

## Index

- Abraham–Lorentz formula, 493–494, 498–501, 577
- Absorption, 418–423
- Absorption coefficient, 428
- Acausality, 447, 452, 495
- Acceleration
  - ordinary, 553
  - proper, 554
- Acceleration field, 465, 487
- Advanced potentials, 452
- Advanced time, 452
- Aharonov–Bohm effect, 247
- Alfvén’s theorem, 358–359
- Alternating current, 315
- Ampere (unit), 215, 223
- Ampère, A. M., xvi
- Ampère dipole, 271, 296
- Ampère’s law, 231–235, 242, 335–340, 571
  - applications, 231–238
  - in matter, 281–284
  - symmetry for, 234
- Ampèrian loop, 231–234, 250
- Amplitude, 393, 395
- Angle
  - azimuthal, 37, 41
  - of incidence, 414
  - polar, 37
  - of reflection, 414
  - of refraction, 414
- Angular frequency, 394
- Angular momentum, 376–378, 384–386
- Angular momentum density, 377
- Anomalous dispersion, 428–429
- Antisymmetric tensor, 566–568
- Atomic polarizability, 167, 207–208
- Auxiliary fields
  - D**, 180–190, 283–285, 576
  - H**, 281–287, 576
- Average
  - electric field, 118, 159–160
  - magnetic field, 263–264
  - potential, 117–118
- Azimuthal angle, 37, 41
- Azimuthal symmetry, 139
- BAC–CAB rule, 7–8
- Back emf, 328, 331
- Ball, defined, 49
- Bar electret, 175, 184
- Bar magnet, 278, 286
- Barn and ladder paradox, 522–524
- Betatron, 354
- Biot–Savart law, 221–226, 357, 564
- Bohr atom
  - lifetime, 491
  - polarizability, 168–169
- Bohr magneton, 263
- Bound charge, 172–178, 193, 343
  - physical interpretation, 175–177
- Bound current, 276–279, 289, 343
  - physical interpretation, 279–281
- Boundary conditions
  - for dielectrics, 184, 189, 193–197, 205, 345–346
  - for electrodynamics, 51, 345–347
  - for electromagnetic waves, 409, 413, 422
  - for electrostatics, 85–88
  - for Laplace’s equation, 118–123
  - for magnetic materials, 286, 295, 345–347
  - for magnetostatics, 249–251
  - for Maxwell’s equations, 341, 345–353, 586
  - for waves on a string, 396–399
- Boundary value problems, 124–147, 193–197
- Bremsstrahlung, 491
- Brewster’s angle, 416
- Buckminsterfullerene, 158
- Canonical momentum, 449
- Capacitance, 102
- Capacitor, 102–105
  - charging, 103–104, 338–339
  - dielectric-filled, 191
  - discharging, 303
  - energy in, 103–104, 197
  - parallel-plate, 72, 102, 191, 237, 558
- Cartesian coordinates, 4, 129–130, 578
- Cauchy’s formula, 429
- Causality, 446, 452, 494, 537
- Cavity
  - in conductor, 97, 120
  - in dielectric, 182–183
  - in magnetic material, 284–285
  - resonant, 440
- Center of energy, 551–552
  - theorem, 551
- Center of momentum, 542

- Cgs units, xviii, 588–590
- Charge, xvii–xviii  
 bound, 172–178, 193, 343  
 conservation of, xviii, 221, *see also*  
   Continuity equation  
     local, 570  
 electric, xvii–xviii, 57  
 enclosed, 67  
 free, 166, 180, 193, 418–419  
 induced, 95–99  
 magnetic, *see* Monopole  
 quantization, xviii, 386  
 uniformly moving, 466–469
- Charge density  
 line, 61  
 surface, 61, 99  
 volume, 61
- Charge invariance, 557
- Child–Langmuir law, 107
- Chromodynamics, xv, xvii
- Circular polarization, 401
- Clausius–Mossotti equation, 207–208
- Coaxial cable, 74, 323, 333, 374, 436–438
- Colliding beam, 546–547
- Collision  
 classical, 514  
 elastic, 545  
 relativistic, 545–548
- Completeness, 134
- Complex amplitude, 395
- Complex notation, 394, 408  
 wave number, 428
- Complex permittivity, 427
- Complex susceptibility, 427
- Component, 4, 38
- Compton scattering, 545–546
- Compton wavelength, 546
- Conductivity, 298–299
- Conductor, 95–109, 166, 298  
 “good” and “poor”, 419  
 perfect, 298, 352, 358, 430  
 surface charge on, 125–126, 128, 301
- Conservation laws, 362–388, *see also* Charge;  
 Energy  
 global, xviii, 362  
 local, *see* Continuity equation  
 relativistic, 541–547
- Conservative force, 24
- Constitutive relation, 187, 287, 344–345, 577
- Continuity equation, xviii, 220, 222, 340,  
 362–363, 365, 373, 569
- Contravariant vector, 532, 574
- Convection current, 313
- Convective derivative, 448
- Coordinates  
 Cartesian, 4, 578, 579  
 curvilinear, 37, 578–584  
 cylindrical, 42–43, 578, 581  
 inversion of, 12  
 rotation of, 10–11  
 spherical, 37–41, 578, 579  
 translation of, 12
- Cosines, law of, 3
- Coulomb (unit), 58, 588
- Coulomb field, generalized, 465
- Coulomb gauge, 446–447, 573
- Coulomb’s law, xviii, 58, 61–62  
 magnetic, 342, 386
- Covariant vector, 532, 574
- Critical angle, 439
- Cross product, 3, 6
- Crystal ambiguity, 185–186
- Curie point, 293
- Curl, 16, 18–19, 582–584  
 of **A**, 243, 442  
 of **B**, 227–231  
 in curvilinear coordinates, 582–583  
 in cylindrical coordinates, 42  
 of **D**, 183–184  
 of **E**, 64, 74–75, 317  
 of **H**, 282  
 in spherical coordinates, 40
- Curl-less fields, 52, 75–77
- Current, 215–221  
 alternating, 315  
 bound, 276–281, 288  
 convection, 313  
 displacement, 336–337  
 eddy, 311–314  
 enclosed, 228, 231, 282, 335–336  
 free, 282, 288  
 induced, 318  
 polarization, 342–344  
 steady, 221
- Current density, 218–221  
 four-vector, 569–570  
 surface, 218  
 volume, 219–220
- Curvilinear coordinates, 37, 578–583
- Cutoff frequency, 434–436
- Cyclotron frequency, 213
- Cycloid motion, 212–213, 550–551
- Cyclotron motion, 211, 550–551
- Cylindrical coordinates, 42–43, 578, 579
- D**, *see* Displacement, electric
- D’Alembertian, 447, 574
- Del operator, 16
- Delta function  
 Dirac, 43–50, 161  
 Kronecker, 163, 369
- Demagnetization field, 284
- Density of field lines, 65, 240–242
- Derivative, 12  
 normal, 88
- Diamagnetism, 268, 273–276, 352, 355
- Dielectric, 166  
 linear, 186–193

- Dielectric constant, 187, 188  
 Diode, vacuum, 106  
 Dipole, electric, 65, 148, 150–156  
   energy of, in electric field, 171  
   energy of interaction of two, 171  
   field of  
     oscillating, 476  
     static, 65, 154–157  
   force on, 169–171  
   induced, 166–169  
   moment, 151  
   perfect, 152, 155  
   permanent, 169  
   physical, 152, 155  
   potential of  
     oscillating, 475  
     static, 148–149, 151  
   radiation, 473–478  
   torque on, 169–170  
 Dipole, magnetic, 252–255  
   of electron, 263  
   Ampère model, 272, 296  
   energy of, in magnetic field, 293  
   energy of interaction of two, 293  
   field of  
     oscillating, 481  
     static, 254, 263–264  
   force on, 269–272, 294–295  
   Gilbert model, 271, 297, 482  
   intrinsic, 384  
   moment, 252–255, 264  
   moving, 575–576  
   perfect, 254–255  
   physical, 253–254  
   potential of  
     oscillating, 481  
     static, 254  
   radiation, 478–482, 486  
   torque on, 269–272  
 Dipole, Thomson's, 386  
 Dirac, P. A. M., 386  
 Dirac delta function, 43–50, 161  
 Dirichlet's theorem, 132  
 Discharge of capacitor, 303  
 Discontinuity  
   in  $\mathbf{B}$ , 250, 286  
   in  $\mathbf{E}$ , 85–87  
 Dispersion, 424–429  
   anomalous, 428  
 Dispersion coefficient, 429  
 Displacement, electric, 181–184  
 Displacement current, 336–339,  
   345, 357  
 Displacement vector  
   finite, 1, 8  
   four-vector, 533  
   infinitesimal  
     Cartesian, 9  
     curvilinear, 578  
     cylindrical, 42  
     spherical, 39  
 Divergence, 16–17, 580–581  
   of  $\mathbf{A}$ , 243  
   of  $\mathbf{B}$ , 227–230  
   in Cartesian coordinates, 17  
   in curvilinear coordinates, 581  
   in cylindrical coordinates, 42  
   of  $\mathbf{E}$ , 64, 68  
   four-dimensional, 570  
   of  $\mathbf{H}$ , 283–285  
   in spherical coordinates, 40  
 Divergence theorem, 31, 581  
 Divergenceless field, 52, 248  
 Domain, 290–292  
 Dot product, 2, 5, 531  
 Drift velocity, 302  
 Drude, P. K. I., 302  
 Dual tensor, 568, 576  
 Duality, 359–360, 482  
 Dumbbell model, 498–501  
  
 Earnshaw's theorem, 118, 205  
 Earth's magnetic field, 223, 348  
 Eddy current, 311–314  
 Ehrenfest's paradox, 524  
 Einstein, A., xiv, xvi, 318, 509–510, 535  
 Einstein summation convention, 532  
 Einstein velocity addition rule, 513–514,  
   528–530  
 Einstein's postulates, 508–513  
 Elastic collision, 545  
 Electret, 175, 184  
 Electric field, 57, 59–60, *see also*  
   Charge; Current; Dipole, electric;  
   Displacement, electric; Energy;  
   Force, electric; Polarization (of a  
   medium); Potential; Susceptibility  
   average over a sphere, 160  
   computer, 109–111  
   in conductor, 95, 298  
   curl of, 64  
   divergence of, 64  
   of dynamic configurations  
     arbitrary charge distribution, 453,  
     484–485  
     oscillating electric dipole, 476  
     oscillating magnetic dipole, 481  
     parallel-plate capacitor, moving,  
     557–559, 564–565  
     point charge, arbitrary motion,  
     461–464  
     point charge, constant velocity,  
     465–466, 559–560  
     point charge moving in straight line,  
     466  
     rotating charged sphere, 349  
     rotating electric dipole, 479  
   induced, 317, 320–324

- Electric field, (*cont.*)  
 macroscopic, 179–180, 199  
 microscopic, 179–180  
 of static configurations  
   bar electret, 175, 184  
   conducting sphere in dielectric medium, 206–207  
   conducting sphere in external field, 144  
   continuous charge distribution, 61  
   dielectric cylinder in external field, 196  
   dielectric sphere in external field, 193–194  
   dipole, 154–156, 160  
   disk, 63  
   finite line, 61–63  
   infinite cylinder, 70–71  
   infinite line, 63, 73  
   infinite plane, 72  
   line charge, 61  
   overlapping spheres, 73, 177–178  
   parallel-plate capacitor, 72–73  
   point charge distribution, 59  
   point charge near conducting plane, 124  
   point charge near dielectric plane, 194–196  
   polarized object, 172–175  
   ring, 63  
   sphere, 63, 68–69  
   spherical shell, 63, 73  
   surface charge distribution, 61  
   uniformly polarized cylinder, 178  
   uniformly polarized object, 172–173, 295  
   uniformly polarized sphere, 174  
   volume charge distribution, 61  
 Electric potential, 76, 113, 442, 572  
 Electromagnetic force between point charges, 465–466  
 Electromagnetic induction, 316–335  
 Electromagnetic mass, 500  
 Electromagnetic radiation, xvii, 472  
 Electromagnetic spectrum, 403  
 Electromagnetic waves, *see* Waves  
 Electromotance, 305  
 Electromotive force (emf), 298–315, 328  
 Electrons  
   dipole moment, 262  
   discovery of, 214  
   spin, 263, 385  
 Electrostatic pressure, 101  
 Electrostatics, 57, 198, 221–222, 231, 238–239  
 Elliptic integral, 259, 266  
 Emf (electromotive force), 298–315, 328  
 Enclosed charge, 67  
 Enclosed current, 228, 231, 282, 335–336  
 Energy  
   of capacitor, 104  
   of charge in static field, 88–89  
   conservation of, 412, *see also* Poynting's theorem, 541  
   of continuous charge distribution, 91–93  
   of dipole, 172, 293–294  
   in electric field, 363–365  
   of electromagnetic wave, 406–408  
   of inductor, 331  
   of linear dielectric, 197–201  
   in magnetic field, 331–335, 363  
   of point charge distribution, 89–91  
   of point charge near  
     conducting plane, 126  
   of spherical shell, 92–94  
   of static charge distribution, 88  
 Energy, relativistic, 541  
   kinetic, 541  
   rest, 541  
 Energy density  
   electromagnetic, 365, 406  
   of electromagnetic wave, 406–408  
   electrostatic, 91–94  
   in linear media, 286  
   magnetostatic, 332  
 Energy flux, 364  
 Energy–momentum four-vector, 541  
 Equipotential, 78, 96  
 Equivalence principle, 507  
 Ether, 60, 337, 510–512  
   drag, 511  
   wind, 510–512  
 Euler's formula, 394  
 Evanescent wave, 439  
 Events, 524  
 Ewald–Oseen extinction theorem, 409  
 Exclusion principle, 268  
  
 Farad (unit), 102  
 Faraday, M., xvi, 316, 347  
 Faraday cage, 99  
 Faraday disk, 311, 348  
 Faraday dynamo, 311  
 Faraday's law, 316–324, 335, 404–405, 571  
 Ferromagnetic domain, 289–293  
 Ferromagnetism, 268, 289–294  
 Feynman, R. P., xiv, 94  
 Feynman disk paradox, 377–379  
 Field, xvii, *see also* Electric field; Field theory; Magnetic field  
   drawing, 109–110  
 Field line, 64–65, 239–242, 347–350  
   drawing, 110–111, 266  
 Field point, 8, 59  
 Field tensor, 566–569, 573  
 Field theory, xvii, 51–53, 557–558  
 Flux  
   electric, 66–68  
   magnetic, 307, 314  
 Flux density, 284

- energy, 364
- Flux integral, 24
- Flux rule, 309–311, 316–317, 509–510
- Flux rule paradox, 310
- Flux tube, 240–241
- Force
  - conservative, 24
  - electric
    - on conductor, 100–101
    - on dielectric, 201–203, 206–207
    - on electric dipole, 169–171
    - on point charge in field, 59, 211
    - on point charge near conducting plane, 125–126
    - on point charge near dielectric plane, 195–197
    - between point charges, 58, 465–466
    - on surface charge, 100–101
  - electromagnetic, between point charges, 465–466
  - Lorentz, 211, 215, 550
  - magnetic
    - on current, 215–216, 219
    - between current loops, 259
    - on magnetic dipole, 270–272, 293
    - on magnetized material, 275
    - between monopoles, 342
    - between parallel currents, 209–210, 224, 227, 553–555
    - between parallel planes, 237
    - on point charge, 210
  - Minkowski, 549, 554, 571, 575
  - ordinary, 547, 549
  - relativistic, 547
- Force density, 368
- Four vector, 530–533
  - acceleration, 553
  - charge/current, 569–570
  - displacement, 533
  - energy/momentum, 541
  - gradient, 574
  - Minkowski force, 549, 554, 571, 575
  - position/time, 530–531
  - potential, 572–575
  - velocity, 538–539
- Fourier series, 132–133
- Fourier transform, 396, 437
- Fourier's trick, 132, 142
- Free charge, 181, 185–186
- Frequency, 394
  - cutoff, 434–436
- Fresnel equations, 416–418
- Fringing field, 201–202
- Fundamental theorem of calculus, 28
  - for curls, 33
  - for divergences, 31, 582
  - for gradients, 29, 580
- Future, 534–535
- Galilean transformation, 525, 532
- Galileo Galilei, 508
  - principle of relativity, 508
  - velocity addition rule, 513–514
- Gauge
  - Coulomb, 446–447, 574
  - Lorentz, 447
  - Lorenz, 446–448, 453, 470, 573–574
  - Poincaré, 261
- Gauge invariance, 445–447, 573
- Gauge transformation, 445–446
- Gauss (unit), 223, 590
- Gaussian “pillbox”, 72, 288–289
- Gaussian surface, 69–71
- Gaussian units, xix, 588–590
- Gauss's law, 66–68, 238, 335, 571
  - applications of, 69–73
  - differential form, 68
  - inside matter, 180–182
  - integral form, 67–68
  - symmetry for, 69–70
- Gauss's theorem, 31
- Gedanken* (thought) experiment, 514
- Generating function, 150
- Generator, 307–315
- Gilbert dipole, 271, 297, 482
- Gradient, 13–16, 579
  - in Cartesian coordinates, 12, 13
  - in curvilinear coordinates, 579
  - in cylindrical coordinates, 42
  - four-dimensional, 574
  - in spherical coordinates, 40
  - theorem, 12, 580
- Green's identity, 55, 124
- Green's reciprocity theorem, 161
- Green's theorem, 31, 55
- Ground, 121
- Group velocity, 424, 434
- Guided wave, 430–438
- Gyromagnetic ratio, 262
- H**, 281–287
- Hall effect, 256
- Harmonic function, 114
- Heaviside, O., xvi, 211, 340, 466
- Heaviside fields, 466, 559–560
- Heaviside–Lorentz units, xix, 590
- Heaviside theta (step) function, 48
- Helical motion, 211
- Helmholtz coil, 259
- Helmholtz theorem, 51, 585–587
- Henry (unit), 327
- Hertz, H., xvi, 337
- Hertz (unit), 403
- Hidden momentum, 551–553
- Homogeneous medium, 189
- Horizon, 461
- Hund's rule, 276

- Hyperbolic geometry, 536–537  
 Hyperbolic motion, 461, 469, 507, 540, 548, 575  
 Hyperfine splitting, 264  
 Hysteresis, 292
- Images, method of, 124–129  
   dipole and conducting plane, 171  
   parallel cylinders, 130  
   point charge and conducting plane, 124–126, 505  
   point charge and conducting sphere, 126–129  
   point charge and dielectric plane, 196
- Incidence  
   angle of, 414  
   plane of, 413–414
- Incident wave, 396, 411
- Induced charge, 95–99, 125–126, 129
- Induced current, 318
- Induced dipole, 166–169
- Induced electric field, 317, 319–324
- Induced emf, 317–318
- Inductance, 325–330  
   mutual, 325–326, 334  
   self, 327–330, 333
- Induction, 284, 316–334
- Inertial system, 508
- Inhomogeneous wave equation, 447
- Insulator, 95, 166
- Integration by parts, 35–36
- Intensity, 407
- Internal reflection, 439
- Internal resistance, 306
- Interval, space-time, 533–535  
   lightlike, 533, 535–537  
   spacelike, 533, 535–536  
   timelike, 533, 535–536
- Intrinsic dipole, 268, 384
- Invariance  
   of charge, 557  
   of mass, 542  
   time-reversal, 452
- Invariant, 532, 542, 565, 569
- Invariant interval, 532–534
- Invariant mass, 542
- Invariant product, 532
- Inversion, 12, 437
- Irrotational field, 52, 75–77
- Isotropic medium, 191
- Jefimenko's equations, 454–456
- Joule heating law, 303
- Jumping ring, 319
- Kinetic energy, 541
- Kronecker delta, 163, 369
- Langevin equation, 208
- Laplace's equation, 81, 113–118  
   in one dimension, 114–115  
   in three dimensions, 116–118  
   in two dimensions, 115–116
- Laplacian, 22  
   in Cartesian coordinates, 21, 113  
   in curvilinear coordinates, 583  
   in cylindrical coordinates, 42  
   of a scalar, 22  
   in spherical coordinates, 40  
   of  $V$ , 81, 85, 113  
   of a vector, 22–23
- Larmor formula, 486–489
- LC circuit, 330
- Left-handed coordinates, 6
- Legendre polynomials, 140, 150
- Lenz's law, 319
- Levi-Civita symbol, 294
- Levitation, 353
- Liénard formula, 489–491, 577
- Liénard–Wiechert potentials, 456–461, 468–469
- Lifetime, 517, 519
- Light, 390–440  
   speed of  
     linear medium, 409–410  
     universal, 512–513  
     in vacuum, 402, 511–512
- Light cone, 535
- Lightlike interval, 533
- Line charge, 61
- Line current, 215–216
- Line element  
   Cartesian, 9  
   curvilinear, 578  
   cylindrical, 42  
   spherical, 39
- Line integral, 24
- Linear algebra, 11
- Linear combination, 132, 396
- Linear equation, 132, 392
- Linear medium, 409–410  
   electric, 184–196  
   magnetic, 286–289
- Linear polarization, 401
- Local conservation, *see* Continuity equation
- Longitudinal wave, 399–400
- Lorentz, H. A., xvi, 498, 512
- Lorentz contraction, 512, 520–524, 527
- Lorentz contraction paradox, 521–522
- Lorentz force law, 209–222, 238, 381, 383, 448, 550, 572, 577  
   in potential form, 448–449
- Lorentz gauge, 447
- Lorentz–Lorenz equation, 208
- Lorentz transformation, 524–531, 574
- Lorenz, L. V., 447
- Lorenz gauge, 446–448, 453, 470, 573–574
- Macroscopic field, 178–180, 199, 281
- Madelung constant, 91

- Magnet, 278, 286
- Magnetic field, 209–210, 238–242, 284,  
 554–557, *see also* Charge; Dipole;  
 Energy; Field line; Flux; Force,  
 magnetic; Magnetization; Potential;  
 Susceptibility  
 average over a sphere, 263  
 curl of, 227–231  
 divergence of, 227–229  
 of dynamic configurations  
 arbitrary charge distribution, 455,  
 484–485  
 charging capacitor, 338–339  
 oscillating electric dipole, 476  
 oscillating magnetic dipole, 481  
 parallel-plate capacitor, moving,  
 560–562  
 point charge arbitrary motion, 462–465  
 point charge constant velocity, 466, 564  
 solenoid moving, 562–563  
 of Earth, 223, 348  
 macroscopic, 281  
 microscopic, 281  
 of rotating magnet, 347–350  
 of static configurations  
 bar magnet, 278, 286  
 in cavity, 284–285  
 circular loop, 225, 266  
 dipole, 254, 262–264  
 finite solenoid, 227  
 finite straight line, 232  
 infinite plane, 233  
 infinite solenoid, 227, 233, 237, 258  
 infinite straight line, 223–224, 227–228,  
 233  
 magnetized object, 276–277, 281  
 solenoid filled with magnetic material,  
 288  
 sphere of linear material in external  
 field, 289  
 spinning sphere, 245–246, 249, 263–264  
 toroidal coil, 235–236  
 uniformly magnetized cylinder, 278  
 uniformly magnetized object, 296, 301  
 uniformly magnetized sphere, 277–278  
 in superconductor, 339  
 work done by, 214, 217–218, 379–384
- Magnetic induction, 284, 316–334
- Magnetic monopole, 239, 258, 271, 341–342
- Magnetic susceptibility, 286–288
- Magnetic velocity Verlet, 264–266
- Magnetization, 268–276, 343–345
- Magnetomechanical ratio, 262
- Magnetostatics, 221–222, 231, 238–239, 249,  
 357, 358
- Mass  
 electromagnetic, 501  
 relativistic, 541  
 rest, 541
- Mass renormalization, 501
- Massless particle, 544–546
- Matrix  
 Lorentz transformation, 530–531  
 rotation, 10
- Maxwell, J. C., xvi, 335–340, 402
- Maxwell stress tensor, 368–372
- Maxwell's equations, 238, 335–342, 570, 574  
 in Gaussian units, 590  
 inside matter, 342–345  
 with magnetic monopoles, 340–341  
 tensor form, 570–571
- Meissner effect, 352–353
- Merzbacher's puzzle, 351
- Method, *see* Images; Numerical; Relaxation;  
 Separation of variables
- Method of assembly, 93
- Michelson–Morley experiment, 511–512
- Microscopic field, 179–180, 281
- Minkowski, H., 535, 577
- Minkowski constitutive relations, 577
- Minkowski diagram, 534
- Minkowski force, 549, 553, 571, 575
- Minkowski metric, 532
- Mks units, xix, 588–590
- Momentum  
 angular, 376–378  
 canonical, 449  
 conservation of, 372–376, 542  
 in electromagnetic field, 366–376  
 in electromagnetic wave, 406–408  
 four-vector, 541  
 hidden, 551–553  
 relativistic, 540–542
- Momentum density, 373–374, 406
- Monochromatic wave, 402–405
- Monopole  
 electric, 149–151, 485  
 magnetic, 238–239, 251–252, 258,  
 341–342, 386
- Motional emf, 306–315, 509–510
- Multipole expansion  
 of electrostatic potential, 147–154  
 of magnetostatic potential, 251–252  
 of radiation fields, 486
- Mutual inductance, 325–326, 334
- Neumann formula, 325–326
- Newton's laws  
 first law, 508  
 second law, 500, 547  
 third law, 259–260, 367–368, 469, 498,  
 548
- Normal derivative, 88
- Normal incidence, 410–412
- Normal vector, 25, 86–88, 251
- Numerical methods  
 fields, 109–110  
 field lines, 110–111, 266  
 particle trajectories, 111–112, 264–267  
 relaxation, 164–165

- Oblique incidence, 412–417  
 Observer, 515  
 Octopole, 148, 152, 163, 487  
 Oersted, C., xvi, 568  
 Ohm (unit), 300  
 Ohm's law, 298–303  
 Operator, 16  
 Optical tweezers, 441  
 Orthogonal coordinates, 578  
 Orthogonal functions, 134, 142  
 Orthogonality, 134–135, 142
- Pair annihilation, 547  
 Paradoxes, *see* Barn and ladder paradox;  
 Ehrenfest's paradox; Feynman  
 disk paradox; Lorentz contraction  
 paradox; Merzbacher's puzzle; Time  
 dilation paradox; Twin paradox  
 Parallel-plate capacitor, 72, 102–103, 190,  
 237, 558–565  
 Paramagnetism, 268–272, 275–276  
 Past, 535  
 Path independence, 24, 29, 51, 76–77  
 Path integral, 24  
 Pauli exclusion principle, 268  
 Perfect conductor, 352  
 Perfect dipole, 155–156, 253–254  
 Permanent magnet, 278, 290–291  
 Permeability, 223, 286–288, 290, 577  
   of free space, 223, 287  
   relative, 287  
 Permittivity, 187, 423, 577  
   complex, 427  
   of free space, 58, 187  
   relative, 187  
 Phase, 393  
 Phase constant, 393, 421  
 Phase transition, 293  
 Phase velocity, 424  
 Photon, 535, 543–546  
 Pillbox, 72, 288–289  
 Pinch effect, 256  
 Planck formula, 544  
 Plane  
   of incidence, 413–414  
   of polarization, 412  
 Plane wave, 402–405  
 Plasma, 256  
 Poincaré gauge, 261  
 Point charge, *see* Electric field; Force;  
 Magnetic field; Monopole; Potential  
 Poisson's equation, 81, 113, 243, 286  
   for  $\mathbf{A}$ , 243  
   for  $V$ , 82, 85, 113  
 Polar angle, 37  
 Polar molecule, 169–170  
 Polarizability  
   atomic, 167  
   tensor, 168  
 Polarization (of a medium), 167, 171–172  
   current, 342–344  
   electric, 167, 171, 342–345  
   induced, 167  
   magnetic, *see* Magnetization  
 Polarization (of a wave), 399–401  
   circular, 401  
   linear, 401  
 Polarization angle, 400  
 Polarization vector, 400  
 Pole (magnetic), 239, 271  
 Position–time four-vector, 530–531  
 Position vector, 8  
 Potential, 51, 113, 442, 454, 587; *see also*  
   Scalar; Vector  
   advanced, 452  
   electric, 76–81, 113  
   in electrodynamics, 442–447  
   four-vector, 573–575  
   Liénard–Wiechert, 456–461, 469  
   magnetic scalar, 244, 248–250, 262  
   magnetic vector, 243–244, 261  
   relativistic, 572–574  
   retarded, 450–453  
 Potential energy, 78  
   of a charge configuration, 90  
   of a point charge, 89  
 Power  
   dissipated in resistor, 303, 365  
   in electromagnetic wave, 406  
   radiated  
     by arbitrary source, 484–487  
     by oscillating electric dipole, 476, 482  
     by oscillating magnetic dipole, 481  
     by point charge, 487–493  
 Poynting vector, 364–365, 373, 406–409, 418  
 Poynting's theorem, 363–365  
 Preacceleration, 495, 498, 506  
 Present, 535  
 Pressure  
   electromagnetic, 370  
   electrostatic, 101  
   radiation, 407  
 Principle of equivalence, 507  
 Principle of relativity, 508, 512  
 Product rules, 20–22  
 Propagation vector, 405  
 Proper, 538  
   charge density, 569  
   force, 549  
   permeability, 577  
   permittivity, 577  
   time, 538  
   velocity, 538–540  
 Pseudoscalar, 12  
 Pseudovector, 12, 211  
 Pulsar, 504



- Quadrupole
  - electric, 149, 152, 163, 486
  - magnetic, 251
  - radiation, 485–486
- Quadrupole moment, 163
- Quantization, xviii
- Quark, xviii
- Quasistatic approximation, 322–323, 455, 456
- Quotient rules, 21
- Radiation, 472–507
  - by arbitrary source, 482–486
  - by electric dipole, 473–478
  - by electric quadrupole, 486
  - electromagnetic, xvii, 472, 486
  - by magnetic dipole, 479–482, 503–505
  - by point charge, 487–493
    - in hyperbolic motion, 507
  - by rotating electric dipole, 478–479
  - by surface current, 505
  - synchrotron, 493
- Radiation damping, 495
- Radiation field, 465, 488
- Radiation pressure, 407
- Radiation reaction, 493–501, 507
- Radiation resistance, 478, 482
- Radiation zone, 475, 481, 484
- Rapidity, 533
- RC circuit, 303
- Reference point
  - for electric dipole, 153–155
  - for magnetic dipole, 253
  - for potential, 77, 78, 80
- Reflection, 410–416
  - angle of, 414
  - at conducting surface, 422–423
  - internal, 439
  - law of, 414
  - waves on a string, 396–399
- Reflection coefficient, 412, 417
- Refraction, 410–418
  - angle of, 414
  - coefficient of, 429
  - index of, 409, 424, 428
  - law of, 414
- Relativistic constitutive relations, 577
- Relativistic dynamics, 547–553
- Relativistic electrodynamics, 554–574
- Relativistic energy, 540–542
- Relativistic kinematics, 542–547
- Relativistic mass, 541
- Relativistic mechanics, 538–553
- Relativistic momentum, 541–542
- Relativistic potential, 572–575
- Relativity
  - principle of, 508–514
  - of simultaneity, 515–522, 527
    - special, xiv, 508–577
- Relaxation, method of, 116, 164–165
- Renormalization
  - of charge, 190–191
  - of mass, 501
- Resistance, 300
- Resistivity, 298–299
- Resistor, 299
- Resonant cavity, 440
- Rest energy, 541
- Rest mass, 541
- Retarded position, 456–458
- Retarded potential, 450–453
- Retarded time, 450
- Reversion of series, 500
- Right-hand rule, 3, 210
- Right-handed coordinates, 6
- RL circuit, 334
- Rodrigues formula, 140, 146
- Rotation, 9
- Rotation matrix, 10
- Runaway motion, 495, 498
- Saturation, 291
- Scalar, 1
- Scalar potential, 51, 76, 442, 459
  - dynamic configurations
    - arbitrary charge distribution, 450, 484
    - oscillating electric dipole, 475
    - oscillating magnetic dipole, 479
    - point charge, arbitrary motion, 459
    - point charge constant velocity, 459–461
  - magnetic, 244, 248–249, 262, 286
  - static configurations
    - average over a sphere, 117
    - conducting sphere in external field, 144
    - continuous charge distribution, 82–83
    - disk, 84
    - electric dipole, 150–151
    - finite cylinder, 85
    - infinite line, 84, 450
    - multipole expansion, 147–154
    - point charges, 82
    - polarized matter, 172–174
    - ring, 84
    - specified charge on surface of sphere, 144–145
    - specified electric field, 77, 262
    - specified potential on surface of sphere, 141–142
    - spherical shell, 80, 83, 146
    - surface charge, 83
    - uniformly charged object, 295
    - uniformly charged sphere, 80, 85
    - uniformly polarized sphere, 174, 177–178
    - volume charge, 83

- Scalar product, 3, 5, 7, 531–533  
 Second derivative, 22–23  
 Second-rank tensor, 11, 566–567  
 Self-force, 498–501  
 Self-inductance, 327–330, 333  
 Semiconductor, 299  
 Separation of variables, 129–147  
   Cartesian coordinates, 129–139  
   cylindrical coordinates, 147  
   spherical coordinates, 139–147  
 Separation vector, xi, 8, 15, 58  
 Shear, 370  
 Shielding, 191  
 SI units, xix, 588–590  
 Simultaneity, 515–516, 527  
 Sinusoidal waves, 393–396  
 Skin depth, 420–421  
 Sky, blueness of, 477  
 Snell's law, 414  
 Solenoid, 227, 233–234  
 Solenoidal field, 52, 248  
 Source charge, 8, 57, 209  
 Source point, 8, 59  
 Sources, xii, 57–59, 62, 209, 239, 305–306,  
   317, 337, 447  
 Space charge, 106  
 Space-time diagram, 533–537  
 Space-time interval, 533–534  
 Spacelike interval, 534  
 Space-time structure, 530–537  
 Special relativity, xiv, 508–577  
 Spectrum, 403  
 Speed  
   of charges in wire, 238, 302  
   of light in linear medium, 408–409  
   of light in vacuum, 402, 511–512  
   of waves on a string, 391  
 Sphere  
   defined, 49  
   terminology for, 49  
 Spherical coordinates, 37–41  
 Spherical surface, 49  
 Spherical volume, 49  
 Spherical wave, 438  
 Standing wave, 390, 393, 435  
 Stationary charge, 58, 222  
 Steady current, 222  
 Step function, 48  
 Stokes' theorem, 33, 53, 54, 583–584  
 Störmer's problem, 267  
 Stress, 370  
 Stress tensor, 368–372  
 String, waves on, 390–401  
 Summation convention, 532  
 Sun, age of, 107–108  
 Sunset, redness of, 477  
 Superconductor, 352  
 Superluminal velocity, 424, 516  
 Superposition principle, 57, 79,  
   94, 158  
 Surface charge, 61, 100–101, 301  
 Surface current, 218–219  
 Surface element, 25, 39  
 Surface integral, 24, 25  
 Susceptibility  
   complex, 427  
   electric, 186–187, 207  
   magnetic, 286–288, 290  
 Susceptibility tensor, 191  
 Symmetric tensor, 567, 568  
 Symmetry  
   for Ampère's law, 234–235  
   azimuthal, 139  
   of **E**, **B**, **D**, and **H**, 296  
   for Gauss's law, 70  
   of Maxwell's equation, 341–342  
 Synchronization, 515–516  
 Synchrotron radiation, 493  
 TE waves, 433–436  
 TEM waves, 432  
 Tensor, 11  
   antisymmetric, 566–568  
   contravariant, 568  
   covariant, 568  
   dual, 568, 576  
   field, 566–569  
   polarizability, 168  
   second-rank, 11, 566–567  
   stress, 368–372  
   susceptibility, 191  
   symmetric, 567–568  
 Terminal velocity, 314–315  
 Tesla (unit), 223, 588  
 Test charge, 57, 209  
 Theta function, 47  
 Third law, 259–260, 366–368, 469, 498, 548  
 Thompson–Lampard theorem, 164  
 Thomson dipole, 386  
 Thomson kink model, 467, 471  
 Three-dimensional wave equation, 402  
 Threshold, 575  
 Time  
   advanced, 452  
   proper, 538–540  
   retarded, 450  
 Time constant, 304, 329, 419  
 Time dilation, 516–519, 527–528  
 Time dilation paradox, 518–519  
 Time reversal, 452  
 Timelike 4-vector, 533  
 TM waves, 432  
 Toroidal coil, 235–236, 334  
 Torque  
   on electric dipole, 169–170  
   on magnetic dipole, 268–272

- Total internal reflection, 439
- Trajectory, 111–112, 264–267
- Transformation
  - gauge, 445–446, 573–574
  - of angles, 524, 530
  - of charge and current density, 570
  - duality, 359–360, 482
  - of electromagnetic fields, 557–564
  - of forces, 549
  - Galilean, 525–526, 533
  - gauge, 445–446, 573–574
  - of lengths, 519–524, 527
  - Lorentz, 524–531, 574
  - of momentum and energy, 541
  - of velocity, 539
- Transformer, 356
- Translation, 12
- Transmission coefficient, 412, 417
- Transmission line, 322, 358, 436
- Transparency, 409
- Transverse wave, 399–400, 404, 420
- Triangle diagram
  - electrodynamics, 468
  - electrostatics, 85–86
  - magnetostatics, 249, 261–262
- Triple product, 7
- Tunneling, 439, 505
- Twin paradox, 519, 530
  
- Uniqueness theorems, 118–123, 206, 262
- Unit vectors, xi, 3–4, 8, 38, 41
  - Cartesian, 4
  - curvilinear, 38, 578
  - cylindrical, 42
  - normal, 86–88
  - spherical, 37, 40
- Units, xviii–xix, 588–590
  - ampere, 215, 223
  - coulomb, 58, 588
  - esu (electrostatic unit), 588
  - farad, 102
  - gauss, 223, 588
  - Gaussian, xix, 588–590
  - Heaviside–Lorentz, xix
  - henry, 327
  - ohm, 300–301
  - SI, xix, 588–590
  - tesla, 223, 588, 590
  - volt, 79
- Universal speed of light, 512
  
- Vector area, 55, 252
- Vector operator, 16
- Vector potential, 52, 243–245, 442–469
  - direction of, 247
  - dynamic configurations
    - arbitrary charge distribution, 452, 484
    - oscillating electric dipole, 475
    - oscillating magnetic dipole, 481
    - point charge, arbitrary motion, 459–460
    - point charge, constant velocity, 459–460
  - static configurations
    - arbitrary current configuration, 243–244
    - finite line current, 249
    - infinite line current, 247–248
    - infinite plane current, 247–248
    - infinite solenoid, 246
    - magnetic dipole, 252–254
    - magnetized material, 276–277
    - multipole expansion, 251–254
    - specified magnetic field, 262
    - spinning sphere, 245, 263
    - uniform magnetic field, 248
- Vector products, 3
  - cross product, 3, 6
  - dot product, 2, 5
  - multiplication by scalar, 2, 5, 531–533
- Vector triple products, 7
- Vector, 1, 9–12
  - addition, 1–2, 4
  - component, 5, 38
  - contravariant, 532
  - covariant, 532
  - displacement, 1, 8–9
  - four, 530–533
  - magnitude, 1
  - polarization, 400
  - position, 8
  - potential, 52, 243–249, 442, 459, 585–587
  - propagation, 405
  - pseudovector, 12, 211
  - separation, xi, 8, 15, 58
  - subtraction, 2
  - unit, *see* Unit vectors
- Velocity, *see also* Speed
  - 4-velocity, 538–540
  - drift, 238, 302
  - group, 424
  - ordinary, 538
  - phase, 424
  - proper, 538–540
  - wave, 424
  - of waves on a string, 391
- Velocity addition rules, 513–514, 528–530
- Velocity field, 465, 487
- Volt (unit), 79
- Voltmeter, 354
- Volume charge, 61
- Volume current, 219
- Volume element
  - Cartesian, 27
  - curvilinear, 580
  - cylindrical, 42
  - spherical, 39
- Volume integral, 24, 27

- Wave equation, 390–393, 401–402
  - for **A**, 447–448
  - for **B**, 401–402
  - for **E**, 401–402
  - general solution, 392–393
  - homogeneous, 392, 402
  - inhomogeneous, 447
  - one-dimensional, 392
  - three-dimensional, 402
  - for  $V$ , 446–448
- Wave guide, 430, 433
- Wave number, 393
- Wave vector, 405
- Wavelength, 393
- Waves
  - complex, 395
  - in conductors, 418–423
  - dispersive, 423–424
  - electromagnetic, 390–440
  - evanescent, 439
  - in free space, 401–407
  - guided, 430–438
  - in linear media, 408–417
  - longitudinal, 399–400
  - monochromatic, 402
  - plane, 402–405
  - sinusoidal, 393–396
  - spherical, 438
  - standing, 393, 434–435
  - on a string, 390–401
  - transverse, 399–400, 403
  - velocity, 392, 402, 424
  - water, 430
- Work
  - and emf, 307, 331
  - and potential, 89
  - relativistic, 548
- Work done, *see also* Energy
  - against back emf, 331
  - in charging a capacitor, 103–104
  - by magnetic forces, 214, 217–218, 379–384
  - in moving a charge, 88–89
  - in moving a dielectric, 195–203
  - in moving a wire loop, 306–310
  - in polarizing a dielectric, 197–206
  - in setting up a charge configuration, 88–91
- Work–energy theorem, 548–549
- World line, 534–535