| action | Lagrangian for Dp-brane, 445 |
|--|--|
| charged point particle, 98 | string ending on D-brane, 448–450 |
| fields and symmetries, 157 | |
| first defined, 78 | |
| free particle in curved space, 99 | Calabi-Yau space, 479 |
| free point particle, 91 | capacitance |
| free scalar field, 196 | and moduli of annuli, 636-641 |
| Nambu-Goto, 111-112, 123, 178 | Born–Infeld electrodynamics, 446 |
| open string and charged endpoints, 368 | Cauchy–Riemann equations, 599 |
| particle and EM field, 99, 356 | Chan-Paton labels, 345 |
| Polyakov string, 582–587 | charge |
| saddle points, 87 | conserved |
| string and Kalb-Ramond field, 357 | |
| transverse string coordinates, 248 | for Lagrangian densities, 158 |
| admissible states, 575 | Lagrangian mechanics, 156 |
| AdS/CFT correspondence | Lorentz, 167 |
| conformal field theory, 537 | momentum, 160, 164 |
| finite temperature, 554-559 | electric, 154-155 |
| holography, 553-554 | chiral fermions, 463-464, 468, 472 |
| large N limit, 533-535 | conformal boundary |
| motivating, 537-541 | AdS, 552 |
| near horizon geometry, 539 | \mathbb{H}_n , 548 |
| parameters, 541-543 | defined, 547 |
| anti-de Sitter | Minkowski space, 564 |
| black hole, 555 | \mathbb{R}_2 , 548 |
| conformal boundary, 552 | conformal gauge, 586 |
| defined, 549 | conformal map, see Schwarz-Christoffel |
| isometries, 537 | constraints |
| metric, 552, 564, 565 | from the Polyakov action, 587 |
| | parameterization, 136, 138, 182, 569 |
| background fields, 361-362, 415-416 | quantum Virasoro, 572–577 |
| black hole | solving in light-cone gauge, 187–189 |
| in anti-de Sitter space, 555 | cosmic strings, 145–149 |
| basics, 513-514 | counting |
| built with D-branes, 519-520 | _ |
| entropy, 514-515, 520-521 | symmetric products, 277 |
| in IIB superstrings, 518-519 | with generating functions, 317–320 |
| temperature, 514 | cross section, 595 |
| Bohm-Aharonov effect, 406 | current |
| Born-Infeld electrodynamics | conserved |
| and T-duality, 443-446 | defined, 154 |
| capacitance, 446 | for Lagrangian densities, 158 |
| energy of a point charge, 441-443, 447 | Lorentz, 167 |
| general theory, 438-443 | momentum, 159-161 |
| Hamiltonian, 447 | electric, 154-155 |
| Lagrangian density, 438 | four-vector, 50 |
| | |

| electromagnetism |
|---|
| |
| gauge potentials, 48 |
| current vector, 50 |
| duality invariance, 376-377 |
| field strength defined, 48 |
| gauge transformations, 46 |
| Maxwell equations, 45 |
| ensemble |
| canonical, 495-498 |
| microcanonical, 495-498 |
| entropy |
| black hole, 514-515, 520-521 |
| defined, 495 |
| of a string, 506, 515–516 |
| extra dimensions |
| Lorentz invariance, 30 |
| |
| compact, 31 |
| large, 67–69 |
| E 1' 502 504 620 |
| Feynman diagram, 592–594, 630 |
| field strength, see electromagnetism |
| fine-structure constant, 62, 294 |
| flux compactification, 484 |
| four-vector, 21 |
| free boundary condition, 114 |
| fundamental domain |
| defined, 32 |
| modular group \mathcal{F}_0 , 651–656 |
| modular group, exercise, 658 |
| modular group, identifications, 65 |
| |
| gamma function |
| analytic continuation, 70 |
| defined, 54 |
| recursion relation, 54 |
| Veneziano amplitude, 625 |
| gauge transformations |
| U(1) structure, 404–406 |
| gravitational field, 60, 210 |
| Kalb–Ramond field, 214 |
| Maxwell and Kalb–Ramond, 368 |
| Maxwell field, 46, 206 |
| geodesic |
| |
| equation, 99 |
| on a cone, 147, 153 |
| graviton states |
| from covariant closed strings, 590 |
| from gravity field, 212 |
| from light-cone closed strings, 29 |
| gravity field |
| degrees of freedom, 212 |
| gauge transformations, 210 |
| light-cone gauge, 211 |
| quantum theory, 209-213 |
| group |
| U(1), 344, 405 |
| U(N), 344 |
| |

| Hagedorn temperature | for Dp-brane with EM fields, 445 |
|--|--|
| bosonic string theory, 505–507 | nonrelativistic string, 81 |
| open superstring theory, 522 | symmetry |
| Hamilton's principle, 79 | defined, 155 |
| Hamiltonian | more general, 159, 173-174 |
| Born-Infeld electrodynamics, 447 | landscape, 10, 482, 489 |
| charged point particle, 99 | light-cone |
| covariant open string, 570, 578 | components of tensors, 213 |
| density for scalar field, 197 | coordinates, 22 |
| density for strings, 127 | energy and momentum, 28 |
| energy for strings, 133 | gauge |
| light-cone closed string, 286, 289, 388 | gravity field, 211 |
| light-cone open string, 238, 262 | Maxwell field, 207 |
| light-cone point particle, 222 | open and closed strings, 187 |
| point particle energy, 92 | point particle, 217 |
| Hardy–Ramanujan, 502 | Hamiltonian, see Hamiltonian |
| Hawking-Page transition, 559 | metric, 24 |
| helicity, 463 | scalar field equation, 200 |
| hierarchy problem, 61, 69 | lightlike |
| Higgs mechanism, 345, 463, 465, 493 | compactification, 42 |
| holography, 549 | separated events, 16 |
| holonomy W | linear fractional transformation |
| as angle variable, 410-412 | constructed from three points, 611, 626 |
| defined, 408 | defined, 610 |
| Wilson line, see Wilson line | number of parameters, 611 |
| hyperbolic space | Lorentz algebra, 231, 234 |
| H ₂ , 544 | Lorentz force law, 46, 69 |
| \mathbb{H}_2 isometric embedding in \mathbb{R}^3 , 562 | Lorentz generators |
| \mathbb{H}_n defined, 545 | quantum open string, 259-262 |
| \mathbb{H}_n metric, 547 | quantum point particle, 229-233 |
| \mathbb{H}_n conformal boundary, 548 | Lorentz transformations |
| | boost, 19 |
| intersection number, 454, 457, 491 | defined, 20 |
| interval, 15 | infinitesimal, 165 |
| | Luscher coefficient, 532 |
| jumping rope | |
| angular momentum, 172 | M-theory, 325, 481 |
| relativistic, 150 | magnetic field |
| | flux quantization, 427, 430 |
| Kalb-Ramond field | motion of open string, 431-432 |
| T ² compactification, 398–399 | on D-branes, 423-429 |
| analysis, 214-215 | related to tilting angle, 425 |
| coupling to a string, 357 | mass-squared |
| coupling to Maxwell field on D-brane, | closed string, 288 |
| 368–370 | closed string with compactification, 387 |
| electric charge density, 359 | DD contribution, 336 |
| gauge transformations, 214 | ND contribution, 350 |
| motion of a string, 374-375 | normal ordering contributions, 349 |
| of a string, 374 | NS sector, 314 |
| particle states, 215 | open string, 263 |
| states from light-cone closed string, 292 | open string (classical), 190 |
| Kaluza-Klein, 390 | open string between D-branes, 341 |
| | R sector, 316 |
| Lagrangian | twisted sector, 302 |
| Born-Infeld electrodynamics, 438 | massive vector field |
| density for nonrelativistic string, 81 | formulation, 215 |
| first defined, 78 | from separated D-branes, 342-343 |

| Maxwell field | number operator |
|--|--|
| coupling to open strings, 368, 415-418 | closed string, 287 |
| gauge transformations, 206 | open string, 264 |
| holonomy, 408 | · - |
| light-cone gauge, 207 | operator |
| photon states, 209 | creation and annihilation |
| quantum theory, 206-209 | closed string, 285 |
| metric | open string, 244-246 |
| conformal, 586 | quantum scalar field, 203 |
| dynamical, 59 | Heisenberg, 218-220 |
| for open string in magnetic field, 432 | open string Heisenberg, 237 |
| induced on surface, 104 | open string Schrödinger, 237 |
| induced on world-sheet, 111 | point particle |
| Minkowski, 17–18 | Heisenberg, 221 |
| transformation under reparameterization, 105 | Schrödinger, 220 |
| world-sheet $h_{\alpha\beta}$, 583 | scalar field operator, 204 |
| mode expansion | Schrödinger, 218–220 |
| closed string coordinate | orbifold |
| no compactification, 284 | T^2/\mathbb{Z}_3 , 41 |
| with compactification, 383 | \mathbb{C}/\mathbb{Z}_N , 35 |
| for X ⁻ open string coordinate, 190 | $\mathbb{R}^1/\mathbb{Z}_2$ |
| for DD open string coordinate, 335 | closed strings, 296-298 |
| for ND open string coordinate, 348 | defined, 35 |
| for NN coordinate derivatives, 186 | twisted sector, 298-303 |
| for NN open string coordinate, 186 | construction, 41 |
| modular group $PSL(2, \mathbb{Z})$ | defined, 35 |
| defined, 655 | spacetime, 43 |
| fundamental domain \mathcal{F}_0 , 656 | orientation |
| generated by S and T, 658 | of an open string, 339 |
| moduli space | orientifold plane |
| of S ¹ compactification, 393 | and coincident Dp-branes, 352 |
| of T^2 compactification with B field, 656 | and Dp-brane, 351 |
| of Riemann surfaces, see Riemann surface | and separated Dp-branes, 352–354 |
| moduli stabilization, 481–484 | closed string spectrum, 305 |
| | |
| Nambu-Goto | particle states |
| free string equations of motion, 113 | Kalb–Ramond states, 215 |
| string action, 111-112, 170, 178 | one-graviton states, 212 |
| Neumann boundary condition, 76 | one-particle, 205–206 |
| Neveu–Schwarz fermions, 312–315 | one-photon states, 209 |
| Newton | role in quantum field theory, 201 |
| constant G, 60 | partition function |
| constant in arbitrary dimension, 63 | defined, 496 |
| constant in terms of g, 294 | relativistic particle, 507-509, 522 |
| gravitational law, 60 | single string, 509-513 |
| nonlinear electrodynamics | partitions of N |
| Born-Infeld theory, 438-443 | P(N; b, f), 505, 522 |
| energy functional, 436, 446 | p(N), 499, 502 |
| field \vec{D} , 436 | $p_b(N)$, 503–504 |
| field \vec{H} , 436 | q(N), 504, 521 |
| general framework, 433-437 | generating functions, 522 |
| non-planar open string diagrams, 642-643 | photon states |
| normal ordering, 251 | from covariant open string, 579-580, 589 |
| null | from light-cone open string, 266-267 |
| states, 577 | from Maxwell field, 209 |
| vector, 21 | physical state |
| vectors orthogonal to, 191 | covariant quantization |

| defined, 577 | generated by Virasoro, 257-259, 277, |
|---|---|
| gravitons, 590 | 289–290 |
| photons, 580 | invariance for particle, 93–94, 234 |
| tachyons, 579 | invariance of area, 103–106 |
| light-cone quantization | invariance of Kalb–Ramond coupling, 373 |
| open string, 266 | Riemann surface |
| point particle, 224 | defined, 599 |
| Planck | moduli space |
| length, mass, time, 61 | $\mathcal{M}_{0,3}$, 616 |
| constant, 36 | $\mathcal{M}_{0,4}$, 611–613, 646 |
| energy, 62 | $\mathcal{M}_{1,0}$, 652 |
| length in arbitrary dimension, 63 | N_3 , 616 |
| point particle | N_4 , 616–617 |
| action if charged, 98 | of annuli, 633 |
| coupled to dynamical EM field, 99 | points approaching each other, 627 |
| covariant quantization, 587 | the annulus, 632–634 |
| free action, 91 | the complex plane C, 598 |
| free equation of motion, 95 | the sphere \mathbb{C} , 609–610 |
| free motion in curved space, 99 | the torus, 646–651 |
| Hamiltonian, when charged, 98 | the upper plane H (bordered), 599 |
| Heisenberg operators, 221 | the upper plane H, 599 |
| Lagrangian when free, 92 | rotating open string |
| light-cone Lorentz generators, 229–233 light-cone momentum generators, 226–229 | coherent states, 530 |
| quantum states, 223 | detailed analysis, 140–142 |
| reparameterization symmetry, 234 | further study, 149 |
| Schrödinger equation, 224 | in light-cone gauge, 191 quantum length, 561 |
| Schrödinger operators, 220 | quantum states, 526–531 |
| primary, see Virasoro primary | quantum states, 320–331 |
| proper time, 27 | scalar field |
| as action, 91–92 | action principle, 195–197 |
| puncture, 602 | degrees of freedom, 199 |
| pure gauge | free equation of motion, 197 |
| defined, 208 | free Hamiltonian, 197 |
| gravity field, 214 | light-cone field equation, 200 |
| Maxwell field, 209 | plane wave solutions, 197–199 |
| states, 577 | quantum theory, 200–206 |
| | Schwarz-Christoffel map |
| quantum field theory | closing off the polygon, 628 |
| gravity field, 209-213 | for four open strings, 618-621 |
| Kalb-Ramond field, 214-215 | for three open strings, 605-608 |
| massive vector field, 215 | in general, 603-605 |
| Maxwell field, 206-209 | turning angle, 603 |
| scalar field, 200-206 | sectors |
| quark-antiquark potential, 531-532 | for open strings between D-branes, 339 |
| quark-gluon plasma | for type II superstrings, 322-324 |
| jet-quenching, 561 | Ramond and Neveu-Schwarz, 312 |
| production, 559 | self-dual radius, 391 |
| viscosity, 560 | Shapiro-Virasoro amplitude, 657 |
| | slope parameter α' |
| Ramond fermions, 315-317 | defined, 168 |
| Ramond-Ramond | related to string length, 170 |
| couplings to D-branes, 371 | related to string tension, 169 |
| fields in closed superstrings, 324 | spacelike |
| Regge trajectory, 527 | separated events, 16 |
| reparameterization | vector, 21 |
| exercise for particle, 98 | spatial surface, 100, 121 |

| sphere | open superstrings, 320-322 |
|--------------------------------------|---|
| arbitrary dimension, 52 | R sector, 315-317 |
| volume, 54 | type I, 324 |
| Standard Model | supersymmetry, 6, 478, 518 |
| first described, 5-6 | symmetry, see Lagrangian, symmetry |
| gauge group, 457-463 | |
| matter content, 463-472 | T-duality |
| string model, 472-479, 492-493 | as torus duality, 376 |
| state space | closed strings |
| closed string | as $X_R \rightarrow -X_R$, 396 |
| no compactification, 290-294 | from spectrum coincidence, 392-394 |
| with compactification, 388-392 | effect on string coupling, 412, 414 |
| Lorentz covariant, 577-580 | open string |
| open string | invariance of Hamiltonian, 413 |
| between Dp- and Dq-branes, 344 | of DN coordinate, 413 |
| Dp-brane, 331–333 | open strings |
| parallel Dp-branes, 338–345 | derivation, 402–404 |
| spacefilling D-brane, 262-268 | effect on D-branes, 404 |
| static gauge | motivated, 400–402 |
| defined, 116 | tachyon |
| string action in, 123 | scattering amplitude, 625 |
| string bit, 515-516, 524 | states in closed string, 291 |
| string charge | states in open string, 266 |
| \vec{Q} , 360, 373 | tachyon potential, 273, 278 timelike |
| behaving as Maxwell current, 362-363 | |
| carried by electric field, 369-370 | separated events, 16 |
| density \vec{j}^0 , 359–361 | vector, 21 transverse oscillation |
| string coordinate, 107 | defined, 73 |
| string coupling | |
| and Newton's constant, 294 | frequencies, 77 wave equation, 75 |
| change under T-duality, 414 | wave equation, 73 |
| related to the dilaton, 294-296 | ultraviolet divergences, 630-631 |
| string endpoints | units |
| are charged, 368 | basic, 13–14 |
| covariant analysis of motion, 127 | Heaviside–Lorentz, 45 |
| exercises on free motion, 149 | natural, 177–178 |
| free motion, 124-125 | Planckian, 60 |
| motion attached to D-branes, 128 | SI system, 13–14 |
| string length, 14 | unoriented |
| defined, 170 | closed strings, 304 |
| related to α' , 170 | open strings, 268, 278, 325 |
| self-dual radius, 391 | type I theory, 324 |
| string number \mathcal{N} , 363 | 3.*** |
| string orientation, 360 | vacuum energy |
| string spatial surface, 121 | associated length scale, 70 |
| string tension | in flux compactification, 486-489, 494 |
| effective, 134 | in the universe, 486 |
| nonrelativistic string, 73 | in toy model, 485, 494 |
| relativistic string, 111, 119 | Veneziano amplitude, 625 |
| supergravity, 518 | Virasoro |
| superstrings | algebra |
| charged D-branes, 371 | as a Lie algebra, 276 |
| closed superstrings, 322-324 | consistency of central extension, 276 |
| GSO truncation, 320-322 | subalgebra, 276 |
| heterotic, 324, 326, 479 | with central extension, 257 |
| NS sector, 312-315 | without central extension, 255 |
| | |

```
descendent, 576-577, 588
                                                                                number, 362
                                                                            string charge, 398
Witt algebra, 255
world-line, 16, 90, 107
   null state, 577
   operators
     covariant closed strings, 580-582
     covariant open strings, 571
                                                                             world-sheet
 covariant open strings, 571 light-cone closed strings, 286–287 light-cone open strings, 250–259 ordering of L_0^{\perp}, 251–253 primary, 575, 588 transverse modes, 189
                                                                               class of parameterizations,
                                                                                      181
                                                                               current \mathcal{P}_{\mu}, 159–161 defined, 100
                                                                                fermion, 309
                                                                                momentum, 290
Weyl transformation, 586
                                                                            Yang–Mills U(1) theory, 344 U(3) vs. SU(3), 458–462 U(N) gauge fields, 344
Wilson line
  defined, 408
  effect on particle spectrum, 410
  holonomy, see holonomy
   with constant A_x, 409
winding
                                                                             zeta-function
  closed strings, 378–381
                                                                               analytic continuation, 275
defined, 253
  defined, 381
```