
Index

- 1PI
 diagram, 132
 effective action, 129, 236, 421
 2PI effective action, 138
- Abel-Plana formula, 501
 adjoint mapping, 177
 adjoint representation, *see* representation, adjoint
 Aharonov–Bohm effect, 347
 anomalous dimension, 253, 256, 261, 267
 anomaly, 312
 axial, *see* chiral anomaly
 from functional measure, 162
 function, 164, 357
 scale, 334
 anti-commutation relations, 67
 asymptotic freedom, 250, 272, 440
 asymptotic safety, 272
 Atiyah–Singer theorem, 168, 200, 201, 370
 axial current, 166, 314, 319
 axial symmetry, *see* chiral symmetry
- background field method, 245
 background field propagator, 526
 Baker–Campbell–Hausdorff formula, 28, 117, 177, 421, 468, 507
 Banks–Casher relation, 463
 baryon
 current, 368
 number, 368
 BCFW recursion, 388, 394, 401, 404, 408, 416
 Berends–Giele recursion, 406, 572
 Berezin integral, *see* Grassmann
- Bern–Carrasco–Johansson, *see* color-kinematics
 duality
 Bern–Kosower rule, 435
 beta function, 253, 254, 339
 Bianchi identity, 188
 Bogoliubov inequality, 113, 115
 Bogomol’nyi inequality, 344, 356
 Boltzmann equation, 500, 545
 Bose–Einstein distribution, 469, 477, 478
 box, *see* master integral
 BPHZ renormalization, 51
 brownian motion, 420, 422
 BRST
 charge, 230
 cohomology, 230
 current, 230
 symmetry, 227, 238, 331, 455, 456
 bubble, *see* master integral
 Buchberger algorithm, 575
- Cabbibo–Kobayashi–Maskawa matrix, 192, 284
 Cachazo–Svrcek–Witten rules, 406, 412
 Callan–Symanzik equation, 252, 256, 257, 259, 307
 canonical quantization
 fermions, 66
 photons (Coulomb gauge), 72
 scalars, 11
 Cartan–Maurer invariant, 359, 363, 369
 Casimir operator, 189, 210
 Cayley’s formula, 542
 center symmetry, 503
 charge conjugation, 79, 94, 287, 309
 charge renormalization, 81
 chemical potential, 471

- chiral anomaly, 164, 166, 316, 322, 323, 448
- chiral gauge theory, 190, 326
- chiral Lagrangian, 307, 368
- chiral symmetry, 109, 163, 190, 282, 300, 313, 448
- chiral transformation, 199
- Christoffel symbol, 324
- classical electrodynamics, 70
- classical field
 - boundary conditions, 517, 525, 526, 535
 - retarded, 510, 512, 517, 524, 526
- clover term, 463
- coherent state, 114, 506
 - fermionic, 426
- Coleman's theorem, 105
- Coleman–Weinberg potential, 135
- collision term, 500
- color glass condensate, 295, 298
- color ordering, 373, 553
 - Feynman rules, 376
- color-kinematics duality, 376, 400, 417
- commutation relations
 - canonical, 11
- composite operator, 256
- conformal transformation, 341
- connected graph, 38, 62, 511
- contact term, 161
- contour ordering, *see* path ordering
- cosmological constant, 282
- counterterm, 50, 83, 233, 241, 254, 263, 316, 339, 483
- covariant derivative, 75, 165, 181, 244, 293, 324, 352, 391, 429, 446
- critical
 - point, 270, 272
 - surface, 272
- cross-section, 17
- current conservation, 13, 71, 81, 230, 261, 312
 - covariant, 188
- curvature tensor, 175, 305, 308, 326, 398
- Cutkosky, *see* cutting rules
- cutting rules, 54, 474, 565
 - generalized, 564
 - QED, 86
- Debye
 - mass, 491
 - screening, 491, 494
- decay rate, 21
- degenerate vacua, 95, 107, 112
- density operator, 465, 471, 495, 516
- derivative expansion, 294
- Derrick theorem, 367
- dilatation current, 335, 340
- dimensional regularization, 42, 45, 315, 558, 578, 579
- Dirac
 - equation, 65, 79
 - Lagrangian, 65, 445
 - matrices, 64, 93
 - operator, 69, 164, 168, 198, 324, 424, 446
 - spinor, 64
- domain wall, 343
- doubler, *see* Lattice doubler
- Duhamel's formula, 178
- dynamical fermion, 449
- Dyson equation, 143
- Eikonal approximation, 205, 391
- electroweak theory, 262, 284
- embedding dimension, 577
- energy–momentum tensor, 336
- Faddeev–Popov
 - ghost, 215, 456
 - method, 215, 454
- Fermi theory, 261, 282
- Fermi–Dirac distribution, 472
- Feynman
 - diagram, 36
 - parametrization, 43, 314, 432
- Feynman propagator, 30
 - fermion, 69
- Feynman rules, 37
 - QED, 76
 - Yang–Mills, 213, 219
- Feynman tree theorem, 547
- field strength, 70, 182, 323, 333, 368, 443
- Fierz identity, 188, 265, 374, 382, 553
- fine structure constant, 1

- Fock state, 17, 426
- form factor, 284
- functional
 - derivative, 27
 - determinant, 127
 - Fourier transform, 124
- fundamental representation, *see* representation,
 - fundamental
- Furry's theorem, 83, 94
- Galilean boost, 7
- gap equation, 485
- gauge fixing
 - axial gauge, 71, 220
 - background field, 246, 391
 - Coulomb gauge, 71
 - covariant gauge, 158, 214, 218
 - Feynman gauge, 159, 213
 - Fock–Schwinger gauge, 310, 439
 - lattice, 454
 - Lorenz gauge, 71, 158, 445, 454, 464
- gauge invariance
 - Abelian, 70
 - non-Abelian, 181
- gauge transformation, 70, 75, 181, 186
 - Abelian, 70, 424
- Gaussian fixed point, 272
- generalized unitarity cut, 565, 570
 - maximal cut, 576
- generating functional, 531
 - fermions, 69
 - of connected graphs, 38
 - of time-ordered products, 27, 468, 506
 - photons, 74
 - QED, 76
- Georgi–Glashow model, 348
- ghost field, *see* Fadeev–Popov, ghost
- Gluon saturation, 296
- Goldstone
 - boson, 105, 112, 300, 305, 366
 - theorem, 95, 105, 192
- gradient approximation, 499
- Grassmann
 - algebra, 151
 - complex variable, 155
 - delta function, 171
 - derivative, 151
 - determinant, 154
 - Fourier transform, 171
 - function, 151
 - Gaussian integral, 153, 154, 427
 - integral, 151, 427
 - Jacobian, 153
 - variable, 151, 426, 448
- gravitational amplitudes, 398
- Green's formula, 517, 520, 522, 524
- Green–Kubo formula, 474
- Gribov copy, 214, 445, 454
- Gröbner basis, 575–577, 579
- Haar measure, 444, 451
- Hamilton's equations, 12
- hard thermal loop, 487, 488, 494
- heat kernel, 418, 458
- heavy quark
 - potential, 452
 - symmetry, 292
- hedgehog field, 349
- Heisenberg model, 111, 369
- Higgs mechanism, 192
- Hilbert's nullstellensatz, *see* theorem of zeroes
- Hilbert–Einstein action, 398
- Hofstadter model, 460
- homogeneous space, 304
- homotopy group, 170, 200, 201, 349, 352, 357, 367
- ideal, 575, 576
 - initial, 577
 - primary decomposition, 580
 - quotient ring, 580
 - radical, 576
- imaginary time formalism, *see* Matsubara, formalism
- infrared divergence, 88, 482
- instanton, 355, 363
- interaction representation, 15
- irreducible representation, *see* representation,
 - irreducible
- irrelevant operator, 272, 280
- Ising model, 268

- Jacobi identity, 177, 228, 244, 416
 JIMWLK equation, 300
- Kadanoff blocking, 268
 Kadanoff–Baym equations, 498
 kaon decay, 262
 Kawai–Lewellen–Tye relations, 400
 Killing form, 361
 kinetic equation, *see* Boltzmann equation
 kinetic theory, 498
 Klein–Gordon equation, 13, 14, 507
 Kleiss–Kuijf relations, 376, 416
 Krull dimension, 580
 Kubo–Martin–Schwinger symmetry, 145, 470, 479, 496
- Landau damping, 492, 494
 Landau gauge, *see* gauge fixing, Lorenz
 largest time equation, 54
 Lattice action, 442
 lattice action, 443
 lattice doubler, 447
 Legendre transform, 131, 139, 149, 239
 Lie algebra, 174
 compact, 185
 simple, 184
 Lie bracket, 174, 177
 Lie group, 173, 354
 light-cone
 coordinates, 206, 297
 quantization, 11, 34
 wave function, 209
 linear sigma model, 107, 368
 link variable, 444
 Liouville equation, 517
 Liouville–von Neumann equation, 516
 little group, 6
 scaling, 384, 399, 415
 loop integral reduction
 Passarino–Veltman, 556
 van Neerven–Vermaseren, 557
 loop integrand reduction, 562, 573
 Lorentz
 group, 3, 4, 379
 transformation, 3
 LSZ reduction formula, 22
 fermions, 68
 photons, 73
 Lyapunov exponent, 540
- Majorana fermion, 309
 Mandelstam variables, 77
 marginal operator, 272, 280
 mass matrix, 97
 master integral, 560, 566, 568–570
 Matsubara
 formalism, 147, 475
 frequency, 147, 475
 maximal cut, *see* generalized unitarity cut
 maximally symmetric space, 304
 Maxwell’s equations, 70, 79
 McLerran–Venugopalan model, 297
 mean free path, 494
 Mermin–Wagner’s theorem, 112
 MHV, *see* scattering amplitude, MHV
 Milne coordinates, 310
 minimal momentum shift, 389
 mode function, 514, 526, 540
 completeness, 529
 monomial
 order, 575, 577, 579
 standard, 577
 monopole
 charge quantization, 347, 352
 Dirac, 346
 non-Abelian, 348
 Moyal–Groenewold equation, 517
- Nambu–Goldstone, *see* Goldstone
 natural units, 9
 Newton’s constant, 398
 Nielsen–Ninomiya theorem, 448
 Noether’s theorem, 13, 161, 312, 335
 nonlinear sigma model, 301, 366
 normal-ordered exponential, 29
 Nullstellensatz, *see* theorem of zeroes
- occupation number, 9
 operator product expansion, 258, 262, 280

- optical theorem, 53
- Ossola–Papadopoulos–Pittau, *see* loop integrand reduction
- Parke–Taylor formula, 394, 397, 406, 409, 416
- partition function, 473
- Parton model, 296
- Passarino–Veltman, *see* loop integral reduction
- path integral
 - classical limit, 120
 - ground state projection, 123
 - quantum mechanics, 116
 - scalar field, 125
 - statistical mechanics, 144
 - time-ordered product, 120
- path ordering, 59, 468
- Pauli statistics, 67
- pentagon, *see* master integral
- pion decay, 167
- Plaquette, 204, 451
- plaquette, 443
- Poincaré group, 5
- polarization tensor, 85, 435
- polarization vector, 73, 382, 399, 571
- polynomial division, 574
- power counting, 40, 48, 280, 317, 386, 432, 505, 509, 511
 - gluon saturation, 298
 - QED, 82
 - Yang–Mills, 234
- principal value, 31
- pure gauge field, 182, 203
- quantum anomaly, *see* anomaly
- quantum effective action, *see* IPI
- quantum electrodynamics, 63, 424, 434
 - scalar, 423, 428, 433, 459
- quark confinement, 452
- quasi-classical approximation, 537, 539
- quasi-particle, 490
 - approximation, 500
- quenched approximation, 449
- rational term, *see* scattering amplitude
- relevant operator, 272, 280, 281
- renormalizability, 49, 281, 303
- QED, 83
- Yang–Mills, 241
- renormalization condition, 51, 85
- renormalization group, 253, 267, 268
 - functional, 273
 - Wilson, 270
- representation, 179
 - adjoint, 179
 - fundamental, 179
 - irreducible, 179
 - singlet, 179
- retarded propagator, 480, 510, 515, 518, 524, 527, 532, 547
- Ricci flow, 308
- running coupling, 250, 255, 339, 440
 - QCD, 247
- R_ξ gauge, *see* gauge fixing, covariant
- scale anomaly, *see* anomaly, 339
- scale invariance, 334
- scattering amplitude, 17, 372, 546, 560, 573
 - MHV, 386, 394, 406
 - next-to-MHV, 407
 - rational term, 561, 562, 564
- Schouten identity, 381, 383, 407, 412
- Schwinger
 - mechanism, 427
 - model, 312
- Schwinger–Dyson equations, 160
- Schwinger–Keldysh
 - formalism, 58, 467, 478, 480, 498, 504, 512, 513, 522, 524, 532, 550
 - propagators, 56, 479, 513, 514, 547
 - retarded basis, 527
- seesaw mechanism, 288
- simple Lie algebra, *see* Lie algebra
- singlet representation, *see* representation, singlet
- skyrmion, 366
- S-matrix, 17, 53, 205, 222, 291
- special conformal transformation, 3, 341
- spectral function, 25, 34, 492
- spin wave, 112
- spin-flavor, *see* heavy quark, symmetry
- spin-statistics theorem, 67, 217

- spinor-helicity formalism, 379
 - polarization vector, 382
 - three-point amplitudes, 382, 399
- spontaneous symmetry breaking, 95, 190, 282, 300, 345, 349, 366
- spurious term, 564
- stabilizer subgroup, 192, 300
- Standard Model, 186, 192, 278, 282, 285
 - anomaly cancellation, 326
- stereographic projection, 367
- Stokes theorem, 197, 321, 348, 358, 518
- strong coupling expansion, 451
- strong CP problem, 199
- strong field, 363, 504, 509, 512
- structure constant, 177, 183, 348
- Sudakov factor, 92
- superficial degree of divergence, 48
- symmetry factor, 14, 38, 61, 76, 149, 225, 541

- tetrad formalism, 325
- theorem of zeroes, 575
- thermal
 - contour, 467, 470, 475
 - ensemble, 465, 473
 - mass, 483
 - propagator, 469, 472, 473, 476
 - sum rules, 492, 502
 - symmetry restoration, 485
- θ term, 194, 357, 363, 364
- 't Hooft anomaly matching, 333
- time evolution operator, 15, 467
- time ordered
 - exponential, 15, 28
 - product, 24
 - propagator, *see* Feynman
- transport coefficient, 474, 494
- tree-loop duality, 548
- triangle, *see* master integral
- triviality, 272
- Trotter formula, 174

- ultraviolet
 - divergences, 44
 - regularization, 45
- unitarity, 53
 - QED, 86
 - Yang–Mills, 223, 232
- universality class, 272

- vacuum graphs, 37
- van Neerven–Vermaseren, *see* loop integral reduction
- van Neerven–Vermaseren basis, 557, 567, 569
- Vierbein, *see* tetrad formalism

- ward identity, 81, 85, 313, 326, 487
 - non-Abelian, 221, 224, 392
- Weierstrass transform, 148, 420
- Weinberg
 - operator, 287
 - theorem, 48
- Wess–Zumino conditions, 329
- Weyl
 - mapping, 147
 - representation, 64, 264
 - spinor, 380
- Wick
 - rotation, 42, 165
 - theorem, 148
- Wigner transform, 148, 498, 516
- Wilson
 - action, 443
 - coefficient, 259, 263
 - line, 202, 429, 444, 460
 - loop, 204, 443, 451
 - term, 447, 463
- worldline representation, 418, 421, 423, 427, 431, 432, 458

- Yang–Mills
 - energy–momentum tensor, 338
 - equation, 187
 - Lagrangian, 181, 212, 443
 - theory, 181, 372
- Yukawa coupling, 191, 287, 288

- ζ -function regularization, 128, 437
- Zinn–Justin equation, 238