Expressive Genetic Programming: Concepts and Applications

A Tutorial at the Genetic and Evolutionary Computation Conference (GECCO-2017, Berlin)

This is an updated version of the tutorial of the same name from GECCO-2016

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ACM ISBN 978-1-4503-4939-0/17/07. http://dx.doi.org/10.1145/3067695.3067699

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Instructors (2)

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Scope and Content (1)

The language used to express evolving programs can significantly impact the dynamics and problem-solving capabilities of a genetic programming system. In GP these impacts are driven by far more than the absolute computational power of the languages used; just because a computation is theoretically possible in a language, doesn't mean it's readily discoverable or leveraged by evolution. Highly expressive languages can facilitate the evolution of programs for any computable function using, as appropriate, multiple data types, evolved subroutines, evolved control structures, evolved data structures, and evolved modular program and data architectures. In some cases expressive languages can even support the evolution of programs that express methods for their own reproduction and variation (and hence for the evolution of their offspring).

This tutorial will present a range of approaches that have been taken for evolving programs in expressive programming languages. We will then provide a detailed introduction to the Push programming language, which was designed specifically for expressiveness in genetic programming systems. Push programs are syntactically unconstrained but can nonetheless make use of multiple data types and express arbitrary control structures, supporting the evolution of complex, modular programs in a particularly simple and flexible way.

Scope and Content (2)

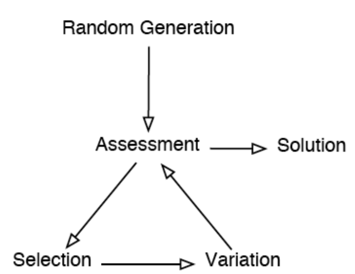
Interleaved with our description of the Push language will be demonstrations of the use of analytical tools such as graph databases to explore ways in which evolved Push programs are actually taking advantage of the language's expressive features. We will illustrate, for example, the effective use of multiple types and type-appropriate functions, the evolution and modification of code blocks and looping/recursive constructs, and the ability of Push programs to handle multiple, potentially related tasks.

We'll conclude with a brief review of over a decade of Push-based research, including the production of human-competitive results, along with recent enhancements to Push that are intended to support the evolution of complex and robust software systems.

Course Agenda

- Genetic programming
- Expressiveness and evolvability
- The Push programming language and PushGP
- Demos
- Results
- Ongoing Research

Evolutionary Computation



Genetic Programming

- Evolutionary computing to produce executable computer programs
- Programs are assessed by executing them
- Automatic programming; producing software

Program Representations

- Lisp-style symbolic expressions (Koza, ...)
- Purely functional/lambda expressions (Walsh, Yu, ...)
- Linear sequences of machine/byte code (Nordin et al., ...)
- Artificial assembly-like languages (Ray, Adami, ...)
- Stack-based languages (Perkis, Spector, Stoffel, Tchernev, ...)
- Graph-structured programs (Teller, Globus, ...)
- Object hierarchies (Bruce, Abbott, Schmutter, Lucas, ...)
- Fuzzy rule systems (Tunstel, Jamshidi, ...)
- Logic programs (Osborn, Charif, Lamas, Dubossarsky, ...)
- Strings, grammar-mapped to arbitrary languages (O'Neill, Ryan, McKay, ...)

Mutating Lisp (1)

```
(+ (* X Y)
   (+ 4 (- Z 23)))
```

Mutating Lisp (2)

```
(+ (* X Y)
   (+ 4 (- Z 23)))
```

Mutating Lisp (3)

```
(+ (- (+ 2 2) Z)
   (+ 4 (- Z 23)))
```

Recombining Lisp

```
(+ (* X Y)
   (+ 4 (- Z 23)))

(- (* 17 (+ 2 X))
   (* (- (* 2 Z) 1)
      (+ 14 (/ Y X))))

(+ (- (* 2 Z) 1)
   (+ 4 (- Z 23)))
```

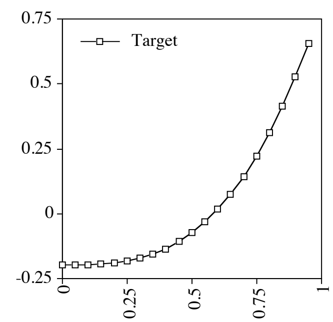
Symbolic Regression

- A simple example
- Given a set of data points, evolve a program that produces y from x.
- Primordial ooze: +, -, *, %, x, 0.1
- Fitness = error (smaller is better)

Genetic Programming Parameters

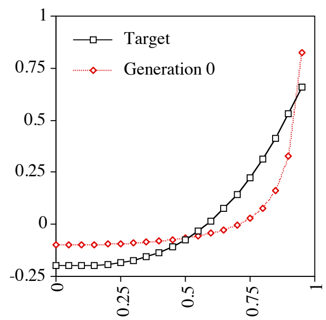
- Maximum number of Generations: 51
- Size of Population: 1000
- Maximum depth of new individuals: 6
- Maximum depth of new subtrees for mutants: 4
- Maximum depth of individuals after crossover: 17
- Fitness-proportionate reproduction fraction: 0.1
- Crossover at any point fraction: 0.3
- Crossover at function points fraction: 0.5
- Selection method: FITNESS-PROPORTIONATE
- Generation method: RAMPED-HALF-AND-HALF
- Randomizer seed: 1.2

Evolving $y = x^3 - 0.2$



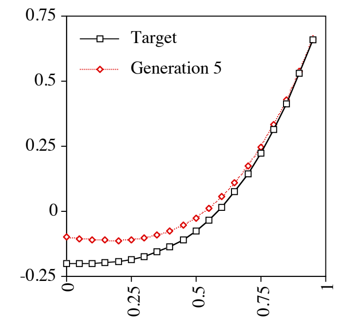
Best Program, Gen 0

```
(- (% (* 0.1
         (* X X))
      (- (% 0.1 0.1)
         (* X X)))
   0.1)
```



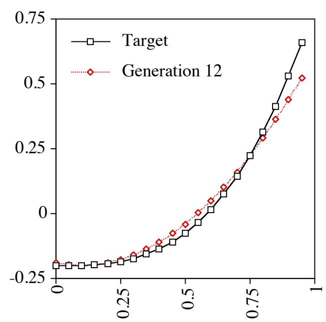
Best Program, Gen 5

```
(- (* (* (% X 0.1)
         (* 0.1 X))
      (- X
         (% 0.1 X)))
   0.1)
```



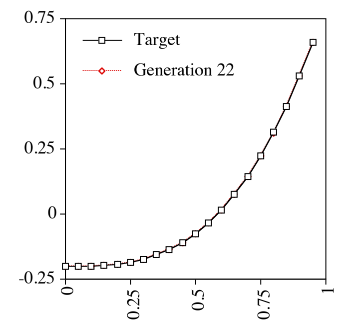
Best Program, Gen 12

```
(+ (- (- 0.1
         (- 0.1
            (- (* X X)
               (+ 0.1
                  (- 0.1
                     (* 0.1
                        0.1))))))
      (* X
         (* (% 0.1
               (% (* (* (- 0.1 0.1)
                        (+ X
                           (- 0.1 0.1)))
                     X)
                  (+ X (+ (- X 0.1)
                          (* X X)))))
            (+ 0.1 (+ 0.1 X)))))
   (* X X))
```



Best Program, Gen 22

```
(- (- (* X (* X X))
      0.1)
   0.1)
```



Expressiveness

- Turing machine tables
- Lambda calculus expressions
- Partial recursive functions
- Register machine programs
- Assembly language programs
- etc.

Evolvability

- The fact that a computation **can be expressed** in a formalism does **not** imply that it **will be produced** in by a human programmer **or** by evolution.
- Research program:
  1. Provide expressiveness
  2. Study/enhance evolvability

Data/Control Structure

- Data abstraction and organization

  Data types, variables, data structures, name spaces, ...

- Control abstraction and organization

  Conditionals, loops, modules, threads, ...

Evolving Structure (1)

- Specialize GP techniques to **directly** support human programming language abstractions
- Examples:
  1. Structured data via strongly typed GP
  2. Structured control via automatically defined functions

Strongly Typed GP (Montana)

- Primitives annotated with types
- Constrained code generation
- Constrained mutation and recombination

Automatically Defined Functions (Koza)

- All programs in the population have the same, pre-specified architecture
- Genetic operators respect that architecture
- Significant implementation costs
- Significant pre-specification
- Architecture-altering operations: more power and higher costs

Evolving Structure (2)

- Specialize GP techniques to **indirectly** support human programming language abstractions
- Map from unstructured genomes to programs in languages that support abstraction (e.g. via grammars)

Evolving Structure (3)

- Evolve programs in a minimal-syntax language that nonetheless supports a full range of data and control abstractions
- For example: orchestrate data flows via stacks, not via syntax
- Minimal syntax + maximal, flexible semantics
- **Push**

Push (1)

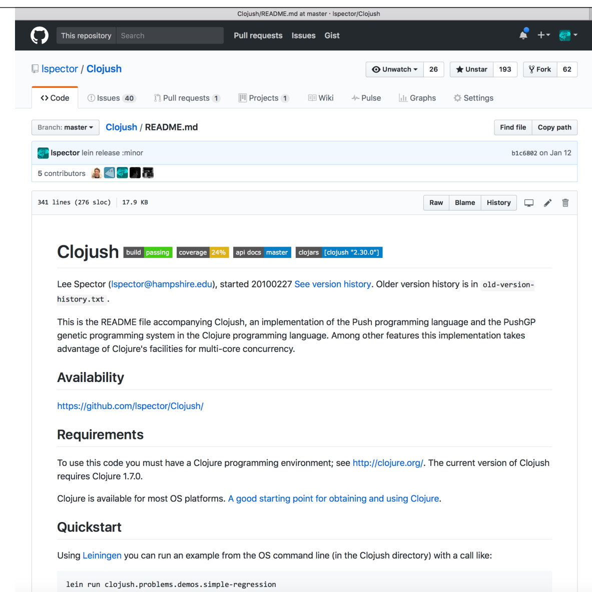
- Designed for program evolution
- Data flows via stacks, not syntax
- One stack per type:
  integer, float, boolean, string, code, exec, vector, ...
- `program → instruction | literal | ( program* )`
- Turing complete, with rich data and control structures

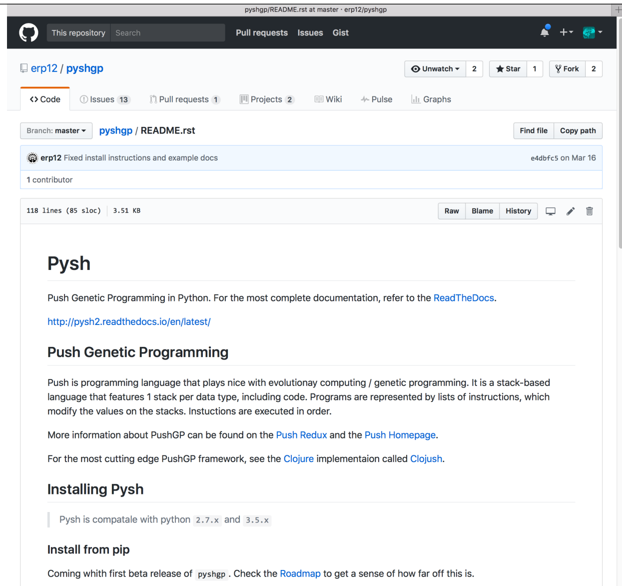
Push (2)

- Missing argument? NOOP
- Argument order: Generally reflect expected order from text of canonical usage
- Time/step limits ensure termination, with results available from stacks in all cases
- PushGP is a GP system that evolves Push programs
- http://pushlanguage.org

Push (3)

- It is simple to write a minimal Push system in any language; instructions can then be added incrementally
- Implementations in C++, C#, Clojure, Common Lisp, Java, Javascript, Python, Racket, Ruby, Scala, Scheme, Swift, ...
- Most examples in this presentation use Clojush, a Push/PushGP implementation in Clojure
- A recent addition that might be more approachable is Pysh, a Push/PushGP implementation in Python





Why Push?

- Expressive: data types, data structures, variables, conditionals, loops, recursion, modules, ...
- Elegant: minimal syntax and a simple, stack-based execution architecture
- Supports several forms of meta-evolution
- Evolvable? At minimum, supports investigation of relations between expressiveness and evolvability

Plush

Instruction	integer_eq	exec_dup	char_swap	integer_add	exec_if	
Close?	2	0	0	0	1	
Silence?	1	0	0	1	0	

- Linear genomes for Push programs
- Facilitates useful placement of code blocks
- Permits uniform linear genetic operators
- Allows for epigenetic hill-climbing

Push Program Execution

- Push the program onto the exec stack.
- While exec isn't empty, pop and **do** the top:
  - If it's an instruction, execute it.
  - If it's a literal, push it onto the appropriate stack.
  - If it's a list, push its elements back onto the exec stack one at a time.

Instructions Implemented for Most Types

- <type>_dup
- <type>_empty
- <type>_eq
- <type>_flush
- <type>_pop
- <type>_rot
- <type>_shove
- <type>_stackdepth
- <type>_swap
- <type>_yank
- <type>_yankdup

Selected Integer Instructions

integer_add integer_dec integer_div
integer_gt integer_fromstring integer_min
integer_mult integer_rand

Selected Boolean Instructions

boolean_and boolean_xor boolean_frominteger

Selected String Instructions

string_concat string_contains string_length
string_removechar string_replacechar

Selected Exec Instructions

Conditionals:
    exec_if exec_when

General loops:
    exec_do*while

“For” loops:
    exec_do*range exec_do*times

Looping over structures:
    exec_do*vector_integer exec_string_iterate

Combinators:
    exec_k exec_y exec_s

Many More Types and Instructions

code_atom code_car print_newline integer_sub integer_inc boolean_stackdepth return_exec_pop vector_integer_eq autoconstructive_integer_rand boolean_pop genome_close_inc string_fromchar vector_string_shove zip_yankdup genome_new vector_float_yankdup exec_yankdup vector_integer_shove integer_yankdup string_flush boolean_swap zip_empty exec_shove vector_boolean_yank code_eq exec_y boolean_yank integer_eq genome_silence string_butlast code_contains string_conjchar code_do*count vector_float_last genome_pop string_substring integer_mult code_length vector_integer_dup boolean_or code_position boolean_empty zip_fromcode print_vector_string vector_boolean_swap return_frominteger vector_float_pushall char_iswhitespace code_cdr exec_do*vector_integer integer_rand vector_string_replacefirst string_first vector_boolean_first exec_do*while exec_string_iterate string_indexofchar vector_float_replace integer_fromstring code_list code_swap char_frominteger genome_gene_randomize vector_integer_emptyvector vector_string_eq vector_float_butlast exec_empty zip_end? exec_fromzipnode string_shove vector_boolean_pushall zip_insert_left_fromcode exec_rot vector_string_concat vector_float_indexof code_pop vector_string_subvec vector_integer_swap code_subst char_pop return_string_pop zip_yank exec_dup vector_integer_butlast vector_float_rest vector_string_flush boolean_fromfloat code_fromziprights float_sin boolean_flush char_isdigit float_lte exec_fromziproot vector_integer_empty print_code vector_string_stackdepth string_reverse exec_k vector_integer_yank float_frominteger char_rot print_char vector_integer_stackdepth vector_boolean_concat boolean_xor integer_gte genome_yankdup vector_float_shove vector_integer_take code_quote string_replacefirst return_fromstring exec_fromziplefts vector_integer_yankdup boolean_shove float_lt vector_string_dup vector_string_occurrencesof vector_integer_replace zip_branch? vector_float_reverse float_mod vector_float_subvec string_last print_boolean boolean_rot vector_string_rest integer_div vector_float_remove integer_fromfloat integer_lte code_fromzipchildren environment_end vector_integer_rot integer_mod string_concat vector_string_butlast genome_swap code_null exec_do*count vector_float_emptyvector vector_string_yankdup integer_rot float_yankdup vector_string_rot zip_replace_fromexec vector_string_take integer_add vector_integer_occurrencesof integer_shove genome_dup return_code_pop char_swap integer_max return_fromexec code_wrap return_float_pop code_flush genome_yank zip_shove vector_integer_flush vector_integer_subvec vector_boolean_indexof vector_float_pop vector_string_remove vector_integer_contains zip_remove code_append vector_float_eq vector_integer_conj string_eq zip_leftmost code_yankdup code_rot integer_stackdepth float_max vector_boolean_set zip_append_child_fromexec zip_next vector_float_conj zip_fromexec string_take zip_left zip_replace_fromcode char_stackdepth return_fromchar genome_eq vector_integer_replacefirst float_stackdepth code_fromziproot float_fromchar float_gt boolean_dup float_fromboolean code_fromzipnode genome_rot vector_float_replacefirst vector_boolean_conj vector_boolean_dup vector_integer_indexof vector_string_swap exec_eq string_emptystring string_swap integer_yank exec_while float_empty print_vector_boolean integer_min exec_swap genome_rotate integer_fromchar vector_string_yank string_stackdepth code_do*range string_replacechar char_allfromstring vector_integer_rest vector_boolean_length char_yank vector_float_empty code_fromfloat genome_parent2 return_fromcode string_pop float_eq vector_boolean_empty zip_insert_child_fromexec vector_string_last string_nth code_do* return_zip_pop vector_string_pop zip_rot vector_integer_nth exec_do*range exec_if char_shove zip_down zip_insert_left_fromexec code_frominteger vector_boolean_remove vector_integer_remove boolean_invert_first_then_and genome_flush print_string integer_fromboolean char_yankdup code_do vector_string_first boolean_frominteger string_setchar vector_integer_last char_isletter genome_gene_dup vector_integer_concat print_integer code_map boolean_eq float_gte return_fromfloat genome_gene_copy string_occurrencesofchar string_replacefirstchar print_float boolean_rand integer_flush float_shove string_replace char_dup float_pop char_eq vector_float_nth vector_string_conj integer_gt return_integer_pop float_sub vector_integer_length vector_float_set vector_string_indexof vector_boolean_rest code_dup vector_boolean_shove zip_eq float_min boolean_not float_mult float_fromstring genome_unsilence code_if vector_integer_pop vector_boolean_last exec_do*times zip_pop zip_rightmost float_dec vector_float_contains genome_gene_copy_range environment_new exec_do*vector_string code_nthcdr string_empty char_empty exec_pop vector_integer_set autoconstructive_boolean_rand vector_float_rot string_yankdup exec_do*vector_float string_removechar code_extract vector_string_replace vector_float_first genome_parent1 return_tagspace char_flush vector_float_occurrencesof vector_string_emptyvector float_add code_stackdepth exec_s zip_insert_right_fromexec float_dup vector_string_nth zip_stackdepth vector_integer_reverse print_vector_integer char_fromfloat code_do*times code_noop zip_swap code_yank integer_lt vector_boolean_eq genome_stackdepth code_fromziplefts noop_open_paren string_containschar string_yank char_rand zip_flush vector_boolean_rot float_swap exec_fromziprights vector_string_pushall vector_string_set vector_boolean_flush exec_noop code_size vector_boolean_stackdepth vector_integer_pushall vector_boolean_reverse integer_swap string_split vector_boolean_contains string_fromboolean return_boolean_pop vector_float_dup vector_boolean_replace integer_dup vector_boolean_nth vector_string_length string_rest zip_insert_child_fromcode float_tan string_rot string_rand exec_yank string_parse_to_chars integer_pop integer_empty vector_float_flush vector_float_yank noop_delete_prev_paren_pair print_exec zip_append_child_fromcode genome_gene_delete code_empty float_inc zip_right vector_float_length float_rand integer_dec string_contains return_fromboolean vector_float_concat vector_float_stackdepth exec_do*vector_boolean vector_integer_first genome_shove code_rand print_vector_float float_rot return_char_pop vector_string_contains vector_boolean_occurrencesof genome_empty zip_prev genome_toggle_silent vector_string_reverse zip_dup code_cons code_member exec_stackdepth float_flush boolean_and vector_boolean_butlast string_length float_cos string_frominteger exec_flush vector_string_empty exec_when vector_float_swap genome_close_dec code_insert vector_boolean_pop float_div zip_insert_right_fromcode code_fromboolean vector_boolean_take code_shove environment_begin vector_float_take boolean_invert_second_then_and code_container code_nth vector_boolean_subvec float_yank zip_up vector_boolean_emptyvector vector_boolean_replacefirst string_fromfloat vector_boolean_yankdup string_dup boolean_yankdup exec_fromzipchildren

```
;; https://github.com/lspector/Clojush/

=> (run-push '(1 2 integer_add) (make-push-state))

:exec ((1 2 integer_add))
:integer ()

:exec (1 2 integer_add)
:integer ()

:exec (2 integer_add)
:integer (1)

:exec (integer_add)
:integer (2 1)

:exec ()
:integer (3)
```

```
=> (run-push '(2 3 integer_mult 4.1 5.2 float_add
               true false boolean_or)
             (make-push-state))

:exec ()
:integer (6)
:float (9.3)
:boolean (true)
```

In other words

- Put 2 × 3 on the integer stack
- Put 4.1 + 5.2 on the float stack
- Put *true* ∨ *false* on the boolean stack

```
=> (run-push '(2 boolean_and 4.1 true integer_div
               false 3 5.2 boolean_or integer_mult
               float_add)
             (make-push-state))

:exec ()
:integer (6)
:float (9.3)
:boolean (true)
```

Same as before, but

- Several operations (e.g., `boolean_and`) become NOOPs
- Interleaved operations

```
=> (run-push
     '(4.0 exec_dup (3.13 float_mult) 10.0 float_div)
     (make-push-state))

:exec ((4.0 exec_dup (3.13 float_mult) 10.0 float_div))
:float ()

:exec (4.0 exec_dup (3.13 float_mult) 10.0 float_div)
:float ()

:exec (exec_dup (3.13 float_mult) 10.0 float_div)
:float (4.0)

:exec((3.13 float_mult) (3.13 float_mult) 10.0 float_div)
:float (4.0)

...

:exec ()
:float (3.91876)
```

Computes 4.0 **× 3.13 × 3.13** / 10.0

```
=> (run-push '(1 8 exec_do*range integer_mult)
             (make-push-state))

:integer (40320)
```

Computes 8! in a fairly “human” way

```
=> (run-push '(code_quote
               (code_quote (integer_pop 1)
                           code_quote (code_dup integer_dup
                                       1 integer_sub code_do
                                       integer_mult)
                           integer_dup 2 integer_lt code_if)
               code_dup
               8
               code_do)
             (make-push-state))

:code ((code_quote (integer_pop 1) code_quote (code_dup
       integer_dup 1 integer_sub code_do integer_mult)
       integer_dup 2 integer_lt code_if))
:integer (40320)
```

A less “obvious” evolved calculation of 8!

```
=> (run-push '(0 true exec_while
                 (1 integer_add true))
             (make-push-state))

:exec (1 integer_add true exec_while (1 integer_add
       true))
:integer (199)
:termination :abnormal
```

- An infinite loop
- Terminated by eval limit
- Result taken from appropriate stack(s) upon termination

```
=> (run-push '(in1 in1 float_mult 3.141592 float_mult)
             (push-item 2.5 :input (make-push-state)))

:float (19.63495)
:input (2.5)
```

Computes the area of a circle with the given radius: 3.141592 × in1 × in1

```
(pushgp
  {:error-function
   (fn [program]
     (vec
       (for [input (range 10)]
         (let [output (->> (make-push-state)
                           (push-item input :input)
                           (run-push program)
                           (top-item :integer))]
           (if (number? output)
             (Math/abs (float (- output
                                 (- (* input
                                       input
                                       input)
                                    (* 2 input input)
                                    input))))
             1000)))))
   :atom-generators (list (fn [] (lrand-int 10))
                          'in1
                          'integer_div
                          'integer_mult
                          'integer_add
                          'integer_sub)
   :population-size 100})
```

Set up run for target $x^3 - 2x^2 - x$

Auto-Simplification

- Loop:
  - Make it randomly simpler
  - Keep simpler if as good or better; otherwise revert
- GECCO-2014 poster: efficiently and reliably reduces the size of the evolved programs
- GECCO-2014 student paper: used as genetic operator
- GECCO-2017 ***GP best paper nominee***: improves generalization

```
SUCCESS at generation 29
Successful program: (5 4 in1 integer_sub in1 integer_mult
integer_sub integer_div integer_mult 6 integer_sub integer_add
in1 5 integer_sub integer_add in1 5 integer_add integer_add
integer_mult in1 integer_mult)
Errors: [0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0]
Total error: 0.0
History: null
Size: 24


Auto-simplifying with starting size: 24
...
step: 1000
program: (5 4 in1 integer_sub in1 integer_mult integer_sub 6
integer_sub in1 5 integer_sub integer_add in1 5 integer_add
integer_add in1 integer_mult)
errors: [0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0]
total: 0.0
size: 20
```

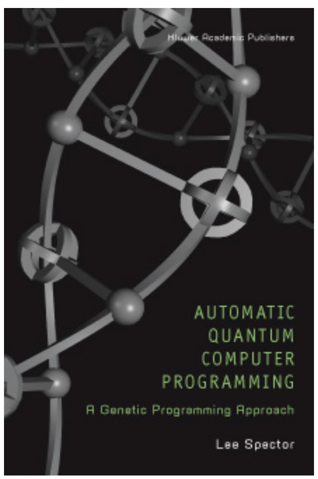
```
SUCCESS at generation 20
Successful program: (boolean_and boolean_shove exec_do*count (exec_swap (integer_empty char_yank boolean_or
integer_fromboolean \space \newline) (exec_dup (char_yank char_iswhitespace string_butlast in1) string_empty boolean_frominteger tagged_275
string_substring) exec_do*times (integer_empty string_dup) string_replacechar print_string string_rot print_char integer_fromboolean
string_length integer_eq string_last boolean_swap integer_yankdup) string_swap string_containschar "Wx{ " exec_stackdepth char_empty
integer_swap integer_rot string_last boolean_swap integer_yankdup string_swap string_containschar "Wx{ " exec_stackdepth char_empty integer_swap
integer_rot integer_fromstring string_pop string_shove char_eq char_empty integer_swap integer_rot integer_fromstring string_pop string_shove
char_rot integer_stackdepth integer_min char_yankdup char_eq char_empty tagged_349 exec_yank string_rot exec_dup (boolean_eq string_removechar
exec_s (exec_dup (boolean_eq exec_rot (exec_s (string_eq string_fromboolean exec_noop char_eq) () (string_butlast) integer_pop) (char_eq
char_empty) (integer_swap integer_rot string_emptystring boolean_stackdepth integer_inc in1 boolean_shove boolean_swap char_isletter integer_gt
integer_yankdup) exec_when (string_emptystring string_nth exec_do*range (\space integer_yankdup string_dup exec_shove (integer_swap
string_removechar exec_yank string_dup exec_empty) char_eq exec_do*times (tagged_349 boolean_pop exec_when (string_removechar integer_mult
integer_inc in1 boolean_shove boolean_swap char_isletter integer_gt string_butlast) integer_mult string_last string_parse_to_chars
boolean_frominteger boolean_yank exec_when (string_nth exec_do*range (\space integer_yankdup string_dup exec_shove (integer_swap
string_removechar exec_yank integer_yank exec_while (boolean_or)) char_isdigit boolean_swap char_isletter) integer_gt integer_yankdup
integer_mult string_last string_parse_to_chars boolean_frominteger char_isletter exec_when (string_nth exec_do*range (\space integer_yankdup
string_dup exec_shove (integer_swap string_removechar exec_yank integer_yank integer_mult integer_inc in1 boolean_shove boolean_swap
char_isletter integer_gt string_butlast) boolean_invert_second_then_and exec_empty string_rot)) boolean_rot char_iswhitespace integer_yank
string_conjchar boolean_dup) integer_add char_dup string_length integer_fromchar string_split char_isdigit boolean_swap boolean_eq char_isdigit
exec_shove (boolean_invert_second_then_and string_empty string_conjchar string_shove) string_fromchar boolean_not string_stackdepth exec_y ()
integer_empty exec_do*range (in1 string_replace)))))) () ()))
Errors: [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
Total error: 0.0
Size: 231

Auto-simplifying with starting size: 231
...
step: 5000
program: (\space \newline in1 string_replacechar print_string "Wx{ "
string_last in1 string_removechar string_length)
errors: [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
Total error: 0.0
Size: 11
```

DEMOS

Problems Solved by PushGP in the GECCO-2005 Paper on Push3

- Reversing a list
- Factorial (many algorithms)
- Fibonacci (many algorithms)
- Parity (any size input)
- Exponentiation
- Sorting



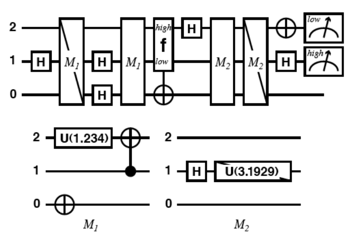


Figure 8.7. A gate array diagram for an evolved version of Grover's database search algorithm for a 4-item database. The full gate array is shown at the top, with M_1 and M_2 standing for the smaller gate arrays shown at the bottom. A diagonal line through a gate symbol indicates that the matrix for the gate is transposed. The "f" gate is the oracle.

Humies 2004
GOLD MEDAL

Genetic Programming for Finite Algebras

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Humies 2008
GOLD MEDAL

29 Software Synthesis Benchmarks

- Number IO, Small or Large, For Loop Index, Compare String Lengths, Double Letters, Collatz Numbers, Replace Space with Newline, String Differences, Even Squares, Wallis Pi, String Lengths Backwards, Last Index of Zero, Vector Average, Count Odds, Mirror Image, Super Anagrams, Sum of Squares, Vectors Summed, X-Word Lines, Pig Latin, Negative to Zero, Scrabble Score, Word Stats, Checksum, Digits, Grade, Median, Smallest, Syllables
- PushGP has solved all of these except for the ones in blue
- Presented in a GECCO-2015 GP track paper

Example: Checksum

Multiple types, looping, and code blocks

Simplified solution:

```
("Check sum is " print_string
  in1 64 exec_string_iterate (integer_fromchar integer_add)
  64 integer_mod
  \space integer_fromchar integer_add char_frominteger
  print_char)
```

Example: Checksum

Multiple types, looping, and code blocks

Simplified solution:

```
("Check sum is " print_string
  in1 64 exec_string_iterate (integer_fromchar integer_add)
  64 integer_mod
  \space integer_fromchar integer_add char_frominteger
  print_char)
```

First: Print out the header

Example: Checksum

Multiple types, looping, and code blocks

Simplified solution:

```
("Check sum is " print_string
  in1 64 exec_string_iterate (integer_fromchar integer_add)
  64 integer_mod
  \space integer_fromchar integer_add char_frominteger
  print_char)
```

Second: Convert each character to an integer, sum, and add to 64.

Example: Checksum

Multiple types, looping, and code blocks

Simplified solution:

```
("Check sum is " print_string
  in1 64 exec_string_iterate (integer_fromchar integer_add)
  64 integer_mod
  \space integer_fromchar integer_add char_frominteger
  print_char)
```

Third: Mod result by 64

Example: Checksum

Multiple types, looping, and code blocks

Simplified solution:

```
("Check sum is " print_string
  in1 64 exec_string_iterate (integer_fromchar integer_add)
  64 integer_mod
  \space integer_fromchar integer_add char_frominteger
  print_char)
```

Third: Add modulus result to 32 and convert to char

Example: Checksum

Multiple types, looping, and code blocks

Simplified solution:

```
("Check sum is " print_string
  in1 64 exec_string_iterate (integer_fromchar integer_add)
  64 integer_mod
  \space integer_fromchar integer_add char_frominteger
  print_char)
```

Fourth: Print resulting char

Example: Replace Space With Newline

Multiple types, looping, multiple tasks

Simplified solution:

```
(\space char_dup exec_dup in1
  \newline string_replacechar print_string
  string_removechar string_length)
```

Example: Replace Space With Newline

Multiple types, looping, multiple tasks

Simplified solution:

```
(\space char_dup exec_dup in1
  \newline string_replacechar print_string
  string_removechar string_length)
```

First: Duplicate space character and input string for use in both tasks

Example: Replace Space With Newline

Multiple types, looping, multiple tasks

Simplified solution:

```
(\space char_dup exec_dup in1
  \newline string_replacechar print_string
  string_removechar string_length)
```

Second: Replace spaces with newlines and print

Example: Replace Space With Newline

Multiple types, looping, multiple tasks

Simplified solution:

```
(\space char_dup exec_dup in1
  \newline string_replacechar print_string
  string_removechar string_length)
```

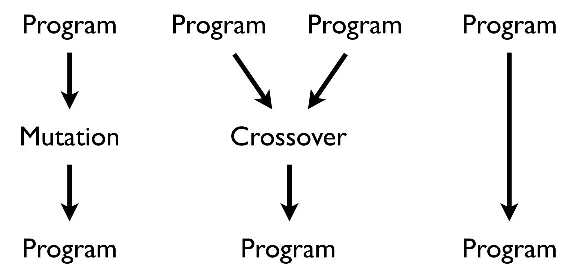
Third: Remove all spaces from second copy of input, and push length of result on integer stack for return

DEMO

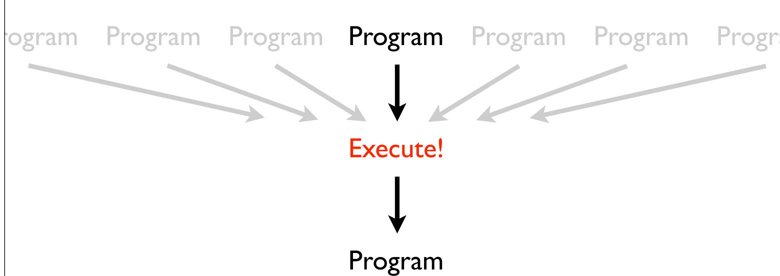
Autoconstructive Evolution

- Individual programs make their own children
- Hence they control their own mutation and recombination methods and rates
- The machinery of reproduction and diversification (i.e., the machinery of evolution) evolves
- In Push, experimentation with autoconstructive evolution is easy and natural

Variation in Genetic Programming



Autoconstruction



Autoconstruction

- It works!
- Evolved solutions to non-trivial problems (e.g., replace-space-with-newlines)
- Only known evolved solution to string-differences
- Slower and less consistent than human engineered operators, but much more work to do
- More to explore

Expressiveness and Assessment

- Expressive languages ease representation of programs that over-fit training sets
- Expressive languages ease representation of programs that work only on subsets of training sets
- Lexicase selection may help: Select parents by starting with a pool of candidates and then filtering by performance on individual fitness cases, considered one at a time in random order

Evolving Modular Programs with Push

- Via code manipulation on the code or exec stacks
- Via naming and a name stack
- Via tags, inspired by Holland's work on arbitrary identifiers with inexact matching
- Evolvability challenges abound! The relationship between evolvability, robustness, and modularity and is complex
- Push facilitates experimentation in this space

Future Work

- Expression of variable scope and environments (implemented, but not yet studied systematically)
- Expression of concurrency and parallelism
- Applications for which expressiveness is likely to be essential, e.g. complete software applications, agents in complex, dynamic environments

Conclusions

- GP in expressive languages may allow for the evolution of complex software
- Minimal-syntax languages can be expressive, and GP systems that evolve programs in such languages can be unusually simple and powerful
- Push has produced significant successes and provides a rich framework for experimentation
- http://pushlanguage.org

Thanks

This material is based upon work supported by the National Science Foundation under Grant Nos. 1617087, 1129139 and 1331283. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation. Thanks also to Thomas Helmuth and the other members of the Hampshire College Computational Intelligence Lab, to Josiah Erikson for systems support, and to Hampshire College for support for the Hampshire College Institute for Computational Intelligence.

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