

Contents

1. Introduction	1
1.1 Problem Solving as Search	2
1.1.1 Microscopic Dynamical System Models	4
1.1.2 Fitness Landscapes	4
1.1.3 Component Analysis	6
1.1.4 Schema Theories	7
1.1.5 No Free Lunch Theorems	8
1.2 What is Genetic Programming?	9
1.2.1 Tree-based Genetic Programming	10
1.2.2 Modular and Multiple Tree Genetic Programming	11
1.2.3 Linear Genetic Programming	13
1.2.4 Graphical Genetic Programming	14
1.3 Outline of the Book	15
2. Fitness Landscapes	17
2.1 Exhaustive Search	17
2.2 Hill Climbing	17
2.3 Fitness Landscapes as Models of Problem Difficulty	19
2.4 An Example GP Fitness Landscape	20
2.5 Other Search Strategies	21
2.6 Difficulties with the Fitness Landscape Metaphor	23
2.7 Effect of Representation Changes	25
2.8 Summary	26
3. Program Component Schema Theories	27
3.1 Price's Selection and Covariance Theorem	28
3.1.1 Proof of Price's Theorem	29
3.1.2 Price's Theorem for Genetic Algorithms	31
3.1.3 Price's Theorem with Tournament Selection	31
3.1.4 Applicability of Price's Theorem to GAs and GPs	32
3.2 Genetic Algorithm Schemata	33
3.3 From GA Schemata to GP Schemata	35
3.4 Koza's Genetic Programming Schemata	38
3.5 Altenberg's GP Schema Theory	39

3.6	O'Reilly's Genetic Programming Schemata	43
3.7	Whigham's Genetic Programming Schemata	45
3.8	Summary	46
4.	Pessimistic GP Schema Theories	49
4.1	Rosca's Rooted Tree Schemata	49
4.2	Fixed-Size-and-Shape Schemata in GP	51
4.3	Point Mutation and One-Point Crossover in GP	56
4.4	Disruption-Survival GP Schema Theorem	60
4.4.1	Effect of Fitness Proportionate Selection	60
4.4.2	Effect of One-Point Crossover	61
4.4.3	Effect of Point Mutation	65
4.4.4	GP Fixed-size-and-shape Schema Theorem	65
4.4.5	Discussion	66
4.4.6	Early Stages of a GP Run	66
4.4.7	Late Stages of a GP Run	67
4.4.8	Interpretation	68
4.5	Summary	68
5.	Exact GP Schema Theorems	69
5.1	Criticisms of Schema Theorems	69
5.2	The Role of Schema Creation	71
5.3	Stephens and Waelbroeck's GA Schema Theory	73
5.4	GP Hyperschema Theory	74
5.4.1	Theory for Programs of Fixed Size and Shape	74
5.4.2	Hyperschemata	77
5.4.3	Microscopic Exact GP Schema Theorem	77
5.4.4	Macroscopic Schema Theorem with Schema Creation ..	80
5.4.5	Macroscopic Exact GP Schema Theorem	82
5.5	Examples	83
5.5.1	Linear Trees	83
5.5.2	Comparison of Bounds by Different Schema Theorems ..	87
5.5.3	Example of Schema Equation for Binary Trees	89
5.6	Exact Macroscopic Schema Theorem for GP with Standard Crossover	89
5.6.1	Cartesian Node Reference Systems	90
5.6.2	Variable Arity Hyperschema	91
5.6.3	Macroscopic Exact Schema Theorem for GP with Standard Crossover	92
5.7	Summary	95
6.	Lessons from the GP Schema Theory	97
6.1	Effective Fitness	97
6.1.1	Goldberg's Operator-Adjusted Fitness in GAs	97
6.1.2	Nordin and Banzhaf's Effective Fitness in GP	98

6.1.3	Stevens and Waelbroeck’s Effective Fitness in GAs . . .	99
6.1.4	Exact Effective Fitness for GP	100
6.1.5	Understanding GP Phenomena with Effective Fitness .	100
6.2	Operator Biases and Linkage Disequilibrium for Shapes	105
6.3	Building Blocks in GAs and GP	107
6.4	Practical Ideas Inspired by Schema Theories	109
6.5	Convergence, Population Sizing, GP Hardness and Deception	110
6.6	Summary	111
7.	The Genetic Programming Search Space	113
7.1	Experimental Exploration of GP Search Spaces	113
7.2	Boolean Program Spaces	114
7.2.1	NAND Program Spaces	114
7.2.2	Three-Input Boolean Program Spaces	119
7.2.3	Six-Input Boolean Program Spaces	119
7.2.4	Full Trees	123
7.3	Symbolic Regression	123
7.3.1	Sextic Polynomial Fitness Function	124
7.3.2	Sextic Polynomial Fitness Distribution	124
7.4	Side Effects, Iteration, Mixed Arity: Artificial Ant	124
7.5	Less Formal Extensions	127
7.5.1	Automatically Defined Function	127
7.5.2	Memory	128
7.5.3	Turing-Complete Programs	128
7.6	Tree Depth	129
7.7	Discussion	130
7.7.1	Random Trees	130
7.7.2	Genetic Programming and Random Search	131
7.7.3	Searching Large Programs	131
7.7.4	Implications for GP	131
7.8	Conclusions	132
8.	The GP Search Space: Theoretical Analysis	133
8.1	Long Random Linear Programs	133
8.1.1	An Illustrative Example	135
8.1.2	Rate of Convergence and the Threshold	136
8.1.3	Random Functions	138
8.1.4	The Chance of Finding a Solution	139
8.2	Big Random Tree Programs	139
8.2.1	Setting up the Proof for Trees	139
8.2.2	Large Binary Trees	142
8.2.3	An Illustrative Example	143
8.2.4	The Chance of Finding a Solution	144
8.2.5	A Second Illustrative Example	144
8.3	XOR Program Spaces	145

8.3.1	Parity Program Spaces	145
8.3.2	The Number of Parity Solutions	146
8.3.3	Parity Problems Landscapes and Building Blocks	148
8.4	Conclusions	150
9.	Example I: The Artificial Ant	151
9.1	The Artificial Ant Problem	151
9.2	Size of Program and Solution Space	154
9.3	Solution of the Ant Problem	157
9.3.1	Uniform Random Search	157
9.3.2	Ramped Half-and-Half Random Search	157
9.3.3	Comparison with Other Methods	158
9.4	Fitness Landscape	158
9.5	Fixed Schema Analysis	159
9.5.1	Competition Between Programs of Different Sizes	160
9.5.2	Competition Between Programs of Size 11	162
9.5.3	Competition Between Programs of Size 12	163
9.5.4	Competition Between Programs of Size 13	164
9.6	The Solutions	167
9.7	Discussion	168
9.8	Reducing Deception	170
9.9	Conclusions	171
10.	Example II: The Max Problem	175
10.1	The MAX Problem	176
10.2	GP Parameters	176
10.3	Results	176
10.3.1	Impact of Depth Restriction on Crossover	178
10.3.2	Trapping by Suboptimal Solutions	178
10.3.3	Modelling the Rate of Improvement	179
10.3.4	Number of Steps to Climb the Hill	182
10.4	Variety	183
10.4.1	Variety in the Initial Population	183
10.4.2	Evolution of Variety	184
10.4.3	Modelling Variety	185
10.5	Selection Pressure	186
10.6	Applying Price's Covariance and Selection Theorem	189
10.7	Conclusions	192
11.	GP Convergence and Bloat	193
11.1	Convergence	193
11.2	Bloat	197
11.2.1	Examples of Bloat	198
11.2.2	Convergence of Phenotype	198
11.2.3	Theories of Bloat	199

11.2.4 Fitness Variation is Needed for Bloat	201
11.3 Subquadratic Bloat	202
11.3.1 Evolution of Program Shapes	203
11.3.2 Experiments	206
11.3.3 Results	207
11.3.4 Convergence	211
11.4 Depth and Size Limits	211
11.5 Discussion	212
11.6 AntiBloat Techniques	214
11.7 Conclusions	216
12. Conclusions	219
A. Genetic Programming Resources	223
Bibliography	225
List of Special Symbols	241
Glossary	247
Index	255