

## Appendix A: Functions and Terminals

Table A.1 shows the name and a reference for functions and terminals (i.e., functions of arity 0) used in this book.

**Table A.1** Functions and terminals

Name	Arity	Full name	Section in this book
+	2	Numeric addition	2.2.1
−	2	Numeric subtraction	2.2.1
*	2	Numeric multiplication	2.2.1
%	2	Protected numeric division	2.2.1
>	2	Greater-than comparative function	7.2.1
<	2	Less-than comparative function	7.2.1
2N3904	0	2N3904 transistor model	10.5.1.4
2N3906	0	2N3906 transistor model	10.5.1.4
ABS_SIGNAL	1	Insert an absolute value block into a controller	3.5.1
ADD_3_SIGNAL	3	Insert a 3-input addition block into a controller	3.5.1
ADD_SIGNAL	2	Insert an addition block into a controller	3.5.1
ADF	Variable	Automatically defined function	3.5.4
AH	0	Connect to Åström-Hägglund controller	13.1.2
B_C_E, ..., E_C_B	0	Transistor lead permutation terminals	10.5.1.4
BIFURCATE_POSITIVE	0	Bifurcate positive end of wire in inserting transistor	10.5.1.4

(Continued)

**Table A.1** (Continued)

Name	Arity	Full name	Section in this book
BIFURCATE_NEGATIVE	0	Bifurcate negative end of wire in inserting transistor	10.5.1.4
C	2	Capacitor-inserting function	4.2.1.3
C-LAYOUT	2	Geographically-aware capacitor-inserting function	5.2.1.3
C_NEW	1	Create a capacitor	4.7.1.3
C00002	0	Concentration of cofactor ATP	8.5.3
C00116	0	Concentration of glycerol	8.5.3
C00162	0	Concentration of fatty acid	8.5.3
C00165	0	Concentration of diacyl-glycerol	8.5.3
CAP_LEVEL	0	Represents gene expression level in a genetic network	7.3.3
CONSTANT_0	0	Connect to time-domain signal with constant 0 value	3.5.2
CONTROLLER_OUTPUT	0	Connect to a controller's output	3.5.2
CR_1_1	4	1-substrate, 1-product reactor block	8.4.1.1
CR_1_2	5	1-substrate, 2-product reactor block	8.4.1.1
CR_2_1	5	2-substrate, 1-product reactor block	8.4.1.1
CR_2_2	6	2-substrate, 2-product reactor block	8.4.1.1
DELAY	1	Insert a delay block into a controller	3.5.1
DIFFERENTIAL_INPUT_INTEGRATOR	2	Insert a differential input integrator block into a controller	3.5.1
DIFFERENTIATOR	1	Insert a differentiator block into a controller	3.5.1
DIV_NUMERIC	2	Protected numeric division for controllers	9.1.1.3
DIV_SIGNAL	2	Insert a division block into a controller	3.5.1
DOWN_OR_RIGHT	0	Parallel-divide down or right	10.1.2
DRAW	2	Drawing turtle function	6.3.1
END	0	Development-ending function	4.2.1.4
F	0	Free variable representing passband boundary	10.3.1.3
F1	0	Free variable representing passband boundary	11.1.1.3

(Continued)

**Table A.1** (Continued)

Name	Arity	Full name	Section in this book
F2	0	Free variable representing stopband boundary	11.1.1.3
FIRST_PRODUCT	1	Selects the first product produced by a chemical reaction	8.4.1.1
FLIP	1	Flip (polarity-reversing) function	4.2.1.3
GAIN	2	Insert a gain block into a controller	3.5.1
GLUCOSE_LEVEL	0	Represents glucose level in a genetic network	7.3.3
HFA3046	0	HFA3046 transistor model	15.3.3
HFA3128	0	HFA3128 transistor model	15.3.3
IF	3	If operator	7.2.1
IF_POSITIVE	3	Insert an if-positive block into a controller	3.5.1
IFGTZ_DEVELOPMENTAL	3	If greater than zero developmental operator	11.1
INPUT_0	2	Connect to a circuit's input	4.7.1.1
INTEGRATOR	1	Insert an integrator block into a controller	3.5.1
INT1, INT2, INT3	0	Intermediate substance terminals	8.5.3
INVERTER	1	Insert an inverter block into a controller	3.5.1
IRF511	0	IRF511 transistor model	15.3.3
IRF9230	0	IRF9230 transistor model	15.3.3
IRFZ44	0	IRFZ44 transistor model	15.3.3
KU	0	Free variable representing plant's ultimate gain	9.2.1.2
L	0	Free variable representing plant's dead time	9.2.1.2
L	2	Inductor-inserting function	10.3.1.4
L1	0	Free variable representing inductance of a specific inductor	10.1.2.4
L_NEW	1	Create an inductor	4.7.1.3
L-LAYOUT	2	Geographically aware inductor-inserting function	5.2.1.3
LACTOSE_LEVEL	0	Represents lactose level in a genetic circuit	7.3.3
LAG	2	Insert a lag block into a controller	3.5.1
LAG2	3	Insert a second order lag block into a controller	3.5.1
LANDMARK	1	Landmark turtle function	6.3.1
LEAD	2	Insert a lead block into a controller	3.5.1
LEFT_1, ..., LEFT_4	0	Takeoff point reference terminals	13.1.2

(Continued)

**Table A.1** (Continued)

Name	Arity	Full name	Section in this book
LIMITER	3	Insert a limiter block into a controller	3.5.1
LOG_F	0	Free variable representing logarithm of passband boundary for filter	10.5.1.4
MTP50P03HDL	0	MTP50P03HDL transistor model	15.3.3
MULT_SIGNAL	2	Insert a multiplication block into a controller	3.5.1
NODE	2	Connect distant points in a circuit	10.1.1
NOP	1	No-operation function	4.2.1.3
OUTPUT_0	2	Connect to a circuit's output	4.7.1.1
PAIR_CONNECT_0	3	Connects a pair of distant points in a circuit	4.2.1.3
PAIR_CONNECT_1	3	Connects a pair of distant points in a circuit	4.2.1.3
PARALLEL-LAYOUT-LEFT	4	Geographically aware parallel division function	5.2.1.3
PARALLEL-LAYOUT-RIGHT	4	Geographically aware parallel division function	5.2.1.3
PARALLEL0	4	Parallel-division function, version 0	4.2.1.3
PARALLEL1	4	Parallel-division function, version 1	4.2.1.3
PARALLEL_NEW	4	New version of parallel division function	10.1.2
PLANT_OUTPUT	0	Connect to a controller's plant output	3.5.2
POW	2	Power function	12.2.3
PROGN	Variable	Connective function	6.3.1
Q	6	Transistor-inserting function	10.1.5
Q_DIODE_NPN	1	Insert an NPN diode into a circuit	4.4.1.4
Q_DIODE_PNP	1	Insert a PNP diode into a circuit	4.4.1.4
Q_GND_EMIT_NPN	1	Insert an NPN transistor whose emitter is connected to ground	4.4.1.4
Q_GND_EMIT_PNP	1	Insert a PNP transistor whose emitter is connected to ground	4.4.1.4
Q_POS5V_COLL_NPN	1	Insert an NPN transistor whose collector is connected to a 5 V power supply	4.4.1.4
Q_POS5V_EMIT_PNP	1	Insert a PNP transistor whose emitter is connected to a 5 V power supply	4.4.1.4
Q_THREE_NPN0 , ... , Q_THREE_NPN11	3	Insert an NPN transistor into a circuit	4.4.1.4

(Continued)

**Table A.1** (Continued)

Name	Arity	Full name	Section in this book
Q_THREE_PNP0, ..., Q_THREE_PNP11	3	Insert a PNP transistor into a circuit	4.4.1.4
R	2	Resistor-inserting function	4.2.1.3
R1	0	Free variable representing inductance of a specific resistor	10.1.2.4
$\mathfrak{R}$	0	Random floating-point constants in specified range	3.5.5.1
$\mathfrak{R}_{\text{integer}}$	0	Random integer constants between 0 and 99	6.3.2
$\mathfrak{R}_p$	0	Random perturbable floating-point value in specified range	3.5.5.2
$\mathfrak{R}_{\text{real}}$	0	Random floating-point constants between 0.0 and 1.0	6.3.2
R_NEW	1	Create a resistor	4.7.1.3
REFERENCE_SIGNAL	0	Connect to a controller's reference signal	3.5.2
REPEAT	2	Repeat turtle function	6.3.1
REPRESSOR_LEVEL	0	Represents repressor level in a genetic network	7.3.3
RETAINING_		Connect to ground	4.3.1.4
THREE_GROUND0	3		
RETAINING_		Connect to ground	4.3.1.4
THREE_GROUND1	3		
RETAINING_		Connect to 5 V power supply	4.4.1.4
THREE_POS5V_0	3		
RETAINING_		Connect to 5 V power supply	4.4.1.4
THREE_POS5V_0	3		
REXP	1	Protected exponential function	9.2.1.3
RIGHT_1, ..., RIGHT_4	0	Takeoff point reference terminals	13.1.2
RLOG	1	Protected natural logarithm function	9.2.1.3
SAFE_CUT	0	Safe-cut developmental function	4.2.1.4
SECOND_PRODUCT	1	Selects the second product produced by a chemical reaction	8.4.1.1
SERIES	3	Series division function	4.2.1.3
SERIES-LAYOUT	3	Geographically aware series division function	5.2.1.3
SIN_THETA	0	Free variable representing sine of a filter's modular angle	10.2.1.4
SUB_SIGNAL	2	Insert a subtraction block into a controller	3.5.1
TAKEOFF	1	New takeoff point function	13.1.1
TARGET	0	Free variable representing identity of target circuit (for squaring/cubing problem and 40/60 dB amplifier problem)	11.3.1.4
TAU	0	Free variable representing plant's time constant	9.1.1.2

(Continued)

**Table A.1** (Continued)

Name	Arity	Full name	Section in this book
THREE_GROUND	3	Three-argument connection to ground	10.2.1.3
TU	0	Free variable representing plant's ultimate period	9.2.1.2
TURN-RIGHT	1	Turn right turtle function	6.3.1
TR	0	Free variable representing plant's rise time	9.2.1.2
TWO_GROUND	2	Two-argument connection to ground	10.2.1.3
TWO_LEAD	3	Two-leaded-component-inserting function	10.1.4
TWO_NEG15V	2	-15 Volt reference voltage source function	11.3.1.3
TWO_POS1V	2	+1 Volt reference voltage source function	11.3.1.3
TWO_POS2V	2	+2 Volt reference voltage source function	11.3.1.3
TWO_POS5V	2	+5 Volt reference voltage source function	11.3.1.3
TWO_POS15V	2	+15 Volt reference voltage source function	11.3.1.3
UP_OR_LEFT	0	Parallel-divide up or left	10.1.2
VIA-TO-GROUND-NEG-LEFT-LAYOUT	3	Geographically aware via to ground function	5.2.1.3
VIA-TO-GROUND-NEG-RIGHT-LAYOUT	3	Geographically aware via to ground function	5.2.1.3
VIA-TO-GROUND-POS-T-LAYOUT	3	Geographically aware via to ground function	5.2.1.3
VIA-TO-GROUND-POS-RIGHT-LAYOUT	3	Geographically aware via to ground function	5.2.1.3
X	0	Represents value on the X-axis for symbolic regression problems	2.2.1

## Appendix B: Control Parameters

Broadly speaking, we have used substantially the same (almost certainly non-optimal) choices of control parameters from problem to problem over a period of years. Although particular problems in this book could possibly be solved more efficiently by means of a different choice of control parameters, we believe that our policy of substantial consistency in the choice of control parameters helps the reader eliminate superficial concerns that the demonstrated success of genetic programming depends on shrewd or fortuitous choices of the control parameters. That is, the results produced by genetic programming are not the fruit of intricate and astute tailoring of control parameters to a particular problem.

This book continues the policy of *Genetic Programming* (Koza 1992a), *Genetic Programming II* (Koza 1994a), and *Genetic Programming III* (Koza, Bennett, Andre, and Keane 1999a) of using a fixed set of default values for most of the minor control parameters throughout the book. Thus, unless otherwise indicated for a specific problem, the values of all control parameters for all problems in this book are the values specified in *Genetic Programming III* (Koza, Bennett, Andre, and Keane 1999a).

In addition to the values of the control parameters inherited from *Genetic Programming III*, tables B.1 and B.2 present the percentages of genetic operations that are used on or before and after generation 5 of runs of the 10 problems in this book employing the architecture-altering operations. Tables B.3 and B.4 present this information for seven additional problems employing the architecture-altering operations. B.5 presents this information for all the remaining problems. Because the architecture-altering operations were not used on any of the problems in table B.5, one table of percentages is applicable to all generations.

Table B.6 shows the migration strategy (A, B, or C) used for the 41 runs in this book employing a parallel computer system. Strategy A is described in section 17.1.1 and strategies B and C are described in section 17.1.2.

The information in these tables can be summarized as follows: Not noteworthy. Many of the differences simply reflect adjustments necessary to accommodate the presence or absence of the architecture-altering operations. Other differences (such as the migration strategy) arise from some another choice (e.g., the computer system or the population size). Most of the other differences reflect the chronology of our work and the evolution of our thinking on how to maximize the efficiency runs of genetic programming in general (as opposed to any special exigency of a particular problem). At least one of the differences (where the column does not add up to 100%) reflects a typographical error made during programming.

**Table B.1** Percentages of operations before generation 5 for 10 problems

	Two-lag plant (section 3.7)	Three-lag plant (section 3.8)	Three-lag plant with five-second delay (section 3.9), non-minimal phase plant (section 3.10), and three-lag plant with a free variable (section 9.1)	Controller for two families of plants (section 9.2)	RC circuit with gain greater than two (section 4.2), Philbrick circuit (section 4.3)	ALU circuit (section 4.5)	Amplifier with layout (section 5.3)
Crossover on internal points	68%	0%	0%	0%	0%	0%	0%
Crossover on terminals	10%	0%	0%	0%	0%	0%	0%
Crossover on non-numeric internal points	0%	45%	45%	46%	50%	50%	50%
Crossover on non-numeric terminals	0%	9%	9%	9%	10%	10%	10%
Crossover on numeric terminals	0%	5%	5%	9%	10%	10%	10%
Reproduction	10%	9%	9%	9%	9%	9%	9%
Subtree mutation	1%	1%	1%	1%	1%	1%	1%
Numeric constant mutation	0%	20%	20%	20%	20%	20%	20%
Subroutine duplication	5%	5%	5%	2%	0%	0%	0%
Argument duplication	0%	0%	0%	0%	0%	0%	0%



Subroutine deletion	1%	1%	2%	0%	0%	0%
Argument deletion	0%	0%	0%	0%	0%	0%
Subroutine creation	5%	5%	2%	0%	0%	0%
Argument creation	0%	0%	0%	0%	0%	0%
Iteration creation	0%	0%	0%	0%	0%	0%
Loop creation	0%	0%	0%	0%	0%	0%
Recursion creation	0%	0%	0%	0%	0%	0%
Storage creation	0%	0%	0%	0%	0%	0%
Max. points for RPB	150	150	150	800	300	300
Max. points for ADF	100	100	100	NA	NA	NA

**Table B.2** Percentages of operations after generation 5 for 10 problems

	Two-lag plant (section 3.7)	Three-lag plant (section 3.8)	Three-lag plant with five-second delay (section 3.9), non-minimal phase plant (section 3.10), and three-lag plant with a free variable (section 9.1)	Controller for two families of plants (section 9.2)	RC circuit with gain greater than two (section 4.2), Philbrick circuit (section 4.3)	ALU circuit (section 4.5)	Amplifier with layout (section 5.3)
Crossover on internal points	76%	0%	0%	0%	0%	0%	0%
Crossover on terminals	10%	0%	0%	0%	0%	0%	0%
Crossover on non-numeric internal points	0%	47%	49%	46%	50%	50%	50%
Crossover on non-numeric terminals	0%	9%	9%	9%	10%	10%	10%
Crossover on numeric terminals	0%	9%	9%	9%	10%	10%	10%
Reproduction	10%	9%	9%	9%	9%	9%	9%
Subtree mutation	1%	1%	1%	1%	1%	1%	1%
Numeric constant mutation	0%	20%	20%	20%	20%	20%	20%
Subroutine duplication	1%	1%	1%	2%	0%	0%	0%
Argument duplication	0%	0%	0%	0%	0%	0%	0%

Subroutine deletion	1%	1%	1%	2%	0%	0%	0%
Argument deletion	0%	0%	0%	0%	0%	0%	0%
Subroutine creation	1%	1%	2%	0%	0%	0%	0%
Argument creation	0%	0%	0%	0%	0%	0%	0%
Iteration creation	0%	0%	0%	0%	0%	0%	0%
Loop creation	0%	0%	0%	0%	0%	0%	0%
Recursion creation	0%	0%	0%	0%	0%	0%	0%
Storage creation	0%	0%	0%	0%	0%	0%	0%
Max. points for RPB	150	150	150	150	800	300	300
Max. points for ADF	100	100	100	100	NA	NA	NA

Table B.3 Percentages of operations before generation 5 for seven problems

	Analog NAND circuit (section 4.4)	Lowpass filter with layout (section 5.2)	Square root computational circuit (section 4.6)	Passive lowpass filter with variable passband boundary (section 10.4)	Lowpass/highpass filter with free variables (section 11.1).	Lowpass/highpass filter with variable passband boundary with a free variable (section 11.2)	Yagi-Uda antennas problem (section 6.5)
Crossover on internal points	79%	79%	0%	0%	0%	60%	
Crossover on terminals	10%	10%	0%	0%	0%	10%	
Crossover on non-numeric internal points	0%	0%	60%	49%	49%	0%	
Crossover on non-numeric terminals	0%	0%	10%	10%	10%	0%	
Crossover on numeric terminals	0%	0%	0%	0%	0%	0%	
Reproduction	10%	10%	9%	9%	9%	9%	
Subtree mutation	1%	1%	1%	1%	1%	1%	
Numeric constant mutation	0%	0%	20%	20%	20%	20%	
Subroutine duplication	0%	0%	0%	5%	5%	0%	
Argument duplication	0%	0%	0%	0%	0%	0%	

Subroutine deletion	0%	0%	1%	1%	0%	1%	0%
Argument deletion	0%	0%	0%	0%	0%	0%	0%
Subroutine creation	0%	0%	5%	5%	0%	5%	0%
Argument creation	0%	0%	0%	0%	0%	0%	0%
Iteration creation	0%	0%	0%	0%	0%	0%	0%
Loop creation	0%	0%	0%	0%	0%	0%	0%
Recursion creation	0%	0%	0%	0%	0%	0%	0%
Storage creation	0%	0%	0%	0%	0%	0%	0%
Max. points for RPB	300	600	600	300	500	300	500
Max. points for ADF	NA	NA	NA	100	NA	100	NA

**Table B.4** Percentages of operations after generation 5 for seven problems

	Analog NAND circuit (section 4.4)	Lowpass filter with layout (section 5.2)	Square root computational circuit (section 4.6)	Passive lowpass filter with variable passband boundary (section 10.4)	Lowpass/highpass filter with free variables (section 11.1), Lowpass/highpass filter with variable passband boundary with a free variable (section 11.2)	Yagi-Uda antennas problem (section 6.5)
Crossover on internal points	79%	79%	0%	0%	0%	60%
Crossover on terminals	10%	10%	0%	0%	0%	10%
Crossover on non-numeric internal points	0%	0%	60%	57%	57.50%	0%
Crossover on non-numeric terminals	0%	0%	10%	10%	10%	0%
Crossover on numeric terminals	0%	0%	0%	0%	0%	0%
Reproduction	10%	10%	9%	9%	9%	9%
Subtree mutation	1%	1%	1%	1%	1%	1%
Numeric constant mutation	0%	0%	20%	20%	20%	20%
Subroutine duplication	0%	0%	0%	1%	1%	0%
Argument duplication	0%	0%	0%	0%	0%	0%

Subroutine deletion	0%	0%	0%	1%	0.50%	0%
Argument deletion	0%	0%	0%	0%	0%	0%
Subroutine creation	0%	0%	1%	0%	1%	0%
Argument creation	0%	0%	0%	0%	0%	0%
Iteration creation	0%	0%	0%	0%	0%	0%
Loop creation	0%	0%	0%	0%	0%	0%
Recursion creation	0%	0%	0%	0%	0%	0%
Storage creation	0%	0%	0%	0%	0%	0%
Max. points for RPB	300	600	500	300	??	500
Max. points for ADF	NA	NA	NA	100	??	NA

**Table B.5** Percentages of operations for the problems not using the architecture-altering operations

	Genetic network for <i>lac</i> operon (chapter 7)	Metabolic pathway for phospholipid cycle (section 8.6), Metabolic pathway for ketone bodies (section 8.7)	Lowpass filter without an explicit test fixture (section 4.7), Zobel network problem (two free variables (section 10.2), Third-order elliptic lowpass filter with variable modular angle (section 10.3), Active lowpass filter with variable passband boundary with free variable (section 10.5), Variable Quadratic/ cubic computational circuit (section 11.3), Variable 40–60 dB amplifier (section 11.4), Improved PID tuning rules (four freevariables) (section 12.3), all three runs of non-PID parameterized controller (with four free variables), Problem of reducing amplifier distortion by means of negative feedback (section 14.2), all 11 runs of the six problems involving post-2000 patented inventions in chapter 15
Crossover on internal points	63%	58.50%	63%
Crossover on terminals	7%	6.50%	7%
Crossover on non- numeric internal points	0%	0%	0%
Crossover on non- numeric terminals	0%	0%	0%
Crossover on numeric terminals	0%	0%	0%
Reproduction	9%	9%	9%
Subtree mutation	1%	1%	1%
Numeric constant mutation	20%	20%	20%
Subroutine duplication	0%	0%	0%
Argument duplication	0%	0%	0%
Subroutine deletion	0%	0%	0%
Argument deletion	0%	0%	0%
Subroutine creation	0%	0%	0%
Argument creation	0%	0%	0%
Iteration creation	0%	0%	0%
Loop creation	0%	0%	0%
Recursion creation	0%	0%	0%
Storage creation	0%	0%	0%
Max. points for RPB	1,000	500	500
Max. points for ADF	NA	NA	NA



**Table B.6** Migration strategy used on the 41 runs

Migration strategy	Problems
A	Two-lag plant (section 3.7), Three-lag plant (section 3.8), Non-minimal phase plant (section 3.10), RC circuit with gain greater than two (section 4.2), Philbrick circuit (section 4.3), NAND circuit (section 4.4), Arithmetic logic unit (ALU) circuit (section 4.5), Layout of lowpass filter (section 5.2)
B	Three-lag plant with five second delay (section 3.9), Lowpass/highpass filter with free variable (section 11.1), Lowpass/highpass filter with variable passband boundary with a free variable (section 11.2)
C	Three-lag plant with free variable (section 9.1), Controller for two families of plants (section 9.2), Square root computational circuit (section 4.6), Lowpass filter without an explicit test fixture (section 4.7), Layout of amplifier (section 5.3), Yagi-Uda antenna (section 6.5), Metabolic pathway for phospholipid (section 8.6), Metabolic pathway for ketone bodies (section 8.7), Zobel network problem (two free variables) (section 10.2), Third-order elliptic lowpass filter with variable modular angle (section 10.3), Passive lowpass filter with variable passband boundary (section 10.4), Active lowpass filter with variable passband boundary with free variable (section 10.5), Variable Quadratic/cubic computational circuit (section 11.3), Variable 40–60 dB amplifier (section 11.4), Improved PID tuning rules (four free variables) (section 12.3), First non-PID parameterized controller (two free variables) (section 13.2.1), Second non-PID parameterized controller (two free variables) (section 13.2.2), Third non-PID parameterized controller (two free variables) (section 13.2.3), Negative feedback (section 14.2), Low-voltage balun circuit (section 15.4.1), Mixed analog-digital variable capacitor circuit (section 15.4.2), High-current load circuit (sections 15.4.3.1 and 15.4.3.2), Voltage–current conversion circuit (section 15.4.4), Cubic function generator (sections 15.4.5 and 15.4.5), Tunable integrated active filter (sections 15.4.6.1, 15.4.6.2, 15.4.6.3, and 15.4.6.4)

The current published literature in the fields of genetic algorithms and genetic programming provides a considerable amount of conflicting advice on the topic of choosing control parameters. Moreover, it is rarely clear how one should go about translating a problem’s high-level statement in English into particular choices of control parameters. Thus, it is not clear how a user of genetic programming would go about shrewdly or optimally tailoring the control parameters for a particular problem even if that were the intent. Of course, if one has sufficient understanding of the dynamics of the evolutionary process and sufficient insight concerning the fitness landscape of an unseen new problem, there is nothing wrong with doing such tailoring if the primary objective is to solve the particular problem at hand.

## Appendix C: Patented or Patentable Inventions Generated by Genetic Programming

Tables C.1 and C.2 provide additional information on the 23 patent-related results (of the 36 human-competitive results produced by genetic programming in table 1.3).

Table C.1 provides additional information on the 21 results that relate to previously patented inventions. Eleven of the 21 results in table C.1 infringe previously issued patents and 10 duplicate the functionality of previously patented inventions in a non-infringing way. The first 10 entries in table C.1 refer to problems that were solved in *Genetic Programming III: Darwinian Invention and Problem Solving* (Koza, Bennett, Andre, and Keane 1999a). The last 11 entries in table C.1 are described in this book. The last six entries in table C.1 relate to patents for analog circuits that were issued after January 1, 2000.

Four of the 21 entries in the body of table C.1 are marked “See text.” These entries relate to groups of previously patented inventions (as opposed to single patents) that are described in detail in *Genetic Programming III: Darwinian Invention and Problem Solving* (Koza, Bennett, Andre, and Keane 1999a). Concerning computational circuits (the 7<sup>th</sup> entry in table C.1), dozens of different computational circuits have been patented, including, for example, square root circuits (Newbold 1962) and logarithmic circuits (Green 1958). Concerning electronic thermometers (the 8<sup>th</sup> entry in table C.1), at least two dozen temperature-sensing circuits have been patented, including, for example, ones by Haeusler (1976) and Massey (1970). Concerning voltage reference circuits (the 9<sup>th</sup> entry in table C.1), Robert C. Dobkin and Robert J. Widlar of National Semiconductor Corporation received U.S. patent 3,617,859 for the voltage reference circuit (Dobkin and Widlar 1971). Subsequent to the renowned Dobkin-Widlar circuit, other patents have been issued for voltage reference circuits, including U.S. patent 3,743,923 to Goetz Wolfgang Steudel of RCA Corporation (Steudel 1973). Hundreds of patents have been issued for amplifiers (the 10<sup>th</sup> entry in table C.1).

Table C.2 shows the two inventions generated by genetic programming for which a patent application has been filed.

**Table C.1** Twenty-one previously patented inventions reinvented by genetic programming

Invention	Date	Inventor	Place	Patent	Reference
1 Darlington emitter-follower section	1953	Sidney Darlington	Bell Telephone Laboratories	2,663,806	Section 42.3 of <i>Genetic Programming III</i>
2 Ladder filter	1917	George Campbell	American Telephone and Telegraph	1,227,113	Section 25.15.1 of <i>Genetic Programming III</i> and section 5.2 of this book
3 Crossover filter	1925	Otto Julius Zobel	American Telephone and Telegraph	1,538,964	Section 32.3 of <i>Genetic Programming III</i>
4 “ <i>M</i> -derived half section” filter	1925	Otto Julius Zobel	American Telephone and Telegraph	1,538,964	Section 25.15.2 of <i>Genetic Programming III</i>
5 Cauer (elliptic) topology for filters	1934 – 1936	Wilhelm Cauer	University of Gottingen	1,958,742, 1,989,545	Section 27.3.7 of <i>Genetic Programming III</i>
6 Sorting network	1962	Daniel G. O’Connor and Raymond J. Nelson	General Precision, Inc.	3,029,413	Sections 21.4.4, 23.6, and 57.8.1 of <i>Genetic Programming III</i>
7 Computational circuits	See text	See text	See text	See text	Section 47.5.3 of <i>Genetic Programming III</i>
8 Electronic thermometer	See text	See text	See text	See text	Section 49.3 of <i>Genetic Programming III</i>
9 Voltage reference circuit	See text	See text	See text	See text	Section 50.3 of <i>Genetic Programming III</i>
10 60 and 96 dB amplifiers	See text	See text	See text	See text	Section 45.3 of <i>Genetic Programming III</i>
11 Second-derivative controller	1942	Harry Jones	Brown Instrument Company	2,282,726	Section 3.7 of this book
12 Philbrick circuit	1956	George Philbrick	George A. Philbrick Researches	2,730,679	Section 4.3 of this book
13 NAND circuit	1971	David H. Chung and Bill H. Terrell	Texas Instruments Incorporated	3,560,760	Section 4.4 of this book
14 PID (proportional, integrative, and derivative) controller	1939	Albert Callender and Allan Stevenson	Imperial Chemical Limited	2,175,985	Section 9.2 of this book

(Continued)

**Table C.1** (Continued)

Invention	Date	Inventor	Place	Patent	Reference
15 Negative feedback	1937	Harold S. Black	American Telephone and Telegraph	2,102,670, 2,102,671	Chapter 14 of this book
16 Low-voltage balun circuit	2001	Sang Gug Lee	Information and Communications University	6,265,908	Section 15.4.1 of this book
17 Mixed analog-digital variable capacitor circuit	2000	Turgut Sefket Aytur	Lucent Technologies Inc.	6,013,958	Section 15.4.2 of this book
18 High-current load circuit	2001	Timothy Daun-Lindberg and Michael Miller	International Business Machines Corporation	6,211,726	Section 15.4.3 of this book
19 Voltage-current conversion circuit	2000	Akira Ikeuchi and Naoshi Tokuda	Mitsumi Electric Co., Ltd.	6,166,529	Section 15.4.4 of this book
20 Cubic function generator	2000	Stefano Cipriani and Anthony A. Takeshian	Conexant Systems, Inc.	6,160,427	Section 15.4.5 of this book
21 Tunable integrated active filter	2001	Robert Irvine and Bernd Kolb	Infineon Technologies AG	6,225,859	Section 15.4.6 of this book

**Table C.2** Two patentable inventions created by genetic programming

Claimed invention	Date of patent application	Inventors	Reference
1 Improved general-purpose tuning rules for a PID controller	July 12, 2002	Martin A. Keane, John R. Koza, and Matthew J. Streeter	Section 12.3 of this book
2 Improved general-purpose non-PID controllers	July 12, 2002	Martin A. Keane, John R. Koza, and Matthew J. Streeter	Section 13.2 of this book

# Bibliography

- Aarts, Emile and Korst, Jan. 1989. *Simulated Annealing and Boltzmann Machines*. Chichester: John Wiley and Sons.
- Aaserud, O. and Nielsen, I. Ring. 1995. Trends in current analog design: A panel debate. *Analog Integrated Circuits and Signal-Processing*. 7(1)5–9.
- Abelson, Harold and diSessa, Andrea. 1980. *Turtle Geometry*. Cambridge, MA: The MIT Press.
- Altshuler, Edward E. and Linden, Derek S. 1998. *Process for the Design of Antennas Using Genetic Algorithm*. U.S. patent 5,719,794. Applied for on July 19, 1995. Issued on February 17, 1998.
- Altshuler, Edward E. and Linden, Derek S. 1999. Design of wire antennas using genetic algorithms. In Rahmat-Samii, Yahya and Michielssen, Eric (editors). *Electromagnetic Optimization by Genetic Algorithms*. New York, NY: John Wiley and Sons. Chapter 8. Pages 211–248.
- Andersson, Bjorn, Svensson, Per, Nordin, Peter, and Nordahl, Mats. 1999. Reactive and memory-based genetic programming for robot control. In Poli, Riccardo, Nordin, Peter, Langdon, William B., and Fogarty, Terence C. 1999. *Genetic Programming: Second European Workshop. EuroGP'99. Proceedings*. Lecture Notes in Computer Science. Volume 1598. Berlin, Germany: Springer-Verlag. Pages 161–172.
- Andre, David, Bennett III, Forrest H, and Koza, John R. 1996. Discovery by genetic programming of a cellular automata rule that is better than any known rule for the majority classification problem. In Koza, John R., Goldberg, David E., Fogel, David B., and Riolo, Rick L. (editors). 1996. *Genetic Programming 1996: Proceedings of the First Annual Conference, July 28–31, 1996, Stanford University*. Cambridge, MA: MIT Press. Pages 3–11.
- Andre, David and Koza, John R. 1995. Parallel genetic programming on a network of transputers. In Rosca, Justinian (editor). *Proceedings of the Workshop on Genetic Programming: From Theory to Real World Applications*. University of Rochester. National Resource Laboratory for the Study of Brain and Behavior. Technical Report 95-2. June 1995. Pages 111–120.
- Andre, David and Koza, John R. 1996a. Parallel genetic programming: A scalable implementation using the transputer architecture. In Angeline, P. J. and Kinnear, K. E. Jr. (editors). 1996. *Advances in Genetic Programming 2*. Cambridge, MA: The MIT Press.
- Andre, David and Koza, John R. 1996b. A parallel implementation of genetic programming that achieves super-linear performance. In Arabnia, Hamid R. (editor). *Proceedings of the International Conference on Parallel and Distributed Processing Techniques and Applications*. Athens, GA: CSREA. Volume III. Pages 1163–1174.
- Andre, David and Teller, Astro. 1999. Evolving team Darwin United. In Asada, Minoru and Kitano, Hiroaki (editors). *RoboCup-98: Robot Soccer World Cup II*. Lecture Notes in Computer Science. Volume 1604. Berlin: Springer-Verlag. Pages 346–352.

- Angeline, Peter J. and Kinnear, Kenneth E. Jr. (editors). 1996. *Advances in Genetic Programming 2*. Cambridge, MA: The MIT Press.
- Angeline, Peter J. 1997. An alternative to indexed memory for evolving programs with explicit state representations. In Koza, John R., Deb, Kalyanmoy, Dorigo, Marco, Fogel, David B., Garzon, Max, Iba, Hitoshi, and Riolo, Rick L. (editors). *Genetic Programming 1997: Proceedings of the Second Annual Conference, July 13–16, 1997, Stanford University*. San Francisco, CA: Morgan Kaufmann. Pages 423–430.
- Angeline, Peter J. 1998a. Multiple interacting programs: A representation for evolving complex behaviors. *Cybernetics and Systems*. 29(8)779–806.
- Angeline, Peter J. 1998b. Evolving predictors for chaotic time series. In Rogers, S., Fogel, D., Bezdek, J., and Bosacchi, B. (editors). *Proceedings of SPIE (Volume 3390): Application and Science of Computational Intelligence*, Bellingham, WA: The International Society for Optical Engineering. Pages 170–180.
- Angeline, Peter J. and Fogel, David B. 1997. An evolutionary program for the identification of dynamical systems. In Rogers, S. (editor). *Proceedings of SPIE (Volume 3077): Application and Science of Artificial Neural Networks III*. Bellingham, WA: The International Society for Optical Engineering. Pages 409–417.
- Arkin, Adam, Shen, Peidong, and Ross, John. 1997. A test case of correlation metric construction of a reaction pathway from measurements. *Science*. 277. Pages 1275–1279. August 29, 1997.
- Armstrong, Edwin Howard. 1914. *Wireless Receiving System*. U.S. patent 1,113,149. Filed October 29, 1913. Issued October 6, 1914.
- &Arlingström, Karl J. and Hägglund, Tore. 1995. *PID Controllers: Theory, Design, and Tuning*. Second Edition. Research Triangle Park, NC: Instrument Society of America.
- Aytur, Turgut Sefket. 2000. *Integrated Circuit with Variable Capacitor*. U.S. patent 6,013,958. Filed July 23, 1998. Issued January 11, 2000.
- Babanezhad, J. N. and Temes, G. C. 1986. Analog MOS computational circuits. *Proceedings of the IEEE Circuits and System International Symposium*. Piscataway, NJ: IEEE Press. Pages 1156–1160.
- Babovic, Vladan. 1996. *Emergence, Evolution, Intelligence: Hydroinformatics*. Rotterdam, The Netherlands: Balkema Publishers.
- Bagchi, Tapan P. 1999. *Multiobjective Scheduling by Genetic Algorithms*. Boston: Kluwer Academic Publishers.
- Balanis, Constantine A. 1982. *Antenna Theory: Analysis and Design*. New York, NY: John Wiley and Sons.
- Banzhaf, Wolfgang, Daida, Jason, Eiben, A. E., Garzon, Max H., Honavar, Vasant, Jakiela, Mark, and Smith, Robert E. (editors). 1999. *GECCO-99: Proceedings of the Genetic and Evolutionary Computation Conference, July 13–17, 1999, Orlando, Florida USA*. San Francisco, CA: Morgan Kaufmann.
- Banzhaf, Wolfgang, Nordin, Peter, Keller, Robert E., and Francone, Frank D. 1998. *Genetic Programming: An Introduction*. San Francisco, CA: Morgan Kaufmann and Heidelberg: dpunkt.
- Banzhaf, Wolfgang, Nordin, Peter, Keller, Richard, and Olmer, Markus. 1997. Generating adaptive behavior for a real robot using function regression with genetic programming. In Koza, John R., Deb, Kalyanmoy, Dorigo, Marco, Fogel, David B., Garzon, Max, Iba, Hitoshi, and Riolo, Rick L. (editors). *Genetic Programming 1997: Proceedings of the Second Annual Conference, July 13–16, 1997, Stanford University*. San Francisco, CA: Morgan Kaufmann. Pages 35–43.
- Banzhaf, Wolfgang, Poli, Riccardo, Schoenauer, Marc, and Fogarty, Terence C. 1998. *Genetic Programming: First European Workshop. EuroGP'98. Paris, France, April 1998 Proceedings*. Lecture Notes in Computer Science. Volume 1391. Berlin, Germany: Springer-Verlag.

- Barnum, H., Bernstein, H.J. and Spector, Lee. 2000. Quantum circuits for OR and AND of ORs. *Journal of Physics A: Mathematical and General*. 33(45)8047–8057. November 17, 2000.
- Bennett III, Forrest H. and Koza, John R. 2002. *Method and Apparatus for Automatic Synthesis, Placement and Routing of Complex Structures*. U.S. patent 6,424,959. Filed June 17, 1999. Issued July 23, 2002.
- Bennett III, Forrest H, Koza, John R., Andre, David, and Keane, Martin A. 1996. Evolution of a 60 decibel op amp using genetic programming. In Higuchi, Tetsuya, Iwata, Masaya, and Lui, Weixin (editors). *Proceedings of International Conference on Evolvable Systems: From Biology to Hardware (ICES-96)*. Lecture Notes in Computer Science, Volume 1259. Berlin: Springer-Verlag. Pages 455–469.
- Bennett III, Forrest H, Koza, John R., Yu, Jessen, and Mydlowec, William. 2000. Automatic synthesis, placement, and routing of an amplifier circuit by means of genetic programming. In Miller, Julian, Thompson, Adrian, Thomson, Peter, and Fogarty, Terence C. (editors). 2000. *Evolvable Systems: From Biology to Hardware. Third International Conference, ICES 2000, Edinburgh, Scotland, UK, April 2000 Proceedings*. Lecture Notes in Computer Science. Volume 1801. Berlin, Germany: Springer-Verlag. Pages 1–10.
- Bennett III, Forrest H, Koza, John R., Keane, Martin A., Yu, Jessen, Mydlowec, William, and Stiffelman, Oscar. 1999. Evolution by means of genetic programming of analog circuits that perform digital functions. In Banzhaf, Wolfgang, Daida, Jason, Eiben, A. E., Garzon, Max H., Honavar, Vasant, Jakiela, Mark, and Smith, Robert E. (editors). 1999. *GECCO-99: Proceedings of the Genetic and Evolutionary Computation Conference, July 13–17, 1999, Orlando, Florida USA*. San Francisco, CA: Morgan Kaufmann. Pages 1477–1483.
- Bennett III, Forrest H, Koza, John R., Shipman, James, and Stiffelman, Oscar. 1999. Building a parallel computer system for \$18,000 that performs a half peta-flop per day. In Banzhaf, Wolfgang, Daida, Jason, Eiben, A. E., Garzon, Max H., Honavar, Vasant, Jakiela, Mark, and Smith, Robert E. (editors). 1999. *GECCO-99: Proceedings of the Genetic and Evolutionary Computation Conference, July 13–17, 1999, Orlando, Florida USA*. San Francisco, CA: Morgan Kaufmann. Pages 1484–1490.
- Black, Harold S. 1928. *Translating System*. U.S. patent 1,686,792. Filed February 3, 1925. Issued October 9, 1928.
- Black, Harold S. 1935. *Wave Translation System*. U.S. patent 2,003,282. Filed August 8, 1928. Issued June 4, 1935.
- Black, Harold S. 1937a. *Wave Translation System*. U.S. patent 2,102,670. Filed August 8, 1928. Issued December 21, 1937.
- Black, Harold S. 1937b. *Wave Translation System*. U.S. patent 2,102,671. Filed April 22, 1932. Issued December 21, 1937.
- Black, Harold S. 1977. Inventing the negative feedback amplifier. *IEEE Spectrum*. December 1977. Pages 55–60.
- Blickle, Tobias. 1997. *Theory of Evolutionary Algorithms and Application to System Synthesis*. TIK-Schriftenreihe Nr. 17. Zurich, Switzerland: vdf Hochschulverlag AG an der ETH Zuerich.
- Boutin, Noel. 2002. Use time-domain analysis of Zobel network. *EDN*. July 27, 2002. Page 86.
- Bower, James M. and Bolouri, Hamid. 2000. *Computational Modeling of Genetic and Biochemical Networks*. Cambridge, MA: MIT Press.
- Boyd, S. P. and Barratt, C. H. 1991. *Linear Controller Design: Limits of Performance*. Englewood Cliffs, NJ: Prentice Hall.
- Bryson, Arthur E., and Ho, Yu-Chi. 1975. *Applied Optimal Control*. New York: Hemisphere Publishing.
- Burke, Gerald J. 1992. *Numerical Electromagnetics Code—NEC-4: Method of Moments—User’s Manual*. Lawrence Livermore National Laboratory report UCRL-MA-109338. Livermore, CA: Lawrence Livermore National Laboratory.

- Callender, Albert and Stevenson, Allan Brown. 1939. *Automatic Control of Variable Physical Characteristics*. U.S. patent 2,175,985. Filed February 17, 1936 in the United States. Filed February 13, 1935 in Great Britain. Issued October 10, 1939 in the United States.
- Campbell, George A. 1917. *Electric Wave Filter*. Filed July 15, 1915. U.S. patent 1,227,113. Issued May 22, 1917.
- Cantu-Paz, Erick. 2000. *Efficient and Accurate Parallel Genetic Algorithms*. Boston: Kluwer Academic Publishers.
- Cauer, Wilhelm. 1934. *Artificial Network*. U.S. patent 1,958,742. Filed June 8, 1928 in Germany. Filed December 1, 1930 in the United States. Issued May 15, 1934.
- Cauer, Wilhelm. 1935. *Electric Wave Filter*. U.S. patent 1,989,545. Filed June 8, 1928. Filed December 6, 1930 in the United States. Issued January 29, 1935.
- Cauer, Wilhelm. 1936. *Unsymmetrical Electric Wave Filter*. U.S. patent 2,048,426. Filed November 10, 1932 in Germany. Filed November 23, 1933 in the United States. Issued July 21, 1936.
- Chung, David H. and Terrell, Bill H. 1971. *Logic NAND Gate Circuits*. U.S. patent 3,560,760. Filed February 2, 1970. Issued February 2, 1971.
- Cipriani, Stefano and Takeshian, Anthony A. 2000. *Compact Cubic Function Generator*. U.S. patent 6,160,427. Filed September 4, 1998. Issued December 12, 2000.
- Coello Coello, Carlos A., Van Veldhuizen, David A., and Lamont, Gary B. 2002. *Evolutionary Algorithms for Solving Multi-Objective Problems*. Boston: Kluwer Academic Publishers.
- Cohn, John M., Garrod, David J., Rutenbar, Rob A., and Carley, L. Richard. 1994. *Analog Device-Level Layout Automation*. Boston: Kluwer.
- Collado-Vides, Julio and Hofstadt, Ralf. 2002. *Gene Regulation and Metabolism*. Cambridge, MA: The MIT Press.
- Comisky, William, Yu, Jessen, and Koza, John. 2000. Automatic synthesis of a wire antenna using genetic programming. *Late Breaking Papers at the 2000 Genetic and Evolutionary Computation Conference, Las Vegas, Nevada*. Pages 179–186.
- Crawford, L. S., Cheng, V. H. L., and Menon, P. K. 1999. Synthesis of flight vehicle guidance and control laws using genetic search methods. *Proceedings of 1999 Conference on Guidance, Navigation, and Control*. Reston, VA: American Institute of Aeronautics and Astronautics. Paper AIAA-99-4153.
- Darlington, Sidney. 1953. *Semiconductor Signal Translating Device*. U.S. patent 2,663,806. Filed May 9, 1952. Issued December 22, 1953.
- Daun-Lindberg, Timothy Charles and Miller, Michael Lee. 2001. *Low Voltage High-Current Electronic Load*. U.S. patent 6,211,726. Filed June 28, 1999. Issued April 3, 2001.
- Deb, Kalyanmoy. 2001. *Multi-Objective Optimization using Evolutionary Algorithms*. Boston: Kluwer Academic Publishers.
- Dewell, Larry D. and Menon, P. K. 1999. Low-thrust orbit transfer optimization using genetic search. *Proceedings of 1999 Conference on Guidance, Navigation, and Control*. Reston, VA: American Institute of Aeronautics and Astronautics. Paper AIAA-99-4151.
- D'haeseleer, Patrik, Wen, Xiling, Fuhrman, Stefanie, and Somogyi, Roland. 1999. Linear modeling of mRNA expression levels during CNS development and injury. In Altman, Russ B. Dunker, A. Keith, Hunter, Lawrence, Klein, Teri E., and Lauderdale, Kevin (editors). *Pacific Symposium on Biocomputing '99*. Singapore: World Scientific. Pages 41–52.
- Dobkin, Robert C. and Widlar, Robert J. 1971. *Electrical Regulator Apparatus Including a Zero-Temperature Coefficient Voltage Reference Circuit*. U.S. patent 3,617,859. Filed May 23, 1970. Issued November 2, 1971.
- Dorf, Richard C. and Bishop, Robert H. 1998. *Modern Control Systems*. Eighth edition. Menlo Park, CA: Addison-Wesley.
- Drechsler, Rolf. 1998. *Evolutionary Algorithms for VLSI CAD*. Boston: Kluwer Academic Publishers.



- Foster, James A., Lutton, Evelyne, Miller, Julian, Ryan, Conor, and Tettamanzi, Andrea G. B. (editors). 2002. *Genetic Programming: 5<sup>th</sup> European Conference, EuroGP 2002, Kinsale, Ireland, April 2002 Proceedings*. Berlin: Springer-Verlag.
- Garey, Michael R. and Johnson, David S. 1979. *Computers and Intractability: A Guide to the Theory of NP-Completeness*. New York, NY: W. H. Freeman.
- Getreu, Ian. 2002. Productivity tools for analog/mixed-signal designs: Ready for prime time? *Electronic Design*. June 10, 2002. Page 40.
- Gilbert, Barrie. 1968. A precise four-quadrant multiplier with subnanosecond response. *IEEE Journal of Solid-State Circuits*. Volume SC-3. Number 4. December 1968. Pages 365–373.
- Gilbert, Barrie. 1979. *Multiplier Circuit*. U.S. patent 4,156,283. Filed October 3, 1977. Issued May 22, 1979.
- Goddard, Robert. 1915. *Method of and Apparatus for Producing Electrical Impulses or Oscillations*. U.S. patent 1,159,209. Filed August 1, 1912. Issued November 2, 1915.
- Goldberg, David E. 1989. *Genetic Algorithms in Search, Optimization, and Machine Learning*. Reading, MA: Addison-Wesley.
- Goldberg, David E. 1990. A note on Boltzmann tournament selection for genetic algorithms and population-oriented simulated annealing. *Complex Systems*. 4(4)445–460.
- Goldberg, David E. 2002. *The Design of Innovation: Lessons from and for Competent Genetic Algorithms*. Boston: Kluwer Academic Publishers.
- Green, Milton. 1958. *Logarithmic Converter Circuit*. U.S. patent 2,861,182. Filed June 16, 1953. Issued November 18, 1958.
- Grimbleby, J. B. 1995. Automatic analogue network synthesis using genetic algorithms. *Proceedings of the First International Conference on Genetic Algorithms in Engineering Systems: Innovations and Applications (GALESIA)*. London: Institution of Electrical Engineers. Pages 53–58.
- Gruau, Frederic. 1992a. *Cellular Encoding of Genetic Neural Networks*. Technical report 92–21. Laboratoire de l'Informatique du Parallélisme. Ecole Normale Supérieure de Lyon. May 1992.
- Gruau, Frederic. 1992b. Genetic synthesis of Boolean neural networks with a cell rewriting developmental process. In Schaffer, J. D. and Whitley, Darrell (editors). *Proceedings of the Workshop on Combinations of Genetic Algorithms and Neural Networks 1992*. Los Alamitos, CA: The IEEE Computer Society Press.
- Haeusler, Jochen. 1976. *Arrangement for Measuring Temperatures*. U.S. patent 3,943,434. Filed February 6, 1974. Issued March 9, 1976.
- Haupt, Randy L. 1994. Thinned arrays using genetic algorithms. *IEEE Transactions on Antennas and Propagation*. Volume 42: Pages 993–999.
- Higuchi, Tetsuya, Iwata, Masaya, and Lui, Weixin (editors). 1997. *Evolvable Systems: From Biology to Hardware: First International Conference, ICES-96, Tsukuba, Japan, October 1996 Proceedings*. Lecture Notes in Computer Science, Volume 1259. Berlin: Springer-Verlag.
- Higuchi, Tetsuya, Niwa, Tatsuya, Tanaka, Toshio, Iba, Hitoshi, de Garis, Hugo, and Furuya, Tatsumi. 1993a. Evolving hardware with genetic learning: A first step towards building a Darwin machine. In Meyer, Jean-Arcady, Roitblat, Herbert L. and Wilson, Stewart W. (editors). *From Animals to Animats 2: Proceedings of the Second International Conference on Simulation of Adaptive Behavior*. Cambridge, MA: The MIT Press. 1993. Pages 417–424.
- Higuchi, Tetsuya, Niwa, Tatsuya, Tanaka, Toshio, Iba, Hitoshi, de Garis, Hugo, and Furuya, Tatsumi. 1993b. *Evolvable Hardware—Genetic-Based Generation of Electric Circuitry at Gate and Hardware Description Language (HDL) Levels*. Electrotechnical Laboratory technical report 93-4. Tsukuba, Japan: Electrotechnical Laboratory.
- Holland, John H. 1975. *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. Ann Arbor, MI: University of Michigan Press. Second edition. Cambridge, MA: The MIT Press 1992.

- Hsu, Feng-Hsiung. 2002. *Behind Deep Blue: Building the Computer That Defeated the World Chess Champion*. Princeton, NJ: Princeton University Press.
- Iba, Hitoshi. 1996. *Genetic Programming*. Tokyo: Tokyo Denki University Press. In Japanese.
- Ikeuchi, Akira and Tokuda, Naoshi. 2000. *Voltage-Current Conversion Circuit*. U.S. patent 6,166,529. Filed February 24, 2000 in the United States. Issued December 26, 2000 in the United States. Filed March 10, 1999 in Japan.
- Ince, D. C. (editor). 1992. *Mechanical Intelligence: Collected Works of A. M. Turing*. Amsterdam: North Holland.
- Irvine, Robert and Kolb, Bernd. 2001. *Integrated Low-Pass Filter*. U.S. patent 6,225,859. Filed September 14, 1998. Issued May 1, 2001.
- Jacob, Christian. 1997. *Principia Evolvica: Simulierte Evolution mit Mathematica*. Heidelberg, Germany: dpunkt.verlag.
- Jacob, Christian. 2001. *Illustrating Evolutionary Computation with Mathematica*. San Francisco: Morgan Kaufmann.
- Jamshidi, Mo, Coelho, Leandro dos Santos, Krohling, Renato A., and Fleming, Peter J. 2003. *Robust Control Systems with Genetic Algorithms*. Boca Raton, FL: CRC Press.
- Johnson, Kenneth S. 1926. *Electric-Wave Transmission*. U.S. patent 1,611,916. Filed March 9, 1923. Issued December 28, 1926.
- Johnson, Walter C. 1950. *Transmission Lines and Networks*. New York: NY: McGraw-Hill.
- Johnson, J. Michael and Rahmat-Samii, Yahya. 1999. Genetic algorithms and method of moments (GA/MOM) for the design of integrated antennas. *IEEE Transactions on Antennas and Propagation*. 47(10)1606–1614. October 1999.
- Jones, Eric A. 1999. *Genetic Design of Antennas and Electronic Circuits*. Ph.D. Thesis. Department of Electrical and Computer Engineering. Duke University.
- Jones, Harry S. 1942. *Control Apparatus*. U.S. patent 2,282,726. Filed October 25, 1939. Issued May 12, 1942.
- Keane, Martin A., Koza, John R., and Rice, James P. 1993. Finding an impulse response function using genetic programming. *Proceedings of the 1993 American Control Conference*. Evanston, IL: American Automatic Control Council. Volume III. Pages 2345–2350.
- Keane, Martin A., Koza, John R., and Streeter, Matthew J. 2002a. *Improved General-Purpose Controllers*. U.S. patent application filed July 12, 2002.
- Keane, Martin A., Koza, John R., and Streeter, Matthew J. 2002b. Automatic synthesis using genetic programming of an improved general-purpose controller for industrially representative plants. In Stoica, Adrian, Lohn, Jason, Katz, Rich, Keymeulen, Didier and Zebulum, Ricardo (editors) 2002. *Proceedings of 2002 NASA/DoD Conference on Evolvable Hardware*. Los Alamitos, CA: IEEE Computer Society. Pages 113–122.
- Keane, Martin A., Yu, Jessen, and Koza, John R. 2000. Automatic synthesis of both the topology and tuning of a common parameterized controller for two families of plants using genetic programming. In Whitley, Darrell, Goldberg, David, Cantu-Paz, Erick, Spector, Lee, Parmee, Ian, and Beyer, Hans-Georg (editors). *GECCO-2000: Proceedings of the Genetic and Evolutionary Computation Conference, July 10–12, 2000, Las Vegas, Nevada*. San Francisco: Morgan Kaufmann. Pages 496–504.
- Keymeulen, Didier, Stoica, Adrian, Lohn, Jason, and Zebulum, Ricardo Salem (editors). 2001. *Proceedings of the Third NASA/DOD Workshop on Evolvable Hardware, Pasadena, California, July 12–14, 2001*. Los Alamitos, CA. IEEE Computer Society.
- Kinnear, Kenneth E. Jr. (editor). 1994. *Advances in Genetic Programming*. Cambridge, MA: MIT Press.
- Kirkpatrick, S., Gelatt, C. D., and Vecchi, M. P. 1983. Optimization by simulated annealing. *Science* 220. Pages 671–680.
- Kitano, Hiroaki. 1990. Designing neural networks using genetic algorithms with graph generation system. *Complex Systems*. 4 (1990) 461–476.

- Kitano, Hiroaki. 2001. *Foundations of Systems Biology*. Cambridge, MA: The MIT Press.
- Koza, John R. 1988. *Nonlinear Genetic Algorithms for Solving Problems*. U.S. patent application filed May 20, 1988.
- Koza, John R. 1989. Hierarchical genetic algorithms operating on populations of computer programs. In *Proceedings of the 11th International Joint Conference on Artificial Intelligence*. San Mateo, CA: Morgan Kaufmann. Volume I. Pages 768–774.
- Koza, John R. 1990a. *Genetic Programming: A Paradigm for Genetically Breeding Populations of Computer Programs to Solve Problems*. Stanford University Computer Science Department technical report STAN-CS-TR-90-1314. June 1990.
- Koza, John R. 1990b. *Non-Linear Genetic Algorithms for Solving Problems*. U.S. patent 4,935,877. Filed May 20, 1988. Issued June 19, 1990.
- Koza, John R. 1992a. *Genetic Programming: On the Programming of Computers by Means of Natural Selection*. Cambridge, MA: MIT Press.
- Koza, John R. 1992b. *Non-Linear Genetic Algorithms for Solving Problems by Finding a Fit Composition of Functions*. U. S. patent 5,136,686. Filed March 28, 1990. Issued August 4, 1992.
- Koza, John R. 1992c. Hierarchical automatic function definition in genetic programming. In Whitley, Darrell (editor). 1993. *Foundations of Genetic Algorithms 2*. San Mateo, CA: Morgan Kaufmann Publishers. Pages 297–318.
- Koza, John R. 1992d. A genetic approach to finding a controller to back up a tractor-trailer truck. In *Proceedings of the 1992 American Control Conference*. Evanston, IL: American Automatic Control Council. Volume III. Pages 2307–2311.
- Koza, John R. 1993. Discovery of rewrite rules in Lindenmayer systems and state transition rules in cellular automata via genetic programming. *Symposium on Pattern Formation (SPF-93), Claremont, California. February 13, 1993*. A copy of this presented, but otherwise unpublished, paper is available at <http://www.smi.stanford.edu/people/koza>.
- Koza, John R. 1994a. *Genetic Programming II: Automatic Discovery of Reusable Programs*. Cambridge, MA: MIT Press.
- Koza, John R. 1994b. *Genetic Programming II Videotape: The Next Generation*. Cambridge, MA: MIT Press.
- Koza, John R. 1994c. *Architecture-Altering Operations for Evolving the Architecture of a Multi-Part Program in Genetic Programming*. Stanford University Computer Science Department technical report STAN-CS-TR-94-1528. October 21, 1994.
- Koza, John R. 1995a. Evolving the architecture of a multi-part program in genetic programming using architecture-altering operations. In McDonnell, John R., Reynolds, Robert G., and Fogel, David B. (editors). 1995. *Evolutionary Programming IV: Proceedings of the Fourth Annual Conference on Evolutionary Programming*. Cambridge, MA: The MIT Press. Pages 695–717.
- Koza, John R. 1995b. Gene duplication to enable genetic programming to concurrently evolve both the architecture and work-performing steps of a computer program. *Proceedings of the 14<sup>th</sup> International Joint Conference on Artificial Intelligence*. San Francisco: Morgan Kaufmann. Pages 734–740.
- Koza, John R. 1995c. Two ways of discovering the size and shape of a computer program to solve a problem. In Eshelman, Larry J. (editor). *Proceedings of the Sixth International Conference on Genetic Algorithms*. San Francisco: Morgan Kaufmann. Pages 287–294.
- Koza, John R. and Andre, David. 1995. *Parallel Genetic Programming on a Network of Transputers*. Stanford University Computer Science Department technical report STAN-CS-TR-95-1542. January 30, 1995.
- Koza, John R., Andre, David, and Tackett, Walter Alden. 1994. *Simultaneous Evolution of the Architecture of a Multi-Part Program to Solve a Problem Using Architecture Altering Operations*. U.S. patent application filed August 4, 1994.

- Koza, John R., Andre, David, and Tackett, Walter Alden. 1998. *Simultaneous Evolution of the Architecture of a Multi-Part Program to Solve a Problem Using Architecture Altering Operations*. U. S. patent 5,742,738. Filed August 4, 1994. Issued April 21, 1998.
- Koza, John R., Andre, David, and Tackett, Walter Alden. 2000. *Simultaneous Evolution of the Architecture of a Multi-Part Program to Solve a Problem Using Architecture Altering Operations*. U. S. patent 6,058,385. Filed March 7, 1997. Issued May 2, 2000.
- Koza, John R., Banzhaf, Wolfgang, Chellapilla, Kumar, Deb, Kalyanmoy, Dorigo, Marco, Fogel, David B., Garzon, Max H., Goldberg, David E., Iba, Hitoshi, and Riolo, Rick. (editors). 1998. *Genetic Programming 1998: Proceedings of the Third Annual Conference*. San Francisco, CA: Morgan Kaufmann.
- Koza, John R., and Bennett III, Forrest H. 1999. Automatic synthesis, placement, and routing of electrical circuits by means of genetic programming. In Spector, Lee, Langdon, William B., O'Reilly, Una-May, and Angeline, Peter (editors). *Advances in Genetic Programming 3*. Cambridge, MA: MIT Press. Chapter 6. Pages 105–134.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 1996a. Automated design of both the topology and sizing of analog electrical circuits using genetic programming. In Gero, John S. and Sudweeks, Fay (editors). *Artificial Intelligence in Design '96*. Dordrecht: Kluwer Academic Publishers. Pages 151–170.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 1996b. Automated WYWIWYG design of both the topology and component values of analog electrical circuits using genetic programming. In Koza, John R., Goldberg, David E., Fogel, David B., and Riolo, Rick L. (editors). *Genetic Programming 1996: Proceedings of the First Annual Conference, July 28–31, 1996, Stanford University*. Cambridge, MA: The MIT Press. Pages 123–131.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 1996c. Reuse, parameterized reuse, and hierarchical reuse of substructures in evolving electrical circuits using genetic programming. In Higuchi, Tetsuya, Iwata, Masaya, and Liu, Weixin (editors). 1997. *Proceedings of International Conference on Evolvable Systems: From Biology to Hardware (ICES-96)*. Lecture Notes in Computer Science, Volume 1259. Berlin: Springer-Verlag. Berlin: Springer-Verlag. Pages 312–326.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 1996d. Toward evolution of electronic animals using genetic programming. In Langton, Christopher G. and Shimohara, Katsunori (editors). 1997. *Artificial Life V: Proceedings of the Fifth International Workshop on the Synthesis and Simulation of Living Systems*. Cambridge, MA: The MIT Press. Pages 327–334.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 1996e. Four problems for which a computer program evolved by genetic programming is competitive with human performance. *Proceedings of the 1996 IEEE International Conference on Evolutionary Computation*. IEEE Press. Pages 1–10.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 1996f. *Method and Apparatus for Automated Design of Electrical Circuits Using Genetic Programming*. U.S. patent application filed February 20, 1996.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 1999a. *Genetic Programming III: Darwinian Invention and Problem Solving*. San Francisco, CA: Morgan Kaufmann.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 1999b. *Method and Apparatus for Automated Designs of Complex Structures using Genetic Programming*. Filed February 20, 1996. U. S. patent 5,867,397. Issued February 2, 1999.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 1999c. *Genetic Programming Problem Solver with Automatically Defined Stores, Loops, and Recursions*. U.S. patent application filed April 12, 1999.

- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 2002. *Method and Apparatus for Automated Design of Complex Structures using Genetic Programming*. U.S. patent 6,360,191. Filed February 20, 1996 and January 5, 1999. Issued March 19, 2002.
- Koza, John R., Bennett III, Forrest H, Andre, David, and Keane, Martin A. 2003. *Genetic Programming Problem Solver with Automatically Defined Stores, Loops, and Recursions*. U.S. patent 6,532,453. Filed April 12, 1999. Issued March 11, 2003.
- Koza, John R., Bennett III, Forrest H, Andre, David, Keane, Martin A., and Brave, Scott. 1999. *Genetic Programming III Videotape: Human-Competitive Machine Intelligence*. San Francisco, CA: Morgan Kaufmann.
- Koza, John R., Bennett III, Forrest H, Andre, David, Keane, Martin A., and Dunlap, Frank. 1997. Automated synthesis of analog electrical circuits by means of genetic programming. *IEEE Transactions on Evolutionary Computation*. 1(2). Pages 109–128.
- Koza, John R., Bennett, Forrest H, III, Hutchings, Jeffrey L., Bade, Stephen L., Keane, Martin A., and Andre, David. 1997. Evolving sorting networks using genetic programming and the rapidly reconfigurable Xilinx 6216 field-programmable gate array. *Proceedings of the 31st Asilomar Conference on Signals, Systems, and Computers*. Piscataway, NJ: IEEE Press. Pages 404–410.
- Koza, John R., Bennett, Forrest H, III, Hutchings, Jeffrey L., Bade, Stephen L., Keane, Martin A., and Andre, David. 1998. Evolving computer programs using rapidly reconfigurable field-programmable gate arrays and genetic programming. *Proceedings of the ACM Sixth International Symposium on Field Programmable Gate Arrays*. New York: ACM Press. Pages 209–219.
- Koza, John R., Bennett III, Forrest H, Keane, Martin A., and Andre, David. 1997. Automatic programming of a time-optimal robot controller and an analog electrical circuit to implement the robot controller by means of genetic programming. In *Proceedings of 1997 IEEE International Symposium on Computational Intelligence in Robotics and Automation*. Los Alamitos, CA: Computer Society Press. Pages 340–346.
- Koza, John R., Bennett III, Forrest H, Keane, Martin A., Yu, Jessen, Mydlowec, William, and Stiffelman, Oscar. 1999. Searching for the impossible using genetic programming. In Banzhaf, Wolfgang, Daida, Jason, Eiben, A. E., Garzon, Max H., Honavar, Vasant, Jakiela, Mark, and Smith, Robert E. (editors). 1999. *GECCO-99: Proceedings of the Genetic and Evolutionary Computation Conference, July 13–17, 1999, Orlando, Florida USA*. San Francisco, CA: Morgan Kaufmann. Pages 1083–1091.
- Koza, John R., Bennett III, Forrest H, and Stiffelman, Oscar. 1999a. Genetic programming as a Darwinian invention machine. In Poli, Riccardo, Nordin, Peter, Langdon, William B., and Fogarty, Terence C. 1999. *Genetic Programming: Second European Workshop. EuroGP'99. Proceedings*. Lecture Notes in Computer Science. Volume 1598. Berlin, Germany: Springer-Verlag. Pages 93–108.
- Koza, John R., Bennett III, Forrest H, and Stiffelman, Oscar. 1999b. *An Invention Machine that Automatically Creates Novel Designs*. U.S. patent application filed April 13, 2000.
- Koza, John R., Deb, Kalyanmoy, Dorigo, Marco, Fogel, David B., Garzon, Max, Iba, Hitoshi, and Riolo, Rick L. (editors). 1997. *Genetic Programming 1997: Proceedings of the Second Annual Conference, July 13–16, 1997, Stanford University*. San Francisco, CA: Morgan Kaufmann.
- Koza, John R., Goldberg, David E., Fogel, David B., and Riolo, Rick L. (editors). 1996. *Genetic Programming 1996: Proceedings of the First Annual Conference, July 28–31, 1996, Stanford University*. Cambridge, MA: MIT Press.
- Koza, John R., and Keane, Martin A. 1990a. Cart centering and broom balancing by genetically breeding populations of control strategy programs. In *Proceedings of International Joint Conference on Neural Networks, Washington, January 15–19, 1990*. Hillsdale, NJ: Lawrence Erlbaum. Volume I, Pages 198–201.

- Koza, John R., and Keane, Martin A. 1990b. Genetic breeding of nonlinear optimal control strategies for broom balancing. In *Proceedings of the Ninth International Conference on Analysis and Optimization of Systems. Antibes, France, June, 1990*. Berlin: Springer-Verlag. Pages 47–56.
- Koza, John R., Keane, Martin A., Bennett III, Forrest H, Yu, Jessen, Mydlowec, William, and Stiffelman, Oscar. 1999. Automatic creation of both the topology and parameters for a robust controller by means of genetic programming. *Proceedings of the 1999 IEEE International Symposium on Intelligent Control, Intelligent Systems, and Semiotics*. Piscataway, NJ: IEEE. Pages 344–352.
- Koza, John R., Keane, Martin A., and Streeter, Matthew J. 2003. Evolving inventions. *Scientific American*. February 2003. 288(2) 52–59.
- Koza, John R., Keane, Martin A., Yu, Jessen, Bennett III, Forrest H, and Mydlowec, William. 2000. Automatic creation of human-competitive programs and controllers by means of genetic programming. *Genetic Programming and Evolvable Machines*. Volume 1. Number 1/2. Pages 121–164.
- Koza, John R., Keane, Martin A., Yu, Jessen, Bennett III, Forrest H, Mydlowec, William, and Stiffelman, Oscar. 1999. Automatic synthesis of both the topology and parameters for a robust controller for a non-minimal phase plant and a three-lag plant by means of genetic programming. *Proceedings of 1999 IEEE Conference on Decision and Control*. Pages 5292–5300.
- Koza, John R., Keane, Martin A., Yu, Jessen, Bennett III, Forrest H, and Mydlowec, William. 2003. *Method and Apparatus for Automatic Synthesis of Controllers*. U.S. patent application filed September 10, 1999. Application number 09/393,863. Allowed October 30, 2002.
- Koza, John R., Keane, Martin A., Yu, Jessen, and Mydlowec, William. 2000. Automatic synthesis of electrical circuits containing a free variable using genetic programming. In Whitley, Darrell, Goldberg, David, Cantu-Paz, Erick, Spector, Lee, Parmee, Ian, and Beyer, Hans-Georg (editors). *GECCO-2000: Proceedings of the Genetic and Evolutionary Computation Conference, July 10–12, 2000, Las Vegas, Nevada*. San Francisco: Morgan Kaufmann. Pages 551–557.
- Koza, John R., Keane, Martin A., Yu, Jessen, Mydlowec, William, and Bennett, Forrest H III. 2000a. Automatic synthesis of both the topology and parameters for a controller for a three-lag plant with a five-second delay using genetic programming. In Cagnoni, Stefano et al. (editors). *Real World Applications of Evolutionary Computing. EvoWorkshops 2000. EvoIASP, Evo SCONDI, EvoTel, EvoSTIM, EvoRob, and EvoFlight, Edinburgh, Scotland, UK, April 2000, Proceedings*. Lecture Notes in Computer Science. Volume 1803. Berlin, Germany: Springer-Verlag. Pages 168–177.
- Koza, John R., Keane, Martin A., Yu, Jessen, Mydlowec, William, and Bennett, Forrest H III. 2000b. Automatic synthesis of both the control law and parameters for a controller for a three-lag plant with five-second delay using genetic programming and simulation techniques. In *Proceedings of the 2000 American Control Conference, Chicago, Illinois, June 28–30, 2000*. Evanston, IL: American Automatic Control Council. Pages 453–459.
- Koza, John R., Mydlowec, William, Lanza, Guido, Yu, Jessen, and Keane, Martin A. 2000a. *Reverse Engineering and Automatic Synthesis of Metabolic Pathways from Observed Data Using Genetic Programming*. Stanford Medical Informatics Technical Report SMI-2000-0851. November 7, 2000. [http://smi-web.stanford.edu/pubs/SMI\\_Abstracts/SMI-2000-0851.html](http://smi-web.stanford.edu/pubs/SMI_Abstracts/SMI-2000-0851.html)
- Koza, John R., Mydlowec, William, Lanza, Guido, Yu, Jessen, and Keane, Martin A. 2000b. Reverse engineering of metabolic pathways from observed data using genetic programming. In Altman, Russ B. Dunker, A. Keith, Hunter, Lawrence, Lauderdale, Kevin, and Klein, Teri (editors). *Pacific Symposium on Biocomputing '99*. Singapore: World Scientific. Pages 434–445.
- Koza, John R., Mydlowec, William, Lanza, Guido, Yu, Jessen, and Keane, Martin A. 2001a. Automated reverse engineering of metabolic pathways by means of genetic programming. In

- Kitano, Hiroaki. 2001. *Foundations of Systems Biology*. Cambridge, MA: The MIT Press. Pages 95–121.
- Koza, John R., Mydlowec, William, Lanza, Guido, Yu, Jessen, and Keane, Martin A. 2001b. Automatic synthesis of both the topology and sizing of metabolic pathways using genetic programming. In Spector, Lee, Goodman, E., Wu, A., Langdon, William B., Voigt, H.-M., Gen, M., Sen, S., Dorigo, Marco, Pezeshk, S., Garzon, Max, and Burke, E. (editors). 2001. *Proceedings of the Genetic and Evolutionary Computation Conference, GECCO-2001*. San Francisco, CA: Morgan Kaufmann. Pages 57–65.
- Koza, John R., and Rice, James P. 1991. Genetic generation of both the weights and architecture for a neural network. In *Proceedings of International Joint Conference on Neural Networks, Seattle, July 1991*. Los Alamitos, CA: IEEE Press. Volume II. Pages 397–404.
- Koza, John R., and Rice, James P. 1992a. *Genetic Programming: The Movie*. Cambridge, MA: MIT Press.
- Koza, John R., and Rice, James P. 1992b. *A Non-Linear Genetic Process for Data Encoding and for Solving Problems Using Automatically Defined Functions*. U.S. patent application filed May 11, 1992.
- Koza, John R., and Rice, James P. 1992c. *A Non-Linear Genetic Process for Use with Plural Co-Evolving Populations*. U. S. patent No. 5,148,513. Filed September 18, 1990. Issued September 15, 1992.
- Koza, John R., and Rice, James P. 1994a. *A Non-Linear Genetic Process for Data Encoding and for Solving Problems Using Automatically Defined Functions*. U. S. patent application filed May 11, 1992. U. S. patent No. 5,343,554. Issued August 30, 1994.
- Koza, John R., and Rice, James P. 1994b. *A Non-Linear Genetic Process for Data Encoding and for Solving Problems Using Automatically Defined Functions*. U.S. patent 5,343,554. Filed May 11, 1992. Issued August 30, 1994.
- Koza, John R., and Rice, James P. 1995. *Process for Problem Solving Using Spontaneously Emergent Self-Replicating and Self-Improving Entities*. U. S. patent application filed June 16, 1992. U. S. patent No. 5,390,282. Issued February 14, 1995.
- Koza, John R., Rice, James P., and Roughgarden, Jonathan. 1992. Evolution of food foraging strategies for the Caribbean *Anolis* lizard using genetic programming. *Adaptive Behavior*. Volume 1, number 2, pages 47–74.
- Koza, John R., Yu, Jessen, Keane, Martin A., and Mydlowec, William. 2000a. Evolution of a controller with a free variable using genetic programming. In Poli, Riccardo, Banzhaf, Wolfgang, Langdon, William B., Miller, Julian, Nordin, Peter, and Fogarty, Terence C. 2000. *Genetic Programming: European Conference, EuroGP 2000, Edinburgh, Scotland, UK, April 2000, Proceedings*. Lecture Notes in Computer Science. Volume 1802. Berlin, Germany: Springer-Verlag. Pages 91–105.
- Koza, John R., Yu, Jessen, Keane, Martin A., and Mydlowec, William. 2000b. Use of conditional developmental operators and free variables in automatically synthesizing generalized circuits using genetic programming. *Proceedings of the Second NASA/DoD Workshop on Evolvable Hardware, July 13–15 2000, Palo Alto, California*. Los Alamitos, CA: IEEE Computer Society Press. Pages 5–15.
- Kruiskamp, Marinum Wilhelmus. 1996. *Analog Design Automation using Genetic Algorithms and Polytopes*. Eindhoven, The Netherlands: Data Library Technische Universiteit Eindhoven.
- Kruiskamp, Marinum Wilhelmus and Leenaerts, Domine. 1995. DARWIN: CMOS opamp synthesis by means of a genetic algorithm. *Proceedings of the 32nd Design Automation Conference*. New York, NY: Association for Computing Machinery. Pages 433–438.
- Laing, Shoudan, Fuhrman, Stefanie, and Somogyi, Roland. 1998. REVEAL: A general reverse engineering algorithm for inference of genetic network architecture. In Altman, Russ B.

- Dunker, A. Keith, Hunter, Lawrence, and Klein, Teri E. (editors). *Pacific Symposium on Biocomputing '98*. Singapore: World Scientific. Pages 18–29.
- Langdon, William B. 1998. *Genetic Programming and Data Structures: Genetic Programming + Data Structures = Automatic Programming!* Amsterdam: Kluwer.
- Langdon, W. B., Cantu-Paz, E., Mathias, K., Roy, R., Davis, D., Poli, R., Balakrishnan, K., Honavar, V., Rudolph, G., Wegener, J., Bull, L., Potter, M. A., Schultz, A. C., Miller, J. F., Burke, E., and Jonoska, N. (editors). 2002. *Proceedings of the 2002 Genetic and Evolutionary Computation Conference*. San Francisco, CA: Morgan Kaufmann.
- Langdon, William B. and Poli, Riccardo. 2002. *Foundations of Genetic Programming*. Berlin: Springer-Verlag.
- Lanza, Guido, Mydlowec, William, and Koza, John R. 2000. Automatic creation of a genetic network for the *lac* operon from observed data by means of genetic programming. Poster paper accepted at First International Conference on Systems Biology in Tokyo on November 14–16, 2000.
- Lee, Sang Gug. 2001. *Low Voltage Balun Circuit*. U.S. patent 6,265,908. Filed December 15, 1999. Issued July 24, 2001.
- Lee, Thomas H. 1998. *The Design of CMOS Radio-Frequency Integrated Circuits*. Cambridge: Cambridge University Press.
- Linden, Derek S. 1997. *Automated Design and Optimization of Wire Antennas Using Genetic Algorithms*. Ph.D. Thesis. Department of Electrical Engineering and Computer Science. Massachusetts Institute of Technology.
- Lindenmayer, Aristid. 1968. Mathematical models for cellular interactions in development, I & II. *Journal of Theoretical Biology*. Volume 18. Pages 280–315.
- Liu, Yong, Tanaka, Kiyoshi, Iwata, Masaya, Higuchi, Tetsuya, and Yasunaga, Moritoshi (editors). 2001. *Evolvable Systems: From Biology to Hardware, 4<sup>th</sup> International Conference, ICES 2001, Tokyo, Japan, October 2001 Proceedings*. Lecture Notes in Computer Science, Volume 2210. Berlin: Springer-Verlag.
- Lohn, Jason, Stoica, Adrian, Keymeulen, Didier, and Colombano, Silvano (editors). 2000. *Proceedings of the Second NASA/DoD Workshop on Evolvable Hardware, July 13–15 2000, Palo Alto, California*. Los Alamitos, CA: IEEE Computer Society Press.
- Loomis, William F. and Sternberg, Paul W. 1995. Genetic networks. *Science*. Pages 269–649. August 4, 1995.
- Luke, Sean. 1998. Genetic programming produced competitive soccer softbot teams for RoboCup97. In Koza, John R., Banzhaf, Wolfgang, Chellapilla, Kumar, Deb, Kalyanmoy, Dorigo, Marco, Fogel, David B., Garzon, Max H., Goldberg, David E., Iba, Hitoshi, and Riolo, Rick. (editors). *Genetic Programming 1998: Proceedings of the Third Annual Conference, July 22–25, 1998, University of Wisconsin, Madison, Wisconsin*. San Francisco, CA: Morgan Kaufmann. Pages 214–222.
- Macbeth, Ian. 2002. FPAAs: Synthesis by construction. *EDN*. November 28, 2002. Pages 44.
- Mahfoud, S. W. and Goldberg, David E. 1995. Parallel recombinative simulated annealing: A genetic algorithm. *Parallel Computing*. Amsterdam: Elsevier Science. Volume 21. Pages 1–28.
- Man, K. F., Tang, K. S., Kwong, S., and Halang, W. A. 1997. *Genetic Algorithms for Control and Signal-Processing*. London: Springer-Verlag.
- Man, K. F., Tang, K. S., Kwong, S., and Halang, W. A. 1999. *Genetic Algorithms: Concepts and Designs*. London: Springer-Verlag.
- Marcano, Diogenes and Duran, Filinto. 1999. Synthesis of linear and planar arrays using genetic algorithms. In Rahmat-Samii, Yahya and Michielssen, Eric (editors). *Electromagnetic Optimization by Genetic Algorithms*. New York, NY: John Wiley and Sons. Chapter 6. Pages 157–179.



- Marenbach, Peter, Bettenhausen, Kurt D., and Freyer, Stephan. 1996. Signal path oriented approach for generation of dynamic process models. In Koza, John R., Goldberg, David E., Fogel, David B., and Riolo, Rick L. (editors). *Genetic Programming 1996: Proceedings of the First Annual Conference, July 28–31, 1996, Stanford University*. Cambridge, MA: MIT Press. Pages 327–332.
- Massey, John. 1970. *Compensated Resistance Bridge-Type Electrical Thermometer*. U.S. patent 3,541,857. Filed November 27, 1968. Issued November 24, 1970.
- Maziasz, Robert L. and Hayes, John P. 1992. *Layout Minimization of CMOS Cells*. Boston: Kluwer.
- Mazumder, Pinaki and Rudnick, Elizabeth M. (editors). 1999. *Genetic Algorithms for VLSI Design, Layout and Test Automation*. Upper Saddle River, NJ: Prentice Hall.
- McAdams, Harley H. and Shapiro, Lucy. 1995. Circuit simulation of genetic networks. *Science*. Volume 269. Pages 650–656. August 4, 1995.
- Mendes, Pedro and Kell, Douglas B. 1998. Nonlinear optimization of biochemical pathways: Applications to metabolic engineering and parameter estimation. *Bioinformatics*. 14(10)869–883.
- Menon, P. K., Yousefpor, M., Lam, T., and Steinberg, M. L. 1995. Nonlinear flight control system synthesis using genetic programming. *Proceedings of 1995 Conference on Guidance, Navigation, and Control*. Reston, VA: American Institute of Aeronautics and Astronautics. Pages 461–470.
- Messina, Paul, Sterling, Thomas, and Smith, Paul H. (editors). 1999. *Petaflops II: Second Conference on Enabling Technologies for Peta(fl)ops Computing, February 15–19, 1999, Santa Barbara*.
- Miller, Julian, Thompson, Adrian, Thomson, Peter, and Fogarty, Terence C. (editors). 2000. *Evolvable Systems: From Biology to Hardware. Third International Conference, ICES 2000, Edinburgh, Scotland, UK, April 2000 Proceedings*. Lecture Notes in Computer Science. Volume 1801. Berlin, Germany: Springer-Verlag.
- Miller, Julian, Tomassini, Marco, Lanzi, Pier Luca, Ryan, Conor, Tettamanzi, Andrea G. B., and Langdon, William B. (editors). 2001. *Genetic Programming: 4<sup>th</sup> European Conference, EuroGP 2001, Lake Como, Italy, April 2001 Proceedings*. Berlin: Springer.
- Mittenthal, Jay E., Ao Yuan, Bertrand Clarke, and Scheeline, Alexander. 1998. Designing metabolism: Alternative connectivities for the pentose phosphate pathway. *Bulletin of Mathematical Biology*. Volume 60. Pages 815–856.
- Moore, Gordon E. 1996. Can Moore's law continue indefinitely? *Computerworld Leadership Series*. 2(6)2–7. July 15, 1996.
- Moretti, Gabe. 2002. The next wave: Synthesis tools help with mixed-signal designs. *EDN*. November 28, 2002. Pages 43–50.
- Mydlowec, William and Koza, John. 2000. Use of time-domain simulations in automatic synthesis of computational circuits using genetic programming. *Late Breaking Papers at the 2000 Genetic and Evolutionary Computation Conference, Las Vegas, Nevada*. Pages 187–197.
- Newbold, William F. 1962. *Square Root Extracting Integrator*. U.S. patent 3,016,197. Filed September 15, 1958. Issued January 9, 1962.
- Newborn, Monty. 2002. *Deep Blue: An Artificial Intelligence Milestone*. New York: Springer.
- Nordin, Peter. 1997. *Evolutionary Program Induction of Binary Machine Code and Its Application*. Munster, Germany: Krehl Verlag.
- O'Connor, Daniel G. and Nelson, Raymond J. 1962. *Sorting System with N-Line Sorting Switch*. U.S. patent 3,029,413. Issued April 10, 1962.
- Ogata, Katsuhiko. 1997. *Modern Control Engineering*. Third edition. Upper Saddle River, NJ: Prentice Hall.

- Ohr, Stephan. 2002. Anadigm fields reconfigurable analog device. *EE Times*. September 2, 2002.
- Olsson, Jan Roland. 1994a. Inductive functional programming using incremental program transformation. *Artificial Intelligence*. Volume 74. Pages 55–81.
- Olsson, Jan Roland. 1994b. *Inductive Functional Programming Using Incremental Program Transformation*. Dr. Scient. thesis. University of Oslo.
- O'Neill, Michael and Ryan, Conor. 2003. *Grammatical Evolution: Evolutionary Automatic Programming in an Arbitrary Language*. Boston: Kluwer Academic Publishers.
- Oszycza, A. 1984. *Multicriterion Optimization in Engineering with FORTRAN programs*. Ellis Horwood Limited.
- Pease, Robert. 1992. What's all this Muntzing stuff, anyhow? *Electronic Design*. July 23, 1992.
- Pease, Robert. 1996. What's all this R-C filter stuff, anyhow? *Electronic Design*. March 18, 1996.
- Pease, Robert. 1999. What's all this logarithmic stuff, anyhow? *Electronic Design*. August 19, 1999.
- Philbrick, George A. 1956. *Delayed Recovery Electric Filter Network*. Filed May 18, 1951. U.S. patent 2,730,679. Issued January 10, 1956.
- Poli, Riccardo, Nordin, Peter, Langdon, William B., and Fogarty, Terence C. 1999. *Genetic Programming: Second European Workshop, EuroGP'99. Proceedings*. Lecture Notes in Computer Science. Volume 1598. Berlin, Germany: Springer-Verlag.
- Poli, Riccardo, Banzhaf, Wolfgang, Langdon, William B., Miller, Julian, Nordin, Peter, and Fogarty, Terence C. 2000. *Genetic Programming: European Conference, EuroGP 2000, Edinburgh, Scotland, UK, April 2000, Proceedings*. Lecture Notes in Computer Science. Volume 1802. Berlin, Germany: Springer-Verlag.
- Prusinkiewicz, Przemyslaw and Hanan, James. 1980. *Lindenmayer Systems, Fractals, and Plants*. New York: Springer-Verlag.
- Prusinkiewicz, Przemyslaw, and Lindenmayer, Aristid. 1990. *The Algorithmic Beauty of Plants*. New York: Springer-Verlag.
- Ptashne, Mark. 1992. *A Genetic Switch: Phage  $\lambda$  and Higher Organisms*. Second Edition. Cambridge, MA: Cell Press and Blackwell Scientific Publications.
- Quarles, Thomas, Newton, A. R., Pederson, D. O., and Sangiovanni-Vincentelli, A. 1994. *SPICE 3 Version 3F5 User's Manual*. Department of Electrical Engineering and Computer Science, University of California. Berkeley, CA. March 1994.
- Rahmat-Samii, Yahya and Michielssen, Eric (editors). 1999. *Electromagnetic Optimization by Genetic Algorithms*. New York, NY: John Wiley and Sons.
- Rechenberg, Ingo. 1965. *Cybernetic solution path of an experimental problem*. Royal Aircraft Establishment, Ministry of Aviation, Library Translation 1112. Farnborough.
- Rechenberg, Ingo. 1973. *Evolutionsstrategie: Optimierung Technischer Systeme nach Prinzipien der Biologischen Evolution*. Stuttgart-Bad Cannstatt: Verlag Frommann-Holzboog.
- Riolo, Rich and Worzel, William. 2003. *Genetic Programming: Theory and Practice*. Boston: Kluwer Academic Publishers.
- Robertson, George. 1987. Parallel implementation of genetic algorithms in a classifier system. In Davis, Lawrence (editor). *Genetic Algorithms and Simulated Annealing* London: Pittman.
- Ryan, Conor. 1999. *Automatic Re-engineering of Software Using Genetic Programming*. Amsterdam: Kluwer Academic Publishers.
- Salamon, Peter, Sibani, Paolo, and Frost, Richard. 2002. *Facts, Conjectures, and Improvements for Simulated Annealing*. Philadelphia: Society for Industrial and Applied Mathematics.
- Samuel, Arthur L. 1983. AI: Where it has been and where it is going. *Proceedings of the Eighth International Joint Conference on Artificial Intelligence*. Los Altos, CA: Morgan Kaufmann. Pages 1152–1157.

- Sanchez, Eduardo and Tomassini, Marco (editors). 1996. *Towards Evolvable Hardware*. Lecture Notes in Computer Science, Volume 1062. Berlin: Springer-Verlag.
- Schaeffer, Jonathan. 1997. *One Jump Ahead: Challenging Human Supremacy in Checkers*. New York: Springer.
- Sechen, Carl. 1988. *VLSI Placement and Global Routing using Simulated Annealing*. Boston, MA: Kluwer.
- Sheingold, Daniel H. (editor). 1976. *Nonlinear Circuits Handbook*. Norwood, MA: Analog Devices, Inc.
- Sipper, Moshe, Mange, Daniel, and Perez-Urbe, Andres (editors). 1998. *Evolvable Systems: From Biology to Hardware. Second International Conference, ICES 98, Lausanne, Switzerland, September 1998 Proceedings*. Lecture Notes in Computer Science 1478. Berlin: Springer-Verlag.
- Smith, Steven F. 1980. *A Learning System Based on Genetic Adaptive Algorithms*. Ph.D. dissertation. Pittsburgh, PA: University of Pittsburgh.
- Song, Bang-Sup and Harjani, Ramesh. 1995. In Chen, Wai-Kai (editor). *The Circuits and Filters Handbook*. Boca Raton, FL: CRC Press. Pages 2072–2127.
- Spector, Lee, Barnum, Howard, and Bernstein, Herbert J. 1998. Genetic programming for quantum computers. In Koza, John R., Banzhaf, Wolfgang, Chellapilla, Kumar, Deb, Kalyanmoy, Dorigo, Marco, Fogel, David B., Garzon, Max H., Goldberg, David E., Iba, Hitoshi, and Riolo, Rick. (editors). *Genetic Programming 1998: Proceedings of the Third Annual Conference*. San Francisco, CA: Morgan Kaufmann. Pages 365–373.
- Spector, Lee, Barnum, Howard, and Bernstein, Herbert J. 1999. Quantum computing applications of genetic programming. In Spector, Lee, Langdon, William B., O'Reilly, Una-May, and Angeline, Peter (editors). *Advances in Genetic Programming 3*. Cambridge, MA: The MIT Press. Pages 135–160.
- Spector, Lee, Barnum, Howard, Bernstein, Herbert J., and Swamy, N. 1999. Finding a better-than-classical quantum AND/OR algorithm using genetic programming. In IEEE. *Proceedings of 1999 Congress on Evolutionary Computation*. Piscataway, NJ: IEEE Press. Pages 2239–2246.
- Spector, Lee, and Bernstein, Herbert J. 2003. Communication capacities of some quantum gates, discovered in part through genetic programming. In Shapiro, Jeffrey H. and Hirota, Osamu (editors). *Proceedings of the Sixth International Conference on Quantum Communication, Measurement, and Computing*. Paramus, NJ: Rinton Press.
- Spector, Lee, Goodman, E., Wu, A., Langdon, William B., Voigt, H. -M., Gen, M., Sen, S., Dorigo, Marco, Pezeshk, S., Garzon, Max, and Burke, E. (editors). 2001. *Proceedings of the Genetic and Evolutionary Computation Conference, GECCO-2001*. San Francisco, CA: Morgan Kaufmann.
- Spector, Lee, Langdon, William B., O'Reilly, Una-May, and Angeline, Peter (editors). 1999. *Advances in Genetic Programming 3*. Cambridge, MA: The MIT Press.
- Spector, Lee and Stoffel, Kilian. 1996a. Ontogenetic programming. In Koza, John R., Goldberg, David E., Fogel, David B., and Riolo, Rick L. (editors). 1996. *Genetic Programming 1996: Proceedings of the First Annual Conference, July 28–31, 1996, Stanford University*. Cambridge, MA: MIT Press. Pages 394–399.
- Spector, Lee and Stoffel, Kilian. 1996b. Automatic generation of adaptive programs. In Maes, Pattie, Mataric, Maja J., Meyer, Jean-Arcady, Pollack, Jordan, and Wilson, Stewart W. (editors). 1996. *From Animals to Animals 4: Proceedings of the Fourth International Conference on Simulation of Adaptive Behavior*. Cambridge, MA: The MIT Press. Pages 476–483.
- Sripamong, Thanwa and Toumazou, Christofer. 2002. The invention of CMOS amplifiers using genetic programming and current-flow analysis. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*. 21(11). November 2002. Pages 1237–1252.

- Stender, Joachim (editor). 1993. *Parallel Genetic Algorithms*. Amsterdam: IOS Publishing.
- Stephens, C. R. and Waelbroeck, H. 1997. Effective degrees of freedom in genetic algorithms and the block hypothesis. In Back, Thomas (editor). 1997. *Genetic Algorithms: Proceedings of the Seventh International Conference*. San Francisco, CA: Morgan Kaufmann. Pages 34–40.
- Sterling, Thomas L. 1998a. Beowulf-class clustered computing: Harnessing the power of parallelism in a pile of PCs. In Koza, John R., Banzhaf, Wolfgang, Chellapilla, Kumar, Deb, Kalyanmoy, Dorigo, Marco, Fogel, David B., Garzon, Max H., Goldberg, David E., Iba, Hitoshi, and Riolo, Rick L. (editors). *Genetic Programming 1998: Proceedings of the Third Annual Conference, July 22–25, 1998, University of Wisconsin, Madison, Wisconsin*. San Francisco, CA: Morgan Kaufmann. Pages 883–887.
- Sterling, Thomas L. 1998b. *Proceedings of Petaflops-Systems Operations Working Review, Bodega Bay, California, June 1–5, 1998*.
- Sterling, Thomas L. and Foster, Ian. 1996a. *Proceedings of Petaflops Architecture Workshop (PAWS '96), April 22–25, 1996*.
- Sterling, Thomas L. and Foster, Ian. 1996b. *Proceedings of Petaflops System Software Summer Study (Peta Soft '96), June 17–21, 1996*.
- Sterling, Thomas L., Salmon, John, and Becker, Donald J., and Savarese, Daniel F. 1999. *How to Build a Beowulf: A Guide to Implementation and Application of PC Clusters*. Cambridge, MA: MIT Press.
- Studel, Goetz Wolfgang. 1973. *Reference Voltage Generator and Regulator*. U.S. patent 3,743,923. Filed December 2, 1971. Issued July 3, 1973.
- Stoica, Adrian, Keymeulen, Didier, and Lohn, Jason (editors). 1999. *Proceedings of the First NASA/DoD Workshop on Evolvable Hardware, Pasadena, California, July 19–21, 1999*. Los Alamitos, CA: IEEE Computer Society.
- Stoica, Adrian, Lohn, Jason, Katz, Rich, Keymeulen, Didier and Zebulum, Ricardo Salem (editors). 2002. *Proceedings of 2002 NASA/DoD Conference on Evolvable Hardware*. Los Alamitos, CA: IEEE Computer Society.
- Stoica, Adrian, Zebulum, Ricardo, and Keymeulen, Didier. 2001. Polymorphic electronics. In Liu, Yong, Tanaka, Kiyoshi, Iwata, Masaya, Higuchi, Tetsuya, and Yasunaga, Moritoshi (editors). *Evolvable Systems: From Biology to Hardware, 4<sup>th</sup> International Conference, ICES 2001, Tokyo, Japan, October 2001 Proceedings*. Lecture Notes in Computer Science, Volume 2210. Berlin: Springer-Verlag. Pages 291–302.
- Streeter, Matthew J., Keane, Martin A., and Koza, John R. 2002a. Iterative refinement of computational circuits using genetic programming. In Langdon, W. B., Cantu-Paz, E., Mathias, K., Roy, R., Davis, D., Poli, R., Balakrishnan, K., Honavar, V., Rudolph, G., Wegener, J., Bull, L., Potter, M. A., Schultz, A. C., Miller, J. F., Burke, E., and Jonoska, N. (editors). 2002. *Proceedings of the 2002 Genetic and Evolutionary Computation Conference*. San Francisco, CA: Morgan Kaufmann. Pages 877–884.
- Streeter, Matthew J., Keane, Martin A., and Koza, John R. 2002b. Routine duplication of post-2000 patented inventions by means of genetic programming. In Foster, James A., Lutton, Evelyne, Miller, Julian, Ryan, Conor, and Tettamanzi, Andrea G. B. (editors). 2002. *Genetic Programming: 5<sup>th</sup> European Conference, EuroGP 2002, Kinsale, Ireland, April 2002 Proceedings*. Berlin: Springer. Pages 26–36.
- Streeter, Matthew J., Keane, Martin A., and Koza, John R. 2003. Automatic synthesis using genetic programming of both the topology and sizing for five post-2000 patented analog and mixed analog-digital circuits. *Proceedings of 2003 Southwest Symposium on Mixed-Signal Design, February 23–25, 2003, Las Vegas, Nevada, U.S.A.* Pages 5–10.
- Stutzman, Warren L. and Thiele, Gary A. 1998. *Antenna Theory and Design*. Second edition. New York, NY: John Wiley and Sons.

- Sweriduk, G. D., Menon, P. K., and Steinberg, M. L. 1998. Robust command augmentation system design using genetic search methods. *Proceedings of 1998 Conference on Guidance, Navigation, and Control*. Reston, VA: American Institute of Aeronautics and Astronautics. Pages 286–294.
- Sweriduk, G. D., Menon, P. K., and Steinberg, M. L. 1999. Design of a pilot-activated recovery system using genetic search methods. *Proceedings of 1998 Conference on Guidance, Navigation, and Control*. Reston, VA: American Institute of Aeronautics and Astronautics.
- Tanese, Reiko. 1989. *Distributed Genetic Algorithm for Function Optimization*. Ph.D. dissertation. Department of Electrical Engineering and Computer Science. University of Michigan.
- Teller, Astro. 1996a. *Evolving Programmers: SMART Mutation*. Technical Report CMU-CS-96. Computer Science Department, Carnegie Mellon University.
- Teller, Astro. 1996b. Evolving programmers: The co-evolution of intelligent recombination operators. In Angeline, Peter J. and Kinnear, Kenneth E. Jr. (editors). *Advances in Genetic Programming 2*. Cambridge, MA: The MIT Press.
- Teller, Astro. 1998. *Algorithm Evolution with Internal Reinforcement for Signal Understanding*. Ph.D. Thesis. Computer Science Department. Carnegie Mellon University. Pittsburgh, Pennsylvania.
- Teller, Astro. 1999. The internal reinforcement of evolving algorithms. In Spector, Lee, Langdon, William B., O'Reilly, Una-May, and Angeline, Peter (editors). 1999. *Advances in Genetic Programming 3*. Cambridge, MA: The MIT Press.
- Teller, Astro, and Veloso, Manuela. 1995a. *Learning Tree Structured Algorithms for Orchestration into an Object Recognition System*. Technical Report CMU-CS-95-101. Computer Science Department, Carnegie Mellon University.
- Teller, Astro, and Veloso, Manuela. 1995b. Program evolution for data mining. In Louis, Sushil (editor). Special Issue on Genetic Algorithms and Knowledge Bases. *The International Journal of Expert Systems*. JAI Press. (3)216–236.
- Teller, Astro, and Veloso, Manuela. 1995c. A controlled experiment: evolution for learning difficult problems. *Proceedings of Seventh Portuguese Conference on Artificial Intelligence*. Springer-Verlag. Pages 165–76.
- Teller, Astro, and Veloso, Manuela. 1995d. Algorithm Evolution for Face Recognition: What Makes a Picture Difficult? *Proceedings of the IEEE International Conference on Evolutionary Computation*. IEEE Press.
- Teller, Astro, and Veloso, Manuela. 1995e. Language Representation Progression in PADO. *Proceedings of AAAI Fall Symposium on Artificial Intelligence*. Menlo Park, CA: AAAI Press.
- Teller, Astro and Veloso, Manuela. 1996. PADO: A new learning architecture for object recognition. In Ikeuchi, Katsushi and Veloso, Manuela (editors). *Symbolic Visual Learning*. Oxford University Press. Pages 81–116.
- Teller, Astro, and Veloso, Manuela. 1997. Neural programming and an internal reinforcement policy. In Yao, Xin, Kim, Jong-Hwan, and Furuhashi, T. (editors). *Simulated Evolution and Learning*. Lecture Notes in Artificial Intelligence. Volume 1285. Heidelberg, Germany: Springer-Verlag. Pages 279–286.
- Thompson, Adrian. 1996. Silicon evolution. In Koza, John R., Goldberg, David E., Fogel, David B., and Riolo, Rick L. (editors). 1996. *Genetic Programming 1996: Proceedings of the First Annual Conference, July 28–31, 1996, Stanford University*. Cambridge, MA: MIT Press. Pages 444–452.
- Thompson, Adrian. 1998. *Hardware Evolution: Automatic Design of Electronic Circuits in Reconfigurable Hardware by Artificial Evolution*. Conference of Professors and Heads of Computing / British Computer Society Distinguished Dissertation series. Berlin: Springer-Verlag.

- Tomita, Masaru, Hashimoto, Kenta, Takahashi, Kouichi, Shimizu, Thomas Simon, Matsuzaki, Yuri, Miyoshi, Fumihiko, Saito, Kanako, Tanida, Sakura, Yugi, Katsuyuki, Venter, J. Craig, Hutchison, Clyde A. III. 1999. E-CELL: Software environment for whole cell simulation. *Bioinformatics*. Volume 15 (1)72–84.
- Turing, Alan M. 1948. Intelligent machinery. Reprinted in Ince, D. C. (editor). 1992. *Mechanical Intelligence: Collected Works of A. M. Turing*. Amsterdam: North Holland. Pages 107–127. Also reprinted in Meltzer, B. and Michie, D. (editors). 1969. *Machine Intelligence 5*. Edinburgh: Edinburgh University Press.
- Turing, Alan M. 1950. Computing machinery and intelligence. *Mind*. 59(236)433–460. Reprinted in Ince, D. C. (editor). 1992. *Mechanical Intelligence: Collected Works of A. M. Turing*. Amsterdam: North Holland. Pages 133–160.
- Uda, S. 1926. Wireless beam of short electric waves. *Journal of the IEE (Japan)*. March 1926. Pages 273–282.
- Uda, S. 1927. Wireless beam of short electric waves. *Journal of the IEE (Japan)*. March 1927. Pages 1209–1219.
- Ullman, Jeffrey D. 1984. *Computational Aspects of VLSI*. Rockville, MD: Computer Science Press.
- Van Valkenburg, M. E. 1982. *Analog Filter Design*. Fort Worth, TX: Harcourt Brace Jovanovich.
- Villagran, Victor and Sbarbaro, Daniel. 1998. A new approach for turning PID controller based on iterative learning. *Proceedings of the 1998 IEEE International Conference on Control Applications*. Volume I. Pages 139–143.
- Vladimirescu, Andrei. 1994. *The SPICE Book*. New York, NY: John Wiley and Sons.
- Voit, Eberhard O. 2000. *Computational Analysis of Biochemical Systems*. Cambridge: Cambridge University Press.
- Wakerly, John F. 1990. *Digital Design Principles and Practices*. Englewood Cliffs, NJ: Prentice Hall.
- Webb, Edwin C. 1992. *Enzyme Nomenclature 1992: Recommendations of the Nomenclature Committee of the International Union of Biochemistry and Molecular Biology*. San Diego, CA: Academic Press.
- Whitley, Darrell, Goldberg, David, Cantu-Paz, Erick, Spector, Lee, Parmee, Ian, and Beyer, Hans-Georg (editors). 2000. *GECCO-2000: Proceedings of the Genetic and Evolutionary Computation Conference, July 10–12, 2000, Las Vegas, Nevada*. San Francisco: Morgan Kaufmann.
- Whitley, Darrell, Gruau, Frederic, and Preatt, Larry. 1995. Cellular encoding applied to neuro-control. In Eshelman, Larry J. (editor). *Proceedings of the Sixth International Conference on Genetic Algorithms*. San Francisco, CA: Morgan Kaufmann. Pages 460–467.
- Whitley, Darrell. 2000. Functions as permutations: Regarding no free lunch, Walsh analysis and summary statistics. In Schoenauer, Marc, Deb, Kalyanmoy, Gunter, Rudolph, Yao, Xin, Lutton, Evelyne, Merelo, Juan Julian, and Schwefel, Hans-Paul (editors). 2000. *Parallel Problem Solving from Nature: 6<sup>th</sup> International Conference, Paris, France, September 2000 Proceedings*. Berlin: Springer. Page 169–178.
- Williams, Arthur B. and Taylor, Fred J. 1995. *Electronic Filter Design Handbook*. Third Edition. New York, NY: McGraw-Hill.
- Witczak, Marcin. 2003. *Identification and Fault Detection of Non-Linear Dynamic Systems*. University of Zielona Gora Press.
- Wolpert, D. H. and Macready, W. G. 1997. No free lunch theorems for optimization. *IEEE Transactions on Evolutionary Computation*. 1(1) 67– 82. April 1997.
- Wong, D. F., Leong, H. W., and Liu, C. L. 1988. *Simulated Annealing for VLSI Design*. Boston, MA: Kluwer.

- Wong, Man Leung and Leung, Kwong Sak. 2000. *Data Mining Using Grammar Based Genetic Programming and Applications*. Amsterdam: Kluwer Academic Publishers.
- Yagi, H. 1928. Beam transmission of ultra short waves. *Proceedings of the IRE*. Volume 26: Pages 714–741. June 1928.
- Yu, Jessen, Keane, Martin A., and Koza, John R. 2000. Automatic design of both topology and tuning of a common parameterized controller for two families of plants using genetic programming. In *Proceedings of Eleventh IEEE International Symposium on Computer-Aided Control System Design (CACSD) Conference and Ninth IEEE International Conference on Control Applications (CCA) Conference, Anchorage, Alaska, September 25–27, 2000*.
- Yuh, Chiou-Hwa, Bolouri, Hamid, and Davidson, Eric H. 1998. Genomic cis-regulatory logic: Experimental and computational analysis of a sea urchin gene. *Science*. 279. Pages 1896–1902.
- Zebulum, Ricardo Salem, Pacheco, Marco Aurelio C., and Vellasco, Marley Maria B. R. 2002. *Evolutionary Electronics: Automatic Design of Electronic Circuits and Systems by Genetic Algorithms*. Boca Raton, FL: CRC Press.
- Ziegler, J. G. and Nichols, N. B. 1942. Optimum settings for automatic controllers. *Transactions of ASME*. (64) 759–768.
- Zitzler, Eckart, Deb, Kalyanmoy, Thiele, Lothar, Coello Coello, Carlos A., and Corne, David (editors). 2001. *Evolutionary Multi-Criterion Optimization, First International Conference, EMO 2001, Zurich, Switzerland, March 2001, Proceedings*. Lecture Notes in Computer Science. Volume 1993. Berlin, Germany: Springer-Verlag.
- Zobel, Otto Julius. 1926. *Electrical Network and Method of Transmitting Electric Currents*. Filed August 9, 1922. U.S. patent 1,603,305. Issued October 19, 1926.
- Zobel, Otto Julius. 1925. *Wave Filter*. Filed January 15, 1921. U.S. patent 1,538,964. Issued May 26, 1925.
- Zobel, Otto Julius. 1928. Distortion correction in electrical circuits with constant resistance networks. *Bell Systems Technical Journal*. July 1928. Page 438.

### Acknowledgment Concerning Figures

Figures 2.1, 4.8, 4.12, 10.4, 16.5, 16.10, 16.11, 16.12, 16.13, and 16.14 of this book were reprinted from *Genetic Programming III: Darwinian Invention and Problem Solving* by John R. Koza, Forrest H Bennett III, David Andre and Martin A. Keane, pages 38, 582, 835, 403, 589, 666, 667, 667, 637, and 641, respectively, Copyright 1999, with permission from Elsevier.

# Index

- Aarts, E. 61, 506  
Aaserud, O. 130  
Abelson, H. 209  
absolute value (ABS<sub>V</sub>) 54, 84  
AC small signal analysis (AC sweep) 187, 295,  
315, 327, 335, 343–4, 349  
active filter 434  
    integrated, dynamically tunable 332  
active lowpass filter 301  
    with free variable for passband boundary 332  
        AI ratio for 339  
        preparatory steps for 333–5  
        results for 335–8  
        routineness for 339  
adder 53, 55, 261  
AI ratio 4–5, 13, 112, 119, 120, 123, 124, 127,  
145, 153, 159, 162, 168, 174, 197, 203, 227,  
275, 278, 291, 300, 312, 324, 332, 339, 348,  
357, 385, 412, 419, 482  
    for genetically evolved results 529  
Alpha 524  
    microprocessor 516  
    parallel computer system 516–17, 523, 525, 527  
Altshuler, E.E. 206–9, 215, 218, 484–5  
amplification 414  
    factor 54  
amplifiers 176, 415  
    40/60 dB amplifier  
        preparatory steps for 364–6  
        results for 366  
    60 dB amplifier problem with layout  
        AI ratio for 203  
        preparatory steps for 197–9  
        results for 199–202  
        routineness for 202–3  
        problem of reducing distortion 413  
analog  
    computational circuits 324  
        design of 425  
    electrical circuits 129–30  
        topology and sizing of 130  
        of naturally occurring genetic operations 29, 31  
    analog-digital circuit 421  
Andersson, B. 62  
Andre, D. 4, 40–1, 45–7, 62–3, 70, 91, 100, 104,  
130, 134–5, 140, 142, 156, 162–3, 169, 174,  
177, 196, 263, 280, 302, 304, 311, 342, 415,  
421, 450, 480, 486–7, 494, 496, 511, 513,  
515, 523, 525, 539, 551  
Angeline, P.J. 47, 62  
antenna-creating program tree 212  
antenna design techniques, conventional 207  
antennas, automatic synthesis of 205  
    AI ratio for 220  
    endfire 208  
    geometry 206–7  
    illustrative problem of 207–9  
    preparatory steps for 212–16  
    repertoire of functions and terminals 209–11  
    results for 216  
    simulation 215  
    wire segments in 69  
Ao Yuan, B.C. 279  
architecture-altering operations 32, 34–5, 72,  
314, 539  
arithmetic functions 34–6  
arithmetic logic unit (ALU) circuit 130  
    two-instruction, automatic synthesis of 159  
    problem  
        AI ratio for 162  
        preparatory steps for 160–61  
        results for 161  
        routineness for 161  
arithmetic-performing subtree 33, 69–71, 103,  
140, 178, 187, 283, 292–3, 308, 326, 343, 434  
Arkin, A. 229–30  
Armstrong, C.M. 15  
Armstrong, E.H. 17, 20  
    positive type of feedback 415  
arrays  
    linear and planar 206  
    thinned, design of 206



- artificial intelligence 3  
 and machine learning, toy problems from  
 various fields 43  
 “artificial-to-intelligence” ratio *see* AI ratio  
 Åström K.J. 50, 57–8, 113–16, 119–20, 122–3,  
 283, 287–9, 292, 295, 367, 375–7, 382  
 Åström and Hägglund  
 block 393  
 four families of plants 291, 367, 370–2, 389,  
 411  
 PID controller 114, 116–18, 122–4, 287–9,  
 295–7, 299, 380, 390, 393–4, 398, 400, 407  
 disturbance rejection ITAE of 387, 394,  
 401, 497  
 maximum sensitivity of 394, 401, 407  
 minimum attenuation of 377, 381, 394  
 performance of 373–4  
 reciprocal of minimum attenuation of 401,  
 407  
 setpoint ITAE of 387, 394, 401, 407  
 transfer function for 370  
 PID tuning rules 22, 27, 368, 370, 380, 384–5,  
 388, 398, 400, 404, 407, 526  
 disturbance rejection ITAE of 377, 381,  
 maximum sensitivity of 377, 381  
 reciprocal of minimum attenuation of 377,  
 381  
 setpoint ITAE of 377, 381  
 sub-controller 391, 404  
 surfaces 374  
 techniques in 115, 283  
 tuning rules 9, 371–2, 369, 374, 391, 412  
 ATP 230, 273  
 cofactor 231, 257  
 AT&T 15, 17, 21  
 attenuator 415  
 audio power amplifier 306  
 automated problem-solving  
 method 101  
 orientations 96  
 automatic controllers 53  
 synthesis, possible approach using genetic  
 programming 62–3  
 automatically defined copy (ADC) 486  
 automatically defined function (ADF) 39–40, 66,  
 68–9, 106–7, 282, 351, 486  
 automatically defined iterations (ADI) 40, 494  
 automatically defined loops (ADL) 40, 495  
 automatically defined recursions (ADR) 40, 495  
 automatically defined stores (ADS) 40, 495  
 Ayur, T.S. 422–3, 437, 452, 553
- Babenezhad, J.N. 425  
 Babovic, V. 47  
 Bade, S.L. 142
- Bagchi, T.P. 93, 480  
 Balakrishnan, K. 47  
 Balanis, C.A. 205, 219  
 balun circuits 427, 450  
 Banzhaf, W. 47, 62  
 Barratt, C.H. 50, 58  
 Becker, D.J. 515  
 beneficial “combination[s] of genes” (schemata)  
 509  
 Bennett III, F. H. 4, 18, 40–1, 45–7, 62–3, 70,  
 80, 91, 100, 104, 110, 118, 123, 127, 130,  
 134–5, 140, 142–3, 151, 156, 157, 161–3,  
 169, 174, 177, 196, 263, 280, 302, 304, 311,  
 342, 415, 421, 450, 486–7, 494–6, 511, 513,  
 515, 523, 525, 539, 551  
 Beowulf-style parallel cluster computer system  
 95, 390, 516–17  
 Beowulf systems, home-built 515  
 Berkeley SPICE, SPICE3 version of 78  
 Bettenhausen, K.D. 62  
 Beyer, H.-G. 47  
 b-galactosidase 222  
 bifurcation point 261, 274  
 Bishop, R.H. 50, 87–8, 104–6, 119  
 Black, H.S. 17–20, 413–14, 417, 419,  
 509, 553  
 negative feedback 413, 415  
 patents 415  
 Blickle, T. 47  
 block diagram 58, 64  
 for controllers 74  
 lines in 55  
 of plant and PID controller 54  
 blocks 53  
 tuning of 54  
 Bode plots 58, 127  
 Bolouri, H. 221, 229  
 Boltzmann equation 61, 506  
 books on genetic programming  
 main points of 42–6  
 Boolean function 154  
 Boutin, N. 306–7, 311  
 Bower, J.M. 229  
 Boyd, S.P. 50, 58  
 Brave, S. 45, 47, 130  
 breath-first order of evaluation 304  
 British Patent Office 21, 300  
 Bryson, A.E. 50  
 Bull, L. 47  
 Burke, E. 47  
 Burke, G.J. 205
- C 42  
 C++ 42  
 Callado-Vides, J. 230

- Callender A. 56–7, 111, 300, 367, 509, 552  
 Callender and Stevenson patent 1939 112, 299  
 Campbell, G.A. 195, 323, 552  
   filter circuit 196  
   ladder topology 8  
   patented ladder filter 324  
 Cantu-Paz, E. 47, 480–1, 515  
 capacitor 84  
   parameterized 497  
   sizing of 318  
 CAP gene 221–2  
 Carley, L.R. 176  
 cascades 480, 486  
 catalysts 234  
 cathode-ray oscilloscopes 136  
 Cauer, W. 552  
   elliptic filter 8, 324  
 Checkers 5  
 Chellapilla, K. 47  
 chemical reaction  
   cycles, preparatory steps 263–7  
   functions 69, 250  
   networks, representation of 263  
   rates of 236  
   types of 234–49  
 Cheng, V.H.L. 61  
 chess 4  
 Chinook checker-playing computer program 5  
 chromosome 503–4, 508  
   for circuit consisting for two identical T-sections 491  
   of offspring 502  
   strings 209, 507  
 Chung, D.H. 157, 552  
 Church-Turing thesis 43  
 Cipriani, S. 424–5, 427, 442, 553  
 circuit-constructing  
   functions 178  
   program tree 132, 139–40, 177, 492, 501  
     developing into single T-section 493  
     evaluation of each individual 187  
     functions in 133  
     preservation of syntactic validity and executability of 501  
   terminals in 133  
 circuits  
   automatic synthesis of 129  
   commercial practicality of genetic programming for 478–81  
   of topology and sizing of 131–5  
   computational 162  
     cubic 425  
   conversion 434  
   defined by chromosomes 501  
   designing, process of 175  
   diagram 131  
   laid-out 175  
   sizing 129, 319, 329, 336  
   topology 129, 329, 336  
     non-symmetric 451  
     and sizing, placement, and routing, automatic synthesis of 175–86, 202  
 closed-loop  
   feedback system 51  
   system bandwidth 115  
 Coelho, L.de S. 61  
 Coello Coello, C.A. 93, 480  
 Cohn, J.M. 176  
 Comisky, W. 219  
 command signal 50, 67  
 commercial circuits 167  
 Comombano, S. 135  
 component-creating functions 178, 179, 305  
   for *npn* transistors, *pnp* transistors 198  
 computational effort 44, 174  
 computational power, exponential growth in 515  
 computer  
   code for implementing genetic programming 42  
   evolution of 159–62  
   power and genetic programming  
     effect of order-of-magnitude on results 526–7  
     increasing, results in synchrony 25  
   programs, automatically creating 45–6  
   systems, five,  
     qualitative nature of results produced by 524  
     used in 15-year period 523–4  
   time 518  
 conditional operators 54, 341  
 connection list 64  
 connective functions 210  
 “constant *K*”  
   highpass filter, design formulas for 352  
   ladder  
     classical 351  
     sections 347  
   lowpass ladder filter 354  
 constrained syntactic structure 33, 38–9, 69, 71, 140, 210, 292–3, 307, 309, 314, 358, 434  
   for program trees 73  
 construction-continuing subtree 140, 198, 343  
 control  
   loops 57  
   parameters 30, 95, 115, 539–49  
   variable 51, 67  
 CONTROLLER\_OUTPUT terminal 67

- controllers 50–2
  - additional representations of 73–86
  - automatic synthesis of 49
  - of topology and tuning of 64–73
  - design
    - considerations for 52–3
    - possible techniques for 58–63
    - genetically evolved 87
    - parameterized, for two families of
      - plants 291
      - AI ratio for 300
      - human-competitiveness of result for 299
      - preparatory steps for 292–6
      - results for 296–300
      - routineness for 300
  - parsimony 402
  - and plant, representation
    - as connection list 75–7
    - as SPICE netlist 78
  - representation
    - by block diagram 53–8
    - as LISP symbolic(s) expression 74
    - in Mathematica 75
    - as program tree 74
    - of transfer function 73
  - signal-processing blocks 62–3, 281
  - synthesis by genetic and evolutionary
    - computation 62
    - topology and tuning for 63
    - for two-lag plant 87
- copy body branch (CBB) 486
- copy control branch (CCB) 486
- Corne, D. 93
- Crawford, L.S. 61
- crossover 29, 31, 34, 501, 503
  - fragment 511
  - and mutation operations, comparison of 511
  - operation 35, 38, 305, 492, 501–2
    - disruptive 302
    - two-offspring version of 32, 38
  - (woofer-tweeter) filter, genetically evolved 497
- cubic function generator 9, 424–7
  - fitness measure for 442
  - results for 461–6
  - test fixture for 432
- cubing circuit 361
- cultural search 7
- current
  - mirrors 480, 486
  - sink 432
- cycles 59
- cyclic graph 134
  - labeled 131–2
- Daida, J. 47
- Darlington emitter-follower 8, 486, 509
  - section 480, 512
- Darlington, S. 552
- Darwinian selection 33, 509
  - probabilistic 506
- Daun-Lindberg, T.C. 422, 424, 427, 440, 553
  - and Miller, parallel FET transistor structure 454
- Davidson, E.H. 221, 230
- Davis, D. 47
- DC
  - operating point analysis 422
  - sweeps 162
- dead time 292, 391
- Deb, K. 47, 93, 480
- Deep Blue 4
- de Garis, H. 135
- delay 54
- delayed-recovery 147
- DELAY function 121
- deletion 72
- Dellinger, J.H. 219
- depth-first evaluation 304–5
- derivative (D-type) control 56
- design of complex structure 49
- Deutsch-Jozsa “early promise” problem 8
- development
  - approach 63
  - process 186
    - analogs of 29
    - in problem solving 500
- developmental genetic programming 41–2
- development-controlling function 140, 178, 186
  - NOOP 198
- development-controlling terminals 146
- Dewell, L.D. 61
- D’haeseller, P. 230
- diacyl-glycerol 230–1, 262, 273
- DIFFERENTIATOR block 56
- digital circuits 129
- digital-to-analog (DAC) converter 425
  - circuit 165
- directors 208
- discrete-time problems 62
- DiSessa, A. 209
- distortion 414
- disturbance rejection *see* integral of time-weighted
  - absolute error
- divider 54
- division (DIVV) 84
- Dobkin, R.C. 551
- Dobkin-Widlar circuit 551
- domain knowledge 96, 99–101
  - human-supplied 101

- dominant pole design technique 369
- donor parents 474–7
- Dorf and Bishop controller 87–8, 104, 109
- Dorf, R.C. 50, 87–8, 104–6, 119
- Dorigo, M. 47
- double-bandpass filter 496
  - circuit, genetically evolved 495–6
- Drechsler, R. 135
- driven elements 207
- DSP-driven algorithm 425
- D-type control 103
- dummy variable (formal parameter) 499
- Dunlap, F. 63, 130, 135, 304
- duplication 72
- Duran, F. 206
  
- E-CELL cell simulation model 231, 234, 266
- Eiben, A.E. 47
- electric filter network 147
- electrical circuit
  - diagram representing 238
  - design process for 129
    - of electrical circuit of resistors and capacitors with gain greater than one 135
- electrical terminology for modeling plants and controllers 52
- embryo 132, 177, 313–14, 342, 428
  - modifiable wires in 139
- embryonic circuit 63
- embryonic neural network 63
- embryonic pattern 63
- embryonic structure, applying functions in
  - program tree of 63
- END terminal 210
- energy level 59
- enzymes 234–5, 279
- Escherichia coli* 221
- established beliefs 413
  - overcoming 20–1
- Euro-GP conferences 47
- evolutionary methods 59
- evolutionary process 103
- executorial steps of genetic programming 10
- explicit test fixture, automatic circuit synthesis
  - without 168–74
  
- fatty acid 230–1, 257
- feedback
  - from plant to controller 50
  - transfer function 118
- field-effect transistors (FETs) 415, 424, 440
  - model IRFZ44 415
- field-programmable analog array (FPAA) 142, 147
- field-programmable gate array (FPGA) 142
- field-programmable transistor array (FPTA) 142, 147
- filter, attenuation of 169
- First International Conference on Evolutionary Multi-Criterion Optimization 93
- FIRST-PRODUCT function 252, 265
- fitness 33, 59
  - cases 33, 139
- fitness measure 12, 30, 33, 35, 59, 131, 145, 230
  - three-element 414
  - two-element 280
- fitness-proportionate selection 37
- fitness-selected parent 510
- fixed hard-wired external entity 139
- fixed-length strings 302, 485
- Fleming, P.J. 61
- floating embryo 169, 307, 333, 428, 479
- floating-point
  - MIPS 426
  - number 210, 484, 504
- Fogel, D.B. 47, 62
- Forgarty, T.C. 47, 135
- Foster, I. 515
- four-argument DIV\_SIGNAL function 66
- Fourier analysis 422, 436–7
- four-rung ladder 194
- Francone, F.D. 47
- free variables 282, 293, 358, 363, 370, 391
- frequency of beneficial genes 509
- frequency-domain
  - analysis 422
  - behavior 501
  - parameters 292
  - simulations 525
- frequency-sweep analyses 436
- frequently-used combinations of components 480
- Freyer, S. 62
- Frost, R. 61, 506
- Fuhrman, S. 230
- function-defining branches 73
- functions
  - repertoire of 65–6, 209
  - set 30
    - identification 11
    - and terminal sets 30, 144
    - and terminals 533–8
- Furuya, T. 135
  
- Gacs-Kurdyumov-Levin (GKL) rule 9
- gain 53
  - block 55–6, 400
  - function 85, 103
- Garey, M.R. 176
- Garrod, D.J. 176

- Garzon, M. 47  
 Gaussian circuits 162  
 Gaussian mutation  
   operation 71  
   on perturbable numerical values 73  
 Gaussian perturbation 71  
 Gelatt, C.D. 61, 506  
 Gen, M. 47  
 genes  
   combination of 507–8, 513  
   deletion 29  
   duplication 29  
 genetic algorithm 59  
   and genetic programming, search by 61  
   operating on fixed-length character strings  
     207–8, 494–5, 503–4  
   operating on variable-length strings 495  
 genetic diversity 20  
 Genetic and Evolutionary Computation  
   Conference (GECCO) 47  
 genetic and evolutionary computation, techniques  
   of 515  
 genetic network problem  
   AI ratio for 227  
   preparatory steps, 224–5  
   results 225  
 genetic networks  
   automatic synthesis of 221  
   functions, repertoire of 223  
   representation by computer programs 223–4  
 genetic operations 34  
 genetic programming 59  
   advanced features of 38–42  
   as automated invention machine 15–23, 530  
   automatic creation of parameterized topologies  
     530  
   executorial steps of 31–8  
   flowchart of genetic programming 32  
   with increasing computer power 531  
   paradigm 43  
   preparatory steps of 29–31  
   sources of additional information 46–8  
   system 96  
 Genetic Programming Conference 47  
 Genetic Programming Problem Solver (GPPS)  
   41, 499  
   architecture-altering operations in 500  
   genetic search method 514  
   genetic switches 69  
   geometry table 205, 207  
 Getreu, I. 129  
 Gilbert, B. 425  
 GLUCOSE 221–2  
 Glycerol 230–1, 253–5, 258  
 Glycerol-3-Phosphate 262  
 Goddard, R. 17  
 Goldberg, D.E. 47, 208, 480, 506, 514–15  
 Goodman, E. 47  
 gradient methods 59  
   search by 60, 505–6, 511–12, 514  
 graph isomorphism algorithm 450  
 greedy search methods 505  
 Green, M. 551  
 Grimbelby, J.B. 135  
 Grover's database search problem 8  
 Gruau, F. 42, 62–3, 132  
  
 Haeusler, J. 551  
 Häggglund, T. 50, 57–8, 113–16, 119–20, 122–3,  
   283, 287–9, 292, 295, 367, 375, 377, 382  
 Halang, W.A. 61  
 Hanan, J. 209–10  
 hardware, evolvable 134–5  
 Hashimoto, K. 229, 231–2, 266  
 Hayes, J.P. 176  
 high-current load circuit 434  
   fitness measure for 440  
   test fixture for 430  
   results for 454–8  
 high-frequency transistors 464, 466  
 high level circuit requirements 175  
 highpass filter 169  
   network 147  
 high-return  
   human-competitive machine intelligence 529  
   meaning of 4  
   of results produced by genetic programming  
     10  
 Higuchi, T. 135  
 hill climbing 59, 505–6, 511–12, 514  
   search by 59–60  
   hits, number of 327  
 Ho, Y.-C. 50  
 Hofstadt, R. 230  
 Holland, J.H. 7, 507–8, 513, 515  
   genetic algorithm 513  
   fundamental theorem of 508  
 Honavar, V. 47  
 Hsu, F.H. 4  
 human-competitiveness 220, 4, 8, 111, 151, 158,  
   195, 299, 382, 411, 418, 481  
   criteria for automatically created result 4  
   meaning of 3–4  
   results in genetic programming 7–10, 26, 46  
 hunting and instability, problems of 56–7  
 Hutchings, J.L. 142  
 Hutchison, C.A.III 229, 231–2, 226  
  
 Iba, H. 47, 135  
 ICONTROL 442–3, 472

- IFGTZ\_DEVELOPMENTAL operator 345, 359–60
- IF\_POSITIVE function 92
- Ikeuchi, A. 422–3, 441, 460, 553
- Ikeuchi-Tokuda circuit 432
- improved general purpose controllers 398
  - AI ratio for 412
  - human-competitiveness of result for 411
  - preparatory steps for 387–90
  - results for 390–410
  - routineness for 412
- improved PID tuning rules
  - AI ratio for 385
  - automatic synthesis of 367
  - human-competitiveness of 382–4
  - preparatory steps for 374–6
  - results for 376–82
- Ince, D.C. 7, 513
- inductor-capacitor rung 509, 512
- inductor, sizing of 319
- information
  - contained in preparatory steps 101
  - stored in population 511
- initial circuit 177
- initial random population of run of genetic programming 102
- in-sample or training cases 330, 372
- Institute of Radio Engineers (IRE) 219
- integral of time-weighted absolute error (ITAE) 52, 78, 86–7, 92, 116–17, 292, 297
  - calculation of 86
  - component of fitness 295
  - for disturbance rejection 292
  - optimum transfer function 87
- integrative (I-type) control 56
- INTEGRATOR function 53, 56, 77
- International Conference on Evolvable Systems 135
- International Society for Genetic and Evolutionary Computation (ISGEC) 47
- intertwined spiral problem 139–42
- invention
  - and evolution, illogical nature of 19–20
  - process, automating 21
- inverter 54, 84
- Irvine, R. 332, 335, 422, 426, 469, 553
- “island” version of parallel genetic programming 516
- isotropic radiator 215
- I-type control 103
- Iwata, M. 135
- Jacob, C. 47
- Jakiela, M. 47
- Jamshidi, M. 61
- Java 42
- Johnson, D.S. 176
- Johnson, J.M. 206
- Johnson, K.S. 324
  - patented “bridged T” filter 324
- Johnson, W.C. 487
- Jones, H. 111, 206, 286, 290, 552
- Jonoska, N. 47
- Kasparov, G. 4
- Katz, R. 135
  - controllers 408
  - PID tuning rules 377
- Keane, M. A. 4, 22–3, 27, 40, 45–7, 62–3, 70, 91, 100, 104, 110, 118, 123, 127, 130, 134–5, 140, 142–3, 151, 156, 157, 161–3, 169, 174, 177, 196, 263, 274, 280, 190, 199, 302, 304, 311, 331, 342, 357, 375, 384, 395, 411, 415, 421, 450, 466, 480, 486–7, 494–6, 511, 513, 515, 523, 525–7, 539, 551
- Kell, D.B. 229–30, 279
- Keller, R. 47, 62
- ketone bodies 230, 233
  - see also* metabolic pathway problem
- Keymeulen, D. 135, 142, 147
- Kinnear, K.E. Jr. 47
- Kirkpatrick, S. 61, 61
- Kitano, H. 42, 63, 132, 230
- KKS (Keane-Koza-Streeter) knock-out time series 266
- knowledge-based methods 101
- Kolb, B. 332, 335, 422, 426, 442, 469, 553
- Korst, J. 61, 506
- Koza, J.R. 4, 22–3, 25, 27, 29, 37–8, 40–3, 45–7, 62–3, 70, 91, 98, 100, 104, 110, 118, 123, 127, 130, 132, 134–5, 139–40, 142–3, 151, 156, 157, 161–3, 169, 174, 177, 196, 219, 221, 263, 274, 280, 282, 290, 299, 302, 304, 311, 331, 342, 357, 375, 384, 395, 411, 415, 421, 450, 466, 480, 486–7, 494–6, 511, 513, 515, 523–7, 531, 539, 551
- Krohling, R.A. 61
- Kruiskamp, M.W. 135
- Kwong, S. 61
- Lackawanna Ferry 16, 19, 413–14, 419
- lac* operon, schematic representation of genetic network, 221–2
- LACTOSE 221–2
- lag 54
  - second-order 54, 66
- Laing, S. 230
- Lamont, G.B. 93, 480
- Lam, T. 62
- Langdon, W.B. 47–8, 481, 508

- Lanza, G. 221, 274  
 Lanzi, P.L. 47  
 Laplace transform variable 74  
 Lee, S.G. 17, 413, 422–3, 427–8, 446, 448, 553  
   circuit 449  
   low voltage balun circuit 447  
   patent 448, 450  
   patented circuit 445–6  
 Leenaerts, D. 135  
 Leong, H.W. 176  
 Leung, K.S. 47  
 LIMITER function 54, 66, 75–6  
 Linden, D.S. 205–9, 215, 218, 484–5  
 Lindenmayer, A. 209–10  
   rewrite rules 63  
   rules for creating structures 42, 132  
   systems 209–10  
 Linux operating system 516–17  
 LISP machine 209, 523–4, 527  
   code 42  
   programming language 35, 64, 251, 255  
   symbolic expressions (S-expressions) 75, 103,  
     107, 131, 206, 230, 264, 342, 360, 362  
   codes 363  
   for crossover (woofer-tweeter) filter 498  
 Liu, C.L. 176  
 Liu, Y. 135  
 logic-driven search 6  
 Logo programming language 209  
 Lohn, J. 135  
 Loomis, W.F. 221, 229  
 low voltage balun circuit  
   fitness measure for 436–7  
   test fixture for 428  
 lowpass/highpass filter  
   results for 344–8  
   with a variable passband boundary, results for  
     350–7  
 lowpass filter 24, 169, 176, 202  
   parameterized 355  
 lowpass filter problem  
   with layout 186  
     AI ratio for 197  
     human-competitiveness of result for 195  
     preparatory steps for 186–8  
     results for 188–95  
   without explicit test fixture  
     AI ratio for 174  
     preparatory steps for 169–73  
     result for 173–4  
     routineness for 174  
 lowpass pre-filter 87, 113  
 lowpass third-order elliptic filter with free variable  
   for modular angle  
     AI ratio for 324  
     results for 318–23  
     routineness for 324  
 lowpass/highpass filter circuit with free variable  
   342  
     AI ratio for 348  
     preparatory steps for 342–4  
 lowpass/highpass filter with variable passband  
   boundary with a free variable 348  
     AI ratio for 357  
     preparatory steps for 349–50  
     routineness for 357  
 low-voltage balun circuit 422–3, 434  
   results for 444–51  
 low-voltage cubic 434  
   function generator 422  
 low-voltage high-current circuit  
   for testing voltage source 422  
   transistor 424  
 Lui, W. 135  
 Macbeth, I. 142, 147  
 machine  
   intelligence 1, 15  
     high-return human-competitive 1, 3–15  
     meaning of 6–7  
   learning 3  
 Macready, W.G. 514  
 Mahfoud, S.W., 506  
 Mange, D. 135  
 Man, K.F. 62  
 Marcano, D. 206  
 Marenbach, P. 62  
 Massey, J. 551  
*mathematica* 64  
 mathematical functions and electrical components,  
   mixing of 83  
 Mathias, K. 47  
 Mats, N. 62  
 Matsuzaki, Y. 229, 231–2, 266  
 Maxwell's equations 205  
 Maziasz, R.L. 176  
 Mazumder, P. 135  
 McAdams, H.H. 221, 229  
 M-derived half-section filter 324  
 measure of merit 59  
 Meltzer, B. 7, 508  
 Mendes, P. 229–30, 279  
 Menon, P.K. 61  
 Messina, P. 515  
 metabolic pathway problem  
   for ketone bodies, synthesis and degradation of  
     275–8  
     AI ratio for 278  
     routineness for 278  
   for phospholipid cycle

- AI ratio for 275
  - results for 267–75
  - metabolic pathways
    - alternative chemical reaction functions 279
    - automatic synthesis of 229
    - designing alternative metabolisms 279–80
    - future work on 278–80
    - minimum amount of data needed 278
    - null enzyme 278
  - metabolism of lactose 222
  - Metropolis algorithm 61, 506
  - Michaelis constant 236
  - Michaelis-Menten
    - equations 229, 236, 238
    - one-substrate 241
    - two-substrate 246–7
    - law 237
    - rate law 245
      - for one-substrate chemical reaction 236
  - Michie, D. 7, 508
  - Michielssen, E. 206
  - migration strategy 549
  - Miller, J.F. 47, 135
  - Miller, M.L. 422, 424, 427, 440, 553
    - parallel FET transistor structure *see*
      - Daun-Lindberg
  - Mittenthal, J.E. 279
  - mixed analog-digital circuits 129, 434
  - mixed analog-digital variable capacitor circuit
    - 422–3
    - fitness measure for 437–40
    - results for 451–4
    - test fixture for 429–30
  - Miyoshi, F. 229, 231–2, 266
  - monoacyl-glycerol 260, 262
  - Moore, G.E. 26, 479, 515, 518, 524
  - Moore's law 26, 28, 479, 515, 518, 521, 532
    - historical perspective on 523
  - Mooreware 28, 532
  - Moretti, G. 129
  - MOSFET transistor 427, 435
  - mRNA 221, 223
  - multi-input circuit 421
  - multiobjective optimization, options 93
  - multi-output circuit 421
  - multiple interacting programs 62
  - multiplication (MULV) 84
  - multiplier 54
  - multipolar single-stage filters 426
  - multi-rung ladder filter 509, 512
  - Muntz, E. 469
  - Muntzing 469
  - mutation 29, 32, 34, 72, 492, 503
    - and crossover, viewing in common framework
      - 510
      - and reproduction operations 35
      - operation 37, 511–12, 514
        - in genetic programming and genetic algorithm 507
  - mutual coupling 207
  - Mydlowec, W. 110, 18, 123, 127, 143, 151, 157, 161, 165, 221, 274, 290, 331, 357
  - NAND function, circuit for 9, 130, 153–9, 163
    - problem
      - AI ratio for 149
      - human-competitiveness of result for 158
      - preparatory steps for 154–6
      - results for 157–8
      - routineness for 159
    - textbook TTL 157, 158
  - NASA/DoD Conference on Evolvable Hardware 135
  - NEC *see* Numerical Electromagnetics Code
  - negative feedback 51, 98, 297, 509
    - amplifier 17
    - invention of 414–15
    - reinvention of 413
  - Nelson, R.J. 552
  - netlist 90, 141, 238
  - network of chemical reactions
    - analog electrical circuit 231
    - constrained syntactic structure 251
    - diagram representing 238
    - problem of synthesis of 274
      - corresponding to metabolic pathway 251, 259
    - program tree 231
    - repertoire of functions in 250
    - representation as 250–5
  - reaction network 231
  - repertoire of terminals 251
  - representation
    - by computer programs 250–63
    - as analog electrical circuit 259–62
    - as symbolic expression 231, 255
    - as system of nonlinear differential equations 256
  - sizing of 229
  - SPICE netlist 231
  - system, nonlinear differential equations 231
  - topology of 229
- neural networks 139
- Newbold, W.F. 551
- Newborn, M. 4
- Newton, A.R. 65, 78, 238, 480
- nicheware 531
- Nichols, N.B. 367, 382
- Nielsen, I.R. 130
- Niwa, T. 135



- n*-lag plants, family of 372
- Noah run 402
- NODE function for connecting distant points 302–3
- No Free Lunch Theorems 514
- non-greedy nature of genetic methods 505–6
- nonlinear mapping (NLM) 69, 335, 405, 407
- non-minimal phase plant problem 125
  - AI ratio for 127
  - preparatory steps for 125–7
  - results for 125
  - routineness for 127
- non-PID controller 9, 370, 518, 526
  - genetically evolved 408, 509
- non-trivial analog electrical circuits 486
- Nordin, P. 47
- npn* transistor 201
- number and complexity of simulations 526
- Numerical Electromagnetics Code* (NEC) 205
  - antenna 213–14
  - code 215
  - simulator 205, 213–14, 220
- numerical parameter values, establishing
  - three approaches for 69–73
- Nyquist criterion 136
- objective function 59
- O'Connor, D.G. 552
- offspring
  - circuit 503
  - programs population of 33
- Ogata, K. 50
- Ohr, S. 142, 147
- Olmer, M. 62
- Olsson, J.R. 43
  - ADATE system 43
- one-argument
  - ABS\_SIGNAL function 66
  - DELAY function 66
  - DIFFERENTIATOR function 65
  - FIRST-PRODUCT function 250
  - GAIN function 77
  - INTEGRATOR function 65
  - INVERTER function 65
  - LANDMARK function 210
  - NOOP (“no operation”) function 186
  - SECOND-PRODUCT function 250
  - TAKEOFF function 388
  - transistor-creating NPN-TRANSISTOR-LAYOUT function 180
  - TURN-RIGHT function 209
- one-input, one-output initial circuit 178
  - with one floating modifiable wire 333, 358
  - with two modifiable wires 314
- one-offspring crossover 72
- one-substrate
  - one-product reaction 234–43
  - two-product chemical reaction 243–4
    - function 253
    - illustrative circuit for 244
- ontogenetic programming 341
- open loop systems 51
- optimal or near-optimal entity 59
- order-of-magnitude increase in computer power 26–8
- O'Reilly, U.-M. 47
- Osyczka, A. 93, 480
- overfitting 327
- overshoot 52–3, 99
- P (proportional)
  - block 369
  - element of controller 74
- Pacheco, M.A.C. 135
- parachutists 506
- parallel cluster computer systems 515
- parallel implementation and computer time 515
- PARALLEL-LAYOUT family of four-argument functions 183
- PARALLEL\_NEW function 308–9, 314, 434
  - five-argument 304
- parallel processing 26
- parallel state-space search, massive 4–5
- parameter values (tuning) for a PID-type controller 110
- parent
  - fitness-selected 511
  - randomly selected 511
  - receiving 476–7
- Parmee, I. 47
- parsimony 323, 389, 409, 414, 443, 469, 472–3
  - element of fitness measure 398, 404, 470
  - equational 310, 323
  - penalty 390, 437, 443
  - progressive improvement in 405
  - types of 310
- Parsytec PowerPC® parallel machine 523–5
  - 64-node 515
- passband 168
  - boundary 24, 312, 321, 476
  - deviation 323
    - of filter, maximum 321
  - ripple 169
  - voltage, minimum acceptable 316
- passing parameters to substructures 497–9
- passive lowpass filter 301
  - with free variable for passband boundary 324
    - AI ratio for 331
    - preparatory steps for 325–7
    - results for 328–31
    - routineness for 331
- patch antennas 206

- patentability 2
- patentable new inventions 2
  - produced by genetic programming 22–3
- patented inventions
- patent law, doctrine of equivalencies of 454
- Patent Office
  - criteria for patent-worthiness 152, 196, 419
  - requirement 449
  - 20th-century and 21st-century, duplicating 2
  - generated by genetic programming 551–3
- payoff 59
- Pease, R. 135–6, 147, 425, 469
  - challenge 135–6, 145
- Pederson, D.O. 65, 78, 238, 480
- Pentium II parallel machine 527
  - 1,000-node 26
- Pentium parallel systems 517–18, 523–4
- Perez-Uribe, A. 135
- performance penalty 437, 443
- permease 222
- perturbable numerical values 69–70, 115, 375
- petacycles, number of 518
- Petaflop computing 515
- Pezeshk, S. 47
- Philbrick circuit 9, 130, 136, 151–3, 159
  - defining characteristics of 149
  - one-input, one-output initial circuit with one modifiable wire 148
  - reinvention of 147–53
- Philbrick circuit problem
  - AI ratio for 153
  - human-competitiveness of the result for 151–2
  - preparatory steps for 148–50
  - results for 150
  - routineness for 152–3
- Philbrick, G. 136, 142, 147, 552
  - patent 149
- phospholipid cycle 231–4, 262
  - see also* metabolic pathway problem
- phosphatidylglycerol 242
- “PI” (proportional-integrative) controller 57
- PID (proportional, integrative, and derivative) block 404
- PID compensator 87, 109, 113
- PID controller 56–8, 77–8, 85, 111, 117, 400, 509
  - rediscovery by genetic programming 299
  - with setpoint weighting 289
  - tuning of 483–4
  - tuning rules 50
    - genetically evolved 377, 384–5
    - patentability 384
    - quality of 367
- PID-D2 controller 111, 286, 291
- PID sub-controller 509
- PID technology, conventional 87
- plant 50
  - representing 67–8
  - response 50, 52, 54
  - test bed of 371–4
  - two-lag 87–113
  - ultimate gain 375, 391
- PLANT\_OUTPUT terminal 67, 106
- pnp* transistor 201
- PNP-TRANSISTOR-LAYOUT function 180
- point-labeled tree 74
- poison pill 509, 512
- pole
  - cancellation 92
  - elimination 92
- Poli, R. 47, 481, 508
- population
  - of randomly generated computer programs 31
  - size 390
- population-based methods employing recombination 514
- post-2000 patent circuits, six, 422
  - AI ratio for 482
  - automated re-invention of 421
  - computer time consumed 478
  - human-competitiveness of results for 481
  - preparatory steps for 428–44
- problems
  - inputs, outputs, and power sources for 434
  - uniformity of treatment of six problems 426–8
  - routineness for 481
- Potter, M.A. 47
- POW function 388
- Preatt, L. 62
- preparatory steps
  - five major, for basic version of genetic programming 10–11
  - knowledge incorporated into 96
- printed circuit board 177
- prior art balun circuit 446, 450
- problem
  - characteristics
    - suggesting use of genetic algorithm 483–4
    - suggesting use of genetic programming 484–514
  - computer time consumed 519–21
  - involving low pass filter 203
    - suitability for genetic programming 483
  - problem-independent executional steps of run of genetic programming 10
  - problem-solving method 4
- problems
  - 40/60 dB amplifier 364–6
    - active lowpass filter with free variable for passband boundary 332–9

- problems *contd.*
- arithmetic logic unit (ALU) circuit 159–62
  - controller for two families of plants 291–300
  - cubic function generator 461–6
  - high-current load circuit 454–8
  - improved PID tuning rules 374–85
  - layout of amplifier 197–203
  - lowpass filter
    - layout of 186–97
    - without explicit test fixture 169–74
  - lowpass/highpass filter
    - circuit with free variable 342–8
    - with variable passband boundary with a free variable 348–57
  - low-voltage balun circuit 422–3, 434
  - metabolic pathway
    - for ketone bodies 275–8
    - for phospholipid cycle 267–75
  - mixed analog-digital variable capacitor circuit 451–4
  - NAND circuit 153–9
  - parameterized controllers (with two free variables) 387–412
  - passive lowpass filter with free variable for passband boundary 324–32
  - Philbrick circuit problem 148–53
  - quadratic/cubic computational circuit with free variable 358–64
  - quadratic polynomial 34–8
  - RC circuit with gain greater than two 142–7
  - square root circuit 162–8
  - third-order elliptic lowpass filter with a free variable for the modular angle 312–24
  - three-lag plant 113–20
    - with a five-second delay 120–4
    - with free variable, parameterized controller for 282–92
  - tunable integrated active filter 466–78
  - two-lag plant 88–113
  - voltage-current conversion circuit 431–58
  - Yagi-Uda antenna 216–19
- programmable microprocessors 381
- program architecture and architecture-altering operations 40
- program trees 35–6, 62–4, 131, 206–7, 230, 263
  - converted to block diagram 63
  - in initial random generation 68
  - representation
    - improved 278
    - of PID controller 75
  - types of functions in 89
- promiseware 531
- Prusinkiewicz, P. 209–10
- Ptashne, M. 221
- P-type control 56, 103
- Q transistor-creating function, new 305–6
  - six-argument 306
- quadratic equation 504
- quadratic polynomial 34–8
- quadratic/cubic computational circuit 358
  - preparatory steps for 358–60
  - results for 360–3
- Quarles, T. 65, 78, 238, 480
- Rahmat-Samii, Y. 206
- rate laws 236
- RC circuit 159
  - with gain greater than two
    - AI ratio for 145–7
    - results for 142–3
- reaction function 244
- reactor 264
- recombination
  - (crossover) operation 505
  - with population in genetic methods 506–14
- reference
  - controlled plant 289
  - controller 289
  - plant 289
  - signal 50, 54
- REFERENCE\_SIGNAL terminal 67, 106
- reflectors 208
- regulatory genes 221
- regulatory proteins 221
- REPRESSOR gene 221–2
- reproduction operation 29, 32, 34, 37, 72, 492
- Riccati equations, algebraic 58
- Rice, J.P. 40, 43, 46, 62, 282
- Riolo, R.L. 47
- rise time 52
- RLC circuit 332
  - model 476–7
- Robertson, G. 515
- root loci 58
- Ross, J. 229–30
- Roughgarden, J. 62
- “routine”, meaning of 5–6
- routineness of transition in problems
  - circuit synthesis without layout to circuit synthesis with layout 196
  - controller synthesis to circuit synthesis 143
  - non-parameterized circuit to parameterized circuit 311
  - non-parameterized controller to parameterized controller 290–1
  - parameterized topologies for controllers to PID tuning rules 385
  - parameterized topology without conditional developmental operators to problem with conditional developmental operators 34

- synthesizing controllers, circuits, circuits with layout, antennas, and genetic networks to synthesis of network of chemical reactions 274
- synthesizing controllers, circuits, and circuit layout to synthesizing an antenna 219–20
- synthesizing controllers, circuits, circuits with layout, and antennas to genetic network synthesis 226–8
- Roy, R. 47
- RTL (Resistor-Transistor Logic) 157
- Rudnick, E.M. 135
- Rudolph, G.47
- Rutenbar, R.A. 176
- Ryan, C. 47
- Saito, K. 229, 231–2, 266
- Salamon, P. 61, 506
- Salmon, J. 515
- Samuel A. 3, 6, 411
  - criterion for artificial intelligence and machine learning 112, 159, 196, 300, 384, 412, 419, 481
- Sanchez, E. 135
- Sangiovanni-Vincentelli, A. 65, 78, 480
- Savarese, D.F. 515
- sawtooth time series 265
- Sbarbaro, D. 125–6
- scalable automatic programming 43
- Schaeffer, J. 5
- Scheeline, A. 279
- schemata, changing mix of 507
- Schema Theorem 513
- Schoenauer, M. 47
- Schultz, A.C. 47
- search techniques 59
- Sechen, C. 176
- SECOND-PRODUCT function 252, 265
- selector function 251
- semantics-preserving architecture-altering operations 521
- semi-isolated subpopulations (demes) of individuals 517
- Sen, S. 47
- sensor noise 53, 292
  - attenuation 373
- serial computer 25
- series composition 495
- SERIES-LAYOUT function 182
- setpoint 50, 67
  - weighting 287, 369–70
- settling time 52
- S-expressions *see* LISP
- Shapiro, L. 221, 229
- Sheingold, D.H. 425
- Shen, P. 229–30
- Shimizu, T.S. 229, 231–2, 266
- Shipman, J. 515
- Sibani, P. 61, 506
- signal-processing
  - blocks 74–5, 69, 77, 389
  - functions 53, 66, 98
- silicon wafer 177
- simulated annealing 59–60, 511–12, 514
  - and genetic methods 506
  - search by 61
- single gene value 507–8
- single numerical value 99
  - of fitness 132
- single parental program tree 510
- single perturbable numerical value 198
- Sipper, M. 135
- sizing 229
- Smith, P.H. 515
- Smith, R.E. 47
- Smith, S.F. 485, 495
  - genetic algorithm operating on variable-length strings 486
- soccer-playing program 8
- soloware 531
- solution, prespecified 485
- Somogyi, R. 230
- source resistor 190
  - RSRC 191
- specificity order 507
- Spector, L. 42, 47, 63, 132
- SPICE (Simulation Program with Integrated Circuit Emphasis) 65, 78, 160, 165, 167, 239, 247, 309, 315, 335, 343, 431, 443
  - commands 91
  - DC sweep 199
  - input file for PID controller, a two-lag plant, and an in-line calculation of ITAE 79–81
  - mathematical functions in 83
  - netlist 64–5, 131, 265
  - simulation 86, 94, 290, 299, 376
  - simulator 65, 78, 91, 93, 99, 100, 107, 141, 146, 156, 167, 170, 187, 205, 213, 220, 238, 265–6, 284–5, 294, 295, 373, 375–6, 389, 391
    - subcircuit, definition in 83
- SPICE3 simulator 480
- square root circuit
  - AI ratio for 168
  - preparatory steps for 162
  - results for 163
  - routineness for 168
- square root computational circuit 130
- squaring circuit 360–1

- Sripamong, T. 480  
 standard block diagram manipulations 109, 117  
 state-space search, massive parallel 4–5  
 Steinberg, M.L. 62  
 Steinmetz, C. P. 18  
 Stender, J. 515  
 Stephens, C.R. 508  
 Sterling, T.L. 515  
 Sternberg, P.W. 221, 229  
 Steudel, G.W. 551  
 Stevenson, A. 56–7, 111, 300, 367, 509, 552  
 Stiffelman, O. 110, 118, 127, 143, 151, 161, 165, 280, 515  
 Stoffel, K. 42, 63, 132  
 Stoica, A. 135, 142, 147  
 stopband 169, 325  
   attenuation 321  
   boundary 312, 316  
   ripple 169, 325, 344  
 Streeter, M.J. 22–3, 27, 375, 384, 395, 411, 466, 526–7  
 strong typing 39  
 Stutzman, W.L. 205  
 subcircuit definition for derivative (DIFFB) 85  
 sub-string producing T-section 495  
 substructures  
   hierarchical references among 496  
   number of 495–6  
   arguments possessed by 500  
   reuse of 486–95  
   type of 499–500  
 subtractor 54  
 subtree 37  
   implementing negative feedback 512  
 sum-integrator 238, 240, 246, 249  
 Svensson, P. 62  
 Sweriduk, G.D. 62  
 symbolic expression 34, 64, 131  
 symbolic regression 34–5  
 symmetric antenna 213  
 symmetry-breaking procedure using geometric coordinates 303–4  
 system  
   bandwidth 106  
   identification 34–5  
  
 T.J. Watson Research Center 4  
 Tackett, W.A. 41  
 Takahashi, K. 229, 231–2, 266  
 TAKEOFF functions 389  
 takeoff point reference terminal 388  
 Takeshian, A.A. 424–5, 427, 442, 553  
 Tanaka, K. 135  
 Tanaka, T. 135  
 Tanese, R. 515  
  
 Tang, K.S. 61  
 Tanida, S. 229, 231–2, 266  
 Taylor, F.J. 312–13, 320, 487  
 Teller, A. 62  
 Temes, G.C. 425  
 terminal HALF-MM-WIRE 210  
 terminal set 71  
   identification 11  
 terminals, repertoire of 67  
 termination criterion 31, 35  
   and results designation 95  
 Terrell, W.H. 157, 552  
 test fixtures 132, 139, 177, 342, 428  
 Tettamanzi, A.G.B. 47  
 Texas Instruments LISP machine *see* LISP  
 Thiele, G.A. 205  
 Thiele, L. 93, 480  
 third-order elliptic filter 319, 323  
 third-order elliptic lowpass filter 301  
   with free variable for modular angle 312–24  
 Thompson, A. 135, 142  
 Thomson, P. 135  
 three-argument  
   ADDITION function 77  
   addition subcircuit 84–5  
   IFGTZ\_DEVELOPMENTAL operator 342  
   IF operators 224  
   IF\_POSITIVE function 66  
   LAG2 66  
   LIMITER function 66, 77  
   LIMIT subcircuit 86  
   THREE\_GROUND function 171, 492–3  
 three-bit digital register 429  
 three-lag blocks 391  
 three-lag plant 113–20, 281, 372  
 three-lag plant problem  
   AI ratio for 119–20  
   preparatory steps for the 114–15  
   results for 115–18  
   routineness for 119  
 three-lag plant with five-second delay 120  
   AI ratio for 123–4  
   preparatory steps for 120–2  
   results for 122–3  
   routineness for 123  
 three-lag plant with free variable, parameterized  
   controller for 282–92  
   AI ratio 291–2  
   preparatory steps 283–6  
   results for 286–90  
 three-ported automatically defined function 497–8  
 three-ported subcircuits 480  
   produced by automatically defined function 496

- three-ported voltage divider subcircuits 480
- three-way decomposition 5
- time constant 391
- time-derivative of deviation 57
- time-domain
  - analysis 421
  - functions 65
  - signals 55
  - simulations 525
  - two parameters 368
- time-integral of deviation 57
- time-steps 59
- time-weighted absolute error *see* integral of time-weighted absolute error (ITAE)
- Tinsley, M. 5
- Tokuda, N. 422–3, 441, 460, 553
- Tomassini, M. 47, 135
- Tomita, M. 229, 231–2, 266
- topologies, parameterized 2, 67
  - automatic creation by genetic programming 23–5
  - for circuits
    - automatic synthesis of 301
    - five new techniques 301–6
  - with conditional developmental operators for circuits, automatic synthesis of 341
  - containing free variables 504
  - for controllers
    - automatic synthesis of 281
    - for multiple plants 291
    - improved, with free variable, automatic synthesis of 387
- topology
  - of controller 55
  - of PID controller with nonzero setpoint
    - weighting of reference signal 369
  - for PID-D2 9
  - and sizing of networks of chemical reactions, automatic synthesis of 230–1
- topology-modifying FLIP function 140
- topology-modifying functions 178, 181–6, 305
  - for series 198
- topology-modifying SERIES function 140
- total harmonic distortion (THD) 414–15, 436–7, 445
- Toumazou, C. 480
- tournament selection 37
- “toy” (proof of principle) problems 43
- training cases 139
- transfer function 64, 109
  - of two-lag plant 87
- transfer of information 507
- transient phenomena 324
- transistor-creating functions 303
- transistor models, (*nmos*) and (*pmos*) 435
- Transtech® transputer machine 525
  - 64-node 523
- trees, functions and terminals in 73
- T-sections 487, 489, 491, 501
  - cascade of identical 487
  - circuit
    - consisting of single, 487, 491
    - consisting of cascade of six identical 489
    - consisting of cascade of two identical 488
- T-shaped subcircuit 487
- TTL (Transistor-Transistor Logic) 157
- tunable integrated 434
  - active filter 422, 426
    - fitness measure for 442–4
    - patented circuit for 467
    - results 466–78
    - test fixture for 432
- tuning 58
  - rules for parameterized PID controller, automatic synthesis of 281
- Turing, A. 1, 6–7, 508, 513
- turtle-controlling functions and terminals 211
- two-argument
  - addition 84
    - subtraction, multiplication, and division functions 66
  - address 391
  - ADD\_SIGNAL, SUB\_SIGNAL, and MULT\_SIGNAL functions 65
  - capacitor-creating LAYOUT-C function 179
  - DIFFERENTIAL\_INPUT\_INTEGRATOR function 65
  - DRAW function 209
  - GAIN function 65
  - inductor-creating L-LAYOUT function 188
  - INPUT\_0 function 170
  - LAG function 66, 77
  - LEAD function 66
  - NODE function 303
  - OUTPUT\_0 function 170
  - POW function 375
  - REPEAT function 209
  - SERIES-LAYOUT function 181
  - SUBTRACT function 77
  - TRANSLATE-RIGHT function 210
  - TWO\_GROUND function 171
- two-dimensional 6 × 11 toroidal mesh 95
- two-input, one-output initial circuit 155
- two-lag plant problem 96
  - AI ratio for 112–13
  - choice of control parameters for 100
  - fitness measure for 90
  - genetically evolved solution to 109
  - high-level requirements for 90
  - human-competitiveness of the result for 111–12

- two-lag plant problem *contd.*
  - preparatory steps for 88
  - results for 102–10
  - terminal set in 97
  - transition to three-lag plant problem 119
- TWO\_LEAD function 171, 433
  - for inserting two-leaded components, new 305
- two-offspring crossover operation 36
- two-substrate
  - one-product chemical reaction function 252
  - one-product reaction 244–8
  - two-product reaction 248–50
- U.S. Patent Office 21, 300
- U.S. patents 417, 426, 442, 446–7, 451–2, 456–8, 460–2, 464, 469–70, 474, 478
- Uda, S. 219
- ULIMIT function 388
- Ullman, J.D. 176
- ultimate gain 292, 368
- ultimate period 292, 368, 391
- unbalanced coaxial video source 429
- United States Code* 21–2, 111, 152, 384, 449
- unity-gain follower 136
- vacuum tube transistor 414
- vagueware 531
- value-setting subtrees 70–2, 172, 198
- Van Veldhuizen, D.A. 93, 480
- variable capacitor circuit 434
- variable-length chromosomes 485
- Vecchi, M.P. 61, 506
- Vellasco, M.M.B.R. 135
- Veloso, M. 62
- Venter, J. C. 229, 231–2, 266
- VIA and PAIR\_CONNECT functions 302–3
- vias 176, 184
- VIA-TO-GROUND-LAYOUT family of
  - three-argument functions 184
- Villagran and Sbarbaro controller 125
- Villagran, V. 125–6
- Vladimirescu, A. 414, 436
- Voigt, H.-M. 47
- Voit, E.O. 221, 229
- voltage
  - adders 238, 244, 246, 249
  - divider subcircuits 486
  - gain stages 480, 486
  - source 238, 246, 249
- voltage-controlled current source (VCCS) 84
- voltage-current 434
  - conversion circuit 422–3
  - fitness measure for 441–2
  - results for 458
  - test fixture for 431
- V-shaped element 216
- VSWR 214–15
- Waelbroeck, H. 508
- Wegener, J. 47
- weighted reference signal 369
- Wen, X. 230
- Westinghouse's "nearly universal idiom" 17
- Whitley, D. 47, 62, 514
- Widlar, R. J. 551
- Williams, A.B. 312–13, 320, 487
- wire antennas 206
  - design of 206, 484
  - method-of-moments (MoM) simulator for 205
- Wolpert, D.H. 514
- Wong, D.F. 176
- Wong, M.L. 47
- woofer speaker of hi-fi system 23
- Workshop of Genetic Programming Theory and Practice 47
- Wu, A. 47
- Yagi, H. 219
- Yagi-Uda antenna 207–8, 220, 485
  - results 216–19
  - topology for 219
- Yasunaga, M. 135
- yield, return measured in terms of A-to-I ratio 5
- Yu, J. 110, 118, 123, 127, 143, 151, 157, 161, 165, 219, 274, 290, 299, 331, 357
- Yugi, K. 229, 231–2, 266
- Yuh, C.-H. 221, 229
- Yousefpor, M. 62
- Zebulum, R.S. 135, 142, 147
- zero-argument
  - automatically defined functions 67
  - END function 141, 186
  - SAFE\_CUT function 141
- Ziegler, J.G. 367, 382
- Ziegler-Nichols
  - PID tuning rules 367
  - tuning rules 9, 22, 27, 368–9, 382, 384–5, 411, 526
- Zitzler, E. 93, 480
- Zobel, O.J. 307, 323, 552
  - "M-derived half section" and "constant K" filter sections 8
- Zobel network problem involving two free variables 301–2, 306–7, 311, 323
  - AI ratio 312
  - preparatory steps for 307–10
  - results 310–11
  - simple 518

# Disclaimer

This DISK (DVD) is distributed by Kluwer Academic Publishers with **\*ABSOLUTELY NO SUPPORT\*** and **\*NO WARRANTY\*** from Kluwer Academic Publishers.

Use or reproduction of the information provided on this DISK (DVD) for commercial gain is strictly prohibited. Explicit permission is given for the reproduction and use of this information in an instructional setting provided proper reference is given to the original source.

Kluwer Academic Publishers shall not be liable for damage in connection with, or arising out of, the furnishing, performance or use of this DISK (DVD).