# Genetic Programming in the Wild: Evolving Unrestricted Bytecode

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# GP: Programs or Representations?

"While it is common to describe GP as evolving **programs**, GP is not typically used to evolve programs in the familiar Turing-complete languages humans normally use for software development."

*A Field Guide to Genetic Programming*
[Poli, Langdon, and McPhee, 2008]

# GP: Programs or Representations?

"While it is common to describe GP as evolving **programs**, GP is not typically used to evolve programs in the familiar Turing-complete languages humans normally use for software development."

"It is instead more common to evolve programs
(or expressions or formulae)
in a **more constrained** and often **domain-specific language**."

*A Field Guide to Genetic Programming*
[Poli, Langdon, and McPhee, 2008]

# Our Goals

### From programs. . .

Evolve actual programs

**written in Java**

### . . . to software!

Improve (existing) software

**written in unrestricted Java**

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Improve (existing) software
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### Extending prior work

Existing work uses **restricted subsets** of Java bytecode as **representation language** for GP individuals

We evolve **unrestricted bytecode**

# Let's Evolve Java Source Code

- Rely on the building blocks in the initial population
- Defining **genetic operators** is problematic
- How to define **good** source code crossover?

**Factorial *(recursive)***

```
class F {
  int fact(int n) {
    int ans = 1;

    if (n > 0)
      ans = n *
        fact(n-1);

    return ans;
  }
}
```

⇐

**Factorial *(iterative)***

```
class F {
  int fact(int n) {
    int ans = 1;

    for (; n > 0; n--)
      ans = ans * n;


    return ans;
  }
}
```

# “Stupid” Example

- **Source-level crossover** typically produces garbage

### Factorial *(recursive* $\overleftarrow{\times}$ *iterative)*

```
class F {
  int fact(int n) {
    int ans = 1;

    if (n >= 1;
      for (;  n > 0;  n--)
        ans = ans * n;  n-1);

    return ans;
  }
}
```

# "Stupid" Example

- **Source-level crossover** typically produces garbage

**Factorial** *(recursive $\overleftarrow{\times}$ iterative)*

```
class F {
  int fact(int n) {
    int ans = 1;

    if (n > = 1;
      for (; n > 0; n--)
        ans = ans * n;  n-1);

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}
```

# Parse Trees

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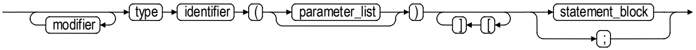
### Just one BNF rule *(of many)*

$\texttt{method\_declaration} ::\Longrightarrow$
$\quad \texttt{modifier}^{*}\ \texttt{type identifier}$
$\quad \text{``(''}\ \texttt{parameter\_list}^{?}\ \text{``)''}\ \text{``[ ]''}^{*}$
$\quad \langle\ \texttt{statement\_block} \mid \text{``;''}\ \rangle$

**method_declaration**



# Bytecode

Better than parse trees:

Let's use **bytecode**!

### Java Virtual Machine *(JVM)*

- Source code is compiled to **platform-neutral bytecode**
- Bytecode is executed with **fast** just-in-time compiler
- High-order, **simple** yet powerful architecture
- **Stack-based**, supports hierarchical object **types**
- Not limited to Java!

  *(Scala, Groovy, Jython, Kawa, Clojure, ...)*

# Bytecode (cont'd)
## *Some basic bytecode instructions*

### Stack ↔ Local variables

| | |
|---|---|
| **iconst** 1 | pushes `int` 1 onto operand stack |
| **aload** 5 | pushes **object** in local variable 5 onto stack<br>*(object **type** is deduced when class is loaded)* |
| **dstore** 6 | pops two-word `double` to local variables 6–7 |

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### Arithmetic instructions *(affect operand stack)*

| | |
|---|---|
| **imul** | pops two `int`s from stack, pushes multiplication result |

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### Arithmetic instructions *(affect operand stack)*

| | |
|---|---|
| **imul** | pops two `int`s from stack, pushes multiplication result |

### Control flow *(uses operand stack)*

| | |
|---|---|
| **ifle** +13 | pops `int`, jumps +13 bytes if value $\leqslant 0$ |
| **lreturn** | pops two-word `long`, returns to caller's stack |

# Bytecode (cont'd)
## *Evolutionary operators*

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- But, bytecode must be **correct** in order to run **correctly**

### Correct bytecode requirements

Stack use is **type-consistent**

*(e.g., can't multiply an `int` by an* **Object***)*

Local variables use is **type-consistent**

*(e.g., can't read an `int` after storing an* **Object***)*

No stack underflow

No reading from uninitialized variables

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- Need **good** genetic operators to produce **correct** offspring

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*(e.g., can't read an `int` after storing an* **Object***)*
No stack underflow
No reading from uninitialized variables

- So, genetic operators are still delicate
- Need **good** genetic operators to produce **correct** offspring
- Conclusion: Avoid **bad** crossover and mutation

# Evolutionary Operators

Unidirectional bytecode crossover:

**Bytecode A**

. . .

. . .

. . .

Section $\alpha$

. . .

. . .

. . .

**Bytecode B**

. . .

. . .

. . .

Section $\beta$

. . .

. . .

. . .

# Evolutionary Operators

Unidirectional bytecode crossover:

**Bytecode A**

...

...

...

Section $\boxed{\alpha}$

...

...

...

**Bytecode B**

...

...

...

Section $\boxed{\beta}$

...

...

...

# Evolutionary Operators

## *Good* and *bad* crossovers

Parent **A**:

### Factorial *(recursive)*

```
class F
{
  int fact(int n)
  {
    int ans = 1;

    if (n > 0)
      ans = n * fact(n-1);

    return ans;
  }
}
```

### Compiled bytecode

```
0  iconst_1
1  istore_2
2  iload_1
3  ifle 16
6  iload_1
7  aload_0
8  iload_1
9  iconst_1
10 isub
11 invokevirtual #2
14 imul
15 istore_2
16 iload_2
17 ireturn
```

Parent **B**:

**Factorial *(iterative)***

```
class F
{
  int fact(int n)
  {
    int ans = 1;

    for (;  n > 0;  n--)
      ans = ans * n;

    return ans;
  }
}
```

**Compiled bytecode**

```
 0 iconst_1
 1 istore_2
 2 iload_1
 3 ifle 16
 6 iload_2
 7 iload_1
 8 imul
 9 istore_2
10 iinc 1, -1
13 goto 2
16 iload_2
17 ireturn
```

# Evolutionary Operators
## *Good and bad crossovers*

Replace a section in **A** with section from **B**

### Bytecode A

```
0  iconst_1
1  istore_2
2  iload_1
3  ifle 16
6  iload_1
7  aload_0
8  iload_1
9  iconst_1
10 isub
11 invokevirtual #2
14 imul
15 istore_2
16 iload_2
17 ireturn
```

⇐

### Bytecode B

```
0  iconst_1
1  istore_2
2  iload_1
3  ifle 16
6  iload_2
7  iload_1
8  imul
9  istore_2
10 iinc 1, -1
13 goto 2
16 iload_2
17 ireturn
```

# Evolutionary Operators
## *Good crossover example*

Stack use is depth- and type-consistent, variables are initialized.

**Bytecode A**

```
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9  iconst_1
10 isub
11 invokevirtual #2
14 imul
15 istore_2
16 iload_2
17 ireturn
```

⇐

**Bytecode B**

```
0  iconst_1
1  istore_2
2  iload_1
3  ifle 16
6  iload_2
7  iload_1
8  imul
9  istore_2
10 iinc 1, -1
13 goto 2
16 iload_2
17 ireturn
```

# Evolutionary Operators
## *Good crossover example*

Stack use is depth- and type-consistent, variables are initialized.

### Bytecode $(A \overleftarrow{\times} B)$

```
 0  iconst_1
 1  istore_2
 2  iload_1
 3  ifle 12
 6  iload_1
 7  iload_2
 8  iload_1
 9  imul
10  imul
11  istore_2
12  iload_2
13  ireturn
```

### Decompiled source

```
class F
{
  int fact(int n)
  {
    int ans = 1;

    if (n > 0)
      ans = n * (ans * n);

    return ans;
  }
}
```

# Evolutionary Operators
## *Bad crossover example*

Stack use is depth- and type-inconsistent.

### Bytecode A

```
0  iconst_1
1  istore_2
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6  iload_1
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8  iload_1
9  iconst_1
10 isub
11 invokevirtual #2
14 imul
15 istore_2
16 iload_2
17 ireturn
```

$\Leftarrow$

### Bytecode B

```
0  iconst_1
1  istore_2
2  iload_1
3  ifle 16
6  iload_2
7  iload_1
8  imul
9  istore_2
10 iinc 1, -1
13 goto 2
16 iload_2
17 ireturn
```

# Evolutionary Operators
## *Bad crossover example*

Stack use is depth- and type-inconsistent.

### Bytecode ($A \overleftarrow{\times} B$)

```
 0 iconst_1
 1 istore_2
 2 iload_1
 3 ifle 13
 6 iload_2
 7 iload_1
 8 invokevirtual #2
11 imul
12 istore_2
13 iload_2
14 ireturn
```

### “Decompiled” source

```
class F {
  int fact(int n)
  {
    int ans = 1;

    if (n > 0)
      ans = ans.fact(n) * ?;

    return ans;
  }
}
```

# Compatible Crossover
## *Constraints of unidirectional crossover* $\mathbf{A} \overleftarrow{\times} \mathbf{B}$

**Good** crossover is achieved by respecting bytecode constraints:
($\alpha$ *is target section in* ***A***, $\beta$ *is source section in* ***B***)

### Operand stack

*e.g.*, $\beta$ doesn't pop values with types incompatible to those popped by $\alpha$

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### Operand stack

*e.g.*, $\beta$ doesn't pop values with types incompatible to those popped by $\alpha$

### Local variables

*e.g.*, variables read by $\beta$ in **B** must be written before $\alpha$ in **A** with compatible types

# Compatible Crossover
## *Constraints of unidirectional crossover* $A \overleftarrow{\times} B$

**Good** crossover is achieved by respecting bytecode constraints:
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### Operand stack

*e.g.*, $\beta$ doesn't pop values with types incompatible to those popped by $\alpha$

### Local variables

*e.g.*, variables read by $\beta$ in **B** must be written before $\alpha$ in **A** with compatible types

### Control flow

*e.g.*, branch instructions in $\beta$ have no "outside" destinations

# Formal Definition
## *(Example of operand stack requirement)*

$\alpha$ and $\beta$ have compatible stack frames up to stack depth of $\beta$: pops of $\alpha$ have identical or narrower types as pops of $\beta$; pushes of $\beta$ have identical or narrower types as pushes of $\alpha$

**Good crossover**

| | $\alpha$ | $\beta$ |
|---|---|---|
| pre-stack | `**AB` | `**AA` |
| post-stack | `**B` | `**C` |
| depth | 3 | 2 |

Stack pops "`AB`" *(2 stop tack frames)* are narrower than "`AA`", whereas stack push "`C`" is narrower than "`B`"

Types hierarchy: $\mathtt{C} \longrightarrow \mathtt{B} \longrightarrow \mathtt{A}$

*(see [Orlov and Sipper, 2009] for full formal definitions)*

# Formal Definition
## *(Example of operand stack requirement)*

$\alpha$ and $\beta$ have compatible stack frames up to stack depth of $\beta$:
pops of $\alpha$ have identical or narrower types as pops of $\beta$;
pushes of $\beta$ have identical or narrower types as pushes of $\alpha$

**Bad crossover**

| | $\alpha$ | $\beta$ |
|---|---|---|
| pre-stack | `**AB` | `**Af` |
| post-stack | `**B` | `**A` |
| depth | 3 | 2 |

Stack pops "`AB`" are not narrower than "`Af`"
*(B and f are incompatible)*;
stack push "`A`" is not narrower than "`B`"

Types hierarchy: `B` $\longrightarrow$ `A`; `f` is a `float`

*(see [Orlov and Sipper, 2009] for full formal definitions)*

# Symbolic Regression
## *As an evolutionary example...*

### Parameters

- Objective: symbolic regression, $x^4 + x^3 + x^2 + x$
- Fitness: sum of errors on 20 random data points in $[-1, 1]$
- Input: **Number** `num` *(a Java type)*

# Symbolic Regression
## *As an evolutionary example...*

### Parameters

- Objective: symbolic regression, $x^4 + x^3 + x^2 + x$
- Fitness: sum of errors on 20 random data points in $[-1, 1]$
- Input: **Number** `num` *(a Java type)*

### Seeding

- Population initialized using seeding

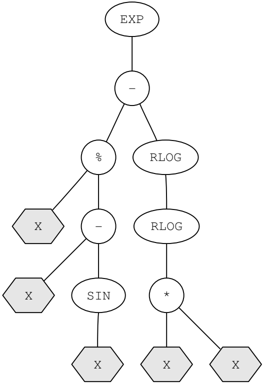
  [Langdon and Nordin, 2000]
- Seed population with clones of Koza's original worst-of-generation-0

  [Koza, 1992]

# *Seeding with Koza's worst-of-generation-0*

Original **Lisp** individual and its **tree** representation:

```
(EXP (- (% X (- X (SIN X))) (RLOG (RLOG (* X
X)))))
```



# Symbolic Regression
## *Seeding with Koza's worst-of-generation-0*

Translation to **unrestricted Java**

```
class Gecco {
  Number simpleRegression(Number num) {
    double x     = num.doubleValue();
    double llsq  = Math.log(Math.log(x*x));
    double dv    = x / (x - Math.sin(x));
    double worst = Math.exp(dv - llsq);
    return Double.valueOf(worst + Math.cos(1));
  }

  /* Rest of class omitted */
}
```

*We added a couple of building blocks in the last line*

### Setup *(similar to Koza's)*

- Population: 500 individuals
- Generations: 51 (or less)
- Probabilities: $p_{\mathrm{cross}} = 0.9$
  ( $\alpha$ and $\beta$ segments are uniform over segment sizes)
- Selection: binary tournament

# Symbolic Regression
## *Setup and Statistics*

### Setup *(similar to Koza's)*

- Population: 500 individuals
- Generations: 51 (or less)
- Probabilities: $p_{\text{cross}} = 0.9$
  ($\alpha$ and $\beta$ segments are uniform over segment sizes)
- Selection: binary tournament

### Statistics

- Yield: 99% of runs successful (out of 100)
- Runtime: 30–60 s on dual-core 2.6 GHz Opteron
- Memory limits: insignificant w.r.t. runtime

# Symbolic Regression
## *Evolved perfect individuals*

**A perfect solution easily evolves:**

*(beware of decompiler quirks!)*

```
class Gecco_0_7199 {
  Number simpleRegression(Number num) {
    double d = num.doubleValue();
    d = num.doubleValue();
    double d1 = d; d = Double.valueOf(d + d * d *
          num.doubleValue()).doubleValue();
    return Double.valueOf(d +
          (d = num.doubleValue()) * num.doubleValue());
  }

  /* Rest of class unchanged */
}
```

*Computes* $(x + x \cdot x \cdot x) + (x + x \cdot x \cdot x) \cdot x \;=\; x(1+x)(1+x^2)$

# Symbolic Regression
## *Evolved perfect individuals*

**Another solution:**

```
class Gecco_0_2720 {
  Number simpleRegression(Number num) {
    double d = num.doubleValue();
    d = d; d = d;
    double d1 = Math.exp(d - d);
    return Double.valueOf(num.doubleValue() *
      (num.doubleValue() * (d * d + d) + d) + d);
  }

  /* Rest of class unchanged */
}
```

*Computes* $x \cdot (x \cdot (x \cdot x + x) + x) + x \;=\; x(1 + x(1 + x(1 + x)))$

# Conclusions

Completely **unrestricted** Java programs can be **evolved**

*(via bytecode)*

**Extant** (bad) Java programs can be **improved**

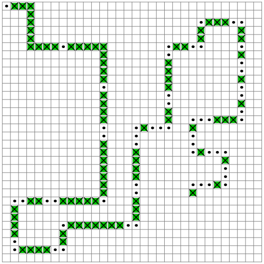
*(e.g., initial regression seed)*

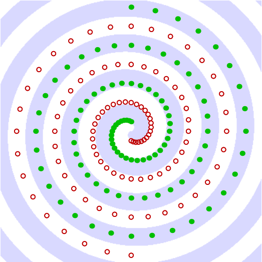
# Future Work

Exhibit **viability** on other problems

*We currentlty have results for:*

*complex regression, artificial ant, intertwined spirals, . . .*





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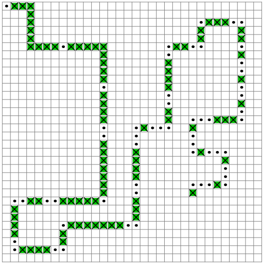

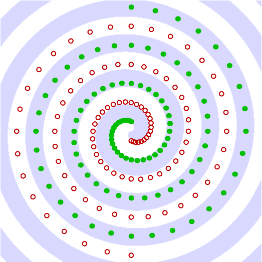

Loops and recursion are not a problem!

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