

Index

- Absolute temperature scale, 271, 298–299
 Absolute zero temperature, 271, 281, 298–299
 Absorption of radiation, 639–647, 650
 absorption spectra, 624–626
 Acceleration
 average, 34
 centripetal, 159–162, 180–182, 184–185,
 197–198
 circular motion and, 158–159
 deceleration, 35
 defined, 31
 of gravity. *See* Free fall; Gravitational
 acceleration
 inclined plane experiments, 43–47, 119
 inertial vs. noninertial reference frames and,
 415
 linear motion, 31–37
 net force and, 125
 Newton's second law, 128–132, 431–432, 454
 uniform, 34, 41, 119
 as vector, 34
 Acoustics. *See* Sound waves
 Action at a distance, 187, 579
 Activity, 726–727. *See also* Radioactivity
 Aeolipile, 260
 Aether. *See* Ether
 Agricultural technology, 266
 Air column, standing waves and, 354
 Air pressure, 294–295
 pressure field, 474–475
 pressure–volume relation, 295–297
 temperature–pressure–volume relation (ideal
 gas law), 297–300, 308–312
 Air resistance, 39
 Alkali metals, 588, 652
 Alpha (α) particles
 artificial transmutation of elements and,
 766–767
 identification as helium nuclei, 736–737
 mass of, 736
 “mousetrap” for, 737–738
 nuclear structure and, 764–765
 radioactivity and, 733, 738–743
 Rutherford scattering, 630–635
 size of nucleus and, 636–637
 Alpha Centauri, 4
 Alternating current (AC), 481, 713
 choice as standard, 525–528
 generator and, 513–514, 516
 Altitude (astronomical measure), 63
 Amber, 459–461, 462
 Amorphous solids, 696
 Ampere
 defined, 494
 unit of charge and, 469
 Ampère, André-Marie, 492–494, 516
 Amplitude, of waves, 339
 Amplitude modulation (AM), 565–566
 Analogue wave, 566
 Andromeda galaxy, 4
 Angle of reflection/angle of incidence, 363
 Ångström, Anders Jonas, 391
 Ångström, defined, 391
 Angular momentum, of electron in orbit,
 668–669
 Angular speed, 157
 Anode, 590
 Antenna, 564

- Antineutrino, 775–777
- Antinodal lines, 348–349, 358–360
- Archeology, 755–756
- Archimedes, 59
- Architecture, sound waves and, 372
- Aristarchus, 76
- Aristotle
- free fall and, 39
 - ideas on cosmology, 9–12, 48, 62, 83, 85
 - laws of motion and, 121–122
 - “natural” vs. “violent” motion, 118–119
 - philosophical approach to physics, 9–10, 12–13
- Artificial transmutation of elements, 766–769
- Artwork, 58, 613, 614
- Astrology, 73
- Astronauts, weightlessness and, 138–140, 155–156
- Astronomy, 57–116
- See also* Stars; Sun; Universe
 - Brahe’s hybrid theory, 91, 106
 - Brahe’s observations, 88–91
 - comets, 200–202
 - Earth’s roundness, 64–65
 - eclipses, 69
 - electromagnetic spectrum and, 573
 - experimental tests of relativity theory and, 436
 - Galileo’s telescope observations and his conclusions, 102–109
 - geocentric theory, 61–62
 - Greek concepts of, 9–12, 48, 62, 83, 85
 - heliocentric theory, 59–60, 76–86, 106–109
 - Kepler’s laws of planetary motion, 94–102
 - Moon’s phases, 69–70
 - observations in antiquity, 63–74
 - period-radius relationship for planets, 81–82
 - positions of the Moon and Sun, 63–64, 67–69
 - projectile motion and moving-Earth hypothesis, 146–150
 - Ptolemaic system, 75–76, 83, 85, 86, 106–108
 - seasons and, 67–69, 77
- Atmosphere
- blue sky, 390–392
 - refraction and, 369
- Atom
- See also* Atomic physics
 - evidence for existence of, 457–458
 - Greek concepts of, 7–8, 453, 457
- Atomic bomb, 439–440, 605, 799–805
- Atomic mass, nuclear binding energy and, 781–782, 786
- Atomic mass number, 749, 751–753, 764, 773–774
- Atomic mass unit, 586–587, 749
- Atomic number, 588, 749–751
- Atomic physics, 585–619, 621–660
- See also* Nuclear physics; Quantum mechanics
 - Bohr’s atomic structure model. *See* Bohr’s atomic structure model
 - cathode rays and, 590–594
 - Einstein’s light-quantum hypothesis, 602–608, 639, 662
 - energy of stationary states, 641–647
 - energy quanta, 606–607, 639, 662
 - excitation of atoms, 642, 647–648, 650
 - Franck–Hertz experiment, 646–648, 650
 - hydrogen spectrum, 626–630, 640–647
 - nuclear charge and size, 635–637
 - orbital radii, 640–642
 - periodic table, 585–590, 648–649, 652–653
 - photoelectric effect, 598–608
 - Rutherford’s atomic structure model, 630–637
 - smallest charge determination, 593–596
 - spectroscopy and, 621–626
 - summary of equations, 656–657
 - Thomson’s atomic structure model, 596–598, 630–631
 - uncertainty principle and the size of atoms, 677–678
 - X rays and, 608–616
- AU (Astronomical Unit), 81
- Aurora borealis, 498
- Autumn equinox, 68, 77
- Aviation technology, 196–197, 393
- Azimuth (astronomical measure), 63
- Bacon, Francis, 214
- Balmer, Johann Jakob, 626–629
- Balmer lines, 626–629, 643, 645
- Balmer’s formula, 626–629, 642–647
- Band theory of metals, 702–705
- Bardeen, John, 706, 714
- Barometer, 295
- Bartholinus, Erasmus, 393
- Battery
- invention of, 274, 480–481
 - light bulb and, 488
 - voltage of, 486

- BCS theory, 706–707
- Beats, sound waves and, 372
- Becker, H., 769
- Becquerel, Henri, 724, 734, 736, 745
- “Becquerel rays,” 727–728. *See also* Radioactivity
- Bell, Alexander Graham, 536
- Bernoulli, Daniel, 302–303
- Berry, George, 266
- Beryllium, artificial transmutation and, 769–771, 793
- Beta (β) particles
- charge of, 734–737
 - discovery of radioactivity and, 733
 - identification as electrons, 736
 - mass of, 736
 - neutron discovery and β decay, 775–777
 - nuclear structure and, 764–765, 774–775
 - radioactive transformations and, 738–743, 774–775
 - transformation rules and, 749–750
- Binding energy, 780–786
- Biomass energy, 541
- Blake, William, 267
- Bloch, Felix, 673, 702–705
- Blodgett, Katherine Burr, 386
- Blue sky, 390–392
- Bohr, Niels, 670
- atomic structure model. *See* Bohr’s atomic structure model
 - biographical summary, 638
 - complementarity principle, 682–684
- Bohr’s atomic structure model, 637–656, 751
- angular momentum of electron in orbit, 668–669
 - de Broglie waves and, 668–669
 - energy of stationary states, 641–647
 - experimental confirmation of, 646–648
 - ground state, 642
 - hydrogen spectrum and, 640–647
 - limitations of, 654–655
 - orbital radii, 640–642
 - periodic table construction, 648–649, 652–653
 - postulates of, 637–640
 - Schrödinger’s wave mechanics and, 672
 - size of hydrogen atom, 640–642
- Boltzmann, Ludwig, 303, 315, 317, 321, 324
- Born, Max, 670, 673, 681, 683, 684
- Bothe, W. G., 769
- Boyle, Robert, 213, 297, 395, 457
- Boyle’s law, 297, 302
- Brackett series, 629, 643, 645
- Brahe, Tycho, 87
- biographical summary, 88–91
 - hybrid solar system theory, 91, 106
 - Kepler and, 91, 92
 - nova observation, 88
- Brattain, Walter, 714
- Breeder reactors, 800–801
- Bright-line spectra, 622–624, 626–630
- Brown, Robert, 312–313
- Browne, Thomas, 462
- Brownian motion, 312–313, 458
- Bruno, Giordano, 110
- Btu, defined, 257
- Bubble chambers, 498
- Bunsen, Robert W., 624
- Caloric fluid, 253–254
- calorie, defined, 255
- Calorie, defined, 257
- calorie, defined, 257
- Camera obscura*, 375
- Carbon-12, atomic mass unit and, 587
- Carbon dating, 755–756
- Carnot, Sadi, 269–273
- Carnot engine, 270–273, 533–534
- Carroll, Lewis, 28
- Cars
- banked curves and, 160
 - energy consumption of, 529, 535, 537
 - history of industry, 536
- Cathode, 590–591
- Cathode rays, 590–594
- charge of, 592–596, 734
 - fluorescence and, 725
 - magnetic field and, 591–593
- Cathode ray tube (CRT), 567
- Cavendish, Henry, 192
- Cavendish balance, 192–194
- Cayley, George, 196
- CD (compact disc), 717
- Celestial sphere, 9, 10, 63–65
- Cell phones, 564
- Celsius temperature scale, 271, 298
- Central force
- inverse-square law, 179–182, 465–466
 - planetary orbits and, 180–182

- Centripetal acceleration, 159–162
 of Moon, 184–185
 planetary orbits and, 180–182
 of space shuttle, 197–198
- Centripetal force, 159–162
 planetary model of atom and, 637–638
- Cerenkov radiation, 577
- CFCs, 575
- Chadwick, James, 766, 771–773
- Chain reaction, 791–796, 799
- Charge, electric, 462–465
See also Current
 cathode rays and, 592–594, 734
 charge on α , β , and γ rays, 734–737
 Coulomb's law, 468–469, 477–479
 electrostatic induction, 471–472
 magnetic fields and moving charges, 495–498
 Millikan oil drop experiment (determination of smallest charge), 593–596
 nuclear charge, 635–637
 unit of, 469–471, 596
- Chemical energy, 258, 274, 456, 505, 530–531
- Chemistry
See also Dalton; Mendeleev
 Bohr atom and chemical properties, 649, 652–653
 integral proportions for compounds, 457, 585–586
 Lavoisier and, 215–217
- Circuits, 481, 521, 523
- Circular motion, 156–162
See also Centripetal acceleration; Centripetal force
 acceleration and, 158–159
 frequency, 157
 period, 156–157
 speed and, 157–158
 velocity and, 157–158
- Clausius, Rudolf, 281, 293, 303, 305, 307
- Clockwork universe, 100, 313, 455
- Closed systems
 conservation of energy and, 273
 conservation of mass and, 215, 217
 conservation of momentum and, 226
 entropy and, 314, 317–319
- Cloud chamber, 767–768
- Coal, as fuel, 530–531
- Coil
 generator and, 509–516
 induction coil and electromagnetic waves, 561–563
 transformer and, 526
- Cold War, 802–804
- Collisions
 artificial transmutation of elements and, 766–767
 discovery of neutron and, 771–773
 elastic, 227–231, 242–243, 320–321, 647–648
 excitation of atoms and, 647–648, 650
 fission and, 790
 Franck–Hertz experiment, 646–648, 650
 inelastic, 232, 650–651
 kinetic energy conservation and, 229–232
 momentum conservation and, 217–222
 reversibility paradox and, 320–321
- Color, 386–392
 blue sky, 390–392
 “body” vs. “surface” color, 389
 wavelengths of visible light, 574
- Columbus, Christopher, 64
- Comets, 200–202
- Communication satellites, 153
- Commutator (generator component), 516, 525
- Compact-disc (CD), 717
- Complementarity principle, 682–684
- Composite bonding, 696–697
- Compton, Arthur H., 663–665
- Compton effect, 664–665, 676
- Computers, 717–719
- Condenser (heat engine component), 262–263, 272
- Conduction band, 704
- Conductors
 Bloch's band theory of metals, 702–705
 classical free-electron model, 700–701
 conducting electrons, 699–701
 convention for current direction, 486
 defined/described, 479
 electron shells and, 652
 Maxwell's electromagnetic theory and, 551–556
- Conservation laws, 211–252
 conservation of energy, 274–278, 457
 early statements of, 274–278
 kinetic energy and, 229–232
 mechanical energy and, 239–243
 neutrino discovery and, 282, 775–777
 neutron discovery and, 771

- conservation of mass, 211–217
- conservation of momentum
 - closed systems and, 226
 - collisions and, 217–222, 227–231
 - derived from Newton's laws, 223–227
 - friction and, 221
 - neutron discovery and, 771
 - for particles, 283
- Constructive interference, 348
- Control rod (reactor component), 796
- Coolidge, William, 615
- Cooper, Leon, 706
- Cooper pairs, 706
- Copenhagen interpretation of quantum mechanics, 684
- Copernicus, Nicolas
 - biographical summary, 59–61
 - conflicts with religious authorities, 85
 - heliocentric theory, 59–60, 76–86, 106–109, 410
 - period–radius relationship for planets, 81–82
 - philosophical approach to physics, 79–80
- Cosmic rays, 437–438
- Cosmology
 - See also* Astronomy; Universe
 - Galileo and, 48
 - Greek concepts of, 9–12, 48, 62, 83, 85
- Coulomb, Charles, 466–468
- Coulomb, defined, 469
- Coulomb's law, 468–469, 477–479
- Counter Reformation, 85, 109
- Cowan, Clyde, 776
- Critical mass, 793
- Crookes, William, 590–592
- CRT. *See* Cathode ray tube
- Crystalline bonding, 696–699
- Curie, Irène, 770
- Curie, Marie, 734, 736
 - biographical summary, 730–731
 - discovery of new elements, 728–733
- Curie, Pierre, 734, 736
 - biographical summary, 730
 - discovery of new elements, 728–733
 - radon discovery, 737
 - temperature of radium sample, 739
- Current
 - See also* Conductors; Generator, electric
 - alternating, 481, 513–514, 516, 713
 - currents acting on currents, 492–494
 - defined/described, 479–481
 - direct, 481, 515–516, 713–714
 - displacement current, 553
 - electromagnetic induction discovery, 507–512
 - magnets and, 488–492, 495–498
 - Maxwell's electromagnetic theory and, 551–556
 - Ohm's law, 486, 499, 699, 701
 - summary of equations, 499
 - transmission systems and, 525–528
 - units of, 469, 494
 - voltage and, 486, 699
- Curves, banked, 160
- Cycles, Universe and, 322–324
- Cyclotron, 439
- Cylinder (heat engine component), 262

- Dalton, John, 457, 585–586
- Dark energy, 205
- Dark-line spectra, 624–626
- Daughter elements, 741–743
- da Vinci, Leonardo, 374, 375
- Davisson, C. J., 667
- Davisson–Germer experiment, 667
- Davy, Humphry, 255, 520
- Debierne, André, 737
- de Broglie, Louis, 665–666
- de Broglie waves, 665–669, 680
- Decay, radioactive. *See* Radioactivity
- Decay rate, 742–746
- Deceleration, 35
- Decibels, 370–371
- Deferent, 75
- Democritus, 7–8, 453
- Density
 - ideal gas law and, 303, 324
 - of medium for wave propagation, 338
- Derham, William, 371
- Descartes, René, 451, 457
 - conservation law debate and, 232
 - ether concept, 182
 - on world machine, 212
- Destructive interference, 348
- Deuterium, 774, 785, 794–795, 805
- Deuteron, 773, 781–782, 809–810
- Dialogue Concerning Two Chief World Systems* (Galileo), 106, 109–110, 149–150

- Diffraction
of electrons, 666–668, 681
of light, 382–386
probability interpretation of quantum mechanics and, 679–681
of sound waves, 373
of water waves, 354–360
wave motion and, 354–360
of X rays, 577, 611–613
- Diffusion, 307
- Digital signals, 566
- Diodes, 710–714
- Dirac, Paul A. M., 670, 671, 673
- Direct current (DC), 481, 515–516, 713–714
and decision to use alternating current as standard, 525–528
- Discorsi* (Galileo), 18, 38–39, 41, 43, 48, 118, 294, 377
- Displacement, wave propagation and, 333–335
- Displacement current, 553
- Doping, 709–710
- Doppler shift, 364
- Double-slit experiments. *See* Two-slit experiments
- Double stars, 202, 436
- DRAM (dynamic random access memory), 717–719
- Drude, Paul, 697–698, 700
- Drude–Lorentz free-electron model, 700–701
- Dynamics, defined, 48, 128
- Dynamo, 512, 513, 517. *See also* Generator, electric
- Dyne, defined, 135
- $E = mc^2$ (Einstein's equation), 433–434, 439, 662, 781
- Earth
age of, 4
global warming, 572–574
ionosphere, 565
knowledge of round Earth in antiquity, 64–65
magnetosphere, 498
projectile motion and moving-Earth hypothesis, 146–150
radius of, 4
- Eastward drift of planets, 71
- Eastward drift of Sun, 67
- Eccentricity of ellipse, 95–97
- Eclipses, 69
- Ecliptic, 67
- Edison, Thomas A., 520–524, 613, 615
- Edison Electric Light Company, 522, 527
- Efficiency, 268–269, 271, 532–534
defined, 269, 271
of power plants, 532–534
- Einstein, Albert
biographical summary, 408–410, 605
Brownian motion and, 313, 458
dark energy and, 205
general relativity theory, 205
light-quantum hypothesis, 662
Maxwell's equations and, 580
Nobel Prize, 602, 606
philosophical approach to physics, 7, 410
photoelectric effect theory, 602–608
on probability in quantum mechanics (“God does not play dice” statement), 685–686
relativity theory, 405–448
on scientific process, 452
separation of fluids of different densities and, 10
specific heat of solids and, 697–699
on theories and their applications, 222
- Einstein's equation $E = mc^2$, 433–434, 439, 662, 781
- Elastic collisions, 227–231, 242–243, 320–321, 647–648
- Elastic potential energy, 238, 240–241
- Electric age, 505–547
See also Electricity; Energy resources
alternating vs. direct current as standard, 525–528
battery invention, 480–481
electric generator, 511–519, 525–528
electric lights, 520–524
electromagnetic induction discovery, 507–512
Faraday's electric motor, 506–507
modern energy consumption, 528–531
motors, 516–519
telephones, 536
transmission systems, 517, 525–528
- Electric field, 477–479, 483–484. *See also* Electromagnetic waves
- Electricity
See also Charge, electric; Conductors; Current; Electric age; Insulators; Resistance; Voltage
Coulomb's law, 468–469, 477–479
early studies of, 459–468

- electric field, 477–479, 483–484
- electric force, 465–471, 477–479
- electric power, 488
- electrodynamics, 463–464
- electrostatic induction, 471–472
- electrostatics, 463–464
- Ohm's law, 486, 499, 699, 701
- summary of equations, 499
- technology and. *See* Electric age
- word origin, 461
- Electric potential energy, 238, 268, 456. *See also* Voltage
- Electrodynamics, 463–464
- Electrolysis, 610–611, 652
- Electromagnetic spectrum, 563–578
 - γ rays. *See* Gamma (γ) rays
 - greenhouse effect, 572–574
 - infrared radiation. *See* Infrared radiation
 - microwaves, 570–571
 - Newton's studies, 386–389
 - ozone depletion and, 575–576
 - radio waves, 564–566
 - ultraviolet radiation, 575–576
 - visible light, 574
 - wavelengths of various types of radiation, 563
 - X rays. *See* X rays
- Electromagnetic waves, 549–584
 - See also* Electromagnetic spectrum
 - ether and, 578–580
 - excitation of atoms and, 648
 - Faraday's suggestion on the nature of light, 549–551
 - Hertz's experimental confirmation of
 - equivalence of light and electromagnetic waves, 560–563
 - Maxwell's principles of, 551–556
 - Maxwell's recognition of light as
 - electromagnetic waves, 559
 - propagation of, 556–560
 - speed of, 557–559
 - as transverse waves, 557
- Electromagnetism
 - See also* Electricity; Electromagnetic waves; Magnetism
 - currents acting on currents, 492–494
 - discovery of effect of currents on magnets, 489–491
 - electric generator, 511–519, 525–528
 - electromagnetic induction discovery, 507–512
 - Maxwell's principles of, 551–556
 - Electron accelerator, 484–485
 - Electron gas, 701
 - Electron gun, 484, 647
 - Electrons
 - See also* Beta (β) particles; Cathode rays
 - angular momentum of electron in orbit, 668–669
 - Compton effect, 676
 - conduction and, 700–704
 - Cooper pairs, 706
 - de Broglie wavelength of, 666–668
 - diffraction of, 666–668, 681
 - mass of, 593
 - Millikan oil drop experiment (charge determination), 593–596
 - nuclear structure and, 764–766
 - photoelectric effect, 598–608
 - two-slit experiments and, 681
 - uncertainty principle and, 675–676
 - Electron shell, 649, 652–653
 - Electron volt, defined, 485
 - Electrostatics, 463–464
 - electrostatic induction, 471–472
 - Elements
 - discovery of new elements, 728–733
 - Greek concepts of, 7–12
 - periodic table, 585–590, 636, 648–649, 652–653
 - transformations of. *See* Fission reactions; Fusion reactions; Radioactivity
 - Ellipses, 95–98, 180–182
 - Emission of radiation
 - Bohr atom and, 639–647
 - emission spectra, 622–624, 626–630
 - heat and, 606–607
 - lasers and, 650–651
 - Empirical laws, defined, 100
 - Endeavor* (spacecraft), 160–162, 195
 - Energy
 - See also* Kinetic energy; Potential energy
 - chemical, 258, 274, 456, 505, 530–531
 - conservation of, 457
 - kinetic energy, 229–232
 - neutrino discovery and, 282, 775–777
 - neutron discovery and, 771
 - origins of conservation law, 274–278
 - Einstein's quantum hypothesis and, 602–608

- Energy (*Continued*)
- electrical, 456
 - electric potential difference. *See* Voltage
 - electron volts, 485
 - energy–frequency relation, 602, 662
 - energy quanta, 606–607, 639–640, 662
 - energy requirements of the human body, 528
 - forces and, 456–457
 - heat as, 253–258, 456
 - light as, 373, 606–607, 662
 - mass–energy relation $E = mc^2$, 433–434, 439, 662, 781
 - mechanical, 456, 505. *See also* Electric age; Heat engines
 - modern energy consumption, 528–531
 - nuclear binding energy, 780–786
 - of photon, 602, 644, 648, 662
 - power and, 267–268
 - of stationary states. *See* Energy states
 - uncertainty principle and, 676
- Energy resources, 530–531
- See also* Nuclear reactors
 - conservation of, 531–537
 - efficiency of power plants, 532–534
 - renewable and alternative sources, 537–542
 - types of, 530
- Energy states, 641–647
- experimental confirmation of, 646–648
 - formula for, 642, 644, 646
 - of hydrogen atom, 627
 - in Schrödinger's wave mechanics, 672
- Engines. *See* Heat engines
- Entropy, 314–315
- defined, 280
 - latent heat of fusion and, 694–696
 - Maxwell's demon, 315–318
 - second law of thermodynamics and, 280–281, 284–285
- Epicycle, 75
- Epicycle-deferent, 75
- Equilibrium, forces in, 122–125, 127
- Equinox, 67–68, 77
- Erg, defined, 257
- Ether, 395–396
- Descartes' concept, 182
 - electromagnetic waves and, 412, 551, 557–558, 578–580
 - gravitation and, 187
 - Maxwell's theory and, 412, 557–558
 - Michelson–Morley experiment, 441–442, 580
- Fajans, A., 749–750
- Fallout, nuclear, 804
- Faraday, Michael, 274, 506–512
- biographical summary, 508
 - electric motor, 506–507
 - electromagnetic induction discovery, 507–512
 - ideas on the electromagnetic nature of light, 549–551
- Faraday disk dynamo, 512
- Feedback, engines and, 262
- Fermi, Enrico, 282, 776, 786–787, 796
- Feynman, Richard P., 82
- Field, 472–479
- defined/described, 472–474
 - electric, 477–479, 483–484
 - magnetic. *See* Magnetic field
 - scalar vs. vector fields, 474–476
- Field effect transistor, 714
- First law of thermodynamics, 278–280
- First principles, 7
- Fission reactions
- chain reactions, 791–796
 - discovery of, 786–791
 - nuclear power plants, 797–799
 - nuclear weapons, 799–805
- Fizeau, Armand H. L., 382, 558–559
- Fluids, wave motion in, 333, 334
- interference patterns, 345–350
 - refraction, 367–369
 - wave fronts and diffraction, 354–360
- Fluorescence, 609, 725
- Fluorescent lights, 590
- Fluoroscope, 613, 615
- Force
- centripetal, 159–162, 637–638
 - electric, 465–471, 477–479
 - energy and, 456–457
 - equilibrium and, 123–125, 127
 - fields and, 472–479
 - forces that do no work, 243–246
 - gravitational force field, 476–477
 - inverse-square law, 179–182, 465–466, 476–477
 - lines of, 492, 506–507, 509, 511–513, 550–551
 - measurement of, 132–136
 - on moving charge in magnetic field, 496–498
 - net force, 124–125
 - Newton's laws and. *See* Newton's laws
 - units of, 135, 454

- vector addition of, 125–127
- weight and, 136–140
- Ford, Henry, 536
- Fossil fuels, 530, 535, 537
 - efficiency of power plants, 533–534
 - greenhouse effect and, 572
- Foucault, Jean B. L., 382
- Fourier, Jean-Baptiste, 344
- Fourier analysis, 344
- Franck, James, 646–647
- Franck–Hertz experiment, 646–648, 650
- Franklin, Benjamin, 308, 463–465, 479–480
- Fraunhofer, Joseph von, 624
- Fraunhofer lines, 624–626
- Free fall, 36–48, 138, 143–144
 - See also* Weightlessness
 - equation for, 42–44
 - inclined plane experiments, 43–47, 119
- Frequency, 157
 - energy–frequency relation, 602, 662
 - harmonics and, 354
 - periodic waves and, 339
 - refraction and, 368
 - of sound waves, 370
 - stationary states and, 639, 644–645
 - thermal radiation and frequency of radiation, 606–607
 - units of, 370
- Frequency modulation (FM), 565–566
- Fresnel, Augustin, 383–385, 393
- Friction
 - conservation of momentum and, 221
 - currents and, 700
 - free fall and, 39
 - heat and, 253–254, 256–257
 - linear motion and, 19
- Frisch, Otto R., 789–790
- Frost, Robert, 313
- Fusion reactions, 440, 785, 805–811
 - fusion reactors, 805–808
 - stars and, 809–810
- Galilean relativity principle, 149–150, 412–414
- Galileo Galilei, 88, 118, 451
 - biographical summary, 16–18
 - conflicts with religious authorities, 109–111
 - cosmology and, 48
 - free fall and, 37–48, 119, 138
 - inclined plane experiments, 43–47, 119, 143–144
 - lift-type pumps and, 294
 - nova observation, 102
 - pendulum experiment, 241
 - phases of Venus and, 106, 108
 - projectile motion and, 143–144, 146–150
 - relativity principle, 149–150, 412–414
 - speed of light and, 377
 - telescope observations, 102–109
 - thought experiment on inclined plane with
 - zero angle of inclination, 120–121
 - uniform acceleration concept, 119
- Galileo* (spacecraft), 105
- Gamma (γ) rays, 577–578
 - neutral charge of, 735–736
 - nuclear binding energy and, 781–782
 - radioactivity and, 733
 - transformation rules and, 749–750
- Gases
 - See also* Ideal gas; Kinetic theory of gases
 - spectra of, 621–626
 - states of matter, 300–302
 - word origin, 301
- Gassendi, Pierre, 457
- Gay-Lussac, Joseph Louis, 297
- Geiger, Hans, 631–634
- Geiger counter, 633–634
- Geissler, Heinrich, 590
- General Electric, 527
- General relativity, 205
- Generator, electric, 511–519
 - See also* Induction, electromagnetic
 - motors and, 516–519
 - transformers and, 525–528
- Geosynchronous orbit, 153
- Geothermal energy, 541
- Germer, L. H., 667
- Gilbert, William, 459–462, 472
- Global positioning satellites, 153–154
- Global warming, 572–574
- Goethe, Johann Wolfgang von, 276, 390
- Goldstein, Eugen, 590–591
- Governor (heat engine component), 262, 264
- Graphite, as moderator in nuclear reactors, 796
- Gravitation, 178–198
 - action at a distance and, 187
 - derivation of inverse-square law, 179–182
 - free fall, 36–48, 119, 138, 143–144
 - gravitational force field, 474, 476–477
 - Kepler's early suggestion of “magnetic force”
 - from the Sun, 101, 183

- Gravitation (*Continued*)
 magnitude of gravitational force, 188–192
 Newton's apple and, 175
 Newton's law of universal gravitation,
 178–198, 454–455, 474, 476–477
 equation for, 191
 projectile motion and, 143–149
 satellites in orbit, 150–156
 tides, 199–200
 weight and, 133, 136–140
 Gravitational acceleration, 44, 138, 194–195,
 197–198
 space shuttle and, 195, 197–198
 weightlessness and, 138–140, 155–156
 Gravitational constant G , 191–198
 measurement of, 192–194
 Gravitational potential energy, 237–241
 Greece, ancient, 6–12, 451–453
See also specific philosophers
 “atom” concept, 453, 457
 “elements” concept, 7–12
 “ether” concept, 396
 ideas on light, 374
 influence on Renaissance Europe, 59
 knowledge of round Earth, 64–65
 Pythagorean ideal, 351
 Greenhouse effect, 572–574
 Ground state of atoms, 642, 678
- Hahn, Otto, 788–789
 Half-life, 743–746
 Halley, Edmund, 175, 201
 Halley's comet, 201
 Halogens, 588–589
 Harmonic motion, 339–340
 Harmonics, musical, 351–354
 HDTV, 569
 Heat, 253–291
See also Infrared radiation; Temperature;
Thermodynamics
 as energy, 253–258, 457, 606–607
 engines. *See Heat engines*
 friction and, 253–254, 256–257
 greenhouse effect, 572–574
 kinetic–molecular theory of. *See Kinetic*
theory of gases
 latent heat of fusion, 694–695
 mechanical equivalent of, 257
 specific heat, 255, 697–699
 summary of equations, 286
 units of, 255–256
 wavelengths of, 563
 “Heat-death” of the Universe, 285, 323
 Heat energy, 253–258, 456, 606–607. *See also*
Infrared radiation
 Heat engines, 259–269
 Carnot engine, 270–273, 533–534
 components of, 262–263, 272
 efficiency of, 268–269, 271, 532–534
 energy consumption and, 529
 examples, 260–267
 internal combustion engine, 272
 origins of thermodynamics and, 269–273
 power of, 267–269
 reversible, 270–272, 280
 second law of thermodynamics and, 280–281
 steam engines, 505
 “Heavy water,” 774, 794–795
 Heisenberg, Werner, 670, 672–675, 765–766, 773
 Heisenberg's uncertainty principle. *See*
Uncertainty principle
 Heliocentric theory, 59–60, 76–86, 410
 arguments against, 82–86
 arguments in support of, 79–82, 106–109
 Helium
 α particles as helium nuclei, 736
 fusion and, 809–810
 nuclear binding energy and, 784–785
 Rutherford's “mousetrap” for α particles,
 737–738
 Henry, Joseph, 509
 Herapath, John, 303
 Heron of Alexandria, 260
 Herschel, John, 624
 Herschel, William and Caroline, 202
 Hertz, defined, 370
 Hertz, Gustav, 646–647
 Hertz, Heinrich, 365, 560–563, 598
 High Definition TV, 569
 High-energy physics, 780
 Highways, banked curves on, 160
 Hittorf, Johann, 590
 Hooke, Robert, 389
 Hoover Dam, 540
 Horsepower, 268
 Human body
 energy requirements of, 528
 radioactivity and, 734, 753
 Huygens, Christian
 collision theory and, 229–230

- light as wave idea, 375, 381
- speed of light measurement, 378
- wave fronts and, 356
- Huygens' principle, 356–360
- Hydroelectric power, 530, 540–541
- Hydrogen
 - Balmer's formula, 626–629, 642–647
 - Bohr's model of, 640–647
 - emission spectra, 626–630
 - energy levels of, 627, 641–647
 - ground state, 642
 - isotopes, 764, 773–774
 - size of hydrogen atom, 640–642
- Hypotheses, Newton and, 186–188
- Ideal gas
 - ideal gas law, 297–300, 308–312
 - Maxwell's velocity distribution for molecules, 303–305
 - pressure–volume relation, 295–297, 302
 - sizes of molecules and, 305, 307–308
- Ideal gas law, 297–300
 - equation for, 298
 - kinetic theory explanation of, 308–312
- Image, reflections and, 362
- Incandescent lighting, 520–524. *See also* Light bulbs
- Inclined plane
 - acceleration and, 43–47, 119
 - projectile motion and, 143–144
 - thought experiment on inclined plane with zero angle of inclination, 120–121
- Induction, electromagnetic, 507–512
 - See also* Electromagnetic waves
 - electric generator and, 512–516
 - transformers and, 525–528
- Induction, electrostatic, 471–472
- Industrial Revolution, 258–267
- Inelastic collisions, 232, 650–651
- Inertia
 - defined, 121
 - mass as, 131, 132
 - Newton's first law, 121–122, 125, 453
- Inertial reference frame, 415
- Infrared radiation, 571–574
 - See also* Heat energy
 - frequency of radiation and, 606–607
 - hydrogen spectrum and, 645
 - semiconductors and, 708
 - wavelengths of, 563
- Inquisition
 - Copernicus and, 85, 109–110
 - Galileo and, 109–111
- Insulators
 - band theory of metals and, 704
 - defined, 479, 700
 - electromagnetic waves and, 553–556
 - examples, 480, 701
- Intensity of sound waves, 370–371
- Interference patterns, 345–350
 - constructive and destructive interference, 348–350
 - nodal and antinodal lines, 348–350
 - Poisson bright spot, 383–385
 - sound waves and, 371–372
 - standing waves and, 350–354
 - two-slit experiments in water, 356, 360
 - two-slit experiments with electrons, 681
 - two-slit experiments with light, 382–384
 - wavelength and, 349–350
- Internal combustion engine, 272
- Inverse-square law for central forces, 179–182, 465–466
- Ionization
 - radioactivity and, 727, 734
 - X rays and, 610–611
- Ionosphere, 565
- Irreversible processes, 284
- Isolated systems. *See* Closed systems
- Isotopes, 746–749, 751, 764, 773–774
- Isotopic tracers, 753–756
- John Paul II (Pope), 111
- Joliot, Frédéric, 770
- Jordan, Pascual, 670, 673
- Joule, defined, 236, 257
- Joule, James Prescott, 236
 - conservation of energy and, 274–277
 - heat studies, 255–257
 - kinetic theory of gases and, 293, 303
- Jupiter
 - measurement of speed of light and, 377–378
 - moons of, 105–106
- Keats, John, 267
- Kelvin, Lord (William Thomson), 284, 299, 308, 320–322
- Kelvin temperature scale, 271, 298–299
- Kepler, Johannes, 88, 92–102, 451
 - biographical summary, 92–94

- Kepler, Johannes (*Continued*)
 Brahe and, 91, 92
 “clockwork universe” concept, 100
 laws of planetary motion. *See* Kepler’s laws of planetary motion
 “magnetic force” suggestion, 101, 183
 philosophical approach to physics, 92–93
 Platonic solids and, 92–93
- Kepler’s laws of planetary motion, 94–102
 derivation of inverse-square law and, 179–182
 first law (law of ellipses), 94–95, 97
 second law (law of areas), 95, 97–98, 101
 third law (harmonic law), 98–100
- Kilby, Jack, 715
- Kilogram, as standard of mass, 134
- Kinematics, defined, 48, 128
- Kinetic energy, 456
 conservation of, 229–232
 conservation of mechanical energy and, 239–243
 defined, 229
 elastic collisions and, 229–231
 electric potential energy and, 484
 inelastic collisions and, 232
 of photoelectrons, 600–604
 work and, 235–236
- Kinetic theory of gases, 293–330
 air pressure and water pumps, 294–295
 Brownian motion and, 312–313
 ideal gas law explanation, 308–312
 Maxwell’s velocity distribution, 303–305
 model for gaseous state, 300–302
 pressure–volume relation, 295–297
 recurrence paradox and, 322–324
 reversibility paradox and, 320–322
 second law of thermodynamics and, 312–315
 sizes of molecules and, 305, 307–308
 speed of molecules, 302–308
 temperature–pressure–volume relation (ideal gas law), 297–300, 308–312
- Kirchhoff, Gustav R., 624
- Kohlrausch, Rudolf, 558–559
- Laborde, A., 739
- Land, Edwin H., 394
- Lanthanum, 788–789
- Lasers, 377, 650–651
- Latent heat of fusion, 694–695
- Latimer, Lewis Howard, 522
- Lavoisier, Antoine Laurent, 215–217
- Lavoisier, Madame (Marie-Anne Paulze), 216
- Lawrence, E. O., 778
- Laws of nature, distinguished from theories, 94
- Lead, 740–742, 747, 750
- Leaning Tower of Pisa, 44, 148–149
- Leblanc, Maurice, 568
- LEDs, 713
- Legge, Alexander, 266
- Leibniz, Gottfried Wilhelm, 231–232, 237, 282
- Length
 length contraction, 428–430, 438
 universal standard of, 134
- Lift pump, 294–295
- Light, 373–396
See also Lasers; Spectroscopy
 characteristics of, 373–375
 color, 386–392
 early ideas about, 373–375
 Einstein’s light–quantum hypothesis, 602–608, 639, 662
 as electromagnetic waves. *See* Electromagnetic waves
 emission and absorption of. *See* Spectroscopy
 as energy, 373, 606–607, 639–640
 equivalence of light and electromagnetic waves, 559–563
 ether as medium for, 395–396
 interference and diffraction of, 382–386
 particle-like behavior of, 662–665
 particle model of, 379–382
 Poisson bright spot, 383–385
 polarization and, 392–395
 propagation of, 375–378
 reflection and refraction of, 378–382
 speed of
 constancy of, 415–418, 436–437
 Maxwell’s determination of speed of electromagnetic waves, 557–559
 measurement of, 377–378
 tests of constancy of, 436–437
 uncertainty principle and, 678
 as transverse waves, 393
 wavelength of, 391, 393, 563, 574
 wave vs. particle concept of, 374–375, 378–382, 608–616
- Light bulbs
 invention of, 520–524
 parallel vs. series circuits, 520, 523
 power and, 268, 488
- Light clock, time dilation and, 422–423

- Lindemann, Frederick A., 699
- Linear motion, 19–32
See also Free fall
 acceleration, 31–37
 equations for, 49
 Galileo's thought experiment on inclined plane with zero angle of inclination, 120–121
 inclined plane experiments, 43–47, 119, 143–144
 speed, 22–30
 velocity, 30–31
- Lines of force, 492, 506–507, 509, 511–513
 light as vibration of, 550–551
- Livingston, M. S., 778
- Lodestone, 459–462, 472
- Longitudinal waves, 393
 defined/described, 334–335
 sound as, 370
- Lorentz, H. A., 701
- Loschmidt, Josef, 320
- Lunar eclipse, 69
- Lyman series, 629, 643, 645
- Mach, Ernst, 319, 324
- MAD (mutually assured destruction), 802
- De Magnete* (Gilbert), 460
- Magnetic field
 cathode rays and, 591–593
 currents and, 488–492, 495–498
 lines of force, 492, 506–507, 509, 511–513, 550–551
 lodestone and, 472
 moving charges and, 495–498
 right-hand rule for, 491, 495
- Magnetism
 currents acting on magnets, 488–492
 Gilbert's work on amber and lodestone, 459–462
 Kepler's "magnetic force" suggestion for solar system force, 101, 183
 summary of equations, 499
- Magnetosphere, 498
- Marconi, Guglielmo, 565
- Marić, Mileva, 409
- Mars, 92–93, 134
- Marsden, Ernest, 631, 633–634
- Mass
 of α particles, 736
 of β particles, 736
 conservation of, 211–217
 distinguished from weight, 133
 of electron, 593
 inertial mass, 131
 mass–energy relation $E = mc^2$, 433–434, 439, 662, 781
 measurement of, 132–136
 Newton's second law and, 130–132
 relativistic effects, 431–432, 438–439
 rest mass, 431
 as scalar, 131
 universal standard of, 133–134
- Mass defect, 781
- Mass number, 749, 751–753, 764, 773–774
- Mass points, 189
- Matter waves, 671. *See also* de Broglie waves
- Maxwell, James Clerk
 on Ampère, 492
 biographical summary, 552
 determination of speed of electromagnetic waves, 557–559
 electromagnetic theory, 405–406, 551–556
 ether concept and, 579
 kinetic theory of gases and, 303–304
 Maxwell's demon, 315–318
 prediction of different frequencies of electromagnetic waves, 561
 recognition of light as electromagnetic waves, 559
 special relativity and, 415–416
- Maxwell's demon, 315–318
- Mayer, Julius Robert, 275–277
- Mechanical energy, 456, 505. *See also* Electric age; Heat engines
- Mechanical waves, 332
- Mechanical world view, 313, 455. *See also* Clockwork universe
- Mechanics, defined, 48, 128
- Medician planets, 105
- Medicine
 radioactivity and, 734, 754
 X rays and, 613–616
- Medium, for propagation of waves, 333–336
 light and, 395–396, 441–442, 551, 557–558, 580
 refraction and, 366–369
 stiffness and density of, 338
- Meitner, Lise, 788–790, 794
- Melville, Thomas, 622
- Mendeleev, Dimitri, 587–588

- Mersenne, Marin, 371
 Meteorology, 474–475
 Meter, as standard of length, 134
 Metric system, 133–134
 Michelson, Albert A., 441–442, 580
 Michelson–Morley experiment, 441–442, 580
 Microchips, 708, 715–716
 Microwave radiation, 570–571
 Milky Way galaxy, 4, 103–104
 Millikan, Robert A., 594–596, 605–606
 Millikan oil drop experiment, 593–596
 Minkowski, Hermann, 443
 Moderator (reactor component), 793, 795, 796
 Molecules
 See also Kinetic theory of gases
 Brownian motion, 312–313, 458
 integral proportions for compounds, 457, 586
 sizes of, 305, 307–308
 speed of, 302–308
 Maxwell's velocity distribution for, 303–305
 Momentum
 angular momentum of electron in orbit,
 668–669
 conservation of
 closed systems and, 226
 collisions and, 217–222, 227–231
 derived from Newton's laws, 223–227
 friction and, 221
 neutron discovery and, 771
 defined, 219
 of photon, 662–664
 uncertainty principle and, 675–676
 Moon
 centripetal acceleration of, 184–185
 distance to, 4
 eclipses, 69
 Galileo's telescope observations of, 103
 observations of position, 63–64
 phases, 69–70
 tides and, 199–200
 Moore, Hiram, 266
 Morley, Edward, 441–442, 580
 Motion, 15–57
 See also Circular motion; Linear motion;
 Special relativity
 Galilean relativity principle, 149–150,
 412–414
 natural, 117–122, 144
 “natural” vs. “violent”, 118–119
 Newton's laws of. *See* Newton's laws
 projectile motion, 143–149
 Motor, electric, 506–507, 516–519
 Muon, 437–438
 Music
 See also String, vibrating
 beats, 372
 harmonics, 351–354
 interference of sound waves and, 372
 standing waves and, 351–354
 Mutually assured destruction (MAD), 802
 Nanometer, defined, 391
 Natural gas, 530
 Natural motion, 117–122
 Nature philosophy (*Naturphilosophie*), 275–278
 Neptunium, 790
 Nernst, Walther, 699
 Neutrino, 775–777
 discovery of, 775–777
 energy conservation and, 282
 Neutron
 decay of free neutron, 776
 discovery of, 769–773
 fission and, 786–796
 nuclear structure and, 773–775
 Neutron physics, 773
New Astronomy: A Celestial Physics (Kepler), 101
 Newcomen, Thomas, 261–262
 Newton, defined, 135, 454
 Newton, Isaac, 88, 451–452, 457
 apple story, 175
 approach to science as model for all physical
 sciences, 204–205
 biographical summary, 171–176
 color theory, 386–389
 comets and, 200
 conservation of momentum and, 218–219
 gravitation theory, 102, 175, 179–198,
 454–455
 hypotheses and, 186–188
 ideal gas theory and, 303
 laws of motion. *See* Newton's laws
 light as particle idea, 374, 380–381, 392–393
 polarization of light and, 393
 spectra and, 386–389
 tides and, 199–200
 Newtonian synthesis, 185–186
 Newtonian world machine, 211–212

- Newton's law of universal gravitation, 178–198
 equation for, 191
- Newton's laws
 conservation of momentum and, 223–227
 derivation of inverse-square law for
 gravitation, 179–182
 first law (law of inertia), 121–122, 125, 453
 forces in equilibrium, 123–125
Principia publication and contents, 175–178
 projectile motion and, 143–146, 152–153
 reversibility paradox and, 320–322
 satellites in orbit and, 150–156
 second law $F = ma$, 128–132, 431–432, 454
 special relativity and, 431–432
 third law (law of action and reaction),
 140–143, 454
- Niagara Falls power plant, 527–528
- Nipkow, Paul, 568
- Nitrogen, artificial transmutation and, 768
- Noble gas, 652, 653
- Nodal lines, 348–350, 358–360
- Noemi, Jean, 715
- Noninertial reference frame, 415
- Northern lights, 498
- North Star, 63, 65, 67, 77
- Nova
 Brahe's observation of, 88
 Galileo's observation of, 102
- Novum Organum* (Bacon), 214
- Noyce, Robert, 715
- n-p junction diode, 710–714
- n-p-n bipolar transistor, 714, 716
- n-type semiconductors, 710–716
- Nuclear binding energy, 780–786
- Nuclear physics, 723–761
 See also Fission reactions; Fusion reactions;
 Nuclear structure
 decay rate and half-life, 742–746
 discovery of new elements, 728–733
 identification of rays emitted in radioactivity,
 733–737
 isotopes, 746–749
 nuclear structure, 763–786
 radioactive transformations, 738–743
 radioactivity discovery, 724–728
 Rutherford's "mousetrap" for α particles,
 737–738
 summary of notation for reactions, 751–753
 transformation rules, 749–750
- uranium–radium decay series, 741–743,
 752–753
- Nuclear reactors
 breeder reactors, 800
 critical size, 793
 efficiency and, 533–534
 fission reactors, 791–799
 fusion reactors, 805–808
 heavy-water reactors, 794–795, 800–801
 light-water reactors, 795, 801
 power plants, 530, 541, 797–799
 slow neutrons and, 793
- Nuclear structure, 763–786
 See also Fission reactions; Fusion reactions
 binding energy, 780–786
 charge of nucleus, 635–637
 discovery of artificial transmutation, 766–769
 mass defect, 781
 neutrinos, 775–777
 neutron discovery, 769–773
 particle accelerators and, 777–780
 proton–electron hypothesis, 765–766
 proton–neutron model, 773–775
 Rutherford's atomic structure model and, 632
 size of nucleus, 636–637
 stability of nucleus, 783–786
- Nuclear weapons, 440, 799–805
- Nucleon, 774, 783–786
- Nuclide, 748, 751–752
- Oersted, Hans Christian, 274, 489–491,
 549–550
- Ohm, Georg Simon, 486–487, 699
- Ohm's law, 486, 499, 699, 701
- Onnes, Kammerlingh, 700
- On the Revolutions of the Heavenly Spheres*
 (Copernicus), 60–61
- Oppenheimer, J. R., 673
- Opticks* (Newton), 389–390
- Orbits
 and forces that do no work, 244–245
 geosynchronous, 153
 Newton's law of universal gravitation and,
 180–182
 orbital radii for atoms, 640–642
 of satellites, 150–156
- Overtones, musical, 354
- Oxygen, artificial transmutation and, 768
- Ozone depletion, 575–576

- Pantheism, 110
- Parallax, stellar, 83
- Parsons, Charles, 517–518
- Particle accelerators, 498
 - nuclear structure and, 777–780
 - relativity theory and, 437–439
- Paschen, Friedrich, 629
- Paschen series, 629, 643, 645
- Pauli, Wolfgang, 282, 673, 775
- Pauli exclusion principle, 703
- Pauling, Linus, 804
- Payne-Gaposchkin, Cecilia, 810
- Pendulum experiments
 - conservation of energy and, 241
 - elastic collisions and, 228–229
 - periodicity and, 339
- “Penetrating radiation,” 726
- Period, 156–157, 339
- Periodic table, 585–589
 - atomic structure and, 589–590
 - Bohr atom and, 648–649, 652–653
 - nuclear charge and, 636
- Periodic waves, 338–342
- Pfund series, 629, 643, 645
- Phase
 - interference patterns and, 349–350
 - wave fronts and, 356
 - wave motion and, 342
- Phase changes, 694–696
- Phases of the Moon, 69–70
- Phases of Venus, 106, 108
- Phosphorescence, 725–726
- Photoelectric effect, 598–608
 - Einstein’s theory of, 602–608
 - kinetic energy of photoelectrons, 600–604
 - semiconductors and, 708
 - stopping voltage, 600, 603
 - work function, 603–604
- Photon
 - Compton effect, 664–665
 - Einstein’s light-quantum hypothesis, 602–608, 639, 662
 - energy of, 602, 644, 648, 662
 - momentum of, 662–664
 - uncertainty principle and, 675–676
- Photovoltaic cells, 537, 539, 708–709, 712–713
- Pile (battery component), 481
- Pitchblende, 729, 731–732
- Pixii, Hippolyte, 516
- Planck, Max, 606–607, 639
- Planck’s constant, 606–607
 - discovery of, 602–603
 - stationary states and, 639, 644
 - uncertainty principle and, 675–676
- Planets
 - Galileo’s observations of, 105–108
 - Kepler’s laws of planetary motion, 94–102, 179–182
 - motions observed in antiquity, 71–74
 - name origins, 72
 - Newton’s law of universal gravitation and, 180–182
 - orbital elongation, 81
 - period–radius relationship for, 81–82
 - retrograde motion of, 71–72, 74–75, 78–79
- Plane waves, 363
- Plasma, 807–808
- Plato
 - astronomical problem, 9
 - ideas on elements, 7–8
 - influence on Kepler, 92
 - influence on Renaissance Europe, 59
 - phases of the Moon and, 69
 - philosophical approach to physics, 7, 9, 79–80
- Platonic solids, 6, 7, 92–93
- Plücker, Julius, 590
- Plum pudding model of atom, 597–598
- Plutonium, 790–791, 800–801, 804
- Poetry
 - cycles in time and, 323
 - Industrial Revolution and, 267
 - Newton and, 178, 390
 - second law of thermodynamics and, 313
- Poincaré, Henri, 283, 323
- Poisson, Simon, 383–385
- Poisson bright spot, 383–385
- Polaris, 63, 65, 67, 77
- Polarization, 335, 392–395
- Poles, magnetic, 461, 462, 489
- Polonium, 731, 741–742, 744, 750
- Pope, Alexander, 178
- Positron, 809
- Potential energy
 - elastic, 238, 240–241
 - electric, 238, 482–486. *See also* Voltage
 - gravitational, 237–241
 - work and, 236–239

- Potential well, 702
- Power
 defined, 267–268
 electric, 488
 electric lights and, 521
 engines and, 267–269
 generators and, 516
 transmission systems and, 525–528
 voltage and, 487–488
- Power, Henry, 295
- Power plants
See also Nuclear reactors
 efficiency of, 532–534
 Niagara Falls power plant, 527–528
- Pressure, 294–295
 defined, 295
 ideal gas law, 297–300, 308–312
 pressure field, 474–475
 pressure-volume relation, 295–297
- Priestley, Joseph, 465–466
- Primary coil, 509, 526
- Principia* (Newton), 88, 151, 171, 175–178, 187, 303, 389
 contents described, 176–178
- Principia Philosophiae* (Descartes), 212
- Probability interpretation of quantum mechanics, 679–681
- Projectile motion, 143–149
 moving-Earth hypothesis and, 146–150
 orbiting satellites and, 150–156
- Propagation of waves, 336–338
 propagation of light, 375–378
 speed of propagation, 338, 340–341
- Protestant Reformation, 59
- Proton, 764–768
- Prout, William, 765
- Ptolemaic system, 75–76, 83, 85, 86, 106–108
- Ptolemy, Claudius, 75–76
- p-type semiconductor, 710–716
- Pulse, 332
- Pumps, water, 294–295
- Pupin, Michael, 613
- Pythagorean ideal, 351
- Quantum mechanics, 661–691
 Bohr atom and, 639–640
 complementarity principle, 682–684
 Copenhagen interpretation, 684
 development of, 670–674
 Einstein's light-quantum hypothesis, 602–608, 639, 662
 Einstein's objections to probability interpretation, 685–686
 particle-like behavior of light, 662–665
 Pauli exclusion principle, 703
 photoelectric effect and, 598–599, 602–608
 probability interpretation, 679–681, 685–686
 Schrödinger's wave mechanics, 670–672, 679, 702
 specific heat and, 697–699
 summary of equations, 686–687
 uncertainty principle, 673–676, 765
 wave-like behavior of particles, 665–669
- Quarks, 596
- Quasi-crystalline bonding, 696–697
- Quintessence (Greek concept), 10, 396
- Radar, 364–366, 565–570
- Radioactivity
 applications of, 753–756
 charge and mass of emitted rays, 734–737
 decay rate and half-life, 742–746
 discovery of, 724–728
 discovery of new elements, 728–733
 identification of emitted rays, 733–737
 isotopes and, 746–749
 radioactive transformations, 738–743
 transformation rules, 749–750
 summary of notation for reactions, 751–753
 uranium–radium decay series, 741–743, 752–753
- Radionuclide, 751
- Radio waves, 564–566
- Radium
 discovery of, 732–733
 isotopes, 747
 radon and, 737–738
 temperature of sample, 739
 uranium–radium decay series, 741–743, 752–753
- Radon, 737–738, 741
- Ramsey, William, 737
- Rate, defined, 22
- Ratio, defined, 22
- Rays
 of light, 375–377
 waves and, 362–363
- Reactor, defined, 793. *See also* Nuclear reactors

- Rectification, 713
- Recurrence paradox, 322–324
- Reference frame
See also Special relativity
 Galilean relativity principle and, 150, 412–414
 inertial vs. noninertial, 415
 relative motion and, 411–412
- Reflection of waves, 359–366, 373, 378–382
- Refraction of waves, 366–369, 378–382
- Reines, Frederick, 776
- Relativity principle, Einstein's, 414–415. *See also* Special relativity
- Relativity principle, Galilean, 149–150, 412–414
- Relativity theory, 405–448. *See also* Special relativity
- Religion
 Copernicus and, 85, 109–110
 Galileo and, 109–111
- Rembrandt, 58
- Renaissance, 58–59
- Resistance
 defined, 701
 electric lights and, 521
 Ohm's law, 486, 499, 699, 701
 power and, 488
 superconductors and, 705–706
- Rest mass, 431
- Retrograde motion of planets, 71–72, 74–75, 78–79
- Reversibility paradox, 320–322
- Reversible engines, 270–272, 280
- Right-hand rule for magnetic field, 491, 495
- Ripple tank, 346–347, 355–356, 367–369
- Roemer, Ole, 377–378
- Rogers, William Barton, 276
- Romantic movement, 276
- Röntgen, Wilhelm Konrad, 608–611, 725
- Roosevelt, Franklin D., 524, 605
- Rope, waves on, 332–333
 periodic waves, 339–342
 polarization and, 335, 394
 reflection, 359–360
 refraction, 366
 standing waves, 350–354
 superposition of waves, 343–344
 transverse waves, 337–338
- Royal Society of London, 171, 228–229, 480
- Royds, T., 737–738
- Rumford, Count (Benjamin Thompson), 254–255
- Rutherford, Ernest, 630–635
 artificial transmutation studies, 766, 768
 on Bohr atom, 654
 estimate of size of nucleus, 636–637
 “mousetrap” for α particles, 737–738
 neutron suggestion, 769
 radioactivity studies, 733
 on scientific progress, 173
 temperature of radium sample, 739
- Rutherford atomic structure model, 630–637
- Rutherford scattering, 630–635
- Rydberg, J. R., 628
- Rydberg constant, 628
- Satellites
 energy sources for, 712
 and forces that do no work, 244–245
 projectile motion and orbits, 150–156
 types of, 153–154
- Satellites, planetary (moons), 105–106, 182. *See also* Moon
- Saturn, 105
- Savery, Thomas, 261
- Sawyer, W. E., 568
- Scalar, defined, 31, 454
- Scalar fields, 474
- Scattering
 atmospheric, 390–392
 Compton effect, 664–665, 676
 Rutherford scattering, 630–635
- Schelling, Friedrich Wilhelm Joseph von, 275–276, 549
- Schmidt, Gerhard, 728
- Schoemaker–Levy comet, 200
- Schrieffer, Robert, 706
- Schrödinger, Erwin, 670–672
- Schrödinger equation, 671–672, 679, 702
- Science and Hypothesis* (Poincaré), 283
- Scientific Revolution, 57–59, 451–459
- Seasons, 67–69, 77–78, 98
- Second, as standard of time, 134
- Secondary coil, 509, 527
- Second law of thermodynamics, 280–281
 Carnot engine and, 272–273
 closed systems and, 317–319
 consequences of, 284–285
 efficiency and, 532
 energy consumption and, 529
 kinetic theory of gases and, 312–315
 Maxwell's demon, 315–318

- reversibility paradox, 320–322
- statistical view of, 315–318
- Seismic waves, 372
- Semiconductors, 704, 707–719
 - doping with impurities, 709–710
 - n-p junction diodes, 710–714
 - n-p-n bipolar transistor, 714, 716
 - n-type, 710–716
 - p-type, 710–716
 - transistors, 714–719
- Shelley, Percy Bysshe, 323
- Ships, sinking over horizon, 65
- Shockley, William, 714
- SI units, 135
- Sky, color of, 390–392
- Slope of a line
 - acceleration and, 35–36
 - Planck's constant and, 606
 - speed and, 29–30
- Soddy, Frederick, 737, 739, 747–750
- Solar eclipse, 69
- Solar power, 537, 539
- Solar system
 - See also* Kepler's laws of planetary motion
 - Brahe's hybrid theory, 91, 106
 - Galileo's observations of, 102–109
 - geocentric theory, 61–62
 - heliocentric theory, 59–60, 76–86, 106–109
 - Newtonian world machine, 211–212
 - period–radius relationship for planets, 81–82
 - Ptolemaic system, 75–76, 83, 85, 86, 106–108
- Solar-thermal energy, 541
- Solids, waves in, 333–334
- Solid state physics, 693–722
 - BCS theory, 706–707
 - Bloch's band theory of metals, 702–705
 - conducting electrons, 699–701
 - formation of a solid, 694–697
 - latent heat of fusion, 694–695
 - phase changes, 694–695
 - quantum solids, 697–699
 - semiconductors, 707–719
 - specific heat, 697–699
 - superconductors, 705–707
- Solstice, 68–69, 77–78
- Sommerfeld, Arnold, 648
- Sonar, 364
- Sound waves, 370–373
 - beats, 372
 - diffraction of, 354, 356, 373
 - interference of, 372
 - as longitudinal waves, 370
 - loudness and intensity, 370–371
 - seismic refraction, 372
 - speed of, 371
 - wave fronts of, 356
- Spacecraft
 - conservation of momentum and, 225
 - crash of Mars probe due to metric confusion, 134
 - energy sources for, 712
 - gravitational acceleration and, 195, 197–198
 - satellites in orbit, 150–156
 - space shuttle, 155–156, 160–162, 195, 197–198
 - weightlessness and, 138–140, 155–156
- Space shuttle, 155–156, 160–162, 195, 197–198
- Spacetime, 443
- Special relativity
 - constancy of the speed of light, 415–418, 436–437
 - experimental tests of, 434–440
 - inertial reference frames, 415
 - length contraction, 428–430, 438
 - light clock, 422–423
 - mass and, 431–432, 438–439
 - mass–energy relation $E = mc^2$ and, 433–434, 439
 - Michelson–Morley experiment, 441–442, 580
 - name origin, 415, 435
 - simultaneous events, 418–420
 - time dilation, 420–428, 437–438
- Specific heat, 235, 697–699
- Spectrograph/spectrometer, 629
- Spectroscopy, 621–626
 - See also* Electromagnetic spectrum
 - absorption spectra, 624–626
 - Balmer's formula, 626–629, 642–647
 - Bohr's atomic structure model and, 639–647
 - continuous spectra, 625
 - emission spectra, 622–624, 626–630
 - hydrogen spectrum, 626–630
 - spectrum analysis, 624
- Speed
 - angular, 157
 - average, 23–30
 - for circular motion, 157–158
 - defined, 22
 - instantaneous, 33
 - of light. *See* Speed of light

- Speed (*Continued*)
 of molecules, 302–308
 of refracted waves, 368
 as scalar, 31
 of sound waves, 371
 of wave propagation, 338, 340–341
- Speed of light
 constancy of, 415–418, 436–437
 Maxwell's determination of speed of
 electromagnetic waves, 557–559
 measurement of, 377–378
 tests of constancy of, 436–437
 uncertainty principle and, 678
- Sports
 average speeds, 23, 25–30
 Newton's laws and, 141–143
- Sprenghel, Hermann, 520
- Spring
 examples of waves in, 333–334
 period of vibration, 339
 spring–mass system, 339
- Standing waves, 350–354
- Stars
 absorption spectra, 624–626
 distance to nearest, 4
 double stars, 202
 fusion reactions in, 440, 809–810
 parallax, 83
- States of matter, 300–302
- Stationary states, 639–641
 energy of, 641–647
 experimental confirmation of, 646–648
- Steam engine, 258–267, 505
- Steam turbine, 517–518
- Stimulated emission, 650–651
- Stopping voltage for photoelectrons, 600, 603
- Strassmann, Fritz, 788–789
- String, vibrating, 332
 elastic potential energy and, 240–241
 standing waves and, 350–354
 tension and, 338
- Strong force, 807
- Strontium-90, 753
- Stukeley, William, 174–175
- Summer solstice, 68–69, 77
- Sun
 age of, 4
 distance to, 4
 eclipses, 69
 Fraunhofer lines, 624–626
 fusion as energy source for, 440, 809–810
 Galileo's telescope observations of, 104–105
 observations of position, 63–64
- Superconductors, 700, 705–707
- Superposition principle, 342–345
 for fields, 479
 Huygens' principle and, 358
 interference patterns and, 345–350
 sound waves and, 372
 standing waves and, 350–354
- Synchro-cyclotron, 439
- Technology
 agricultural, 266
 aviation, 196–197, 393
 batteries, 274, 480–481, 486, 488
 cars, 160, 529, 535, 537
 cell phones, 564
 compact discs, 717
 computers, 717–719
 electricity and. *See* Electric age
 lasers, 377
 medical, 613–616, 754
 microchips, 708, 715–716
 nuclear power. *See* Nuclear reactors
 radar and sonar, 364–366, 570
 radioactivity and, 753–756
 radio waves and, 564–566
 semiconductors and, 707–719
 spacecraft. *See* Spacecraft
 superconductors and, 705–706
 telephones, 536
 television, 484–485, 565–570
 transistors, 707, 714–719
- Telephone, 536
 cell phones, 565
- Telescope, 102–109
- Television, 565–570
 High Definition TV, 569
 picture tube, 484–485, 566
 signals, 565–570
- Temperature
 absolute scale, 271, 298–299
 absolute zero, 271, 281, 298–299
 ideal gas law, 297–300, 308–312
 “third” law of thermodynamics and, 281
- Tennessee Lake, 540
- Tennessee Valley Authority, 524
- Tension, and wave propagation, 338
- Terrestrial sphere, 10

- Terrorism, 798
Theory of Light and Color (Newton), 175
 Thermal radiation. *See* Infrared radiation
 Thermodynamics
 See also Heat
 Carnot and, 269–273
 first law of, 278–280
 Maxwell's demon, 315–318
 origins of conservation law, 274–278
 second law of, 280–281
 Carnot engine and, 272–273
 closed systems and, 317–319
 consequences of, 284–285
 efficiency and, 532
 energy consumption and, 529
 kinetic theory of gases and, 313–315
 Maxwell's demon, 315–318
 reversibility paradox, 320–322
 statistical view of, 315–318
 summary of equations, 286
 “third” law of, 281
 Thompson, Benjamin (Count Rumford), 254–255
 Thomson, G. P., 667–668
 Thomson, James, 390
 Thomson, J. J., 592, 667–668
 atomic structure model, 596–598, 630–631
 determination of charge of cathode rays, 592–594, 734
 photoelectric effect and, 598
 X-ray research, 610–611
 Thorium, 728–729, 741–742, 748, 750
Through the Looking Glass (Carroll), 28
 Tides, 199–200
 Time
 recurrence paradox and, 322–324
 reversal of, 427
 reversibility paradox, 320–322
 simultaneous events, 418–420
 time dilation, 420–428, 437–438
 uncertainty principle and, 676
 universal standard of, 134
 Torricelli, Evangelista, 294
 Torsional waves, 334–335
 Torsion balance, 192–194, 466
 Towneley, Richard, 295
 Tractors, 266
Traité Élémentaire de Chimie (Lavoisier), 215
 Trajectory, 144
 Transformers, 525–528
 Transistors, 707, 714–719
 Transmission of electricity, 517, 525–528
 Transportation, energy consumption and, 529, 535, 537
 Transuranium elements, 787–791
 Transverse waves
 defined/described, 334–335
 electromagnetic waves as, 557
 light as, 393
 on rope, 337–338
Treatise on Electricity and Magnetism (Maxwell), 559
 Tritium, 805
 Tropic zone, 69
 Turbine, 517–519
Two New Sciences (Galileo), 18, 38–39, 41, 43, 48, 118, 294, 377
 Two-slit experiments
 electrons and, 681
 light and, 382–384
 water and, 356, 360
 Ultraviolet radiation, 563, 575–576
 Uncertainty principle, 673–676
 consequences of, 676–678
 nuclear structure and, 765
 United States
 atomic bomb and, 799–805
 efficiency of automobiles in, 535, 537
 energy consumption in, 528–530
 energy resources, 530–531
 global warming and, 574
 Universal constants of nature
 gravitational constant as, 416
 Planck's constant as, 607
 speed of light as, 416
 Universal first principles, 7
 Universal laws of nature, 128, 185, 203, 457
 Universal standard of mass, 133–134
 Universe
 age of, 4
 clockwork universe, 100, 313, 455
 “heat-death” of, 285, 323
 recurrence paradox and, 322–324
 size of, 4
 Uranium
 atomic bomb and, 800–801
 chain reactions and, 792–796
 discovery of radioactivity and, 725–728
 fission and, 786–791

- Uranium (*Continued*)
 isotopes, 747–749
 transuranium elements, 787–791
 uranium–radium decay series, 741–743,
 752–753
- Valence band, 704
- Van Allen radiation belts, 498
- Vector
 acceleration as, 34
 defined, 30–31, 454
 vector addition, 124–127
- Vector fields, 474–476, 478–479
- Velocity
 for circular motion, 157–158
 defined, 30–31
 Maxwell’s velocity distribution for molecules,
 303–305
- Velocity field, 474–475
- Venus, phases of, 106, 108
- Vernal equinox, 68, 77
- Villard, P., 733
- Volt, defined, 482
- Volta, Alessandro, 274, 480–481
- Voltage (electric potential difference), 482–486
 of battery, 486
 current and, 486, 699
 generator and, 513
 Ohm’s law, 486, 499, 699, 701
 power and, 487–488
 stopping voltage for photoelectrons, 600, 603
 transmission systems and, 525–528
 units of, 483
- Voltaire, 176
- Volume
 ideal gas law, 297–300, 308–312
 pressure–volume relation, 295–297
- Voyager* (spacecraft), 105
- Wallis, John, 229
- Water
 phase changes, 694–695
 water pumps, 294–295
 wave motion in. *See* Fluids, wave motion in;
 Ripple tank
- Watt, defined, 488
- Watt, James, 262–264, 268
- Wave fronts, 356–357
- Wavelength
 Balmer’s formula, 626–629, 643–646
 de Broglie waves and, 666–668
 interference patterns and, 349–350
 of light, 391, 393
 momentum of photon and, 663–664
 of periodic waves, 340–341
 refraction and, 368
 scattering and, 390–392
 for standing waves, 352, 354
 stationary states and, 626–629, 641–645
 of various types of radiation, 563
- Wave mechanics, 670–672, 679, 702
- Wave–particle duality
 complementarity principle, 682–684
 particle-like behavior of light, 662–665
 polarization of light and, 392–395
 probability interpretation and, 679–681
 reflection and refraction of light and, 378–382
 wave-like behavior of particles, 665–669
 X rays and, 611–612
- Waves, 331–403
See also Fluids, wave motion in; Rope, waves
 on; Sound waves
 defined/described, 331–336
 diffraction, 354–360
 Doppler shift, 364
 examples, 331–333
 Fourier analysis of, 344
 Huygens’ principle, 356–360
 interference patterns, 345–350
 light as. *See* Electromagnetic waves; Light
 longitudinal, 334–335, 370, 393
 nodal and antinodal lines, 358–360
 periodic, 338–342
 phase of, 342, 356
 plane waves, 363
 polarized, 335
 propagation, 336–338
 propagation vs. waves that don’t propagate,
 336
 pulse, 332
 radar and sonar, 364–366
 reflection of, 359–366
 refraction of, 366–369
 simple harmonic motion, 339–340
 speed of propagation, 338, 340–341
 standing, 350–354

- superposition of, 342–350. *See also*
 - Diffraction; Interference patterns
- torsional, 334–335
- transverse, 334–335, 337–338, 393, 557
- traveling, 350
- wave fronts, 356–357
- wavelength for standing waves, 352, 354
- wavelength–speed–frequency relation, 340–341
- waves of displacement, 333
- Weather satellites, 153
- Weber, Wilhelm Eduard, 558–559
- Web sites
 - for Curie information, 756
 - for Einstein information, 444
 - for space shuttle information, 160
 - for this course, xi
- Weight, distinguished from mass, 133
- Weightlessness, 138–140, 155–156
- Westinghouse, George, 526
- Westinghouse Electric Company, 527
- Wheat fields, waves in, 335–336
- Wheatstone, Charles, 549
- Whispering galleries, 373
- Wilson, C. T. R., 767
- Wind energy, 539–541
- Winter solstice, 68–69, 78
- Wollaston, William, 624
- Work, 233–243, 457
 - See also* Heat engines
 - defined, 233–235
 - electric potential difference and, 482–486
 - first law of thermodynamics and, 279
 - forces that do no work, 243–246
 - kinetic energy and, 235–236
 - mechanical energy and, 241–242
 - potential energy and, 236–239
 - units of, 236
- Work function, 603–604
- World War II
 - atomic bomb, 799–805
 - radar and sonar, 364–366
- Wren, Christopher, 229
- Wright, Wilbur and Orville, 196
- X rays, 576–577, 608–616
 - compared to Becquerel rays, 727–728
 - Compton effect, 664–665, 676
 - diffraction of, 577, 611–613
 - discovery of, 608–609, 725
 - properties of, 609–611
 - public reaction to discovery, 612–613
 - technology and, 613–616
 - wavelengths of, 563
 - wave vs. particle nature of, 611–612
- Year, defined, 64
- Young, Thomas, 382–384, 391, 393
- Zodiac, 73
- Zworykin, Vladimir Kosma, 568, 569

