

# Index

- Additive effects, 37, 64, 251, 273, 291n2.3. *See also* Epistasis
- Aggregate effects. *See* Modules, aggregate effects of
- Algorithmic paradigms, 8–12, 20, 68–70  
of evolution, xi, xii, xiii, xiv, 8–12, 20, 199, 219, 250, 263, 272, 276, 277, 278, 285, 286, 289
- Allele, 6
- Allopolyploidy, 196
- Baldwin effect, 257, 258, 259
- Bayesian optimization algorithm (BOA), 183, 272
- Behe, Michael, 1, 19, 39, 40, 41, 152, 277, 289
- Beneficial variations, likelihood of, xii, 30, 59, 65, 92, 94, 279, 288
- Benefit of sex. *See* Sex, benefit of
- Biased exploration, 65, 93, 95
- Bloat, 207, 208, 213, 214
- Building block hypothesis, 65, 66, 184, 292n3.9
- Building blocks, 25, 66, 68, 70, 71, 72, 82, 83, 132, 134, 184, 222, 223, 286  
exploitation of, 225  
in nature, 246  
scale of, 73, 248  
scaling up, 245
- Chromosomal reassortment. *See* Sexual recombination, chromosomal reassortment
- Classifier systems, 80
- Coadaptation, 95. *See also* Coevolution
- Coevolution, 18, 34, 87, 88, 97–99, 135, 146, 216, 248, 255
- Coexistence, 169, 268
- Competing conventions problem, 85, 87, 98, 211
- Competition, 169, 252
- Competitive exclusion, 18, 35, 87, 88, 90, 95, 169, 268
- Complex adaptations, 288
- Complexity  
increases in, 285  
ceiling, 265, 266, 276
- Complex systems, 8, 11, 15, 218
- Compositional evolution, xiii, 2, 3, 6, 16, 98, 285  
biased exploration via, 18, 54, 65, 91, 93, 94, 188, 199, 275  
vs. gradual evolution (*see* Gradual evolution, vs. compositional evolution)  
mechanisms of, 45, 55  
models of, 55  
requirements for, via sexual recombination, 191  
via sexual recombination, prerequisites for, 186
- Compositional mechanisms, 259, 280  
in nature, 279  
spectrum of, 45, 193, 196
- Concatenated trap function, 71, 72, 73, 75, 132, 133, 136, 137, 138, 139
- Contexts, 201  
for evaluation, 235, 262 (*see* Evaluation, in contexts)  
number required, 239, 240, 243
- Context-sensitivity, 18, 94, 140, 144, 145, 201  
of fitness, 203
- Continuous HIFF. *See* HIFF, continuous version of
- Convergence controlled variation, 181
- Cooperation, 264
- Cooperative coevolution, 76, 86–88, 211, 214, 287
- Credit assignment problem, 87, 211, 215
- Crossover, xiv, 2, 34, 46, 47, 50, 65, 71, 82, 83, 97, 98, 137, 166, 187, 252. *See also* Sexual recombination  
availability of fitness improvements under, 229  
complementary pair, 168, 169  
masks, 222  
one-point, 50  
vs. uniform, 177  
preserving similarity of parents, 181  
rate of, 254  
two-point, 50  
uniform, 49, 50, 165, 247 (*see also* Free recombination)  
simulation experiments, 175  
simulation results, 176, 185  
utility of, 98, 183, 287
- Crowding. *See* Deterministic crowding
- Darwin, Charles, xi, 1, 22, 29, 30, 272, 273, 276, 277, 278, 286, 289
- Dawkins, Richard, 1, 19, 25, 63, 86, 248, 253, 277, 289
- Deception, 138, 139, 140
- Decomposition, 11, 68, 69, 70, 74, 81, 87, 101, 157, 244, 287. *See also* Divide-and-conquer problem  
decomposition  
decomposability, 14, 73, 111, 113  
example, 114
- Deme, 251. *See also* Subdivided population
- Dependency, 9, 17, 82, 83, 182  
intramodule vs. intermodule, 95, 110, 111, 122, 125, 132, 133, 138, 282  
matrix, 120  
overlapping, 107, 134  
structure of, 282, 283
- Deterministic crowding, 88, 164, 167, 168, 169–172, 175, 180, 187, 213  
simulation results, 185

- Deterministic mutation hypothesis, 60, 62  
Differential reproduction, 265  
Dimensional reduction, 12, 74, 112, 119, 120, 123, 292n6.2  
Diploidy, 45  
Directed change, 92  
Disruption analysis, 82, 83, 181, 184  
Diversity, 39, 82, 164, 167, 169, 187, 252, 286  
  maintenance of, 82, 88, 169, 170, 184, 185, 213, 217, 233, 248, 253  
Divide-and-conquer problem decomposition, xiii, 9, 11, 68, 69, 70, 73, 76, 80, 87, 97, 98, 183, 218, 276, 278, 286. *See also* Decomposition  
Drift. *See* Genetic drift  
Dynamical system, 143  
Ecosystem, 170  
Emergent effects. *See* Modules, emergent effects  
Encapsulation, 17, 54, 55, 74, 124  
Endosymbiosis, 6, 8, 46, 52, 77  
Epistasis, 17, 37, 42, 64, 103, 154, 252, 273, 283, 291n2.3. *See also* Interdependency  
  assumptions about, 273  
  correspondence with physical linkage (*see* Physical linkage, correspondence with epistasis)  
  with environment, 98, 146, 192, 197, 200, 217  
  in HIFF, 154  
  in nature, 154  
  positive and negative, 61  
  sign, 89  
  structure of, 269  
  types of, 103–105  
Equilibrium models, 72  
Eukaryote, 52  
Evaluation, 31  
  in contexts, 235, 238  
  in groups, 25, 204, 207, 210, 260, 261, 262, 264  
  in SEAM, 256  
Evolution  
  algorithmic paradigms of (*see* Algorithmic paradigms, of evolution)  
  open-ended, 245, 266  
Evolutionary algorithms, 2, 32. *See also* Genetic algorithm  
  as evolutionary models, 34  
Evolutionary computation, vs. evolutionary biology, xi, 42, 72, 98, 104, 272  
Evolutionary difficulty, xiii, 3, 15, 35–43, 98, 101, 109, 149, 156, 245, 276, 277, 285, 287. *See also* Evolvability; Gradualism, path of monotonic improvement  
  in HIFF, 149–157  
  of modular interdependency, 150  
Evolutionary processes, common assumptions, 35, 42, 98  
Evolvability, xiii, 3, 8, 11, 12, 15, 19, 42, 99, 156, 161, 218, 277. *See also* Evolutionary difficulty  
Exaptation, 90  
Fisher, Ronald, xi, 29, 30, 57, 59, 60, 61, 62, 250, 253, 272  
Fisher–Muller model, 57, 58  
Fitness, xi, 31, 98, 102  
  epistasis with environment, 217  
  local gradients of, 37, 38, 96  
  multidimensional treatment of, 18, 88, 89, 202, 268  
Fitness landscape, 9, 36, 42, 98, 102, 104, 133, 135, 149, 252, 257. *See also* NK landscape  
  classes of, 281  
  coevolution of, 146  
  dynamics, 145, 146  
  epistasis with environment, 146  
  fractal, 15, 123, 128, 133, 149  
  in nature, 245  
  neighborhood of, 36, 96, 246, 259, 292n3.10  
  niches, 146  
  subspaces of, 146  
Fitness saddles, 13, 38, 103, 245  
  width of, 107, 116, 117, 122, 150, 182, 256 (*see also* Evolutionary difficulty)  
  in HIFF, 151  
Fitness sharing, 87, 88, 170, 216, 217  
Free recombination, 49, 98. *See also* Crossover, uniform  
  experiments with, 175  
Frequency dependent fitness, 88  
Frustration of variables, 37  
Gene duplication, 91  
Gene invariant genetic algorithm (GIGA), 221, 223  
Generalists, 18  
Generational, 32  
Genes as modules, 284  
Genetic algorithm, xiv, 2, 31–34, 165. *See also* Evolutionary algorithm; Simple genetic algorithm  
  simulation results, 185, 209, 210  
  utility of, 66, 73, 183, 286, 287  
Genetic drift, 251, 252  
Genetic integration, 74, 252  
Genetic map, 16, 17, 63, 64, 137, 210, 243, 254, 255. *See also* Physical linkage  
  in nature, 188, 284  
  random, xii, 16, 71, 137, 178, 179, 211 (*see also* Shuffled HIFF)

- sex and dependence on, 174–179  
 tight, 17, 82, 179, 183, 185, 188
- Goldberg, David, 66, 72, 75, 84, 133, 138, 139, 140, 213, 214, 293n7.3
- Gradual evolution, 42  
 vs. compositional evolution, xiii, xiv, 3–12, 4, 146, 183, 243, 266, 274, 281, 282, 287  
 mechanisms, 259
- Gradualism, xiii, 1, 4, 21, 23, 29, 99, 174, 274, 277, 278, 288. *See also* Gradualist framework of evolution; Incremental improvement  
 necessity of, 276  
 path of incremental improvements, 15, 23, 40, 41, 151, 161, 220, 277, 288  
 path of monotonic improvement, 15, 19, 23, 41, 155, 220, 277, 278, 288, 289  
 strict, xiii, 274, 286  
 successive slight variations, xi, xii, 1, 20, 29, 38, 286, 289
- Gradualist framework of evolution, xii, xiii, xiv, 1–4, 10, 15, 19–24, 29, 30, 31, 99, 147, 155, 172, 274, 275–278, 286–289. *See also* Incremental improvement; Gradualism
- Greedy optimization, 10, 68, 208, 261, 262, 263, 264
- Hamming distance, 36
- Haploidy, 46
- Headless chicken test, 152
- Heritability, 265  
 tension with innovation, 95, 265
- Hierarchical encapsulation, 6
- Hierarchical if-and-only-if (HIFF), 101, 125–129, 133, 155, 254  
 continuous version of, 121, 123, 125, 133  
 vs. continuous version of, 128, 153  
 compared with deception, 139  
 definition of, 127  
 fitness landscape, 128, 149  
 simulation results, 185
- Hierarchical modular interdependency, 117
- Hierarchical selection, 265
- Hierarchy, 14, 25, 79, 80, 120, 287  
 cooperation in, 144  
 and modularity, 117, 140, 283
- Hill climbing, xiii, xiv, 9, 10, 32, 36, 37, 42, 69, 71, 73, 108, 116, 137, 166, 183, 272, 273, 278, 286, 289  
 sufficiency of, 285  
 time complexity, 155
- Hitchhiking, 68, 87, 215
- Holism, 118, 122
- Holland, John, 25, 27, 32, 66, 82, 134, 185, 281
- Hopeful monster, 30, 39, 291n2.1
- Horizontal gene transfer, xii, xiii, 46, 51, 95, 196, 284
- Hybridization, xii, 46, 98
- Hyperplane defined functions, 134
- Idealized SEAM, 234, 235, 238
- If-and-only-if, 107, 108, 125, 144
- Incremental improvement, xi, xii, xiii, 1, 23, 41, 63, 244, 286, 288, 289  
 vs. gradualist framework of evolution, 2, 20
- Individuality, 53
- Innovation, 3, 21, 98, 276  
 tension with heritability, 95, 265
- Intelligent design, 9, 10
- Interaction system, 64, 250
- Interdependency, 25, 101, 103, 104, 105, 106, 107–109  
 definition, 106  
 hierarchically modular, 117–129  
 intermodule, 145  
 modular, 109–117  
 pairwise, 103  
 pairwise weighted sum, 108  
 types of, 141
- Irreducible complexity, 39, 40–42, 153, 154, 277, 288. *See also* Gradualism, path of incremental improvements; Incremental improvement of HIFF, 152
- Ising models, 142, 143
- Landscape. *See* Fitness landscape
- Large changes, 3, 7, 23, 29, 30, 65, 91, 92, 94, 274, 275, 277. *See also* Gradualism within a lineage, 90, 91
- Lateral gene transfer. *See* Horizontal gene transfer
- Levels of organization, xiv, 265, 266
- Linear chromosomes, 32
- Linkage. *See* Physical linkage
- Linkage disequilibrium, 56, 57, 59–63, 71  
 positive, 56
- Linkage learning, 182, 211
- Local optima, 37, 38, 42, 103, 109, 116, 251, 252, 273, 279  
 absence of, 229  
 absence of under crossover, 225  
 escape from, 252 (*see also* Fitness saddles)  
 in HIFF, 151, 155  
 location of, 232
- Macroevolution, vs. microevolution, 245–267
- Macromutation, 34, 51, 65, 71, 185
- Macromutation hill climber, 71, 137, 156
- Major evolutionary transitions, xiv, 54, 191, 267, 279, 285, 287

- Margulis, Lynn, xii, 1, 8, 11, 21, 45, 52, 53, 268, 276, 285
- Maximal set, 112, 114, 115, 157
- Maynard Smith, John, 7, 22, 54, 144, 191, 245, 276
- Meiosis, 47
- Messy GA, 75, 84, 86, 87, 210, 212, 213, 287
- Microevolution, vs. macroevolution, 245–267
- Migration, 7, 169, 251 *See also* Population subdivision  
rate of, 169, 170
- Mitochondria, 52, 280
- Modern synthesis, xi, 253
- Modular interdependency, 14, 109–113, 186, 282, 287  
example, 114, 144  
generalization, 129, 130, 131, 132, 133
- Modularity, 2, 9, 12, 69, 74, 101, 102–147, 278, 282, 286  
concepts of, 111  
context-sensitivity of utility, 110  
discovery of, 188, 211, 215, 260, 287  
in dynamical systems, 142  
engineering examples of, 270  
examples of, 147  
indentification of, 261  
interaction between, 124  
in nature, 280, 281, 282, 283, 284, 285  
repeated structures, 90, 91  
types of, 24, 147
- Modules, aggregate effects of, 117, 118, 119, 121, 129, 130, 140  
emergent effects of, 122, 124  
genes as, 284  
interaction between, 118 (*see also* Modular interdependency)  
representation of, 200
- Moving-locus representations, 75, 83, 84, 212
- Muller's ratchet, 59, 62
- Multilocus models, 63
- Multiobjective optimization, 217
- Multiple inheritance, 275
- Mutation, 7, 149, 196, 286  
vs. crossover, 270  
rates of, 158  
simulation results, 157  
sufficiency of, 174
- Mutation walk, 123, 149, 150
- Mutual benefit, 264
- Mutually exclusive characters, 194, 199
- Natural selection, xi, xii, xiii, 265, 277, 288, 289
- Nearly decomposable systems, 14, 115, 117, 140, 141, 287
- Neutral evolution, 39
- Niche, 88, 95, 102, 167, 169, 170, 203
- NKC landscapes, 110, 133, 135, 136, 282
- NK landscapes, 26, 39, 109, 133, 134, 135, 136, 142, 282
- “No free lunch,” 26, 184, 281
- Ontogenic mechanisms, 90
- Organelle, 52
- Panmictic population, 64, 165, 166
- Pareto coevolution, 88, 89, 98, 202, 207, 211, 212, 215, 216, 217
- Partial evaluation, 86  
in SEAM, 200, 201
- Partially specified individuals, 75, 82, 83, 84, 200, 201, 210, 212, 213, 258, 263  
in SEAM, 198
- Path of small changes. *See* Gradualism, path of incremental improvements; Incremental improvement
- Physical linkage, 17, 50, 56, 57, 64, 82, 83, 98, 98, 164, 165, 174, 182, 187, 188, 191, 243, 252, 253, 287. *See also* Genetic map  
correspondence with epistatic dependencies, 17, 65, 164, 179, 183  
natural structure of, 254, 284  
none, 175 (*see also* Free recombination)  
strong, 56
- Polyploidy, 46, 91, 194, 196
- Population genetics, 30, 34, 37, 45, 55, 57, 63–65, 72, 103, 244–247, 253, 268, 273
- Population size, 165, 166, 206, 219, 221, 233, 234
- Premature convergence, 39, 82, 90, 167, 172, 185, 220. *See also* Population diversity
- Preselection, 170
- Problem/solution metaphor, 103
- Punctuated equilibria, 24
- Purging deleterious mutations, 60, 61
- Random Boolean networks, 142
- Random genetic map. *See* Genetic map, random
- Random mutation hill climber, xi, 155, 157, 158, 205, 272  
simulation results, 159, 185
- Random search, 69
- Recombination. *See* Sexual recombination
- Recombinative hill climber, 220, 226, 233
- Renormalization groups, 143
- Reproductive fidelity, 265
- Ridley, Mark, 21, 22, 279
- Rowers analogy, 86, 248. *See also* Selection, on individual alleles

- Royal Road function, 70, 71, 72, 73, 132, 133, 136, 137, 138, 282
- Ruggedness, 38, 39  
in HIFF, 151
- Saltation, xii, 24, 30, 291n2.1
- Scalability of evolution, 110, 120, 199, 219, 245–257, 265, 266, 268, 269  
with symbiotic encapsulation, 255
- Scale invariant, 122, 256, 257
- Schema, 66, 86  
order of and defining length, 67
- Schema theorem, 27, 67, 184
- SEAM. *See* Symbiogenic evolutionary adaptation model
- Segregating alleles, 59
- Selection, 31  
on combinations of alleles, 25, 62, 64, 66, 98, 104, 250, 251, 252, 254, 255, 272  
on combinations of blocks, 72  
on individual alleles, 62, 66, 68, 98, 250, 255, 264, 272 (*see also* Rowers analogy)  
scale of units (*see* Units of selection)  
in SEAM, 256
- Selfish gene, 25, 63, 64, 192, 200, 262, 264
- Self-similarity, 92
- Separability, 26, 69, 73, 109, 110, 112, 113, 133, 139, 141, 220, 224, 282, 286, 287, 292n4.1  
time complexity analysis, 221–225
- Serial endosymbiosis theory, 53, 268, 276
- Sex, 45–51. *See also* Sexual recombination  
benefit of, 55, 98, 269, 270  
prerequisites for benefit, 284
- Sexual recombination, xiii, xiv, 3, 6, 16, 45–48, 49, 55, 84, 93, 98, 137, 163, 196, 247, 268, 286. *See also* Crossover  
analysis, 219  
vs. asexuals, 65  
benefit of (*see* Sex, benefit of)  
biased exploration and the genetic map, 18, 65, 94, 188, 199  
chromosomal reassortment, 46, 47  
vs. combination, 212  
crossover rate in simulation experiments, 169  
vs. encapsulation, 195  
mechanisms, 163  
rate, 47, 63–65, 180  
simulations with HIFF, 163–189
- Shifting balance theory, 8, 25, 250, 251, 268
- Shuffled HIFF, 136, 165, 178, 179, 180, 182  
simulation results, 185, 209, 210
- Simon, Herbert, 14, 115, 117, 118, 119, 120, 140, 141, 142, 281, 287
- Simple genetic algorithm, 32–34, 165, 166, 167, 184
- Simulation results  
mutation, 158, 159, 160  
sex/crossover in panmictic population/simple GA, 165, 166, 167  
sex/crossover in subdivided population/ GA with crowding, 167, 171, 175, 176, 180  
shuffled HIFF/random genetic map, 180  
summary of, 185, 186, 187, 209, 210  
symbiotic encapsulation/SEAM, 205, 207, 208
- Specialists, 18, 76, 208
- Splice operator, 75, 85, 210
- Stability of symbiotic joins. *See* Symbiotic joins, stability of
- Stochastic lookaheads, 215, 261, 262, 263
- Strict gradualism. *See* Gradualism, strict
- Subdivided population, xii, 7, 164, 167, 169, 251
- Successive slight variations. *See* Gradualism, successive slight variations
- Symbiogenesis, xii–xiv, 1, 17, 45, 46, 52, 53, 54, 77, 193, 267, 276, 279, 286, 287, 288. *See also* Symbiotic encapsulation  
in EC models, 77–81
- Symbiogenic evolutionary adaptation model (SEAM), 18, 191, 205, 206, 256. *See also* Idealized SEAM  
requirements for, 218  
simulation results, 205, 209, 210  
simulations with HIFF and shuffled HIFF, 191–209  
time complexity of, 234–243
- Symbiosis, xii, 3, 22, 52, 77, 276, 285
- Symbiotic encapsulation, 3, 6, 8, 17–19, 55, 196, 198, 259, 265, 268, 288. *See also* Symbiogenic evolutionary adaptation model  
genetic operator, 198  
requirements for, 191, 200  
scaling-up evolution with, 255–265  
simulation models of, 191–244
- Symbiotic groups, 263, 264
- Symbiotic joins, 198, 199, 265  
stability of, 192, 202, 203, 264, 265, 271
- Symbiotic scaffolding, 257, 258, 259, 261
- Template differencing, 214, 215
- Templating, 75, 86, 214
- Tight linkage. *See* Genetic map, tight
- Time complexity, 219, 220, 234, 269  
of HIFF, 225, 227, 230  
of mutation, 155  
of SEAM, 237, 242  
of sexual recombination, 225–234  
of symbiotic encapsulation, 234–243

- Uniform crossover. *See* Crossover, uniform
- Units of selection and variation, 63, 249, 253, 245–  
255, 255, 257, 264, 265, 269  
in SEAM, 256  
in sexual populations, 247
- Variation, 31, 265  
distribution of, 93, 94, 275  
random change, 92  
rate of, 261  
in SEAM, 256  
size of, xi–xiii, 29, 30, 269, 285 (*see also*  
Gradualism, successive slight variations; Large  
changes)  
undirected, xii, 30
- Wright, Sewell, 25, 30, 36, 38, 41, 64, 103, 250, 251,  
252, 253