gradient in or out and so makes induced-magnetic-field gradient around. Faster change makes larger gradient.

Electric and magnetic fields interact, so they push/pull adjacent electric and magnetic fields. Interaction is strong and happens at light speed, so adjacency effect travels at light speed. Interaction is constant, so light speed is constant. All interactions are elastic, with no losses to heat or other energy, so induction has same effect later as at beginning.

Transverse effect travels inward and outward at light speed. Outward effect sees only undisturbed field line and so is the only effect and carries energy outward. Inward effect sees restoring force from stretched field line and so forces cancel and line returns to equilibrium, with no energy carried.

Electric-field increase (or decrease) causes magnetic-field increase (or decrease) that opposes electric-field increase (or decrease), by energy conservation.

See Figure 3. Induced magnetic field increases over time. Changing magnetic-field flux (perpendicularly changing magnetic force) through an area causes relativistic length contraction transverse to area (in same plane) and electric-force change around area (in same plane), and so causes induced electric field around area. Electric force has gradient in or out and so makes induced-electric-field gradient in or out. Faster change makes larger gradient.

Magnetic-field increase (or decrease) causes electric-field increase (or decrease) that opposes magnetic-field increase (or decrease), by energy conservation.

Changing electric field and magnetic field are in phase, because they both increase together and both gradients are in same direction.

Gradient and wave leading edge travels outward at constant light speed.

See Figure 3. Horizontal electric-field lines continue moving at constant velocity, because lines have same momentum, inertia, and kinetic energy as before.

See Figure 4. As electron slows down more, electric-field-line points at electron edge slow down more, so horizontal electric-field lines have greater transverse component. Electric-field upward transverse component increases more over time and so makes bigger induced-magnetic-field gradient. Induced magnetic field increases more over time and so makes bigger induced-electric-field gradient. Transverse fields have potential energy, so horizontal electric-field lines at transverse fields have less kinetic energy. Horizontal electric-field lines continue moving at constant velocity, because lines have same momentum, inertia, and kinetic energy as before.

See Figure 5. Metal plate stops electron within one electron width, so distance and time are small, and deceleration is high. Electron is at zero velocity, so current is zero. Electron has no kinetic energy and momentum. Original electric field is symmetric. Original electric field has same potential energy. Original magnetic field is zero. Original magnetic field has no potential energy.

See Figure 5. As electron stops, electric-field-line ends stop, so horizontal electric-field lines have maximum transverse component. As electron stops, electric-field upward transverse component has increased to maximum over time and so makes induced-magnetic-field gradient. Induced magnetic field has increased to maximum over time and so makes induced-electric-field gradient. Induced electric field is maximum.

See Figure 5. Horizontal electric-field lines continue moving at constant velocity, because lines have momentum, inertia, and kinetic energy.

See Figure 6. Deceleration has stopped, so electron and adjacent fields stop feeling upward force. Transverse electric-field stays constant at zero, and so makes no magnetic-field gradient and no magnetic field. Magnetic-field line feels no force, so transverse magnetic field stays constant at zero, and so makes no electric-field gradient and no electric field. Electron and adjacent electric-field line have no velocity, momentum, or kinetic energy. Gradient and wave leading edge travels outward at constant light speed. Adjacent virtual photon leaves electron and travels horizontally at light speed. Transverse electric-field-line component stretches farther downward. Transverse electric-field-line component moves outward at light speed. All interactions are elastic, with no losses to heat or other energy, so gradient has same effect later as at beginning. Original virtual photons of horizontal electric-field lines continue moving at constant velocity, because lines have momentum, inertia, and kinetic energy.

phase

When stationary charge accelerates to constant velocity, electric-field and magnetic-field transverse component increase in same direction and at same time (in phase). When constant-velocity charge decelerates to zero velocity, electric-field and magnetic-field transverse component decrease in same direction and at same time (in phase).

induction

Electric-field change over time (flux) through an area makes magnetic field around area, because of relativistic length contraction. Electric current makes magnetic-field torus around current. See Figure 1.

Magnetic-field change over time (flux) through an area makes electric field around area, because of relativistic length contraction. Magnetic-field flux change through torus cross-section makes electric field around torus cross-section. Current goes through torus hole, around, and back again to complete the circuit (displacement current). See Figure 1.

Stationary electric field has constant force, and so uses no energy to make magnetic field. Moving electric field changes over time and makes constant magnetic-field gradient, because electric-field-movement kinetic energy increases magnetic-field potential-energy over space. Accelerating electric field makes increasing magnetic-field gradient, because electric-field force increases magnetic-field acceleration over space. Accelerating magnetic or electric fields over space have force that causes increasing electric or magnetic fields over time. Fields over space have potential energy, and fields over time have kinetic energy, so energy alternates between kinetic and potential, making waves.

Constant stationary magnetic field has no affect, because it has no force, so magnetic-field energy remains potential energy. Moving magnetic field changes over time and makes constant electric-field gradient, because magnetic-field-movement kinetic energy increases electric-field potential-energy over space. Accelerating magnetic field makes increasing electric-field gradient, because magnetic-field force increases electric-field acceleration over space.

induction: energy conservation

Increasing (or decreasing) magnetic field increases (or decreases) electric field, which makes magnetic field that opposes original magnetic field, by energy conservation. Decreasing (or increasing) electric field decreases (or increases) magnetic field, which makes electric field that opposes original electric field, by energy conservation.

For downward current, acceleration increases magnetic field, and that makes upward electric field, which decreases magnetic field. For downward current, deceleration decreases magnetic field, and that makes downward electric field, which increases magnetic field.

Charge deceleration is against restoring force and builds potential energy. When deceleration stops, restoring force pulls back toward equilibrium, but potential energy transfers to kinetic energy and carries past equilibrium until restoring force pulls back to equilibrium.

Energy goes into adjacent electric-field transverse movement, as interchange between electric and magnetic fields makes wave travel outward. Therefore, energy dies down at past points.

Magnetic-field and electric-field changes have same displacement amount, but electric field has approximately one hundred times more energy. Most light-wave energy is in electric field, not magnetic field, because magnetism is relativistic effect.

To make electric field, virtual photons stream outward at light speed from electron in all directions. Electric-field lines are virtual photon streams. At electron constant velocity, photons also have same velocity as electron, so electric-field lines are straight.

The figure shows virtual photons streaming outward horizontally from electron transverse to electron motion direction. Electron and electric-field lines move downward at same velocity.

Because electric-field and magnetic field interact along line, line has tension, just as a taut string has tension, so line has restoring force if accelerated sideways, just like a taut string has restoring force. All interactions are elastic, with no heat losses, so forces and energies are the same all along electric-field lines from beginning to infinity.

Deceleration can knock field lines through space. Stronger deceleration makes farther and stronger fields.

gradient

Field induction around area circumference makes space gradients as tangents to circumferences. When electric-field flux change through area makes magnetic field around area, magnetic field has gradient around area. When magnetic-field flux change through area makes electric field around area, electric field has gradient around area.

speed

Because electric force is strong, electric and magnetic fields interact at light speed. Because magnetic field and electric field couple {electromagnetic wave induction}|, transverse field-line component moves outward along electric-field line at light speed. Electromagnetic interaction strength is constant, so light speed is constant.

wave

Waves are local effects that travel. Traveling field changes are independent of original charges.

For downward current, deceleration decreases magnetic field, and that makes downward electric field, which increases magnetic field. Electric and magnetic fields are in phase. Electric-field-line disturbance moves away from charge at light speed in a straight line. Transverse component makes traveling wave half {half-wave, wave}. All disturbances to electric-field lines travel outward at light speed. Previous points have no more disturbances, so only one half-wave exists at any time. No disturbances are left behind, because all energy has traveled away. Disturbance reaches farther positions in sequence out to infinity. See Figure 1 through Figure 7. Wave exists only at induction point and can only go straight-ahead. Wave has no physical effect except at moving single point.

elastic

Electric and magnetic interactions are elastic, with no losses to heat or other energies. Therefore, disturbances travel without losing energy. Inductions continue to infinity.

strength with distance

Inductions and other electric-field-line disturbances are transverse to electric-field lines. Because electric field oscillates in a plane, not area, intensity decreases directly with distance, not with distance squared. Transverse effects happen in one dimension, so wave strength decreases directly with distance: 1/r. At later times, transverse field component stretches more over space.

electric-field-line tension and restoring force

Guitar-string molecules attract each other by electric forces. Taut guitar strings have tension from these restraining forces. Pulling string sideways puts potential energy into the string, by stretching string electric forces, like springs. After releasing string, electric forces, like springs, pull string back by restoring force. Potential energy transfers to kinetic energy. Molecule kinetic energy carries molecules past equilibrium point, so they pull on string molecules in other direction.

Adjacent to pull and release point, molecule electric forces pull-and-restore adjacent string molecules, so transverse waves travel along string. Wave speed depends on molecule electric-force strength. Wave takes energy with it, so no energy is left at original disturbance point, and it no longer oscillates. Molecule electric forces bring displacement back to equilibrium at zero.

Electric-field lines are like strings. Like guitar strings, electric-field lines have tension, because electric fields couple to adjacent magnetic fields, and magnetic fields couple to adjacent electric fields. Electric-field and magnetic-field inductions cause adjacent electric-field line points to attract, like molecule electric forces. Pushing electric-field line sideways adds potential energy. Electric-field and magnetic-field inductions make restoring force that transfers potential to kinetic energy.

Electric-field-line-point transverse disturbance displaces adjacent points, which displace their adjacent points, so disturbance travels outward along electric-field line. Electromagnetic interactions are at light speed, so wave has light speed. Wave takes energy with it, so no energy is left at original disturbance point, and it no longer oscillates. After disturbance, electric-field and magnetic-field mutual-induction restoring force brings displacement back to equilibrium at zero.

metal plate

Plate-molecule electric force decelerates electron and so decelerates electric-field line and magnetic-field line at electron edge, transverse to motion direction.

electric and magnetic forces

When electric-field-line disturbance reaches test charges far away from original charge, test charges move along charge-motion direction, because transverse electric field is voltage and electromotive force. Electric-field change and magnetic-field change reach test charge at same time. Magnetic-force effect is one-hundredth electric force. For far-away test charges, radial electric force is smaller than disturbance force, because radial force decreases with distance squared but transverse force decreases with distance. Original-charge velocity and acceleration have only negligible effect on far test charges, because waves move at light speed but charges move much slower.

Test charges along accelerating-charge direction have no transverse effects, because push or pull is in same direction as accelerated charge.

not stationary

Stationary oscillating electromagnetic fields cannot exist, because electromagnetic induction requires field movement. Standing waves result from traveling-wave superposition.

medium

Light needs no medium, because electric/magnetic fields are their own medium.

situations: antenna

Alternating current accelerates many charges back and forth along one orientation (antenna), making transverse electric-field waves that expand in planes that go through acceleration direction. Electric-field lines transverse to oscillation direction have maximum transverse component. Electric-field line along oscillation direction has no transverse components. Electric-field lines between transverse and oscillation direction have decreasing transverse component.

Electric-field change causes magnetic-field change one quarter cycle later, by relativistic length contraction, and magnetic-field change causes electric-field change one quarter cycle later, by relativistic length contraction, so phases lag each other by 90 degrees. If magnetic-field gradient first increases to north, then electric-field gradient increases to east, then magnetic-field gradient increases to south, then electric-field gradient increases to west, and then magnetic-field gradient increases to north, and so on, because each drives the other along by transverse electric force. Inductions are at right angles, rotating around direction of motion by 90 degrees. 90-degree rotations result in linearly polarized waves.

Source charge accelerations affect electric and magnetic fields at same time, so changing electric field makes magnetic field and changing magnetic field makes electric field simultaneously, so electric field and magnetic field are always in phase.

As electric field increases, magnetic field increases, because magnetic fields are relativistic effects of electric fields. As electric field decreases, magnetic field decreases. When electric field maximizes, becomes zero, or maximizes in opposite direction, magnetic field maximizes, becomes zero, or maximizes in opposite direction. Magnetic-field and electric-field changes increase and decrease in synchrony (phase), because both fields couple. Transverse magnetic-field and electric-field accelerations are equal, in phase, and perpendicular.

When electric field and magnetic field are zero, and potential energy is zero, electric-field change and magnetic-field change maximize in space and time. When electric field and magnetic field maximize, and potential energy maximizes, electric-field change and magnetic-field change are zero in space and time. When electric-field change is zero and electric field maximizes, voltage maximizes and current is zero. When electric-field change maximizes and electric field is zero, voltage is zero and current is zero. When magnetic-field change is zero and magnetic field maximizes, voltage is zero and current maximizes. When magnetic-field change maximizes and magnetic field is zero, voltage maximizes and current is zero.

Fields elastically exchange potential and kinetic energy and make harmonic oscillations. Photons continue at same frequency.

Starting from stationary charge, voltage accelerates charge and adds kinetic energy. Increasing magnetic field increases electric field until increasing electric field has slowed increasing magnetic field and both are maximum, with potential energy maximum. The slower changing electric field decreases magnetic field, which decreases electric field, so both fall in phase, as potential energy becomes kinetic energy. As kinetic energy becomes potential energy in the opposite direction, and then potential energy becomes kinetic energy, the half-cycle repeats in the opposite direction, to complete one cycle. Oscillating current repeats the cycle, and the cycles move outward at light speed. Oscillating current induces electromagnetic waves of same frequency.

Light waves have electric-field and magnetic-field linear polarizations, at right angles. Electric field oscillates in plane that goes through charge-motion direction. Magnetic field oscillates in plane perpendicular to charge-motion direction.

Leading edge of wave rises transversely at angle determined by frequency, which depends on deceleration amount. Higher frequencies have steeper angles. Higher frequencies have greater curvatures at maximum displacement, because higher frequency means turnaround is faster.

situations: dipoles

For dipoles, charge acceleration increases as charge separation increases.

situations: atoms

Atom and molecule electrons can accelerate or decelerate and so change orbits, absorbing or making radiation. Molecule dipoles can rotate, vibrate, or translate, and so accelerate electrons, absorbing or making radiation.

situations: devices

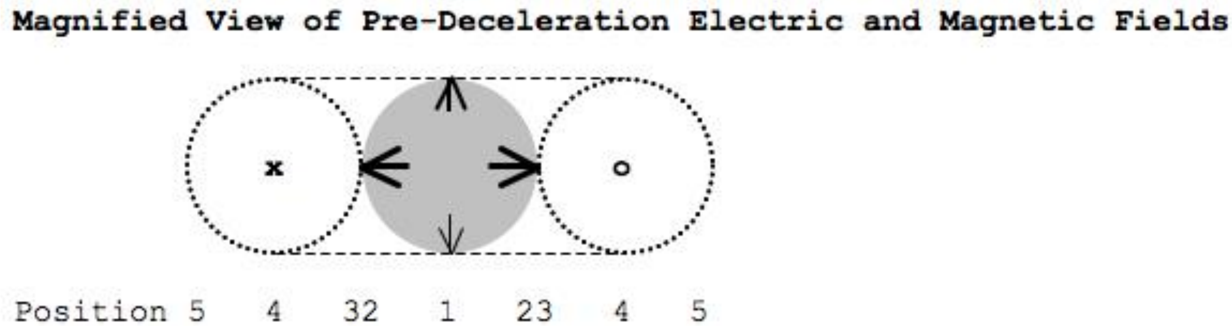
Free charges in electric and magnetic fields accelerate free charges, as in vacuum tubes. When moving electrons hit metal plates, they decelerate and can make x-rays.

Figure 1
Time 0 - Constant-Velocity Electron, with No Electromagnetic Waves

At position 1, before stopping at metal plate, electron (gray) travels vertically downward at constant velocity. Its electric and magnetic fields have the same constant velocity. Electric field and magnetic field begin at electron edge, which emits virtual photons.

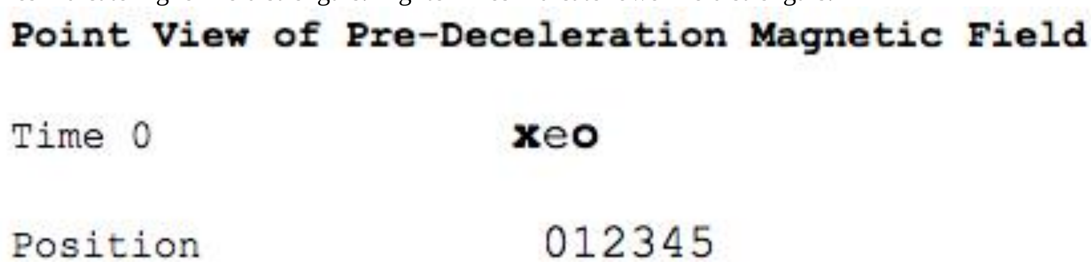
Relativistic length contraction makes electric field (arrows) appear stronger horizontally (positions 2) to observer. Electric field appears weaker vertically (position 1) to observer. Vertical electric field is foreshortened in motion direction. Vertical electric field is lengthened opposite to motion direction.

Positions 5 through 3 and 3 through 5 have adjacent magnetic force as a torus around moving electron. Electron has negative charge, so magnetic field is out on left and in on right, by right-hand rule.

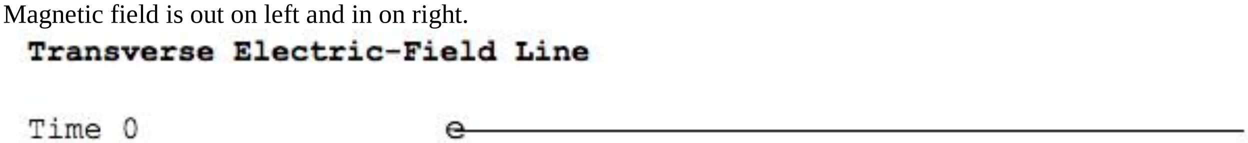


Observation line is through electron center, perpendicular to vertical-motion line.

x's represent points, as vectors coming out of paper plane. Circles represent points, as vectors going into paper plane. Displayed vectors indicate electric-field push/pull direction. They have no spatial length through space.
Bolder lines indicate higher field strengths. Lighter lines indicate lower field strengths.



Magnetic field is out on left and in on right.



Virtual photons stream straight outward at light speed from electron in all directions.

Figure 2
Time 1 - Deceleration Begins, and Kinetic Energy Changes to Potential Energy

At position 1, force causing electron deceleration also puts transverse upward pushing force on field lines and distorts electric-field lines.

At position 1, as electron slows down, electric-field upward transverse component increases over time. Position-1 has induced magnetic field. Position-2 begins induced magnetic field.

At position 1, induced magnetic field increases over time. Position-1 has induced electric field. Position-2 begins induced electric field.

At positions 2 and higher, horizontal electric-field lines continue moving at constant velocity. Transverse electric-field-line component stretches downward. Transverse electric-field-line component moves outward at light speed.

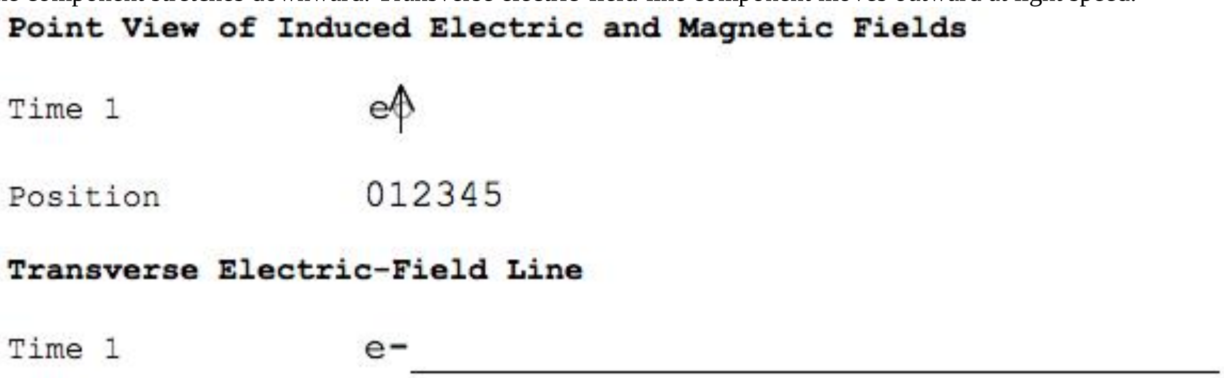


Figure 3
Time 2 - Deceleration Middle - Restoring Force Changes Kinetic Energy into Potential Energy

At position 1, as electron slows down more, electric-field-line points at electron edge slow down more, so horizontal electric-field lines have greater transverse component.

At position 1, electric-field upward transverse component increases over time and so makes induced-magnetic-field gradient. Position-1 has bigger induced magnetic field. Position-2 has induced magnetic field.

At position 1, induced magnetic field increases over time and so makes induced-electric-field gradient. Position-1 has bigger induced electric field. Position-2 has induced electric field.

At position 2, position-1 electric-field upward transverse component increases over time and so makes induced-magnetic-field gradient. Position-2 has induced magnetic field. Position-3 begins induced magnetic field.

At position 2, position-1 induced magnetic field increases over time and so makes induced-electric-field gradient. Position-2 has induced electric field. Position-3 begins induced electric field.

At positions 3 and higher, horizontal electric-field lines continue moving at constant velocity. Transverse electric-field-line component stretches farther downward. Transverse electric-field-line component moves outward at light speed.

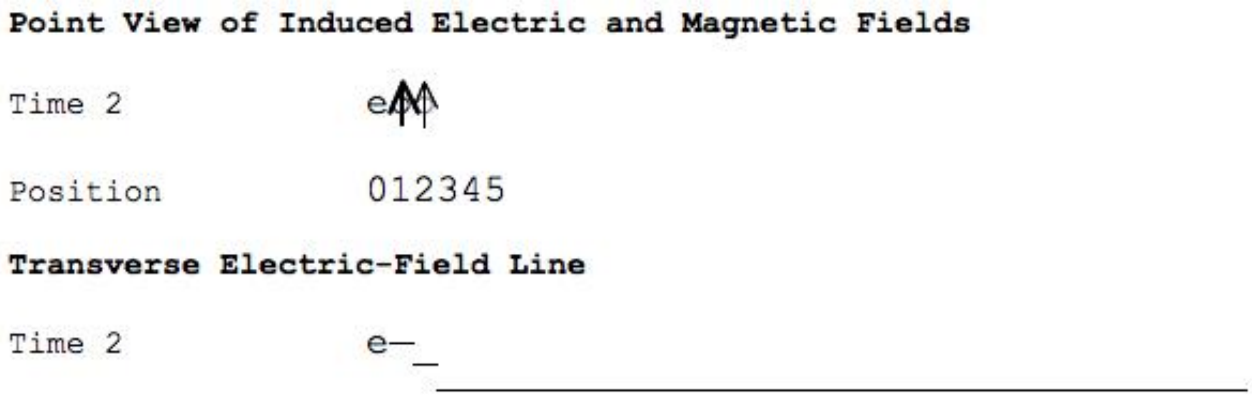


Figure 4
Time 3 - Deceleration End - Restoring Force Changes All Kinetic Energy into Potential Energy

Metal plate stops electron within one electron width.

At position 0, electron is at zero velocity, original electric field is symmetric, and original magnetic field is zero.

At position 1, electric-field-line ends stop, so horizontal electric-field lines have maximum transverse component.
At position 1, electric-field upward transverse component has increased to maximum over time and so makes induced-magnetic-field gradient. Position-1 has biggest induced magnetic field. Position-2 has induced magnetic field.
At position 1, induced magnetic field has increased to maximum over time and so makes induced-electric-field gradient. Position-1 has biggest induced electric field. Position-2 has induced electric field.

At position 2, position-1 electric-field upward transverse component increases over time and so makes induced-magnetic-field gradient. Position-2 has big induced magnetic field. Position-3 has induced magnetic field.
At position 2, position-1 induced magnetic field increases over time and so makes induced-electric-field gradient. Position-2 has big induced electric field. Position-3 has induced electric field.

Position 3 is like position 2 in Figure 3.

At positions 4 and higher, horizontal electric-field lines continue moving at constant velocity. Transverse electric-field-line component stretches farther downward. Transverse electric-field-line component moves outward at light speed.

Point View of Induced Electric and Magnetic Fields

Time 3 e

Position 012345

Transverse Electric-Field Line

Time 3 e—_
_
____

Figure 5
Time 4 - After Deceleration End - Transverse Electric-Field-Line Component Stretches

At position 1, transverse electric-field stays constant at zero.
At position 1, transverse magnetic field stays constant at zero.
At position 1, electron and electric-field line have no velocity.
At position 1, virtual photon travels horizontally at light speed.

Position 2 is like position 1 in Figure 4.

Position 3 is like position 2 in Figure 4.

Position 4 is like position 3 in Figure 4. Gradient and wave leading edge travel outward at constant light speed.

At positions 5 and higher, horizontal electric-field lines continue moving at constant velocity. Transverse electric-field-line component stretches downward. Transverse electric-field-line component moves outward at light speed.

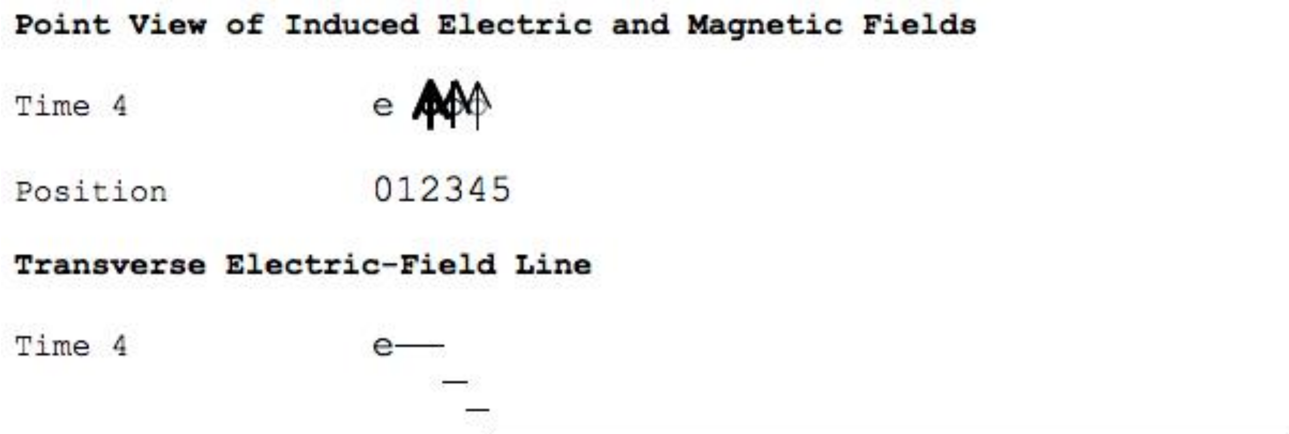


Figure 7
Time 6 - Traveling Half-Wave

Position 1 is like position 1 in Figure 6.

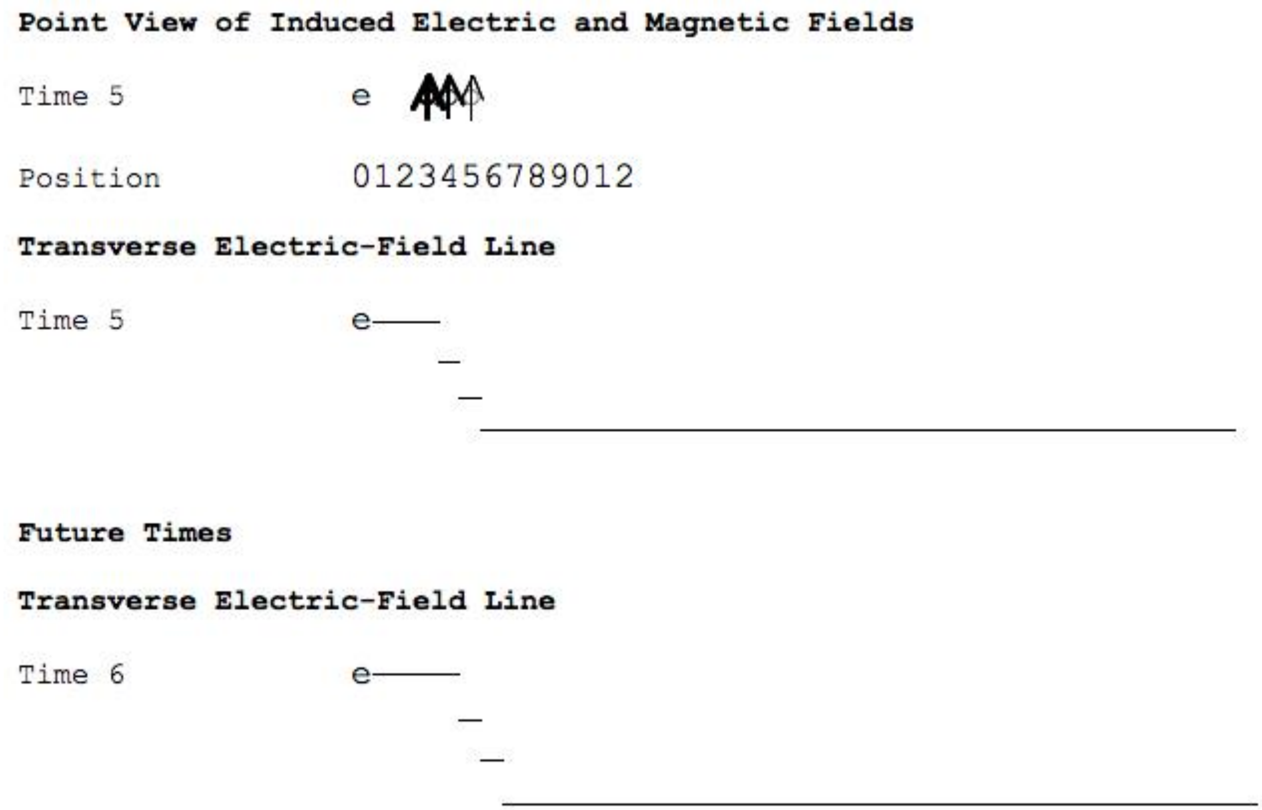
Position 2 is like position 1 in Figure 6.

Position 3 is like position 2 in Figure 6.

Position 4 is like position 3 in Figure 6.

Position 5 is like position 4 in Figure 6. Gradient and wave leading edge travel outward at constant light speed.

At positions 6 and higher, horizontal electric-field lines continue moving at constant velocity. Transverse electric-field-line component stretches farther downward. Transverse electric-field-line component moves outward at light speed.



Times 6 and up continue same pattern as at Time 5, because all interactions are elastic.

initiation and propagation

Electric-charge accelerations start electromagnetic waves {wave initiation} {initiation, wave}, because force makes radial electric field have transverse component adjacent to charge. Transverse component travels outward along electric-field line {wave propagation} {propagation, wave}, because electric-field (and magnetic-field) changes interact at light speed, because electromagnetic force is strong. Waves travel away from charges, because all energy travels outward, so no energy is left behind, and only wave leading edge (wave front) exists at any time. Wave has kinetic energy directly proportional to force that caused charge acceleration.

charge: stationary

Stationary charge makes constant electric field and no magnetic field. See Figure 1.

charge: moving

Charge moving at constant speed makes moving electric field and constant magnetic field. See Figure 2. Magnetic field is perpendicular to electric field, because magnetic field comes from relativistic length contraction that causes increased charge density along charge-motion direction, which observers see from side.

charge: acceleration

Accelerating charge increases current, because charge speed increases. Increasing current makes increasing magnetic field. Accelerating charge makes faster moving electric field. See Figure 3. (Decelerating charge decreases current, decreases magnetic field, and makes slower moving electric field.)

initiation

As charge accelerates, electric and magnetic fields accelerate, and magnetic field increases. See Figure 4.

propagation

Electric-field (and magnetic-field) change cause magnetic-field (and electric-field) gradient, by Maxwell's laws, so electric and magnetic fields interact. Interaction is at light speed. See Figure 5.

When induced electric field and magnetic field reach far-away test charge, electric-field vertical component accelerates test charge. See Figure 6.

When induced electric field and magnetic field pass far-away test charge, test charge continues at constant velocity. See Figure 7.

propagation: direction

Electromagnetic-induction is only at wave front, because all energy is there. Behind wave front, electric and magnetic fields return to zero, as fields, coming from many points with all phases, cancel. Waves propagate outward from accelerated charge, because electromagnetic-induction electric and magnetic fields behind have all phases and cancel.

propagation: no medium

Electromagnetic waves can propagate through empty space, because electric and magnetic fields are their own medium.

propagation: induction rate and wave speed

Electric-force strength determines electromagnetic-induction rate, which is light speed. Material electric charges, relativistic apparent electric charges, other electric fields, and other magnetic fields exert force on electromagnetic waves, and so reduce electromagnetic-wave speed.

Unaccelerated Charge Makes No Electromagnetic Wave

Unaccelerated moving charge makes moving constant electric field and constant concentric magnetic field. See Figure 4. No acceleration makes no force, so fields stay constant. Only radial force affects test charge, so it has no transverse motion.

Charge Acceleration Makes Traveling Electric Field

See Figure 5. Collision, gravity, or electric force can accelerate charge. Acceleration makes force, so fields change. Acceleration is transverse to radial electric-field line, so test charge has transverse motion. See Figure 6.

pure electric waves

There are no pure electric non-magnetic waves, because waves require electric-field changes, which always make transverse relativistic electric fields, which are magnetic fields. There are no pure magnetic non-electric waves, because waves require magnetic-field changes, which always make transverse relativistic electric fields.

Figure 1

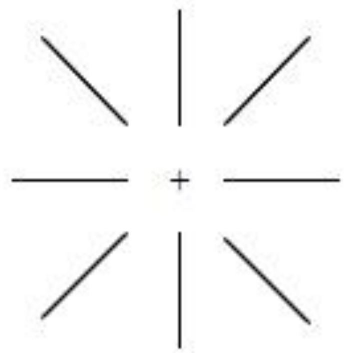


Figure 2

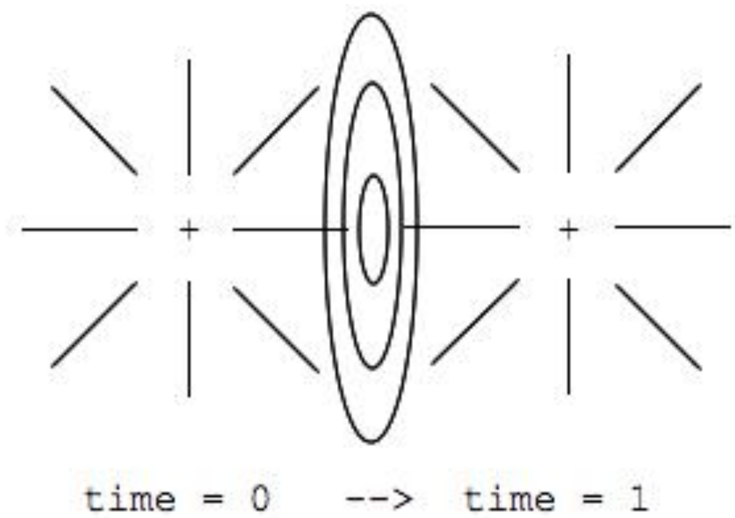
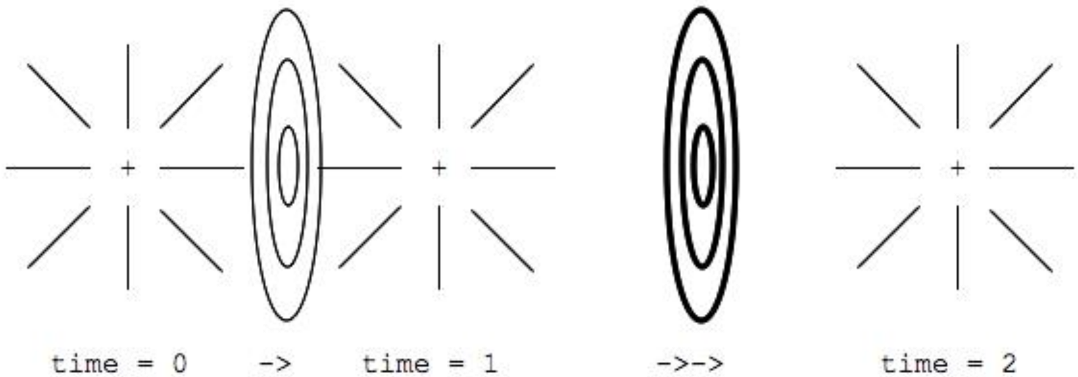


Figure 3

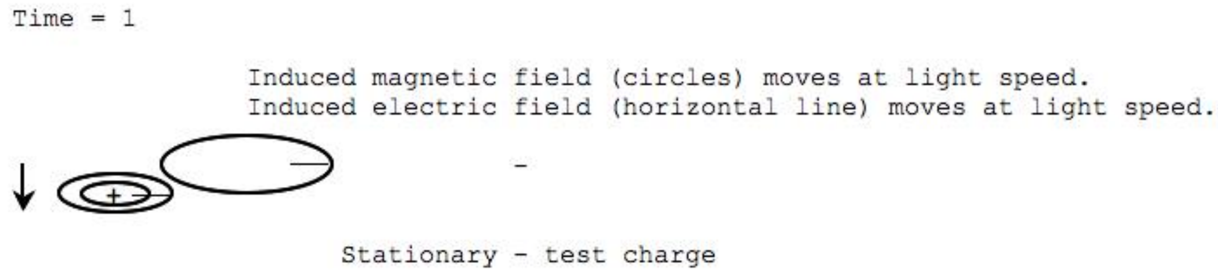


Note: Bolder lines indicate greater field strength.

Figure 4

+ charge begins to accelerate downward.
Electric field (horizontal line) starts to shift downward.
Magnetic field (circles) starts to increase, as current increases.

Figure 5



+ charge has moved downward.
Acceleration has stopped, at higher velocity.
Magnetic field (circles) has increased and moved downward.
Electric field (horizontal line) has moved downward.

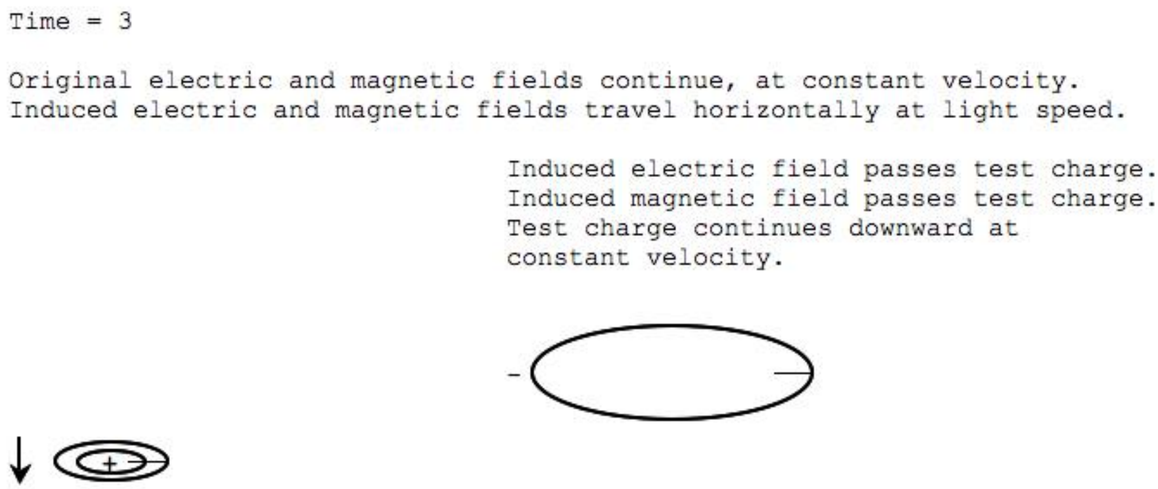
Figure 6

Time = 2

Original electric and magnetic fields continue, at higher constant velocity.
Induced electric and magnetic fields travel horizontally at light speed.

Induced electric field reaches test - charge.
Test - charge accelerates downward.
Induced magnetic field reaches test - charge.
Test - charge accelerates downward,
by right-hand rule.

Figure 7


Time = 3
Original electric and magnetic fields continue, at constant velocity.
Induced electric and magnetic fields travel horizontally at light speed.
Induced electric field passes test charge.
Induced magnetic field passes test charge.
Test charge continues downward at
constant velocity.
-
+

light

Waves {light}| {electromagnetic wave} can begin by charge accelerations or electronic transitions and propagate by electromagnetic induction. Charge-acceleration or electronic-transition energy change determines electromagnetic-wave frequency.

far field

Accelerating charge makes a photon field, which differs near source {near field} and far from source {far field}. Far field is what lenses, mirrors, and instruments see. Point charges or nearby detectors can examine near field.

Maxwell equations

Equations {Maxwell's equations} {Maxwell equations} can find all electric and magnetic properties. For stationary and moving charges, electric-field and magnetic-field relations are Gauss's law, Gauss's law for magnets, Faraday's law, and Ampere's law.

stationary

Partial derivative of electric field with distance equals negative of partial derivative of magnetic field with time. Partial second derivative of electric field with distance equals electric permittivity times magnetic permeability times partial second derivative of electric field with time.

tensors

Maxwell's equations are equivalent to two equations. For magnetostatics and magnetodynamics equations, exterior derivative of electromagnetic-field tensor F equals zero: $dF = 0$. Electromagnetic-field tensor is a linear operator on velocity vector. Electromagnetic-field tensor has covariant components. This tensor is equivalent to delta function. For electrostatics and electrodynamics equations, exterior derivative of electromagnetic-field-tensor dual F* equals four times pi times four-current dual J*: $dF^* = 4 * \pi * J^*$. This tensor is equivalent to delta scalar product.

current

The four-current has one component for charge density and three components for current densities in three spatial directions.

duals

Rank-x antisymmetric tensors relate to rank 4 - x antisymmetric tensors {dual, tensor}. Dual of dual gives original tensor, if rank is greater than two.

invariant

Electromagnetism invariant is current squared minus light speed times charge density squared, which equals negative of momentum times light speed squared.

retarded and advanced

Electromagnetic-field changes follow charge accelerations {retarded solution}. However, field changes can happen before charge accelerations {advanced solution}, because equations are symmetric. Other solutions can be linear retarded-solution and advanced-solution combinations.

light speed

Light speed {speed of light} {light speed}| is the same relative to any observer, moving or not. Light speed is invariant and absolute, in space with no electric fields.

speed

Light speed depends on electric-force strength, which determines electromagnetic-induction strength. In vacuum, light speed is 3.02×10^8 m/s (Hippolyte Fizeau and Bernard Foucault) [1849]. Light speed is fast, because electric forces are strong. All zero-rest-mass particles travel at light speed, because added energy does not affect them. Gravity does not affect zero-rest-mass particles.

space

Light does not travel through time, because it has no medium and so no reference frame or space-time. Light only travels through space, not time. Light has zero time.

cause

Observers see invariant speed, because light never has time component and so cannot go slower. Light cannot go faster, because it uses all of space already. When observers see light, light length appears to be zero and time appears to be at maximum dilation. Observer motion does not affect light speed observed, because light has no medium. Observer motion contracts length and dilates time, but light already has maximum length and shortest time. If observer moves at higher velocity, both time dilation and space contraction happen, so light speed stays the same.

space-time velocity

All objects travel through space-time at light speed. Light travels only in space. Stationary objects travel only in time. Moving masses travel in space and time.

terminal velocity

Light speed is like terminal velocity through space-time. Electromagnetic induction pushes wave, and forces in universe retard wave. Resistance to light motion can come from effects of all universe masses and charges.

mass

No object with mass can go faster than light. For mass at light speed, stationary observers see infinite mass, zero length, and zero time. To make infinite mass requires infinite energy. Infinite mass exerts infinite gravitational force. Infinite mass attracts and red-shifts light, dimming universe. Infinite mass, moving at light speed, appears to have infinite frequency and zero wavelength.

phase velocity

Light pulses contain wave sets. Light-pulse envelope carries energy. Envelope speed {group velocity} must be light speed or less. However, individual waves can have speed higher or lower than light speed {phase velocity}. Negative refraction cannot exist.

luminiferous ether

Perhaps, light travels in a stationary medium {luminiferous ether} {the ether} {æther}, not vacuum. As such, because light has constant velocity in any reference frame, æther is an absolute reference frame. It is fluid but does not disperse, has no viscosity, and has high tension and is rigid. It has zero rest mass and is transparent, continuous, and incompressible. Perhaps, it appears rigid to high-velocity objects or high-frequency waves but fluid to low velocity objects or low-frequency waves. Michelson and Morley [1887] measured interference of light traveling in Earth-motion direction and in opposite direction {Michelson-Morley experiment} and found no interference and no Doppler effect, leaving no physical properties to ether and so indicating that there was no ether.

photoelectric effect

Light can carry enough electric energy to knock electrons out of atoms {photoelectric effect}|. If light frequency is below threshold for material, atoms emit no electrons, because photoelectric effect requires minimum energy. Light with higher frequency than threshold imparts more speed to liberated electrons but does not emit more electrons. Higher-intensity light, which has more photons with enough energy, makes more electrons leave.

radiation entropy

Radiation has entropy {entropy, radiation} {radiation entropy}. If space is isotropic and unpolarized, entropy S equals four times energy U divided by three times temperature T: (4*U) / (3*T). If system has more wavelengths or more directions, radiation entropy increases. Universe can absorb radiation and everything else without limit, so entropy continually rises.

PHYS>Physics>Wave>Electromagnetic>Photon

photon of light

Light has subatomic particles {photon, light}|. Photon is like wave packet. Continuous light {light ray} {ray, light} is many wave packets.

straight

Light rays and photons travel in straight lines.

energy

Photon energy E is frequency v times Planck constant h: E = h*v.

observers

What do people see as photon goes past? In empty space, people see particle contracted to zero length, with no mass but with frequency and wavelength. People see time standing still on photon.

What does photon see? In empty space, photon travels at light speed. Other objects pass by at light speed, with infinite mass and zero wavelength. Photon sees time as standing still on other things. Photon sees only point straight-ahead, and sees nothingness on sides, so photon sees along one-dimensional line.

plasmon

Light can travel in two dimensions {plasmon}| and so travel in plane. Photons that hit interface between conductor and insulator induce surface electrons to vibrate at same or similar frequency and cause traveling wave. Wave reflections make resonances. Plasmons {plasmonics} can have same or shorter wavelength as impinging light.

PHYS>Physics>Wave>Electromagnetic>Intensity

illuminance

Light intensity {illuminance}| is light flux (in lumens) per area. Light intensity depends on amplitude squared, photon number, and frequency squared.

Poynting vector

Light intensity {Poynting vector} has maximum of half times light speed times permittivity e times electric field E squared: 0.5 * c * e * E^2. Poynting vector equals half times electric field E times magnetic field H: 0.5 * E * H.

Kerr effect

At high intensity, wave electric field can affect molecule electric fields {Kerr effect} {optical Kerr effect}.

radiation pressure

Radiation has pressure {radiation pressure} {pressure, radiation} from photon flow. Pressure P equals energy U divided by three times volume V: P = U / (3*V).

photometer

Light meters {photometer}| can measure light intensity.

PHYS>Physics>Wave>Electromagnetic>Frequency

radiation frequency

Radiation has frequency {radiation frequency}.

PHYS>Physics>Wave>Electromagnetic>Frequency>Radiation Types

Bremsstrahlung radiation

Deceleration as electrons hit metal makes radiation {Bremsstrahlung radiation}| with wavelength 10^-12 meters.

Cerenkov radiation

Beta-particle electrons, with velocity higher than light speed in water, emit blue light {Cerenkov radiation}| {blue glow} as shock waves when they enter water. Water surrounding nuclear-reactor cores, which emit high-velocity electrons, has blue glow.

process

Electrons traveling in water use some energy to polarize water molecules along travel direction. After electrons pass, polarized water molecules emit light. If electrons travel slower than light speed in water, emitted radiation appears low, because electromagnetic waves emitted by molecules along path are random and destructively interfere. If electrons travel faster than light speed in water, emitted radiation appears high because electromagnetic waves emitted by molecules along path are shock waves that constructively interfere.

Raman scattering

Infrared-light rotational and vibrational energies cause differences in visible light reflected from molecules {Raman scattering}|.

spallation

In atmosphere, secondary cosmic rays {spallation}| arise if cosmic ray hits atomic nucleus.

synchrotron radiation

Charged particles accelerated by spiraling in magnetic field can emit microwaves {synchrotron radiation}|. Synchrotron radiation happens when electric field is parallel to electron-orbit plane.

PHYS>Physics>Wave>Electromagnetic>Frequency>Radiation Types>Spectrum

spectrum

Electromagnetic radiation has frequency range and wavelength range {spectrum, light}|.

low frequency

electric wave. radio wave. short wave. very-high-frequency TV wave. ultra-high-frequency TV wave. microwave radiation. infrared ray.

visible

Visible light is 4 x 10^14 Hz with wavelength 6.8 x 10^-7 meters for red light, orange, yellow, wavelength 5.5 x 10^-7 meters for yellow-green, green, wavelength 4.4 x 10^-7 meters for blue light, indigo or ultramarine, and 7.5 x 10^14 Hz with wavelength 4.1 x 10^-7 meters for violet light.

Violet is 380 to 435 nanometer, with middle at 408 nanometer. Blue is 435 to 500 nanometer, with middle at 463 nanometer. Cyan is 500 to -520 nanometer, with middle at 510 nanometer. Green is 520 to 565 nanometer, with middle at 543 nanometer. Yellow is 565 to 590 nanometer, with middle at 583 nanometer. Orange is 590 to 625 nanometer, with middle at 608 nanometer. Red is 625 to 740 nanometer, with middle at 683 nanometer.

high frequency

near ultraviolet. ultraviolet. far ultraviolet. X ray. gamma ray. secondary cosmic ray. cosmic ray. primary cosmic ray.

electric wave

Smallest frequencies and longest wavelengths {electric wave}| are 3 to 60 Hz and 10^8 to 5 x 10^6 meters.

radio wave

Next smallest frequency and wavelength {radio wave}| are 10^3 Hz and 3 x 10^5 meters.

short wave

High-frequency radio waves {short wave}| are for global communication.

very high frequency

Typical TV frequencies and wavelengths {very high frequency TV wave}| (VHF) are 10^8 Hz and 3 meters.

ultra high frequency

higher TV frequencies and wavelengths {ultra high frequency TV wave}| (UHF).

microwave

frequencies below infrared {microwave radiation}|.

infrared light

Heat-ray {infrared}| frequency is 10^12 Hz, with wavelength 3 x 10^-4 meters.

visible light

Light {visible light}| can have wavelength 400 nm to 700 nm. Visible light has same wavelengths as diameters of, and energy changes in, atoms and molecules. Matching diameters allows people to focus on objects, because light is not too diffracting or too strong. Matching energy changes allows absorption, emission, and chemical reactions.

red light

Smallest visible-light frequency {red light}| is 4 x 10^14 Hz, with wavelength 6.8 x 10^-7 meters.

violet light

Highest visible-light frequency {violet light}| is 7.5 x 10^14 Hz, with wavelength 4.1 x 10^-7 meters.

ultraviolet

higher frequency than violet {ultraviolet}|.

far ultraviolet

Light {far ultraviolet}| {black light} can have frequency 1.5 x 10^15 Hz and wavelength 2 x 10^-7 meters.

X ray

higher frequency than far ultraviolet {X ray}| {x ray}.

gamma ray

Next-to-highest frequency {gamma ray, spectrum}| is 10^23 Hz, with wavelength 3 x 10^-15 meters.

cosmic ray

Highest frequency {cosmic ray}| {primary cosmic ray} is 10^25 Hz, with wavelength 3 x 10^-17 meters. Quasars and powerful energy sources make cosmic radiation.

PHYS>Physics>Wave>Electromagnetic>Frequency>Color

monochromatic

Light {monochromatic light}| can have one wavelength.

polychromatic

Light {polychromatic light}| can have many wavelengths.

primary pigment

Magenta, yellow, and green pigments {primary pigment}| mix to make black.

dichroism

Variations {dichroism}| in absorbed-light color can depend on light-polarization direction. Dichroism indicates molecule orientation, which can be linear, circular {circular dichroism}, or elliptical. Microvilli rhabdom can lie parallel, exhibit dichroism, and detect polarized-light polarization plane.

PHYS>Physics>Wave>Electromagnetic>Polarization

polarization

If one photon accelerates, light-wave electric field vibrates in one plane {plane polarized wave} {polarized light}, and light-wave magnetic field vibrates in perpendicular plane {polarization, wave}|. Typically, many charges accelerate in all possible planes, so there is no polarization.

materials

Materials can allow only light with one electric-field plane to transmit. Polaroid plastic and tourmaline can polarize light.

circular

Asymmetric-molecule electric forces cause substances to rotate electric-field planes {circularly polarized wave} around light travel direction.

PHYS>Physics>Wave>Electromagnetic>Polarization>Dispersion

dispersion of light

Optical activity can vary with light frequency {dispersion, light}|. Higher frequencies cause more rotation, because photons have more energy.

Cotton effect

If polarized light with different wavelengths passes through asymmetric medium, shorter wavelengths rotate plane more than longer wavelengths {optical rotatory dispersion} {Cotton effect}.

optical activity

Materials with asymmetric-molecule electric forces can have refractive index different for left and right circularly polarized light {optical activity}|. Carbon can bond four different atoms, in two mirror-image forms.

PHYS>Physics>Wave>Electromagnetic>Action

Fermat principle

Light takes shortest path, and so least time, between two points {Fermat's principle} {Fermat principle}.

least-action principle

Action is energy times time, or momentum times distance, or angular momentum times angle. Light uses path with least action between two points {Hamilton's principle} {principle of least action, Hamilton} {least-action principle, light}|. In quantum mechanics, action has quanta, which have size Planck constant h, so photons have energy quanta h * frequency, momentum quanta h / wavelength, and angular-momentum quanta h / 2 * pi.

PHYS>Physics>Wave>Electromagnetic>Coherence

coherent light

Lasers produce light waves {coherent light}| that have same phase.

collimate

Light passed through consecutive slits {collimate}| has many light waves in phase.

laser

Devices {laser}| {Light Amplification by Stimulated Emission of Radiation} can emit many photons in phase [1960].

light source

Flash tube excites atom electrons into highest orbital. Below highest orbital are one or two lower-energy levels, and below them is ground-state level.

light

Electrons spontaneously fall to intermediate-energy level by vibration, rotation, or radiation.

Then previous photon causes electron to fall to next-lower level {lase}, which simultaneously makes another photon, so both photons are in phase and photon number doubles. This process repeats to make many in-phase photons. Lasers can emit light axially or transversely.

collimation

Photons conserve momentum, so they have same direction.

amplitude

Mirrors can build power by repeated lasing and reflecting, until shutter opens {Q switching} and light releases. Shutter can be rotating mirror, Pockels cell, photochemical, or exploding film. Current modulation can modify laser amplitude. Lasers can pulse or be continuous. Laser can be tunable to different light frequencies.

materials

Lasers can use helium-neon, helium-cadmium, argon, krypton, carbon dioxide, and gallium arsenide. Ruby lasers emit red light. Gallium-nitride lasers emit blue light. Zinc selenide can also make blue light.

purposes

Lasers can align exactly, measure distances by reflection from corner reflectors, attach retinas by burning them on, weld, and make holographs. Lasers can separate atom isotopes, by exciting only one isotope. Lasers can measure thickness, drill holes, and carve miniature circuit blocks. Lasers can implode pellet to start nuclear fusion in tube {hohlraum}.

fiber optics

Laser light passed down non-linear optical fiber {microstructure fiber} broadens in wavelength {supercontinuum light}. Light can alter material, which then alters light {self-phase modulation}.

timing

Lasers {mode-locked laser} can make one-femtosecond microwave or light pulses at 1-GHz. Frequencies are visible light within 150-nm wavelength interval. Superposition makes pulses have few wavelengths. Phase {offset frequency} increases slightly with each pulse. Wave-train pulses have higher net frequencies until cycling again, with equal spacing. Pulses are beats, so pulse frequency is lower-frequency frequency difference. Given reference frequency, beat frequency can determine unknown frequency.

hologram

Storing light-wave interference patterns {hologram}| on photographic plates {holograph} allows display of three-dimensional images [Gabor, 1946].

production

Coherent light can shine directly on photographic plate and can reflect from static scene onto plate. Wave-front superposition makes interference pattern that photographic plate can record.

projection

Shining coherent light on or through photographic plate can project scene wave front into space. Plate positions contribute to all image points, whereas photograph points contribute to one image point. Observer sees wave front coming from three-dimensional space, rather than from surface. Observer can view image from different points to see image from different perspectives.

Shining coherent light on part of plate makes whole image but with lower resolution, because number of contributions is less, so standard error is more. Using longer-wavelength coherent light to reconstruct image can magnify image size. Using shorter wavelength coherent-light to reconstruct image reduces image size.