Index

Bold page numbers indicate a page where a term is defined, either formally or informally. *Page numbers in italics* indicate that the term is used in a theorem, proposition, lemma, or corollary.

0-prong singularity, 276 1-density, 169 integrand, 170 transverse measure, 170 1-point compactification, 70 1-prong singularity, 276 Δ (symmetric difference), 493 $|g|_{\mathbf{x}}, \, \mathbf{299}, \, \mathbf{306}$ $\{g_1, g_2\}_{\mathbf{x}}, \, \mathbf{299}, \, \mathbf{306}$ $\{\{g_1, g_2\}\}_{\mathbf{x}}, \, \mathbf{299}, \, \mathbf{306}$ Γ -tree, see Gamma tree Ω_{Γ} , see regular set Σ (set of singularities), **169** ∞ vertex, 127 Abelian differential (holomorphic 1-form), 415, 427stratum, 452, 453, 453, 460, 462, 463 absolutely continuous group action, 501, 503, 501-504 accident, 227, 234-241 analyzing, 236-237 simple, 238 accidental parabolic, 62, 66 enrichment, 67 accumulation point, set, 38 Agol, Ian, 163 Ahlfors, Lars, 135, 157, 160, 163 Ahlfors conjecture, 163 Ahlfors finiteness theorem, 157, 156-162, 164 Ahlfors measure theorem, 162 Ahlfors-Weill section, 158 algebraic convergence, 51 algebraic integer, 359, 359 algebraic intersection number, 515 algebraic limit, 66 algebraic number, 354, 356

algebraic number field, 354 bilinear form nondegenerate, 357 canonical embedding, 361, 361 characteristic polynomial, 356 degree of. 354 discriminant of, 362 embeddings, 355 integer of, 359 order in, 360 primitive element, 355 ring of integers, 361 totally real, 356 alternating group, 98 amalgamated (free) product, see amalgamated sum amalgamated sum, 87, 349, 350, 349-350 generators and relations, 93 first Klein-Maskit combination theorem, 87 analytic type (rank 2 cusp), 124 annular density (point of), 506 arc of geodesic (notation), 138 Archimedes, 155 arithmetic Fuchsian group, 379 arithmetic hyperbolic orbifold, 368 arithmetic Kleinian group, 354, 378 co-compact, 367 from quadratic form, 367 geometrically finite, 131 quaternions, 373–385 three types, 354 Athreya, Jayadev, 452 Aut \mathbb{H}^2 , 6, 19 Aut \mathbb{H}^3 see also parabolic, elliptic, hyperbolic 2×2 complex matrices, 5, 19 axis of, 23 classifying, 22-23 composition of flips, 27 dimension of, 6 elliptic, 22, 23 flip, 26, 26 halfspace model, 23-25, 25 hyperbolic, 22, 23 identified with $PSL 2(\mathbb{C})$, 19, 20 extending to $\partial \mathbb{H}^3$, 21

Aut \mathbb{H}^3 , cont. loxodromic, 22 parabolic, 22, 23 rotation around axis, 23 translation along axis, 23 Aut \mathbb{H}^n , 4, 4–6 equals $SO^+(n, 1), 4, 5$ orientation-preserving automorphisms, 4 Aut X (automorphisms $X \to X$), 4 automorphisms of \mathbb{H}^3 , see Aut \mathbb{H}^3 automorphisms of \mathbb{H}^n , see Aut \mathbb{H}^n , axis hyperbolic, 23, 320 of automorphism, 23 of flip, 26 tree, 260, 260, 298 backwards ergodic average, 441, 441 Baillif, M., 386 Baire category theorem, 236 ball model of hyperbolic space, 12, 11-14 geometry of, 12 inner product, 13pros and cons, 15 Riemannian metric of, 13 Banach-Alaoglu theorem, 475 base frame, 73 basis of neighborhoods for weak topology, 194 Bel(X), see Beltrami form, 158 Beltrami form, 251-252 Γ-invariant, 158, 162, 164, 165, 448 horizontal foliation, 252, 317 support in limit set, 164, 164-165, 165, 166 support in regular set, 158 vertical foliation, 252, 317 bending laminations, 229, 229, 227-233 bind S - P, 231 convex hull of limit set, 229 support of transverse measure, 230bending locus, 227, 228, 229 bending measure, 227-233 Bers, Lipman, 157, 160, 255 Bers inequality, 255, 256 Homeland analogy, 258 weaker form, 257 Bers simultaneous uniformization map, 257 Bers simultaneous uniformization theorem, 251

Bers slice (compactness), 258, 255-259 "single limit" theorem, 258 compactness, 258 Homeland analogy, 258 Bianchi, Luigi, 113 Bianchi group, 113, 113, 116, 362-367 geometrically finite, 131 $PSL_2 \mathcal{O}(\mathbb{Q}\sqrt{-3}), 114-116$ $PSL_2 \mathcal{O}(\mathbb{Q}\sqrt{-5}), 362-367$ Ford fundamental domain, 363-364 Bianchi manifold, 362 bi-JS (bi-Jenkins-Strebel), 428 binding lamination, 209, 209, 210 Birkhoff-Khinchin ergodic theorem, 442 Birman, Joan, xiii, 191, 399 Birman-Series theorem, 191, 399 Boltzmann, Ludwig, 444 Bonahon, Francis, 185, 210 Borel measure, 231 Borromean rings, 122 bounded parabolic, 125 bounded rank 1 cusp, 125 Bridson, Martin, 69 Brouwer fixed point theorem, 156 Brown, Ken, 327 bundle of projective spaces, 7 (C, C')-quasi-geodesic, see quasi-geodesic (C, C')-quasi-isometric map, see quasiisometric map (C, C')-quasi-isometry, see quasi-isometry Calegari, Danny, 163 Canary, Richard, 87, 163, 255 Cantan-von Neumann theorem, 72 Cantor set, 225 and continuum, 213 Carathéodory, Constantin, 444 Carroll, Lewis, 75 Cayley graph, 262 Cayley-Hamilton theorem, 330, 357 CCC space, 343, 345 pointed, 344 Čech cohomology, 426 Čech nerve, 428 center of quaternion algebra, 374 central simple algebra, 373

Chab (G), 69, 71, 72 $G = \mathrm{PSL}_2\mathbb{C}, 70$ $G = \mathrm{PSL}_2 \mathbb{R}, 70$ $G = \mathbb{R}^2, 69$ $G = \mathbb{R}^3$. 69 geometric topology on, 70 Chabauty, Claude, 69, 76 Chabauty topology, 58, 70, 76, 69-81 see also geometric topology Chéritat, Arnaud, 228 Chern class first, 521 in terms of zeros, 523 relative, 522, 522, 524-526 Chiswell, Ian, 295 Chiswell function, 295, 296, 304, 307 constructing Γ -tree, 296 defining minimal G-tree, 312functions converging to, 303, 303 Otal's compactness theorem, 303 properties, 296 Chiswell's theorem, 296 Chuckrow, Vicki, 50, 51 Chuckrow's theorem, 51, 51-53 classical Schottky group, 110 Clifford algebra, 381, 381 closed 1-form, 512 closed density, 169 co-compact Kleinian group, 367 co-cycle condition, 502 cofactors (matrix of), 330 cofinal subset, 386 collar around cusp, around geodesic, 49 collar function, 302 commutative algebra, 327-329 commutator, 41 compactifying hyperbolic space, 7 compactness conjugacy class of representations, 56, 57 $\mathcal{F}_K(a,b,c), 147$ of Bers slices, 258 of quasiconformal maps, 147 Otal's compactness theorem, 303 complete hyperbolic manifold, 32, 32 complex analysis Ahlfors finiteness theorem, 156

complex analysis, cont. link with hyperbolic geometry, 5, 8, 19, 32, 34, 156 link with topology, 172 no wandering domain theorem, 157 complex line bundle, 525 complex of Banach spaces, 423 concatenation, 345 cone angle, 97, 101, 101 cone over unit stratum, 456 cone point of orbifold, 97, 97 conformal barycenter, 149, 150, 153 and convex hull, 153 conformal structure on boundary of \mathbb{H}^n , 8 on manifold, 7 when induced by Riemannian metric, 7 conical limit set, 126 conical point, 126 conjugacy class of representations compactness, 56, 57 space of, 51 connected component, see stratum conservative group action, 501, 503, 504 invariant Beltrami form, 507 convergence algebraic, 51, 68 geometric, 76, 68-81 convex core, 79, 82 McMullen's rigidity theorem, 164 of hyperbolic manifold, 81 quilts, 226 convex hull, 36, 81, 153, 227, 228 bending locus, 228 boundary, 228 of limit set, 228, 229 convex set hull of extreme points, 476 covering map, 342 of orbifold, 100, 100-103 trivial, 343 universal, 343 covering space theory, 342–349 and Galois theory, 342 critical graph of measured foliation, 170, 172 459, 460

critical leaf, 170 "herding" noncritical leaves, 171 critical trajectory, 205 cross ratio substitute in higher dimensions, 144 CT^1 , see cone over unit stratum current, 212 cusp, 367 bounded rank 1, 125 classification, 124doubly unbounded rank 1, 125 rank 1, **49**, 125, 134 rank 2, 49, 124, 133 rank of, 124 singly unbounded rank 1, 125 \mathbf{D}^n , see ball model of hyperbolic space \mathbf{D}^2 , denoted **D** in Volume 1, 12 deck transformation, 343 decompositionq-rectangular, 485 matrix relating two decompositions, 486, 486 Dedekind, Richard, 358, 362 Dedekind lemma, 358 degenerates into \mathbb{R} -tree, 258, 294 degenerating sequence, 304, 304 degree of algebraic number field, 354 density 1-density, 169 closed, 169desingularization, 234, 417, 419 normalization, 418 developing map, 89 devil's staircase, 213 dihedral angle, 106 dihedral group (footnote), 31 Diophantine approximation, 496 Dirichlet fundamental domain, 77, 127, 127, 368, 369 algorithm for computing, 369 face. 127 discontinuity, set of, see regular set discrete group, 29 limit set Λ_{Γ} , **34** regular set Ω_{Γ} , **34** discrete representation, 51 closed, 51

discriminant of algebraic number field, 362 dissipative group action, 501, 503, 506 dissipative set measure 0, 506 distance in \mathbb{H}^n , 6, see also hyperbolic distance division algebra, 374, 375, 375 conditions for, 375 domain, see integral domain Douady, Adrien, 457 Douady-Earle extension, 135, 147, 149, 151 not necessarily homeomorphism, 151 when quasi-isometry, 151 double limit theorem, 318, 323 Homeland analogy, 258 special case, 319 doubly unbounded rank 1 cusp, 125 E_{μ} (measure on \mathcal{M}), **196** ϵ -thick part of hyperbolic manifold, 48 ϵ -thin part of hyperbolic manifold, **48**, 50 $E^{3,1}, 3, 20$ Minkowski space, 3 $E^{n,1}, \mathbf{3}, 3$ \mathbb{H}^n is subset of, 3 edge-stabilizer, 292 compared to point-stabilizer, 285 small, 284, 303 eigenline, 43 Eilenberg-MacLane space, 510, 522 Einstein, Albert, 4 Eisenbud, David, 327 electromagnetism, 4 elementary group, 30 elementary Kleinian group, 30, 30, 32, 37, 339 elementary representation, 51 elliptic automorphism, 22, 27 axes of flips, 27 fixed points, 23 limit case of hyperbolic, 23 trace real, 23 end of geometrically finite manifold, 132 end of group, 396-397 end of topological space, 386, 388, 390, 392, 394, 395, 386-396 when space is locally connected, 392 ending lamination conjecture, 255 endpoint compactification, 391, 417

endpoint compactification, cont. building fiber by fiber, 422 functor, 395 universal property of, 396 endpoint of geodesic lamination, 196 enriched dynamics, 66 enriched group, enrichment, 58-61, 63, 64-67 enriched Kleinian group, 59, 66 equivalent measured foliations, 173 ergodic average, 442 backwards, 441, 441 ergodic flow, 434 ergodic measure, 435 ergodic measured foliation, 473 ergodic theorem, 168 for flows, 433, 442 for maps, 433, 435 ergodic theory, 434-445 ergodic transformations, 434 ergodic transverse measure, 473, 476, 476-479 ergodicity criterion for, 447 diagonal action, 448geodesic flow, 448Teichmüller flow, 451 Escher's "Circle Limit III", 12 Eskin, Alex, xiii, 452 essentially surjective functor, 348 étale fundamental group, 342 Euclidean inversion, $\mathbf{24}$ Euler characteristic, 513, 524 bound for, 160 modified, 513, 514 of orbifold, 97 of Z_{Γ} , 160 event (in special relativity), 4 space-like, 4 time-like, $\mathbf{4}$ exchange of sheets, 174 extension of quasi-isometry, 144 extreme point, 476 $(\mathcal{F}, D_{\mathcal{F}})$, see measured foliation F-distance, 271, 272 F_P (harmonic function), 83 faces isometric, 105, 106

faces, cont. of Dirichlet fundamental domain, 127 faithful representation, 51 Fatou, Pierre, 35 Fernández-Bretón, David, 386 Fib, see fiber functor fiber, 342, 345 fiber functor Fib, 347, 348, 350 fiber map, 249 fibration over circle, 242, 242 integral points, 512 often many, 510 Thurston semi-norm, 512 field, 328-337 imaginary quadratic, 113, 362, 367, 377 totally real number field, 356, 379 figure-eight knot, 114, 116 complement of fibers over circle, 243-248 hyperbolic structure of complement, 116-121 presentation, 120 triangulation of complement, 117 finite field, 333 finite index, 339 finite Kleinian group, 30 finite lamination, 199, 199-203 dense in laminations, 201 maximal, 199, 201, 201 structure of, 200 finitely generated Kleinian group not geometrically finite, 131, 259 first Chern class, 521, **521** higher dimensions, 523-524 of line bundle, 522 fixed point \mathbb{R} -tree isometry, 260 in limit set, 35 no common, 27 of automorphisms, 23, 35, 36 of elementary group, 37 flip, 26, 26-29, 43, 105 classifying automorphisms, 27 composition, 27 elliptic, 26 rotation, 26 flow, 445 ergodic, 434, 434

flow rectangle, 471 foliation, see horizontal, measured, vertical Ford fundamental domain, 113, 113, 125, 363.368 forward ergodic average, 435 free product with amalgamation, see amalgamated sum, Freudenthal, Hans, 386, 396 Fuchsian group, 30 Fuchsian representation, 304 functor. 343 essentially surjective, 348 fully faithful, 348 when isomorphism of categories, 348 fundamental domain, 34, 103, 110, 110, 111 Bianchi group, 114 Dirichlet, 368 Ford, 368 polyhedron, 106 fundamental group, 349 action, 345 Γ chart, Γ -orbifold chart, see orbifold chart $\mathcal{G}^3_{R,r}(\mathbf{x}_0)$ (subset of Chab(Aut \mathbb{H}^3)), 80 limit set depends continuously on Γ , 80 G-SET, 348 isomorphism of, 348 G-tree, Γ -tree, see Gamma-tree Gabai, David, 163 Galois theory and covering space theory, 342 Gamma-tree, 262, 272 axis of, 298 base point, 295 characterization by Chiswell, 295 constructing measured foliation, 272 from Chiswell function, 296 isometries, 262 minimal, 263, 311,312 when leaf space, 284, 286Gauss-Bonnet theorem for orbifolds, 97 general theory of relativity, 4 genus of knot, 514 geodesic, 3, 138, 141, see also simple geodesic extrinsic thinking, 3 in \mathbb{H}^n , 6 notation for arc, 138

geodesic, cont. on cone, 101 on orbifold, 100, 100 pinned homotopy, 266 geodesic coordinate map, 102 geodesic flow, 100, 100, 101, 446, 446-447 continuous, 100 on complete hyperbolic orbifold, 100 on hyperbolic manifold, 448 preserves Liouville measure, 446 geodesic lamination, 185, 185-203 approximated by finite laminations, 201 area 0, 190, 414 binding S - P, 209 compact, 191 data topological, 198, 197-199 finite, see finite lamination finitely many leaves go to punctures, 191 leaf, 185 maximal, 185 nowhere dense (footnote), 191 set of endpoints, 196 topological data, 198 train tracks, 192 transversal to, 192 transverse measure, 192 viewed from infinity, 195-197 when maximal, 185 geodesic metric space, 96 geometric convergence, 69, 70, 76 Thurston equivalent to Chabauty, 76 geometric Gromov product, 299 and Gromov product, 300 geometric limit of Kleinian groups, 66, 70, 58 - 81enrichment, 60 injectivity radius, 81 limit in Hausdorff topology, 58 non-elementary group, 68 flagpole picture, 60 geometric topology, 58, 70, 76, 69-81 inside view (Thurston and Gromov), 74-75 spaceship analogy, 74-75 geometrically finite Kleinian group, 123, 123, 122-134, 165 examples, 131

geometrically finite manifold, 123, 132 compactness, 132 ends of, 132, 132 gluing hyperbolic 3-manifolds, 82, 87 along harmonic separator, 82 gluing hyperbolic manifold to itself, 94, 95 gluing hyperbolic manifolds together, 87 incomplete annulus, 90Goujard, Elise, 452 Grauert direct image theorem, 422 gravitation, 4 Greenberg, Leon, 157, 160 Gromov, Mikhail Leonidovich, xvii, 74, 76 Gromov hyperbolic space, xvii, 138 Gromov product, 295 and geometric Gromov product, 300 geometric, 299Grothendieck, Alexander, 342 group dihedral, 31, 98 elementary, 30 end of, 396-397 generated by reflections, 110 icosahedral, 31, 98 infinitely generated, 505 non-elementary, 30octahedral, 31, 98 solvable, 338, 339 tetrahedral, 31, 98 group action, 345, 502 absolutely continuous, 501, 503, 501-504 conservative, 501, 503, 507 dissipative, 501, 506 \mathcal{H}_P , see harmonic hull \mathbb{H}^2 , \mathbb{H}^3 , \mathbb{H}^n , see hyperbolic space \mathbf{H}^n , see halfspace model of hyperbolic space halfspace model of hyperbolic space, 14-15 horoballs, 18 lines, planes, balls of, 18 pros and cons, 15Riemannian metric of, 14 Hamilton, Richard, xv Hamiltonian flow, 447 Hamiltonian mechanics, 446-447 Hamiltonian quaternion, 374 handlebody, 244, 245

harmonic function, 83 harmonic hull, 82, 83, 84 harmonic separator, 82, 83, 83, 84, 85, 112 subset of convex hull, 83 Harpe, Pierre de la, 69 Hatcher, Allen, 273, 521 on local coefficients, 427 Hatcher's construction, 272, 272-284 example, 283 ways to foliate triangle, 275 Hausdorff, Felix, 76 Hausdorff dimension, 398 dimension 1, 191 of Sierpinsky gasket, 398 of union of simple geodesics, 399, 398-414 Hausdorff measure, 398 Hausdorff metric, 69 geometric topology induced by, 70 Hausdorff topology, 58 Hawaiian earring no universal covering space, 343 Heisenberg group (in footnote), 69 hemisphere model of hyperbolic space, 15, 16 hyperbolic metric of, 18 pros and cons, 15 Herm₂, 19, 22 determinant on, 22 Hermitian matrix, 19, 19–20 and $E^{3,1}$ (table), 20 and spacetime (table), 20 Higman, Graham, 351 Hilbert cube, 69 Hilbert Nullstellensatz, 327, 334 variant, 333, 333 Hilbert ring, see Jacobson ring h-JS (horizontally Jenkins-Strebel), 428 HNN extension, 94, 351, 351-353 as fundamental group, 353 Klein-Maskit combination theorem, 94 stable element of, 351 Hölder, 153 holomorphic quadratic differential, 204 holonomy map, 242, 242 computing, 246-248 Homeland analogy, 258-294 homology class represented by submanifold, 513

homotopy, pinned, 266 Hopf, Eberhard, 434, 448 Hopf, Heinz, 249, 396 Hopf invariant, 249 Hopf's argument, 434, 447, 451, 456 horizontal foliation, 172, 252 horizontal trajectory and hyperbolic geodesic, 204 horoball, 9, 9, 10, 40, 41 in ball model, 14 in upper halfspace model, 18 horocyclic limit set, 126 horocyclic neighborhood, 124 when in convex core, 124 horocyclic point, 126 horosphere, 9, 10 hyperbolic 3-manifold complications when gluing, 82 gluing along harmonic separator, 82, 85 gluing to self, 94 hyperbolic automorphism, 22, 27 axes of flips, 27 fixed points, 23 trace, 23 hyperbolic axis, 320 hyperbolic ball in ball model, 14 in upper halfspace model, 18 hyperbolic distance, 6 hyperbolic geometry and complex analysis, 5, 8, 19, 32, 34, 156 hyperbolic isometry, 260 hyperbolic line, 3, 3 in ball model, 14 hyperbolic manifold, 32 complete, 32, 32 convex core, 79 ϵ -thick and ϵ -thin parts, 48, 48, 50 geodesic flow on, 448geometrically finite, 123, 132, 132 hard to see sphere at infinity, 32hyperbolization theorem, 242injectivity radius, 39 plumbing caricature for 3-manifolds, 46 quotient of \mathbb{H}^3 , of \mathbb{H}^n , 33 smooth topological family, 72, 73

hyperbolic manifold, cont. thin and thick part, 48, 48 when isometric to \mathbb{H}^n , 32 hyperbolic metric, hemisphere model, 18 hyperbolic orbifold, 96, see orbifold, 95-99, 100 "mental image", 97 2-dimensional, 97 3-dimensional, 98 complete, 101 covering map, **100**, 100–103 geodesic on, **100**, *100* singular locus of, 97 universal covering space, 95, 101 hyperbolic polyhedron, 104 hyperbolic space, 2 "living in", 3 ball model, 12, 13, 11-15 Beltrami-Klein model, 10 boundary, 7 Cayley-Klein model, 10 compactification, 7 degenerates into quadratic differentials, 295 degenerates into R-tree, 258, 294, 303 distance in, 6 geodesic in, 6 halfspace model, 14-15 hemisphere model, 15-18 hyperboloid model, 2-10, 15 isometries, 5 Klein model, 10, 10, 10–11, 15 line, 3 Riemannian manifold, 2 subspace of, 3 table comparing models, 15 hyperbolization theorem, 242 easy direction, proof, 249–250 hard direction, sketch of, 251-255 main construction, 252 representation ρ_n , **253** representation ρ_{∞} , 253 hyperboloid model of hyperbolic space, 2–10 pros and cons, 15 pseudo inner product, 3 hypercohomology, 415 icosahedral group (footnote), 31 ideal, 328

ideal, cont. maximal, 328, 328, 333, 334 prime, 328, 328 proper, 328, 328 ideal boundary, 158, 159 ideal class group, 354, 362, 367, 367 relation with arithmetic groups, 363 ideal tetrahedron, 145, 146, 240 filling of quilt, 226 inner diameter of, 144, 146 skew, 146 ideal triangle, maximal geodesic lamination, 185 imaginary quadratic number field, 113, 362, 367, 377 imPer (period coordinates), 235 incomplete gluing, 90 incompressible torus, $\mathbf{249}$ peripheral, 249 index of section, 523infinitely generated group, 505 infinitesimal hyperbolic metric, 2 infinity vertex, 127 injectivity radius, 39, 75, 81 McMullen's rigidity theorem, 164 of convex core, 226 of pleated surface, 225 of quasi-Fuchsian manifold, 225-241 Inn Γ , see inner automorphism InnD(T), see inner diameter inner automorphism, 168, 374 inner diameter, 144, 145, 145, 146 computed from cross ratio, 144 of ideal tetrahedron, 145, 145, 146 related to skew, 146, 147 Int(P) (interior of P), **109** integer of algebraic number field, 359 integral class, 513 integral closure, 359, 418 integral domain, 327 integral over ring, 328, 328 integral point, 519 integral quadratic form, 367, 368 integral quaternion, 377 integrally closed, 377 interval exchange map, 288, 289, 289 invariant Beltrami form, 500

invariant Beltrami form, cont. conservative group action, 507on limit set, 162 on regular set, 158 invariant line field, 165 inverse limit, 386, 390, 392 Cantor set, 390 universal property, 387 isometric circle, 24, 509 isometric hemisphere, 24, 25, 363 isometry of \mathbb{H}^n , 5, **260** isomorphism of categories, 347 Jacobian, 502, 502-503, 507 co-cycle condition, 502 Jacobson, Nathan, 330 Jacobson ring, 330, 331, 333 examples, 331 examples not Jacobson, 331 Jenkins-Strebel, see bi-JS, h-JS, v-JS Jordan curve theorem, 516 Jørgensen, Troels, 41 Jørgensen's inequality, 41, 41-46 application of, 50 Julia, Gaston, 35 Julia set analogous to limit set, 35 covering space theory, 343 Sullivan dictionary, (footnote), 111 \mathbf{K}^n , see Klein model of hyperbolic space $[K:\mathbb{Q}], 354$ K-quasiconformal map, see quasiconformal map Kleiman, Steven, 327 Kleinian group, 30 accumulation set, 38 Ahlfors finiteness theorem, 156 and rational function (table), 35 arithmetic, 354 classical Schottky group, 110 classification, 30 co-compact, 367 elementary, 30, 30, 30, 30, 36 enriched, 59 figure-8 knot, 117 finite, 30 Fuchsian preserves plane, 30 geometric limit, 58-81

Index: page numbers in italics indicate theorems, propositions, etc.

Kleinian group, cont. geometrically finite, 123, 123, 122-134, 165 limit set Λ_{Γ} , 33, 34, 34, 35, 38 Margulis lemma, 47 non-elementary, 30, 30, 36 normality, 38 not geometrically finite, 131, 259 presentation of, 107 regular set Ω_{Γ} , 33, 38 solvable, 339 when groups have torsion, 95–103 Kleinian-like action, 503, 503 Klein-Maskit combination theorems first (amalgamated sums), 87 second (HNN extensions), 94 Klein model of hyperbolic space, 10, 10-11 geometry of, 12 hyperbolic and Euclidean convex hulls, 10 not good for lengths and angles, 11 pros and cons, 15 Kleptsyn, Victor, 69 knot figure-eight, 243 genus of, 514 Seifert surface, 243 Kontsevich, Maxim, 452 Kra, Irwin, 157, 160 $l(\gamma)$ (length of rectifiable curve), 138 Lam(X), 191 $\operatorname{Lam}_{\operatorname{fin}}(X), 199$ lamination, see measured lamination lattice, 518 complete, 378leads to, 174, 177, 177, 204 leaf, see also critical leaf of geodesic lamination, 185, 185 of measured foliation, 170, 171 of measured lamination, 210 positive mass, 210 usually dense, 171 leaf space, 264-284 \mathcal{F} -distance, 271 γ -trees, 270 of measured foliation, 272, 272 of quadratic differential, 265 point is pinned leaf, 270

leaf space, cont. punctured torus, 265, 283 Skora's theorem, 286 small edge-stabilizer condition, 285 travel on vertical trajectory, 265 Lebesgue density of annuli, 506 Lebesgue density theorem, 163, 164 variant of, 505 Leray cover, 428, 428 Lie algebra, 339 Lie group, 20, 68, 70, 339 light cone, 4, 4, 7, 8 positive rays are points at infinity, 7 light ray, 4 light-like vector, 4 lim inf of sequence of sets, 78 limit set Λ_{Γ} , 34, 37, 38, 40 approximating simple closed curve, 111 Beltrami forms, 164 conical, **126** continuity of, 78, 80, 81 convergence of, 78 covering space theory, 343 fixed points in, 35 horocyclic, 126 Julia set, correspondence with, 35 limit of, 79 lower semicontinuous, 78, 79 of discrete group, 34 of non-elementary Kleinian group, 36, 36-38 of normal subgroup, 37 Peano curve, 253 Schottky group, 110 sphere at infinity, 324 subgroup of finite index, 339 when Cantor set, 110 when minimal closed invariant subset, 36 lim sup of sequence of sets, 78 Lindsey, Kathryn, 111 line bundle first Chern class of, 522 line field, 165 linking number, 246, 246-249, 514 higher dimensions, 248 Hopf invariant, 249 Liouville measure, 446 local coordinate, 415

local ring, 331 Lorentz, Hendrik, 4 Lorentz metric, 3, 4 loxodromic automorphism, 22 Lusin, Nikolai Nikolaevich, 164 Lusin point, 165 Lusin's theorem, 164, 508 Lyndon, Roger, 295 \mathcal{M} (unordered pairs of points at ∞), 195 $E_L \subset \mathcal{M}$ (endpoints of leaves of lift), **196** ordinary measure on, 195 Maclachlan, Colin, 373 manifold, see also hyperbolic manifold 4-dimensional unclassifiable, 103 split, 243, 243-245 map (Lewis Carroll), 75 mapping torus, 242 Marden, Albert, 166 Marden tameness conjecture, 163 Margulis constant, 47 Margulis lemma, 46, 47 alternate version, 338 analogue of collaring theorem, 48proof, 47, 340-341 variant, 48marked point (puncture), 169 Masur, Howard, xiii, 451, 452, 481, 491, 496 mating of Fuchsian groups, 257 matrix of cofactors, 330 Matsuzaki, K., 122 maximal finite lamination, see finite lamination maximal geodesic lamination, 185, 185 4g - 4 + 2n ideal triangles, 190 associated to quadratic differential, 207 compact, 192 maximal ideal, 328, 328, 333, 334 maximal lamination, 235 pleated surface, 215 maximal stratum, 234, 234, 419, 432 McMullen, Curt, 135, 164, 451, 500 McMullen's rigidity theorem, 135, 164, 164-165 compared to Sullivan's, 500 key hypothesis, 225 measurable functions, 434 almost continuous (Lusin), 164

measure ergodic, 435 Hausdorff, 398 invariant, 434 Liouville, 446 on unit tangent bundle, 6 ordinary measure on \mathcal{M} , 195 regular transverse, 471 transverse, 170 vertical invariance, 474 measured foliation, 169, 169, 170, 171, 272 all singularities simple, 172, 172 critical graph, 170 critical leaf, 170 defined by 1-density, 169 equivalent, 173 ergodic, 473 example, 171 leaf, 170 leaf space of, 272 minimal, 473 minimal but not ergodic, 473, 491-499 multiplicity of, 170 nonrealizable, 183 normalized, 474 quadratic differential, 169, 172 realizable, 172, 172, 172, 174 singularity of, 170, 170 transverse measure, 170 uniquely ergodic, 473, 471-479, 480 vertical foliation of quadratic differential, 169 Whitehead moves, 172 measured geodesic lamination, see measured lamination measured lamination, 193, 192-195 associated to quadratic differential, 207, 209 binding, 209, 209, 210 constructed from quadratic differential, 203 - 208constructing quadratic differential, 208-214 data topological, 198 viewed from infinity, 195-197 meromorphic quadratic differential, 170 metric, see hyperbolic, Lorentz, pseudo Meyerhoff, G. Robert, 47 Milnor, John, 35

minimal Γ-tree, 263, 311, 312 minimal measured foliation, 473 minimal stable set, 177, 177, 179 Minkowski, Hermann, 4 Minkowski space, 3, 4 Minsky, Yair, 226 Mirzakhani, Maryam, xiii, 452 MLam, see measured lamination Möbius transformation, 37 isometry of faces, 105 moduli space, 454 Mor (set of morphisms), 348 Mostow, George, 135, 166, 168 Mostow's rigidity theorem, 166, 433 consequences, 168 original proof, 168 proof of general case (exercise), 167 multi-zeta value, 466 multiplicity of measured foliation at a singularity, ${\bf 170}$ Mumford compactness theorem, 46 $N_s(L)$ (closed *s*-neighborhood of *L*), **138** negative tangency, 527, 528, 532 negatively curved space, xvii neighborhood horocyclic, 124 of convex core, 123, 123 Neumann, Bernhard, 351 Neumann, Hanna, 351 Neveu, Jacques, 434 no wandering domain theorem, 157 non-elementary group, 30, 68 enriched is discrete, 68non-elementary Kleinian group, 30, 30, 41 limit set, 37 non-Jacobson ring, 331, 332 non-singular closed 1-form, 529 nonsmooth point of orbifold, 96, 97, 98 norm, 193 of algebraic number, 356 of quaternion, 375, **375** Thurston, 514 normal family, 38 normal subgroup, limit set of, 37 normalization, see desingularization

normalized measured foliation, 474 normalized transverse measure, 475, 476 finite dimensional, 478 infinite dimensional, 478 norm-Euclidean ring, 383 NRep(Γ), [NRep](Γ), **54**, 54, 56, 57 NT, see normalized transverse measure Nullstellensatz, 327, 333, 333, 334 number field, see field O(n, 1) (orthogonal group of Q), 5, 5 $O^+(n,1), 5, 6$ isometries of \mathbb{H}^n , 6 octahedral group (footnote), 31 Okunkov, Andrei, xiii, 452 once-punctured torus, 325 isometries of \mathbb{H}^n , 6 Opti, 66 orbifold, 96, 96-99, 106, 454 see also hyperbolic orbifold 2-dimensional, 97 complete hyperbolic, 100 cone point of, 97 covering map, 100, 100-103 covering space, 95 Euler characteristic of, 97 Gauss-Bonnet theorem for, 97 geodesic on, **100**, *100* hyperbolic, 95, 96, 101 nonsmooth point of, 96, 97, 98 other definitions, 96 replacing by manifold, 327 singular locus of, 97 singular point of, 96 smooth point of, 96 orbifold chart, 96 ord_z (order), **430**, 430 in algebraic number field, 360 order in quaternion algebra, 377, 378 of measured foliation at singularity, 170 orientable hyperbolic orbifold, 96, 96-99 2-dimensional, 97 nonsmooth points, 98 origami, see square-tiled surface Otal's compactness theorem, 303 Out Γ , see outer automorphism

outer automorphism, 168 of fundamental group, 168 \mathcal{P}_i (open cells making up P_i), 104 paired polyhedron, 105, 131 parabolic, see parabolic automorphism parabolic automorphism, 22, 27 accidental, 62, 67 axes of flips, 27 persistent, 62 single fixed point, 23 trace, 23 parabolic subgroup bounded, unbounded, 125 classification, 30, 124-125 rank of, 124 path (in tree), 259 path metric space, 260 Peano curve, 253 Pereleman, Grigori, xviii period coordinate, 415, 417, 457 defined on stratum, 424-429 for fixed surface, 429-432individual Riemann surface, 429, 430 on stratum, 415 period element of volume, 455 period map, 425 derivative of, 428 local coordinate, 425 real and imaginary parts, 429 real part diffeomorphism, 432 variant, 235 period volume, 455 invariant under Teichmüller flow, 455 peripheral element, 272 peripheral torus, 249, 249, 250 persistent parabolic, 62 Petersen, Carsten, 149 Picard-Lefschetz action, 263 pigeon-hole principle, 292 Skora's theorem, 290 pinned geodesic, 267, 267 pinned homotopy, 266 pinned leaf, 270, 270, 269-271 pinned path, 266, 266 Platonic solid, 98 pleat, 215

pleated surface, 185, 215, 214-225, 235 hyperbolic structure, 216, 216-225 injectivity radius bounded, 225 structure of, 216 top of quilt, 226 plumbing caricature for 3-manifolds, 46 Poincaré, Henri, 444 Poincaré duality, 513 Poincaré-Hopf index theorem, 175, 524 Poincaré model, see ball model Poincaré polyhedron theorem. 106, 113 Poincaré presentation theorem, 107 Poincaré recurrence, 444, 444-445, 502 point of density (footnote), 163 point-stabilizer, 285 pointed CCC space universal covering map, 344 universal covering space, 345 pointed map, **344**, 345 pointed space, 344 pointed UC-space, 349 Poisson integral formula, 149 3-dimensional, 83 Poisson kernel, see Poisson measure Poisson measure, 148, 149, 154, 163 polyhedron hyperbolic, 104 Poincaré polyhedron theorem, 106 unit ball, 518 when fundamental domain, 106poset (partially ordered set), 386 cofinal subset, 386 directed, 386, 387 positive path, 174 positive tangency, 527, 528 positive vector, 174 $\mathbb{P}Q(M)$ (bundle of projective spaces), 7 Prasad, Gopal, 166 presentation of group limitations, 103 presentation theorem (Poincaré), 107 prime ideal, 328, 328 primitive element, 355 projective limit, see inverse limit projective module of rank 1, 367 projective spaces, bundle of, 7

prong (at singularity or marked point), 169-170 proper ideal, 328 when prime, 328 proper submersion fibration, 511 pseudo-Anosov double limits, 325 pseudo-Anosov homeomorphism, 242, 248, 251 pseudo inner product, 3, 8 pseudolength, 370 pseudo-metric, 2, 3 pseudo-orthogonal, 370 $PSL_2\mathbb{C}, 4, 5$ element of as composition, 25 identified with Aut \mathbb{H}^3 , 19, 20 $\operatorname{PSL}_2 \mathcal{O}(K)$ for $K = \mathbb{Q}(\sqrt{-3})$, 114–116 for $K = \mathbb{Q}(\sqrt{-5}), 362 - 367$ pulling tight, 198, 203 puncture (marked point), 169 effect of Whitehead move, 172 punctured sphere, 157, 160, 161, 199 punctured torus, 161, 243, 245, 246 leaf space, 265, 283 pure quaternion, 375, 375 push forward, 434 qc-map, 485 q-locally constant vector field, 427 Q(M) (vector bundle of quadratic forms), 7 $Q^+(M)$ (positive definite quadratic forms, 7 QF, see quasi-Fuchsian representation [QF], see quasi-Fuchsian representation, conjugacy classes $\mathcal{QF} \pmod{\mathrm{T}_X \times \mathcal{T}_{X^*} \to \mathrm{Rep}(G)}, 257$ quadratic differential, 204bi-JS (Jenkins-Strebel), 428, 429 constructed from measured lamination, 208-214, 210 constructing measured lamination, 203-208 ends of leaves, 204 h-JS (horizontally Jenkins-Strebel), 428 horizontal and vertical foliations, 169 Jenkins-Strebel, 428 leaf space of, 264-271 measured foliation, 169, 172 meromorphic, 170 order of, 430

quadratic differential, cont. v-JS (vertically Jenkins-Strebel), 428 quadratic form, 103 quadratic space, 381 quasiconformal extension, 144, 144 quasiconformal homeomorphism Douady-Earle extension of, 151 quasiconformal map, 159 compact set uniformly Hölder, 148 compactness, 147 when compact, 152 when Hölder, 153 quasi-Fuchsian group, 83 bending lamination, 229 isometry of \mathbb{H}^3 , 83 quasi-Fuchsian manifold injectivity radius of, 225-241 injectivity radius of, in convex core, 226 quasi-Fuchsian representations conjugacy classes of, 257 limit, 324 space of, 257 quasi-geodesic, 137, 138, 141 and geodesics, 138 in hyperbolic space, 137 ray, 137 quasi-isometric map, 135 locally wild, 136 quasi-isometry, 135, 135-147, 166 compact metric space quasi-isometric to point, 136 equivalence relation, 136 examples, 136 extends continuously, 144 inner diameter of, 145 quasiconformal extension when n = 3, 144when isometry, 136 quasi-surjective map, 135 quaternion, 373, 373 integral, 377 norm, 375, 375 pure, 375, 375 trace, 375, 375 quaternion algebra, 103, 354, 373, 374, 373-385 center of, 374 central simple algebra, 373

quaternion algebra, cont. Hamiltonian quaternion, 374 order in, 377, 378 scalar, 374 quilt (convex core), 226 quotient of regular set, 156, 156 Euler characteristic of, 160 R-lattice, 378 **R**-tree, **259** axis, 260 isometries of, 260 path metric space, 260 radius of injectivity, see injectivity radius Radon-Nikodym derivative, 436, 436, 502-503 Radon-Nikodym theorem, 435, 435 rank 1 cusp, 49, 125, 134 rank 2 cusp, 49, 124, 133 real tree, see \mathbb{R} -tree realizable measured foliation, 172, 172, 174, 272 false counterexample, 184 recurrent point, 444, 444 reflection group generated by, 110 with respect to plane, 25 regular function, 418 regular neighborhood, 243, 243 regular set, 34 analogous to Fatou set, 35 Beltami forms, 158 normal families, 38 of Kleinian group, 33, 34 quotient of by Γ , 156, 157 regular transverse measure, 471 weak* limit, 471 Reid, Alan, 373 relative Chern class, 521, **522**, 522, 524-526 relative hyperbolic atlas, 73 relative hyperbolic coordinate, 73 relativity, 4, 19 $\operatorname{Rep}(\Gamma), 51$ $[\operatorname{Rep}](\Gamma), 51$ nasty, not Hausdorff, 53 representation algebraic convergence of, 51 analytic family, 62, 62 discrete, 51, 51

representation, cont. elementary, 51 injective, 51 representation space, 51, 51, 66 algebraic variety, 51 finite dimensional, 51 Riemann surface complex curve, 415 of \sqrt{q} , **176**, 416 universal family, 421 Riemannian manifold, 2 Riemannian metric, 2, 7, 14 inducing conformal structure, 7 of ball model, 13 of upper halfspace model, 14, 14 Riemannian structure, 7 Riesz representation theorem, 231 rigidity of pseudo-Anosov double limits, 325 rigidity theorems McMullen, 164, 164-165, 225 Mostow, 166, 166-168 Sullivan. 500 Riley, Robert, 114, 116 ring integral over, 328 Jacobson, 330, 331, 333 local, 331 non-Jacobson, 331, 332 norm-Euclidean, 383 when domain, 328 when field, 328 ring homomorphism, 327 rotation, 24, 25 around axis, 23 Rudin, Walter, 505 S_A , see isometric hemisphere S_P , see harmonic separator Saric, Dragomir, 191 scalar quaternion, 374 Schori, Richard, 69 Schottky group, 110, 110 second law of thermodynamics, 444 section, index of, 523 Seifert surface, 243, 244 Selberg, Atle, 336 Selberg's lemma, 78, 157, 327, 336, 507

semi-norm, see also Thurston semi-norm integral values, 518 separator, see harmonic separator sequence, degenerating, 304 Series, Caroline, xiii, 191, 399 Serre, Jean-Pierre, 249 set of discontinuity, see regular set sheaf, topologists' aversion to, 427 Sierpinsky gasket Hausdorff dimension of, 398 simple accident, 238 simple geodesic, 191, 398-414 band model, 187 central segment close, 400combinatorial description of, 402-413 noncompact case, 413 three classes, 399 union has Hausdorff dimension 1, 399 simplicial tree, 260, 261 simultaneous uniformization map (Bers), **294**, *294* singly unbounded rank 1 cusp, 125 singular curve, 416 singular locus of orbifold, 97 dihedral, icosahedral, octahedral, 98 singular point of orbifold, 96 singularity of measured foliation, 170, 170 prong at, 170 skew, 146, 146 and inner diameter, 147 skew field, 374, see also division algebra skinning lemma, 2 Skolem-Noether theorem, 374 Skora's theorem, 286, 284-286 interval exchange map, 288 small edge-stabilizer, 284 condition, 284, 285, 286 smooth morphism, 423 smooth point of orbifold, 96smooth topological family of hyperbolic manifolds, 72, 73 SO(3), finite subgroups of, 31, 98 SO(n), 6 $SO^+(3,1), 4, 5$ 2×2 matrices, 19

 $SO^+(n,1), 4-6$ connected, 6 equals Aut \mathbb{H}^n matrices with det 1, 5 solvable group, 338, 339 space-like vector, 4 spacetime, 4 and Hermitian matrices (table), 20 span (of subset of \mathbb{R} -tree), 260 special theory of relativity, 4 sphere \mathbb{H}^3 natural conformal structure, 7 no natural Riemannian structure, 7 sphere at infinity, 7 split manifold, 243, 242-245 square-tiled surface, 429, 457, 457, 460, 465 cut into cylinders, 458 stabilizer, 49, 84 rank 1, 125 rank 2, 124 stable element of HNN extension, 351 stable manifold, 448, 449 stable set, 177, 177, 179 minimal, 177, 177, 179 Stallings, John, 386, 397 $\mathbb{S}(TM)$, see unit sphere bundle standard collar, 187 stereographic projection, 16, 14-17 stratum, 419, 419 complex dimension, 460 connected component, 451, 452, 453, 460, 481 cutting into simplices, 463, 465 dimension of connected component, 460 maximal, 419 of quadratic differentials, 415, 451 problem with earlier definition, 452 Riemann sum, 463 unit, 455 volume of (example), 466-470 stretch factor, 251 Sullivan, Dennis, 157, 500 Sullivan dictionary, 35, 111, 157 Sullivan's rigidity theorem, 500, 500-509 compared to McMullen's, 500 finitely generated, 505 surface of finite type, 169

surgery, 516 symmetric difference, 493 symmetric group, 98 Tabachnikov, S., 491, 496 tangency negative, 527 positive, 527 tangent space to light cone, 8 Taniguchi, M., 122 Teichmüller flow, 453 ergodic, 451, 451 Teichmüller geodesic, 451 convergent, 484 Teichmüller space, see also Teichmüller flow Bers slice, 258 dimension in terms of generators, 158mating of Fuchsian groups, 257 of disjoint union, 157 period coordinates, 415–432 simultaneous uniformization, 257 structure of pleated surface, 216 tetrahedral group (footnote), 31 tetrahedron, see also ideal tetrahedron inner diameter, 145 truncated, 117 thermodynamics, second law of, 444 thick part of hyperbolic manifold, 48 thin part of hyperbolic manifold, 48, 48 Thurston, Dylan, 273 Thurston, William complement of figure-eight knot, 114 convex hull, 36 double limit theorem, 255 geometric limits, 74, 76 injectivity radius of q-F manifold, 226 Klein-Maskit theorems, 87 laminations, pleated surfaces, 168 seeing \mathbb{H}^n from inside, 3, 5 Thurston norm, 514, 514 difficult to compute, 514 genus of knot, 514 Thurston semi-norm, 514, 514, 518 convex, 517 fibration over circle, 512 locally linear, 526 relative Chern class, 526

Thurston semi-norm, cont. simplest link, 515 surgery, 516 unit sphere, 529, 529 time-like event, 4 time-like vector, 4 topological space, end of, 392, 394, 395 topology Chabauty, 69, 70 link with complex analysis, 172 of algebraic convergence, 68, 74 of geometric convergence, 70, 68-81 torsion-free group, subgroup, 40, 40, 336 torus incompressible, 249, 249 mapping, 242 peripheral, 249, 249, 250 triangulation of, 116, 118 totally geodesic surface, 82 totally real algebraic number field, 356, 379 trace conjugacy class of representations, 56, 57 eliminating, 336 of algebraic number, 356, 356 of automorphism, 23, 41 of quaternion, 375, 375 train-RoW, see train right-of-way train track, right-of-way, 211, 211 trajectory, 171, see also leaf critical, 205 noncritical, 205 typical, 479, 480 translation along axis, 23 transversal to geodesic lamination, 192 transverse length, 170 transverse measure, 170, 192, 193, 471 ergodic, 473 mass of, 475 normalized. 475 of measured foliation, 170 regular, 471 tree, see also Gamma-tree R-tree, 259, 260 isometries of, 260 simplicial, 260, 261 tree axis, 260, 298

tree axis, cont. of composition, 263 triangle inequality, 340 triangulation of torus, 116, 118 trivial covering map, 343truncated tetrahedron, 117 typical trajectory, 479, 479, 480 UC space, **343**, 346 pointed, 349 unique ergodicity, 448, 473, 480, 481 full measure, 481, 484 unit ball, when rational polyhedron, 518 unit sphere bundle, 446 unit stratum, 454 finite period volume, 455unit tangent bundle, 6 universal covering map, 343 construction of, 344-345functorial, 345 of pointed space, **344** universal covering space, 88, 343, 343 functor of pointed space, 344, 345 Hawaiian earring has none, 343 hyperbolic orbifold, 101 not functor, 343 not necessarily CCC, 343, 345 unstable manifold, 448, 449 upper halfspace model, see halfspace model van Kampen, Egbert, 349 van Kampen's theorem, 342, 349 Veech, William, xiii, 451, 452 vertical foliation, 172, 252 of quadratic differential, 169, 209, 232 pulling tight, 210 vertically invariant measure, 474 visual measure, 163 visual sphere, 82, 84, 163 v-JS (vertically Jenkins-Strebel), 428 Vlamis, Nicholas, 386 von Neumann, John, 19 Voronoi, Georgy, 114 Voronoi cell, 369 Voronoi cellulation, 114 Wada, Masaaki, 66 weak topology, 194

weak topology, cont. basis of neighborhoods for, 194 convergent sequence, 195 weak* limit, 471 weak* topology, 476 West, James, 69 Whitehead move, 170, 172, 172-173, 179-184 edge on which to perform, 177 measured foliation realizable, 172 two kinds, 172, 173 window (of lift of lamination), 206, 207 word problem (words in generators), 103 Wu, Chenxi, 510 $X^{\wedge S}$, see split manifold Z_{Γ} (quotient of regular set Ω_{Γ} by Γ), **156**, 156, 157, 156-162Zorich, Anton, 452 Zorn's lemma, 328