

# Index

- Abraham-Lorentz formula, 489, 492–496, 573
- Absorption, 412–417
- Absorption coefficient, 422
- Acausality, 441, 446–447, 490
- Acceleration
  - ordinary, 549
  - proper, 549
- Acceleration field, 460, 482
- Advanced potentials, 446
- Advanced time, 446
- Alfven's theorem, 352
- Ampere (unit), 216, 224
- Ampère, A. M., xvi
- Ampère dipole, 269, 294
- Ampère's law, 233, 243, 332–337, 567
  - applications of, 233–241
  - in matter, 279–282
  - symmetry for, 237
- Amperian loop, 233, 249
- Amplitude of wave, 385
- Angle
  - azimuthal, 38, 43
  - of incidence, 407
  - polar, 38
  - of reflection, 407
  - of refraction, 407
- Angular frequency, 386
- Angular momentum, 370–373, 378–380
- Angular momentum density, 372
- Anomalous dispersion, 422–423
- Antisymmetric tensor, 562–564
- Atomic polarizability, 168, 208–209
- Auxiliary fields
  - D**, 181–189, 281–283, 573
  - H**, 279–285, 573
- Azimuthal angle, 38, 43
- Azimuthal symmetry, 141
- BAC-CAB rule, 8
- Back emf, 325, 328
- Ball, defined, 51
- Bar electret, 176, 184
- Bar magnet, 276, 284
- Barn and ladder paradox, 516–518
- Betatron, 348
- Biot-Savart law, 224–228, 351, 560
- Bohr atom
  - lifetime, 487
  - polarizability, 169–170
- Bohr magneton, 263
- Bound charge, 173–179, 192, 340
- Bound currents, 274–277, 287, 340
  - physical interpretation of, 277–279
- Boundary conditions
  - for dielectrics, 185, 188, 192–197, 206, 342–344
  - for electrodynamics, 53, 342–344
  - for electromagnetic waves, 402, 406, 416
  - for electrostatics, 88–91
  - for Laplace's equation, 119–124
  - for magnetic materials, 284, 293, 342–344
  - for magnetostatics, 249–251
  - for Maxwell's equations, 338, 342–347, 583
  - for waves on a string, 388–391
- Boundary value problems, 124–150, 192–197
- Bremsstrahlung, 487
- Brewster's angle, 410
- Buckminsterfullerene, 161
- Canonical momentum, 443
- Capacitance, 105
- Capacitor, 104–107
  - charging, 106–107, 336–337
  - dielectric-filled, 190
  - discharging, 302
  - energy in, 106–107, 197
  - parallel-plate, 75, 105, 190, 240, 553
- Cartesian coordinates, 4, 130–131, 575
- Cathode rays, 216
- Cauchy's formula, 424
- Causality, 441, 446–447, 489, 531
- Cavity
  - in conductor, 99–100, 120
  - in dielectric, 183–184
  - in magnetic material, 282–283
  - resonant, 435
- Center of energy, 546–547
- Center of momentum, 537
- Cgs units, xviii, 585–588
- Charge
  - bound, 173–179, 192, 340
  - conservation of, xvii, 222, 339 (*see also* Continuity equation)
  - local, 566
  - electric, xvii–xviii, 59
  - enclosed, 69
  - free, 167, 181, 192, 412–413
  - induced, 98–102
  - magnetic (*see* Monopole)
  - quantization, xvii–xviii, 380
  - uniformly moving, 461–463, 560

- Charge density
  - line, 63
  - surface, 63, 102
  - volume, 63
- Charge invariance, 553
- Child-Langmuir law, 109
- Circular polarization, 393
- Clausius-Mossotti equation, 208–209
- Coaxial cable, 76, 431–432
- Colliding beam, 541–542
- Collision
  - classical, 508
  - elastic, 540
  - relativistic, 540–543
- Completeness, 135
- Complex amplitude, 387
- Complex notation, 387, 400
  - wave number, 422
- Complex permittivity, 421
- Complex susceptibility, 421
- Component, 5, 39
- Compton scattering, 540–541
- Compton wavelength, 541
- Conductivity, 296–297
- Conductors, 97–112, 167, 296
  - “good” and “poor,” 412
  - perfect, 296, 346, 352, 425
  - surface charge on, 125–126, 129, 299
- Conservation laws, 356–381. *See also* Charge; Energy
  - global, xvii, 356
  - local (*see* Continuity equation)
  - relativistic, 536–542
- Conservative force, 25
- Constitutive relation, 186, 285, 342, 573
- Contact term, 163–164, 264, 276
- Continuity equation, xvii, 222, 224, 338, 356–357, 359, 367, 565
- Contravariant vector, 526, 570
- Convective derivative, 443
- Coordinates
  - Cartesian, 4, 575, 576
  - curvilinear, 38, 575–581
  - cylindrical, 43–45, 575, 576
  - inversion of, 12
  - rotation of, 10–12
  - spherical, 38–43, 575, 576
  - translation of, 12
- Cosines, law of, 3
- Coulomb (unit), 60, 585
- Coulomb field, generalized, 460
- Coulomb gauge, 440–441, 569
- Coulomb’s law, xviii, 60, 63–64
  - magnetic, 339
- Covariant vector, 526–527, 570
- Critical angle, 433
- Cross product, 3, 6
- Curie point, 291
- Curl, 16, 18–19, 579–581
  - of **A**, 243, 436
  - of **B**, 229–233
  - in curvilinear coordinates, 580–581
  - in cylindrical coordinates, 44
  - of **D**, 184–185
  - of **E**, 66, 77–78, 313
  - of **H**, 280
  - in spherical coordinates, 42
- Curl-less fields, 53, 78–80
- Current, 216–223
  - bound, 274–279, 287
  - displacement, 334–335
  - enclosed, 230, 233, 280, 333–334
  - free, 280, 287
  - induced, 315
  - polarization, 340–341
  - steady, 223
- Current density, 220–223
  - four-vector, 565–566
  - surface, 220
  - volume, 220–221
- Curvilinear coordinates, 38, 575–581
- Cutoff frequency, 429–431
- Cycloid motion, 213–215, 545–546
- Cyclotron motion, 212–213, 544–545
- Cylindrical coordinates, 43–45, 575, 576
- D**. *See* Displacement, electric
- D’Alembertian, 441–442, 570
- Del operator, 16
- Delta function
  - Dirac, 45–52, 164
  - Kronecker, 165, 363
- Density of field lines, 67
- Derivative, 13
  - normal, 90
- Diamagnetism, 266, 271–274, 346, 349
- Dielectric, 167
  - linear, 185–193
- Dielectric constant, 186, 187
- Diode, vacuum, 109
- Dipole moment, 155
- Dipoles, electric, 67, 151, 154–160
  - energy of, in electric field, 172
  - energy of interaction of two, 172
  - field of
    - oscillating, 470
    - static, 67, 158–160
  - force on, 170–172
  - induced, 167–170
  - perfect, 155, 159
  - permanent, 170
  - physical, 155, 159
  - potential of
    - oscillating, 469
    - static, 151–152, 154–155
  - radiation, 467–473
  - torque on, 170–171
- Dipoles, magnetic, 252–255
  - Ampère model, 269, 294
  - of electron, 263
  - energy of, in magnetic field, 291
  - energy of interaction of two, 292
  - field of
    - oscillating, 475–476
    - static, 255, 263–265
  - force on, 267–270, 292–293
  - Gilbert model, 269, 294, 477
  - moment, 253–254, 265
  - moving, 571–572
  - perfect, 254–255
  - physical, 254–255
  - potential of
    - oscillating, 475–476
    - static, 255

- radiation, 473–477, 482
- Thomson's dipole, 380
- torque on, 266–270
- Dirac, P. A. M., 380
- Dirac delta function, 45–52, 164
- Dirichlet's theorem, 134
- Discharge of capacitor, 302
- Discontinuity
  - in **B**, 250, 284
  - in **E**, 88–90
- Dispersion, 417–424
  - anomalous, 422–423
- Dispersion coefficient, 424
- Displacement, electric, 181–185
- Displacement current, 334–337, 342, 352
- Displacement vector
  - finite, 1, 8–9
  - four-vector, 528
  - infinitesimal
    - Cartesian, 9
    - curvilinear, 575
    - cylindrical, 44
    - spherical, 40
- Divergence, 16, 17, 577–579
  - of **A**, 243
  - of **B**, 229–232
  - in Cartesian coordinates, 17
  - in curvilinear coordinates, 578
  - in cylindrical coordinates, 44
  - of **E**, 66, 71
  - four-dimensional, 566
  - of **H**, 282–283
  - in spherical coordinates, 42
- Divergence theorem, 32, 579
- Divergenceless fields, 54, 249
- Domain, 288–290
- Dot product, 2, 5, 526
- Drift velocity, 300
- Drude, P. K. I., 300
- Dual tensor, 564, 573
- Duality transformation, 353–354, 477
- Dumbbell model, 492–493
- Earnshaw's theorem, 118, 206
- Earth's magnetic field, 224
- Eddy currents, 310
- Ehrenfest's paradox, 518
- Einstein, A., 314, 503–504
- Einstein summation convention, 527
- Einstein velocity addition rule, 507–508, 523–524
- Einstein's postulates, 501–507
- Elastic collision, 540
- Electret, 176, 184
- Electric field, 59, 61–62. *See also* Charge; Current; Dipoles, electric; Displacement, electric; Energy; Force: electric; Polarization (of a medium); Potential; Susceptibility
  - average over a sphere, 163
  - in conductor, 98, 296–297
  - curl of, 66
  - divergence of, 66
  - of dynamic configurations
    - arbitrary charge distribution, 448, 479–480
  - oscillating electric dipole, 470
  - oscillating magnetic dipole, 476
  - parallel-plate capacitor, moving, 553–555, 560–561
  - point charge, arbitrary motion, 456–460
  - point charge, constant velocity, 460–461, 555–556
  - point charge moving in straight line, 462
  - rotating electric dipole, 473
- induced, 313–314, 316–321
- macroscopic, 179–181, 199
- microscopic, 179–181
- of static configurations
  - bar electret, 176, 184
  - conducting sphere in dielectric medium, 207–208
  - conducting sphere in external field, 146–147
- continuous charge distribution, 63
- dielectric cylinder in external field, 196
- dielectric sphere in external field, 192–194
- dipole, 158–160, 163
- disk, 65
- finite line, 64–65
- infinite cylinder, 73–74
- infinite line, 65, 76
- infinite plane, 74
- line charge, 63
- overlapping spheres, 76, 178–179
- parallel-plate capacitor, 75
- point charge distribution, 61
- point charge near
  - conducting plane, 124–125
- point charge near dielectric plane, 194–197
- polarized object, 173–176
- ring, 65
- sphere, 65, 71–72
- spherical shell, 65, 76
- surface charge distribution, 63
- uniformly polarized cylinder, 179
- uniformly polarized object, 173–174, 293
- uniformly polarized sphere, 174–176
- volume charge distribution, 63
- Electromagnetic force between point charges, 460–461
- Electromagnetic induction, 312–332
- Electromagnetic mass, 495
- Electromagnetic paradox, 495
- Electromagnetic radiation, xvi–xvii, 466
- Electromagnetic spectrum, 396
- Electromagnetic waves. *See* Waves
- Electromotance, 304

- Electromotive force (emf),  
 296–312, 325
- Electron  
 dipole moment, 263  
 discovery of, 216  
 spin, 263–264, 379
- Electrostatic pressure, 104
- Electrostatics, 59, 199, 223, 234,  
 241–242
- Emf (electromotive force),  
 296–312, 325
- Enclosed charge, 69
- Enclosed current, 230, 233, 280,  
 333–334
- Energy  
 of capacitor, 107  
 of charge in static field, 91–92  
 conservation of, 405, 536 (*see also* Poynting's theorem)  
 of continuous charge  
 distribution, 94–96  
 of dipole, 172, 291–292  
 in electric field, 357–359  
 of electromagnetic wave,  
 398–400  
 of inductor, 328  
 of linear dielectric, 197–202  
 in magnetic field, 328–332,  
 357  
 of point charge distribution,  
 92–94  
 of point charge near  
 conducting plane, 127  
 of spherical shell, 95–96  
 of static charge distribution,  
 91
- Energy, relativistic, 536  
 kinetic, 536  
 rest, 536
- Energy density  
 electromagnetic, 359,  
 398–399  
 of electromagnetic wave,  
 398–400  
 electrostatic, 94–97  
 in linear media, 198  
 magnetostatic, 329–330
- Energy flux, 358
- Energy-momentum four-vector,  
 536
- Equipotential, 80, 98
- Equivalence principle, 501
- Ether, 504–506  
 drag, 505  
 wind, 504–506
- Euler's formula, 387
- Evanescent wave, 434
- Events, 519
- Ewald-Oseen extinction  
 theorem, 401
- Farad (unit), 105
- Faraday, M., xvi, 312
- Faraday cage, 102
- Faraday's law, 312–321, 332,  
 395–397, 568
- Ferromagnetic domain, 288–290
- Ferromagnetism, 266, 288–292
- Feynman disk paradox, 371–373
- Field, 54. *See also* Electric field;  
 Magnetic field
- Field line, 67–68
- Field point, 9, 61
- Field tensor, 562–565, 569
- Field theory, xvi, 52–55,  
 553–554
- Flux  
 electric, 68–70  
 magnetic, 306, 311
- Flux density, 282  
 energy, 358
- Flux integral, 24
- Flux rule, 307–310, 313–314,  
 503–504
- Flux rule paradox, 309
- Force  
 conservative, 25  
 electric  
 on conductor, 103–104  
 on dielectric, 202–204,  
 207–208  
 on electric dipole, 170–172  
 on point charge in field, 61,  
 212  
 on point charge near  
 conducting plane,  
 126–127  
 on point charge near  
 dielectric plane, 194–197  
 between point charges, 60,  
 460–461  
 on surface charge, 103–104  
 electromagnetic, between  
 point charges, 460–461  
 Lorentz, 212, 217, 545  
 magnetic  
 on current, 217–218, 220–221  
 between current loops, 259  
 on magnetic dipole,  
 267–270, 292  
 on magnetized material, 273  
 between monopoles, 339  
 between parallel currents,  
 210–212, 226, 229,  
 549–551  
 between parallel planes, 240  
 on point charge, 212  
 Minkowski, 545, 549, 568,  
 571  
 ordinary, 542, 545  
 relativistic, 542
- Force density, 362
- Four vector, 525–528  
 acceleration, 549  
 charge/current, 565–566  
 displacement, 528  
 energy/momentum, 536  
 gradient, 570  
 Minkowski force, 545, 549,  
 568, 571  
 position/time, 525–526  
 potential, 569–571  
 velocity, 533–534
- Fourier series, 134
- Fourier transform, 388, 432
- Fourier's trick, 134, 144
- Frequency, 386  
 cutoff, 429–431
- Fresnel equations, 409–411
- Fringing field, 202–203
- Fundamental theorem of  
 calculus, 29  
 for curls, 34  
 for divergences, 31–32, 579  
 for gradients, 29–30, 577
- Future, 529–530

- Galilean transformation,  
     519–520, 527  
 Galileo Galilei, 502  
     principle of relativity, 502  
     velocity addition rule, 507, 508  
 Gauge  
     Coulomb, 440–441, 569  
     Lorentz, 441–442, 464, 570  
 Gauge invariance, 570  
 Gauge transformation, 439–440  
 Gauss (unit), 224, 588  
 Gaussian “pillbox,” 74–75  
 Gaussian surface, 71–74  
 Gaussian units, xviii, 586–588  
 Gauss’s law, 68–70, 241, 332, 567  
     applications of, 71–76  
     inside matter, 181–183  
     symmetry for, 72–73  
 Gauss’s theorem, 32  
*Gedanken* (thought) experiment, 508  
 Generator, 305–312  
 Gilbert dipole, 269, 294, 477  
 Gradient, 13, 14, 576  
     in Cartesian coordinates, 13, 14  
     in curvilinear coordinates, 576  
     in cylindrical coordinates, 44  
     four-dimensional, 570  
     in spherical coordinates, 42  
     theorem, 29, 577  
 Green’s identity, 57, 124  
 Green’s reciprocity theorem, 164  
 Green’s theorem, 32, 57  
 Ground, 121  
 Group velocity, 418, 429  
 Guided wave, 425–432  
 Gyromagnetic ratio, 263  
  
**H**, 279–285  
 Hall effect, 257  
 Harmonic function, 114  
 Heaviside fields, 461–462, 555–556  
 Heaviside-Lorentz units, xviii, 587  
 Heaviside theta function, 50  
 Helical motion, 213  
 Helmholtz coil, 259  
 Helmholtz theorem, 52–53, 582–584  
 Henry (unit), 324  
  
 Hertz, H., xvi, 335  
 Hidden momentum, 547–549  
 Homogeneous medium, 189  
 Horizon, 456  
 Hyperbolic geometry, 530–532  
 Hyperbolic motion, 456, 463–464, 501, 535, 543, 571  
 Hysteresis, 290  
  
 Images, method of, 124–130  
     dipole and conducting plane, 172  
     parallel cylinders, 131  
     point charge and conducting plane, 124–127, 500  
     point charge and conducting sphere, 127–130  
     point charge and dielectric plane, 196  
 Incidence  
     angle of, 407  
     plane of, 406–407  
 Incident wave, 388, 403  
 Induced charge, 98–102, 125–126, 130  
 Induced current, 315  
 Induced dipole, 167–170  
 Induced electric field, 313–314, 316–321  
 Induced emf, 313–314  
 Inductance, 321–327  
     mutual, 321–323, 332  
     self, 324–327, 331  
 Induction, 282, 312–332  
 Inertial system, 502  
 Inhomogeneous wave equation, 442  
 Insulator, 97, 167  
 Integration by parts, 36–37  
 Intensity, 399  
 Internal reflection, 433  
 Internal resistance, 304, 305  
 Interval, spacetime, 528–529  
     lightlike, 528, 530–531  
     spacelike, 528, 530–531  
     timelike, 528, 530–531  
 Invariance  
     of charge, 553  
     of mass, 537  
  
     time-reversal, 447  
 Invariant, 526, 536–537, 562, 565  
 Invariant interval, 526–529  
 Invariant product, 526  
 Inversion, 12, 432  
 Irrotational field, 53, 78–80  
 Isotropic medium, 190  
  
 Jefimenko’s equations, 449–451  
 Joule heating law, 301  
 Jumping ring, 316  
  
 Kinetic energy, 536  
 Kronecker delta, 165, 363  
  
 Langevin equation, 209  
 Laplace’s equation, 84, 113–119  
     in one dimension, 114–115  
     in three dimensions, 117–119  
     in two dimensions, 115–117  
 Laplacian, 23  
     in Cartesian coordinates, 22, 114  
     in curvilinear coordinates, 581  
     in cylindrical coordinates, 44  
     of a scalar, 23  
     in spherical coordinates, 42  
     of  $V$ , 84, 88, 113  
     of a vector, 23–24  
 Larmor formula, 481, 484  
 LC circuit, 327  
 Left-handed coordinates, 6  
 Legendre polynomials, 142, 153  
 Lenz’s law, 315–316  
 Levi-Civita symbol, 292  
 Levitation, 347  
 Liénard formula, 485, 573  
 Liénard-Wiechert potentials, 451–456, 463–464  
 Lifetime, 511, 513  
 Light, 382–435  
     speed of  
         linear medium, 401–402  
         universal, 506–507  
         in vacuum, 394, 505–506  
 Light cone, 530  
 Lightlike interval, 528  
 Line charge, 63

- Line current, 216–217
- Line element
  - Cartesian, 9
  - curvilinear, 575
  - cylindrical, 44
  - spherical, 40
- Line integral, 24
- Linear algebra, 11
- Linear combination, 133, 387–388
- Linear equation, 133, 385
- Linear medium, 401–402
  - electric, 185–193
  - magnetic, 284–287
- Linear polarization, 393
- Local conservation. *See*
  - Continuity equation
- Longitudinal wave, 391–392
- Lorentz, H. A., xvi, 492, 506
- Lorentz contraction, 506, 514–518, 522
- Lorentz contraction paradox, 515–516
- Lorentz force law, 210–223, 241, 375, 378, 545, 568, 573
  - in potential form, 442–444
- Lorentz gauge, 441
- Lorentz-Lorenz equation, 208
- Lorentz transformation, 519–526, 570–571
- Lorenz gauge, 440–442, 448, 464, 570
  
- Macroscopic field, 179–181, 199, 279
- Madelung constant, 94
- Magnet, 276, 284
- Magnetic field, 210–212, 282, 550–552. *See also*
  - Charge; Dipole; Energy; Flux; Force: magnetic; Magnetization; Potential; Susceptibility
- average over a sphere, 263–264
- curl of, 229–234
- divergence of, 229–232
- of dynamic configurations
  - arbitrary charge distribution, 450, 479–480
  - charging capacitor, 336–337
  - oscillating electric dipole, 470
  - oscillating magnetic dipole, 475–476
  - parallel-plate capacitor, moving, 556–558
  - point charge, arbitrary motion, 228, 456–461
  - point charge, constant velocity, 462, 560
  - solenoid, moving, 558–559
- of earth, 224, 498
- macroscopic, 279
- microscopic, 279
- of static configurations
  - bar magnet, 276, 284
  - in cavity, 282–283
  - circular loop, 227
  - dipole, 255, 263–265
  - finite solenoid, 229
  - finite straight line, 225
  - infinite plane, 235
  - infinite solenoid, 229, 236, 240, 259
  - infinite straight line, 225–226, 229–230, 235
  - magnetized object, 274–275, 279
  - solenoid filled with magnetic material, 286
  - sphere of linear material in external field, 287
  - spinning sphere, 246–247, 249, 263–264
  - toroidal coil, 238–239
  - uniformly magnetized cylinder, 276
  - uniformly magnetized object, 293, 299
  - uniformly magnetized sphere, 275–276
  - in superconductor, 337
  - work done by, 373–378
- Magnetic induction, 282, 312–332
- Magnetic monopole, 241–242, 252–253, 258, 269, 339
- Magnetic susceptibility, 284–286
- Magnetization, 266–274, 340–342
- Magnetomechanical ratio, 263
- Magnetostatics, 223, 234, 241, 249, 351–352
- Mass
  - electromagnetic, 495
  - relativistic, 536
  - rest, 536
- Mass renormalization, 495
- Massless particle, 538–541
- Matrix
  - Lorentz transformation, 525–526
  - rotation, 11
- Maxwell, J. C., xvi, 332–335, 394
- Maxwell stress tensor, 362–366
- Maxwell's equations, 241, 332–339, 567, 570
  - in Gaussian units, 588
  - inside matter, 340–342
  - with magnetic monopoles, 337–338
  - tensor form, 567
- Meissner effect, 346–347
- Merzbacher's puzzle, 346
- Method. *See* Images; Relaxation; Separation of variables
- Michelson-Morley experiment, 505–506
- Microscopic field, 179–181, 279
- Minkowski, H., 530, 573
- Minkowski diagram, 529
- Minkowski force, 545, 549, 568, 571
- Minkowski's formula, 382
- mks units, xviii, 585–588
- Momentum
  - angular, 370–373
  - canonical, 443
  - conservation of, 366–370, 536
  - in electromagnetic field, 360–370
  - in electromagnetic wave, 398–400
  - four-vector, 536
  - hidden, 547–549
  - relativistic, 535–537

- Momentum density, 367–368, 399
- Monochromatic wave, 394–398
- Monopole  
   electric, 152, 154–155, 481  
   magnetic, 241–242, 252–253, 258, 339, 380
- Motional emf, 305–312, 503–504
- Multipole expansion  
   of electrostatic potential, 151–158  
   of magnetostatic potential, 252  
   of radiation fields, 481
- Mutual inductance, 321–323, 332
- Neumann formula, 322–323
- Newton's laws  
   first law, 502  
   second law, 495, 542  
   third law, 360–362, 464, 492, 544
- Normal derivative, 90
- Normal incidence, reflection and transmission at, 403–405
- Normal vector, 26, 89–90, 251
- Oblique incidence, 405–411
- Observer, 509
- Octopole, 152, 156, 165, 482
- Oersted, C., xv–xvi, 564
- Ohm (unit), 298–299
- Ohm's law, 296–303
- Operator, 16
- Orthogonal coordinates, 575
- Orthogonal functions, 136, 144
- Orthogonality, 135–136, 144
- Paradoxes. *See* Barn and ladder paradox; Ehrenfest's paradox; Electromagnetic paradox; Feynman disk paradox; Lorentz contraction paradox; Merzbacher's puzzle; Time paradox; Twin paradox
- Parallel-plate capacitor, 75, 105–106, 190, 240, 553–555
- Paramagnetism, 266–270, 273–274
- Past, 530
- Path independence, 24–25, 30, 53, 79–80
- Path integral, 24
- Permanent magnet, 276, 288–289
- Permeability, 224, 284–286, 288, 573  
   of free space, 224, 285  
   relative, 285
- Permittivity, 186, 573  
   complex, 421  
   of free space, 60, 186  
   relative, 186
- Phase, 385
- Phase constant, 385, 415
- Phase transition, 291
- Phase velocity, 418
- Photon, 530, 538–541
- Pill box, 74–75
- Pinch effect, 256
- Planck formula, 539
- Plane  
   of incidence, 406–407  
   of polarization, 405
- Plane wave, 394–398
- Plasma, 256
- Point charge. *See* Electric field; Force; Magnetic field; Monopole; Potential
- Poisson's equation, 84, 113, 244, 284  
   for  $\mathbf{A}$ , 244  
   for  $V$ , 84, 88, 113
- Polar angle, 38
- Polar molecule, 169–170
- Polarizability  
   atomic, 168  
   tensor, 169
- Polarization (of a medium), 168, 172–173  
   current, 340–341  
   electric, 168, 172, 340–342  
   induced, 168  
   magnetic (*see* Magnetization)
- Polarization (of a wave), 391–393  
   circular, 393  
   linear, 393
- Polarization angle, 393
- Polarization current, 340
- Polarization vector, 392
- Pole (magnetic), 241–242, 269
- Position-time four-vector, 525–526
- Position vector, 8–9
- Potential, 584. *See also* Scalar; Vectors  
   advanced, 446  
   electric, 78–83  
   in electrodynamics, 436–442  
   four-vector, 569–571  
   Liènard-Wiechert, 451–456, 464  
   magnetic scalar, 249–250, 262  
   magnetic vector, 243–245, 262  
   magnetostatic scalar, 245  
   retarded, 444–448
- Potential energy, 80  
   of a charge configuration, 93  
   of a point charge, 92
- Power  
   dissipated in resistor, 301, 359  
   in electromagnetic wave, 399  
   radiated  
     by arbitrary source, 479–482  
     by oscillating electric dipole, 471, 477  
     by oscillating magnetic dipole, 476  
     by point charge, 482–488
- Poynting vector, 358, 398–402
- Poynting's theorem, 357–360
- Preacceleration, 490, 492, 500
- Present, 530
- Pressure  
   electromagnetic, 364  
   electrostatic, 104  
   radiation, 400
- Product rules, 20
- Propagation vector, 397
- Pseudoscalar, 12
- Pseudovector, 12, 212
- Pulsar, 498



- Quadrupole
  - electric, 152, 156, 165, 481–482
  - magnetic, 252
  - radiation, 480–481
- Quadrupole moment, 165
- Quasistatic approximation, 319–320, 450, 451
- Quotient rules, 21
- Radiation, 466–501
  - by arbitrary source, 477–482
  - by electric dipole, 467–473
  - by electric quadrupole, 482
  - electromagnetic, xvii, 466–467, 482
  - by magnetic dipole, 473–477, 497–499
  - by point charge, 482–488
    - in hyperbolic motion, 501
  - by rotating electric dipole, 473–474
  - by surface current, 499
  - synchrotron, 488
- Radiation damping, 490
- Radiation field, 460, 483
- Radiation pressure, 400
- Radiation reaction, 488–496, 501
- Radiation resistance, 472, 477
- Radiation zone, 469, 475–476, 479
- Rapidity, 528
- RC circuit, 302
- Reference point
  - for electric dipole, 157–158
  - for magnetic dipole, 254
  - for potential, 79, 81, 83
- Reflection, 403–411
  - angle of, 407
  - at conducting surface, 416–417
  - internal, 433
  - law of, 407
  - waves on a string, 388–391
- Reflection coefficient, 405, 411
- Refraction, 403–411
  - angle of, 407
  - coefficient of, 424
  - index of, 401, 418, 422
  - law of, 407
- Relativistic constitutive relations, 573
- Relativistic dynamics, 542–549
- Relativistic electrodynamics, 550–570
- Relativistic energy, 535–537
- Relativistic kinematics, 537–542
- Relativistic mass, 536
- Relativistic mechanics, 532–549
- Relativistic momentum, 535–537
- Relativistic potentials, 569–571
- Relativity
  - principle of, 502–508
  - of simultaneity, 509–510, 521–522
  - special, xiv, 502–574
- Relaxation, method of, 116
- Renormalization
  - of charge, 189–190
  - of mass, 495
- Resistance, 298
- Resistivity, 296–297
- Resistor, 297
- Resonant cavity, 435
- Rest energy, 536
- Rest mass, 536
- Retarded position, 451–454
  - potentials, 444–448
- Retarded position time, 445
- Reversion of series, 494
- Right hand rule, 3
- Right-handed coordinates, 6
- RL circuit, 331
- Rodrigues formula, 142, 149
- Rotation, 10
- Rotation matrix, 11
- Runaway motion, 490, 492
- Saturation, 289
- Scalar, 1
- Scalar potential, 53, 436–464
  - dynamic configurations
    - arbitrary charge
      - distribution, 445, 479
    - oscillating electric dipole, 469
  - oscillating magnetic dipole, 473–474
  - point charge, arbitrary
    - motion, 454
  - point charge, constant
    - velocity, 454–456
- magnetic, 245, 249–250, 262, 284
- static configurations
  - average over a sphere, 117–118
  - conducting sphere in
    - external field, 146–147
  - continuous charge
    - distribution, 84–85
  - disk, 87
  - electric dipole, 154–155
  - finite cylinder, 87
  - infinite line, 85–87
  - multipole expansion, 151–158
  - point charges, 84–85
  - polarized matter, 173–176
  - ring, 87
  - specified charge on surface
    - of sphere, 147–148
  - specified electric field, 79, 262
  - specified potential on
    - surface of sphere, 143–144
  - spherical shell, 82, 86, 149
  - surface charge, 85
  - uniformly charged object, 293
  - uniformly charged sphere, 83, 88
  - uniformly polarized sphere, 174–175, 178–179
  - volume charge, 85
- Scalar product, 2, 5, 7, 526–528
- Second derivative, 22–23
- Second-rank tensor, 11–12, 562–563
- Self-force, 492–496
- Self-inductance, 324–327, 331
- Semiconductor, 297
- Separation of variables, 130–150



- Cartesian coordinates, 130–141
- cylindrical coordinates, 150
- spherical coordinates, 141–150
- Separation vector, xii, 9, 15, 60
- Shears, 364
- Shielding, 190
- SI units, xviii, 585–588
- Simultaneity, 509–510, 521–522
- Sinusoidal waves, 385–388
- Skin depth, 413–414
- Sky, blueness of, 471
- Snell's law, 407
- Solenoid, 229, 236–237
- Solenoidal field, 54, 249
- Source charge, 9, 59, 210
- Source point, 9, 61
- Space charge, 109
- Spacelike interval, 528
- Spacetime, structure of, 525–532
- Spacetime diagram, 528–532
- Spacetime interval, 528–529
- Special relativity, xiv, 502–574
- Speed
  - of charges in wire, 242, 300
  - of light in linear medium, 401–402
  - of light in vacuum, 394, 505–506
  - of waves on a string, 384
- Spheres
  - defined, 51
  - terminology for, 51
- Spherical coordinates, 38–43
- Spherical surface, 51
- Spherical volume, 51
- Spherical wave, 432
- Standing waves, 385, 429
- Stationary charge, 60, 223
- Steady current, 223
- Step function, 49
- Stokes' theorem, 34, 55, 56, 580–581
- Stress, 364
- Stress tensor, 362–366
- String, waves on, 382–393
- Summation convention, 527
- Sun, age of, 110–111
- Sunset, redness of, 472
- Superconductor, 346
- Superluminal velocity, 418, 510
- Superposition principle, 59, 82, 97, 162
- Surface charge, 63, 103–104, 299
- Surface current, 220–221
- Surface element, 26, 40
- Surface integral, 24, 26
- Susceptibility
  - complex, 421
  - electric, 185–186, 208
  - magnetic, 284–286, 288
- Susceptibility tensor, 190
- Symmetric tensor, 563, 564
- Symmetry
  - for Ampère's law, 237
  - azimuthal, 141
  - of **E**, **B**, **D**, and **H**, 293
  - for Gauss's law, 72–73
  - of Maxwell's equation, 338–339
- Synchronization, 509–510, 512–513, 521–522
- Synchrotron radiation, 488
- TE waves, 427–431
- TEM waves, 427
- Tensor, 11–12
  - antisymmetric, 562–564
  - contravariant, 565
  - covariant, 565
  - dual, 564, 573
  - field, 562–565
  - polarizability, 169
  - second-rank, 11–12, 562–563
  - stress, 362–366
  - susceptibility, 190
  - symmetric, 563–564
- Terminal velocity, 311–312
- Tesla (unit), 224, 586
- Test charge, 59, 210
- Theta function, 49
- Third law, 360–362, 464, 492, 544
- Thomson, J. J. 216
- Thompson-Lampard theorem, 166
- Thomson's dipole, 380
- Three-dimensional wave
  - equation, 394
- Threshold, 571
- Time
  - advanced, 446
  - proper, 532–535
  - retarded, 445
- Time constant, 302, 326, 412
- Time dilation, 510–514, 521–522
- Time paradox, 512–514
- Time reversal, 447
- Timelike interval, 528
- TM waves, 427
- Toroidal coil, 238–239, 331
- Torque
  - on electric dipole, 170–171
  - on magnetic dipole, 266–270
- Total internal reflection, 433
- Transformation
  - of angles, 518, 524
  - of charge and current density, 566
  - duality, 353–354, 477
  - of electromagnetic fields, 553–560
  - of forces, 545
  - Galilean, 519–520, 527
  - gauge, 439–440
  - of lengths, 514–518, 522
  - Lorentz, 519–526, 570–571
  - of momentum and energy, 536
  - of velocity, 534
- Transformer, 350
- Translation, 12
- Transmission coefficient, 405, 411
- Transmission line, 319, 352, 431–432
- Transmission of waves on a string, 388–391
- Transparency, 401
- Transverse wave, 391–393, 395–396, 414
- Triangle diagram
  - electrodynamics, 463
  - electrostatics, 88
  - magnetostatics, 249, 259–261

- Triple product, 7
- Tunneling, 434, 500
- Twin paradox, 513–514, 524–525
- Uniqueness theorems, 119–124, 207, 262
- Unit systems. *See* Gauss; Heaviside-Lorentz units; SI units
- Unit vectors, xii, 3–4, 9, 39, 42
  - Cartesian, 4
  - curvilinear, 39, 575
  - cylindrical, 43
  - normal, 89–90
  - spherical, 38, 42
- Units, 585–588
  - ampere, 216, 224
  - coulomb, 60, 585
  - esu (electrostatic unit), 585–586
  - farad, 105
  - gauss, 224, 586
  - henry, 324
  - ohm, 298–299
  - tesla, 224, 585, 586
  - volt, 82
- Universal speed of light, 506
- Vector area, 57, 253
- Vector operator, 16
- Vector potential, 54, 243–245, 436–464
  - direction of, 247–248
  - dynamic configurations
    - arbitrary charge
      - distribution, 445, 479
    - oscillating electric dipole, 469
    - oscillating magnetic dipole, 475–476
    - point charge, arbitrary
      - motion, 454–455
    - point charge, constant
      - velocity, 454–456
  - static configurations
    - arbitrary current
      - configuration, 244–245
    - finite line current, 249
    - infinite line current, 248–249
    - infinite plane current, 248–249
    - infinite solenoid, 247
    - magnetic dipole, 253–255
    - magnetized material, 274–275
    - multipole expansion, 252–255
    - specified magnetic field, 262
    - spinning sphere, 245–246, 263–264
    - uniform magnetic field, 248
- Vector products, 3
  - cross product, 3, 6
  - dot product, 2, 5
  - multiplication by scalar, 2, 5, 526–528
- Vector triple products, 7
- Vectors, 1
  - addition, 1–2, 5
  - component, 5, 39
  - contravariant, 526
  - covariant, 526–527
  - displacement, 1, 8–9
  - four, 525–528
  - magnitude, 1
  - polarization, 392
  - position, 8
  - propagation, 397
  - pseudovectors, 12, 212
  - separation, xii, 9, 15, 60
  - subtraction, 2
  - unit (*see* Unit vectors)
- Velocity. *See also* Speed
  - 4-velocity, 532–535
  - drift, 242, 300
  - group, 418
  - ordinary, 533
  - phase, 418
  - proper, 532–535
  - wave, 418
  - of waves on a string, 384
- Velocity addition rules, 507–508, 523–524
- Velocity field, 460, 482
- Visible range (electromagnetic spectrum), 396
- Volt (unit), 82
- Voltmeter, 349
- Volume charge, 63
- Volume current, 220
- Volume element
  - Cartesian, 27
  - curvilinear, 577
  - cylindrical, 43–44
  - spherical, 40
- Volume integral, 24, 27–28
- Wave equation, 382–385, 393–394
  - for **A**, 441–442
  - for **B**, 393–394
  - for **E**, 393–394
  - general solution, 384–385
  - homogeneous, 384, 394
  - inhomogeneous, 442
  - one-dimensional, 384
  - three-dimensional, 394
  - for **V**, 441–442
- Wave guide, 425, 428
- Wave number, 385
- Wave vector, 397
- Wavelength, 385
- Waves
  - complex, 387
  - in conductors, 412–417
  - dispersive, 417–418
  - electromagnetic, 382–435
  - evanescent, 434
  - in free space, 393–400
  - guided, 425–432
  - in linear media, 401–411
  - longitudinal, 391–392
  - monochromatic, 394
  - plane, 394–398
  - sinusoidal, 385–388
  - spherical, 432
  - standing, 385, 429–430
  - on a string, 382–393
  - transverse, 391–393, 395
  - velocity, 384, 394, 418
  - water, 424
- Work
  - and emf, 306, 328

	Index	599
and potential, 91–92		
relativistic, 543		
Work done. <i>See also</i> Energy		
against back emf, 328		
in charging a capacitor, 106–107		
	by magnetic forces, 215, 218–220, 373–378	
	in moving a charge, 91–92	
	in moving a dielectric, 202–204	
	in moving a wire loop, 305–308	
		in polarizing a dielectric, 197–202
		in setting up a charge configuration, 91–94
		Work energy theorem, 543–544
		World line, 529–530