Automatic Test Data Generation using Constraint Programming and Search Based Software Engineering Techniques

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Pattern Trace Identification, Detection, and Enhancement in Java
SOftware Cost-effective Change and Evolution Research Lab

Motivation

Every year inadequate infrastructure software costs the U.S. economy around $60 billion.

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- At least five deaths;
- Several other patients were severely affected by radiation.

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- Several other patients were severely affected by radiation.

Only a high quality software can reduce errors costs.

Software testing

Expensive

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- Costs more than 50% of the budget of critical software;

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Difficult

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- Exhaustive testing!

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- Costs more than 50% of the budget of critical software;

Difficult

- Exhaustive testing! is not possible

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- Costs more than 50% of the budget of critical software;

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- Exhaustive testing! is not possible
- Random testing!

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- Selecting and generating an adequate subset of test data!

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Challenge

Automation of test-data generation

Software testing

Expensive

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Challenge

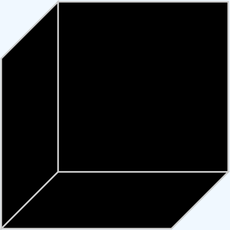
Automation of test-data generation can significantly reduce the cost of software

Software testing

Strategies

Functional Criteria

- Focus on the specification;



Black-box Testing

Software testing

Strategies

Functional Criteria

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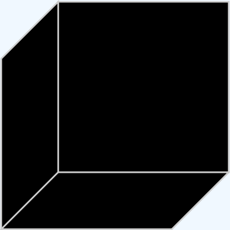
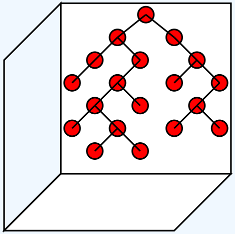


Black-box Testing

Structural Criteria

- Focus on the internal structure;



White-box Testing

White-box Testing(Goal)

```
int foo(int x,int y, float z, String s1,String s2) {
    if(y==z)
        if(y>0)
            if(x==10)
                return s1.length()+s2.length();
    y= x<<y;
    x=y+x/y;
    String s=s1+s2;
    if((s.equals("OK") && (x>0) && s.length()>x)
        return y/s1.length();
    return 0;
}
```

White-box Testing(Goal)

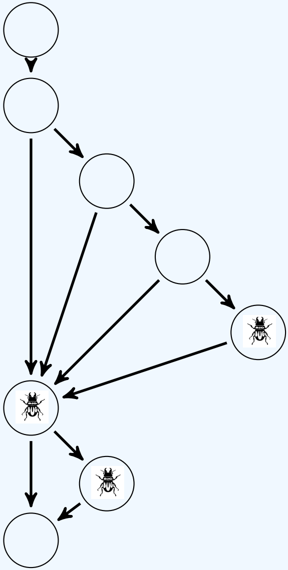
```
1   int foo(int x,int y, float z, String s1,String s2) {
2       if(y==z)
3           if(y>0)
4               if(x==10)
5                   return s1.length()+s2.length();
6       y= x<<y;
7       x=y+x/y;
8       String s=s1+s2;
9       if((s.equals("OK") && (x>0) && s.length()>x)
10          return y/s1.length();
11      return 0;
12  }
```

Unhandled Exceptions

- Line 5: undefined behavior if $s1$ or $s2$ is null.
- Line 6: undefined behavior if y is negative or >31;
- Line 7: undefined behavior if $y = 0$;
- Line 8: undefined behavior if $s1$ or $s2$ is null;
- Line 10: undefined behavior if $s1 =$ “” or is null.

White-box Testing(Requirements)

Control Flow Graph of foo

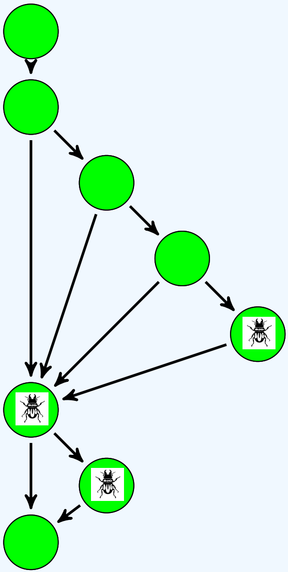


Coverage Criteria

- All-statement;
- All-branch;
- All-paths.

White-box Testing(Requirements)

Control Flow Graph of foo



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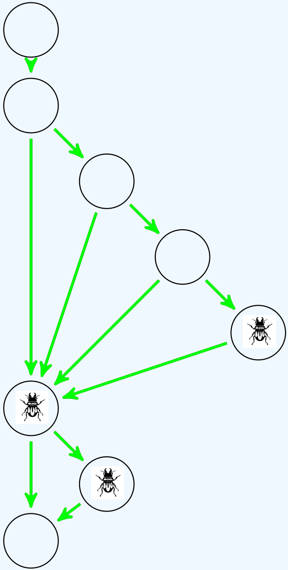

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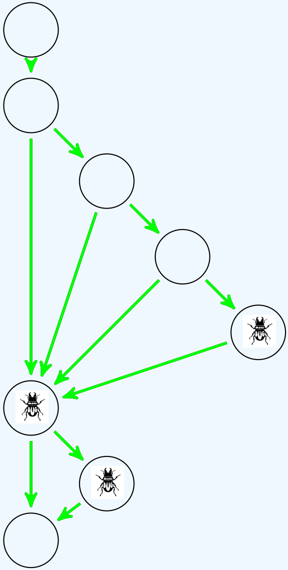

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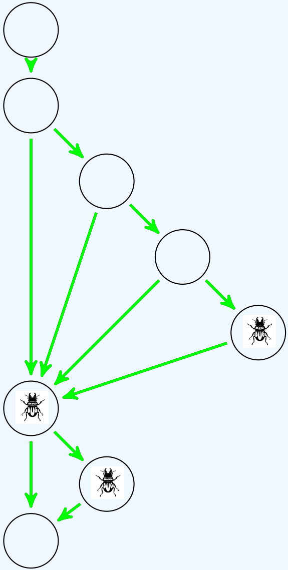


Coverage Criteria

- All-statement;
- All-branch;
- All-paths.

Challenge

- Finding the set of vectors (x,y,z,s1,s2) that satisfy a given coverage criterion.

Test-Data Generation for Unit Class Testing

Difficulties

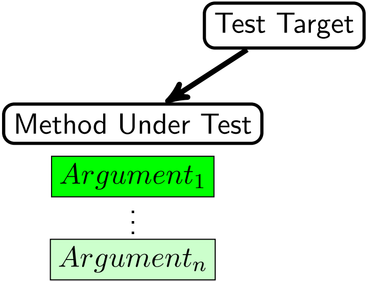
- **Encapsulation**: the state of a class is accessible only through some public methods.
- **Abstraction**: some classes are not directly instantiable;
- **Anonymous Classes**: some classes are not visible outside of the method where they are declared;

Test-Data Format of Object-Oriented Programming (OOP) is complex.

Test-Data Generation for Unit Class Testing

```
public class FooClass{
private int y;
private float z;
private String s2;
public void setY(int y1) {y=y1};
public void setZ(float z1) {z=z1};
public void setS2(String s) {s2=s};
public int fooCaller(int a, String str){
     foo(a,str);...
}
private int foo(int x, String s1){
    if(y==z)
        if(y>0)
            if(x==10)
                return s1.length()+s2.length();
    y= x<<y;
    x=y+x/y;
    String s=s1+s2;
    if((s.equals("OK") && (x>0) && s.length()>x)
        return y/s1.length();
    return 0;
}
}
```

Test-Data Format of OOP



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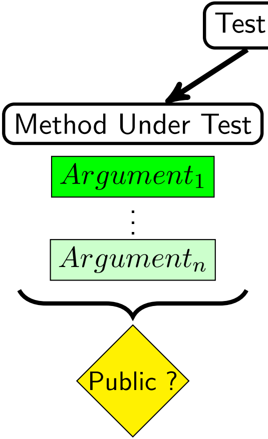

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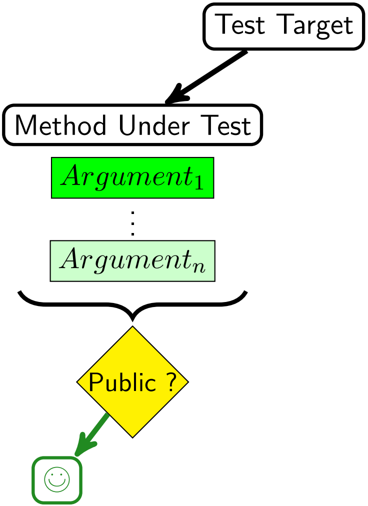

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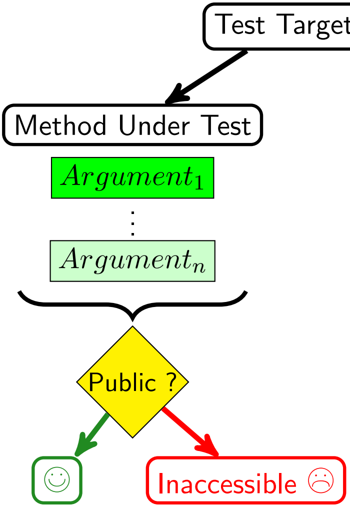

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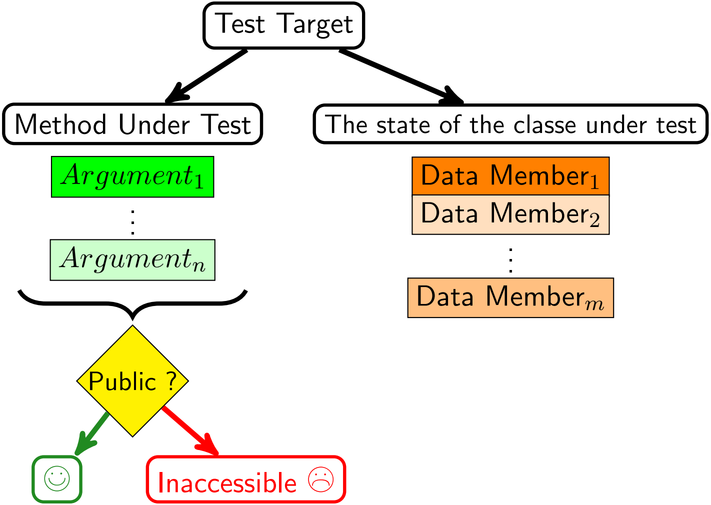

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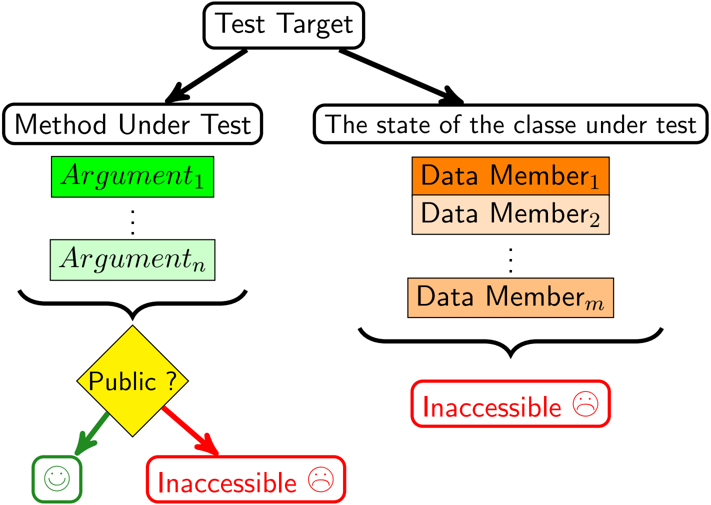

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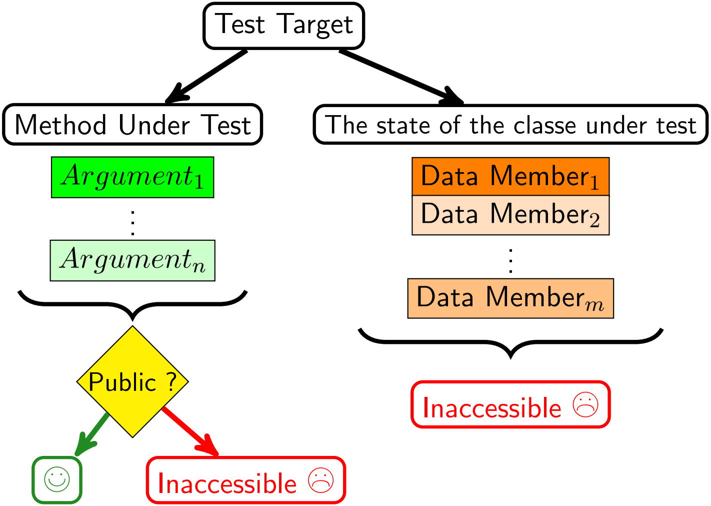


Public methods to reach inaccessible parts.

Test-Data Format of OOP

Challenge

1. Finding an instance of the class under test;
2. Finding a sequence of method calls;
3. Finding an instance of each required argument.

- The number of sequence of method calls may be unlimited;
- The number of different instances of a given class may be large.

Test-Data Format of OOP

Challenge

1. Finding an instance of the class under test;
2. Finding a sequence of method calls;
3. Finding an instance of each required argument.

- The number of sequence of method calls may be unlimited;
- The number of different instances of a given class may be large.

Pb1: The search space is a problem

Automation

Search Based (SB-STDG)

Source Code

↓

Instrumentation

↓

Instrumented Source Code

↓

Meta-heuristic and Fitness Function

↓

Test Data

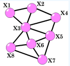
Constraint Based (CB-STDG)

Source Code

↓

Symbolic Execution

↓



Constraint Satisfaction Problem (CSP)

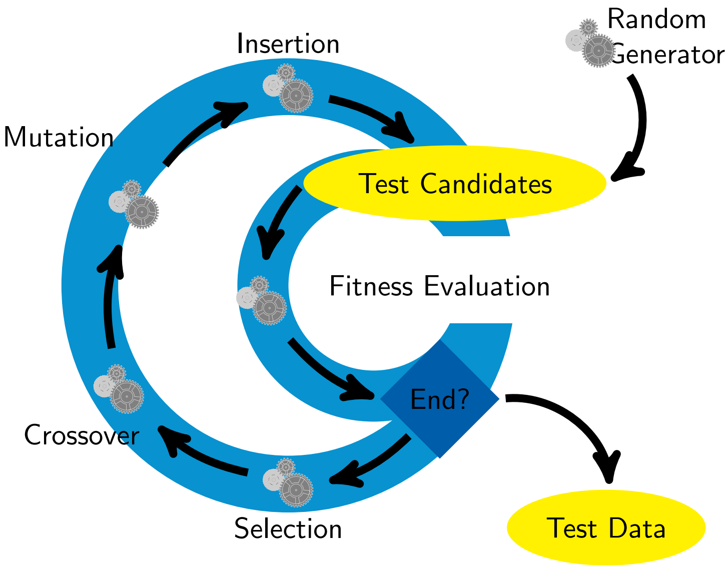
↓

Solver

↓

Test Data

Search Based(Genetic Algorithms)



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Search Based

```
int foo(int x,int y,float z, String s1, String s2){
  if(y==z)
    if(y>0)
      if(x==10)
        return s1.length()+s2.length();//Target
  ...
}
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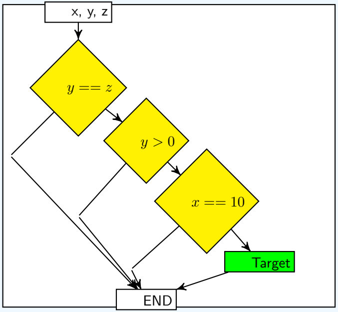

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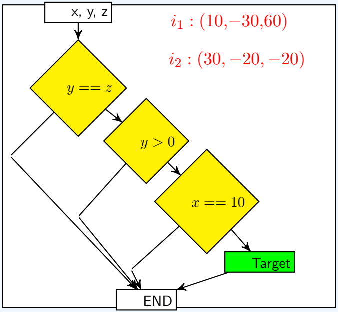

Search Based

```
int foo(int x,int y,float z, String ↩
        s1, String s2){
    if(y==z)
        if(y>0)
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                     length();//Target
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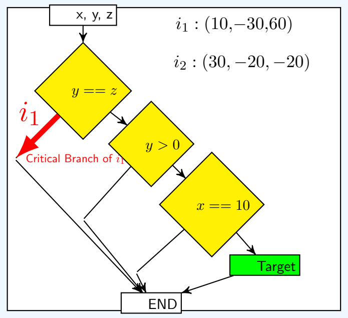

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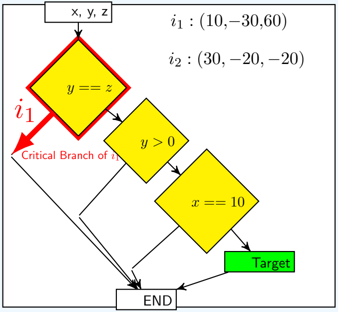

Test candidate	f_{AL}	f_{SE}
i_1	3	
i_2		

Search Based

```
int foo(int x,int y,float z, String s1, String s2){
    if(y==z)
        if(y>0)
            if(x==10)
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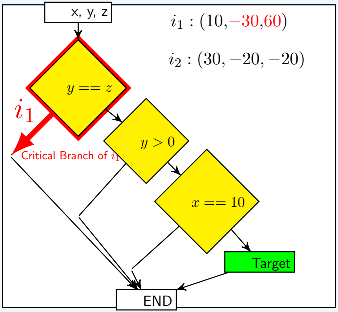

Test candidate	f_{AL}	f_{SE}
i_1	$3+\frac{90}{91}$	
i_2		

Search Based

```
int foo(int x,int y,float z, String s1, String s2){
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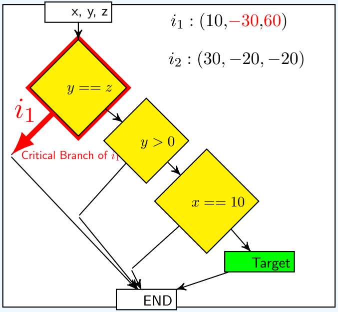

Test candidate	f_{AL}	f_{SE}
i_1	$3+\frac{90}{91}$	$\frac{90}{91}$
i_2		

Search Based

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int foo(int x,int y,float z, String s1, String s2){
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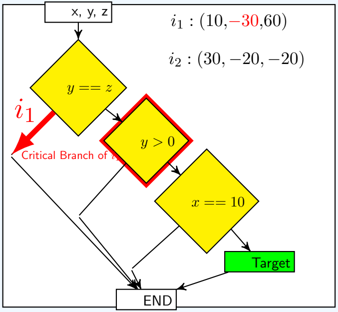

Test candidate	f_{AL}	f_{SE}
i_1	$3+\frac{90}{91}$	$\frac{90}{91} + \frac{31}{32}$
i_2		

Search Based

```
int foo(int x,int y,float z, String s1, String s2){
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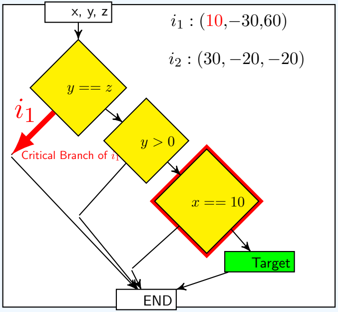

Test candidate	f_{AL}	f_{SE}
i_1	$3+\frac{90}{91}$	$\frac{90}{91}+\frac{31}{32}+0$
i_2		

Search Based

```
int foo(int x,int y,float z, String s1, String s2){
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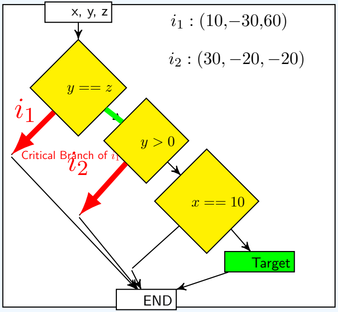

Test candidate	f_{AL}	f_{SE}
i_1	$3+\frac{90}{91} = 3.9890$	$\frac{90}{91} + \frac{31}{32} + 0 = 1.9577$
i_2	$2 + \frac{21}{22} = 2.9545$	$0 + \frac{21}{22} + \frac{20}{21} = 1.9068$

Search Based

```
int foo(int x,int y,float z, String s1, String s2){
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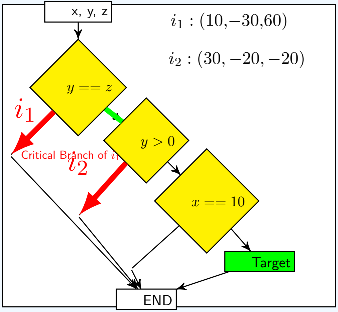

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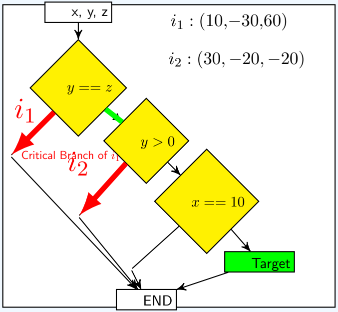

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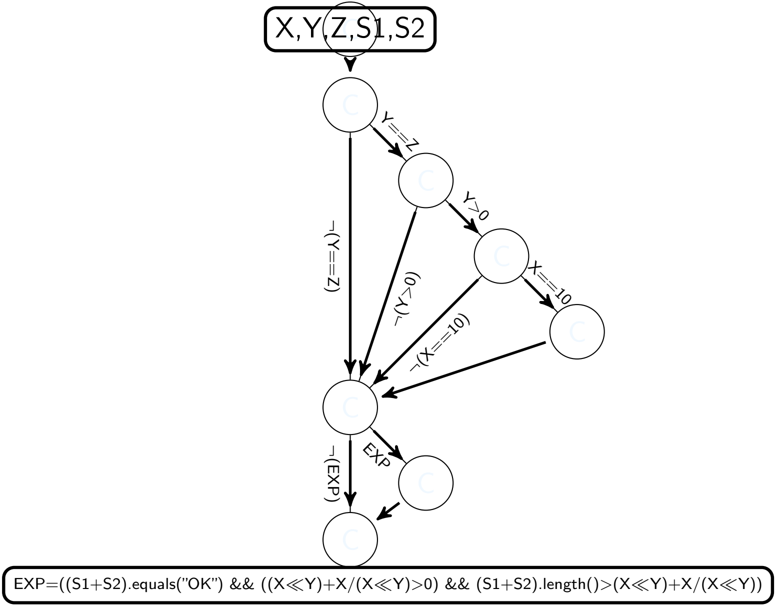
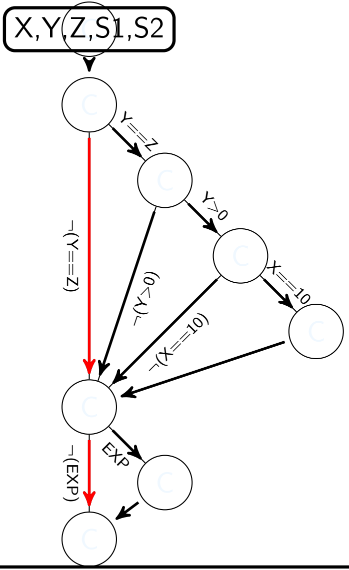
Pb2: SB-STDG may fail to generate test data to reach Line 5

Constraint Based(Symbolic Execution)



Constraint Based(Symbolic Execution)

CP1=¬(Y==Z)∧ ¬(EXP)

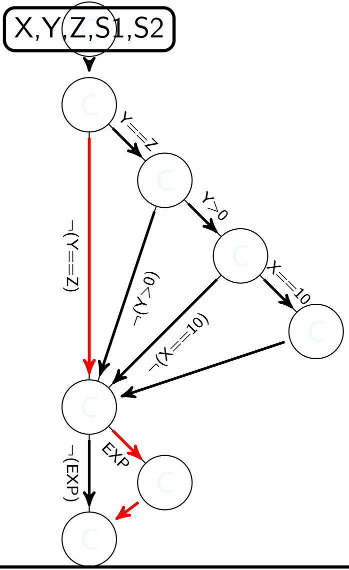


EXP=((S1+S2).equals("OK") && ((X≪Y)+X/(X≪Y)>0) && (S1+S2).length()>(X≪Y)+X/(X≪Y))

Constraint Based(Symbolic Execution)

CP1=¬(Y==Z)∧ ¬(EXP)

CP2=¬(Y==Z)∧ (EXP)



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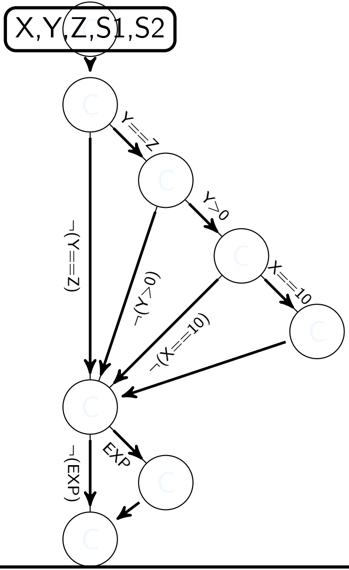
Constraint Based(Symbolic Execution)

CP1=¬(Y==Z)∧ ¬(EXP)

CP2=¬(Y==Z)∧ (EXP)

Pb3: There is no CP solver that can solve these constraints



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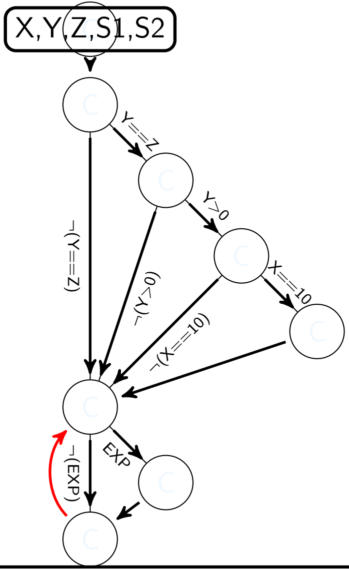

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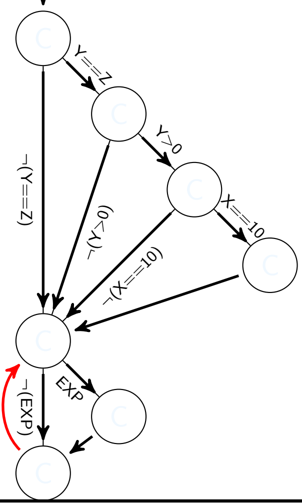
Constraint Based(Symbolic Execution)

X,Y,Z,S1,S2

CP1=¬(Y==Z)∧ ¬(EXP)

CP2=¬(Y==Z)∧ (EXP)



Pb3: There is no CP solver that can solve these constraints

Pb4: Exploring the Symbolic Tree

EXP=((S1+S2).equals("OK") && ((X≪Y)+X/(X≪Y)>0) && (S1+S2).length()>(X≪Y)+X/(X≪Y))

SB-STDG versus CB-STDG

SB-STDG

- + Scalable;
- − Incomplete;
- − Depends on many parameters.

Derives its advantages from the dynamic analysis.

CB-STDG

- − Not Scalable;
- + Complete;
- + Precision in test data generation.

Derives its advantages from the static analysis.

SB-STDG versus CB-STDG

SB-STDG

- + Scalable;
- − Incomplete;
- − Depends on many parameters.

Derives its advantages from the dynamic analysis.

CB-STDG

- − Not Scalable;
- + Complete;
- + Precision in test data generation.

Derives its advantages from the static analysis.

These approaches use complementary analyses that give them a potential for combination.

Thesis

The Goal

Improving the efficiency and effectiveness of SB-STDG for object-oriented testing and revealing bugs at an earlier stage.

The Way

- Using the main advantages of SB-STDG and CB-SDTG;
- Dynamically analyzing source code to monitor the actual execution;
- Statically analyzing source code to identify and extract relevant information;
- Exploiting relevant information to guide SB-STDG process either directly or through CB-STDG;

Contributions

Combining CB-STDG and SB-STDG

- CPA-STDG, a new CB-STDG approach;
- CSB-STDG, a new approach that combines CPA-STDG and SB-STDG;
- CB-FF, a novel constraint based fitness functions ;

Lightweight Static Analyses to improve SB-STDG

- IG-PR-IOOCC, a new SB-STDG approach for unit-class testing.

Constraint Programming Approach for Software Test Data Generation (CPA-STDG)

CPA-STDG

Idea of CPA-STDG

Idea

- Delegating the exploration of the symbolic tree to a CP Solver;
- Creating one CSP for the whole program under test and its CFG.

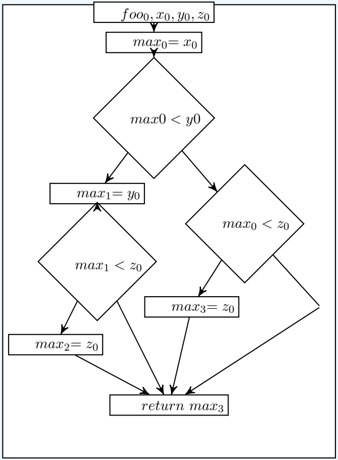
Advantages

- + Avoid the symbolic evaluation cost;
- + Benefit from the large number of search heuristics that are implanted in a Solver;
- + Avoid exploring infeasible sub-paths;
- + Easy identification of the program structure.

CPA-STDG

Constraints Generation

foo CFG

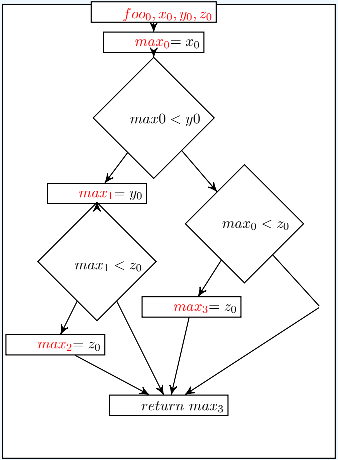


CSP of foo

CPA-STDG

Constraints Generation

foo CFG



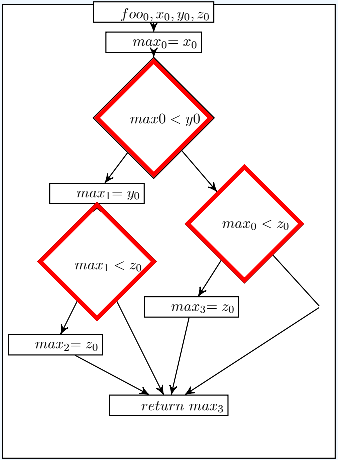
CSP of foo

Var int foo_0, x_0, y_0, z_0, max_{0-3}

CPA-STDG

Constraints Generation

foo CFG



CSP of foo

Var int foo_0, x_0, y_0, z_0, max_{0-3}
Var int nD_{0-2} in {-1,0,1}

CPA-STDG

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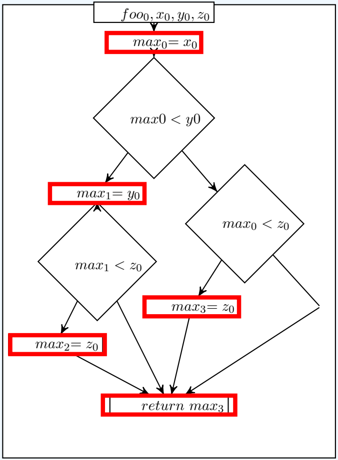


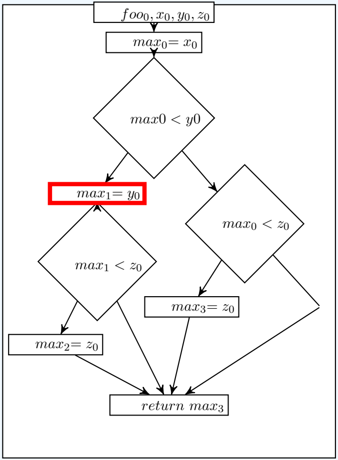
CSP of foo

Var int foo_0, x_0, y_0, z_0, max_{0-3}
Var int nD_{0-2} in {-1,0,1}
Var int nS_{0-4} in {0,1}

CPA-STDG

Constraints Generation

foo CFG



CSP of foo

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$nS_1 = 0 \Rightarrow max_1 = max_0$

CPA-STDG

Constraints Generation

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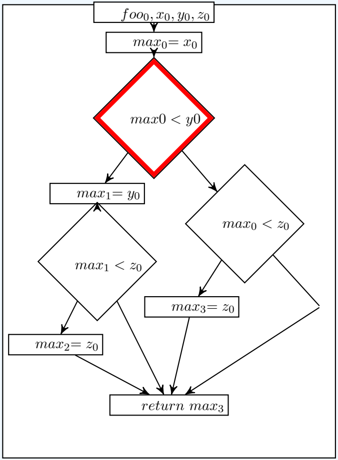

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$nS_1 = 0 \Rightarrow max_1 = max_0$

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$nD_0 = -1 \Rightarrow \neg(max_0 < y_0)$

CPA-STDG

Constraints Generation

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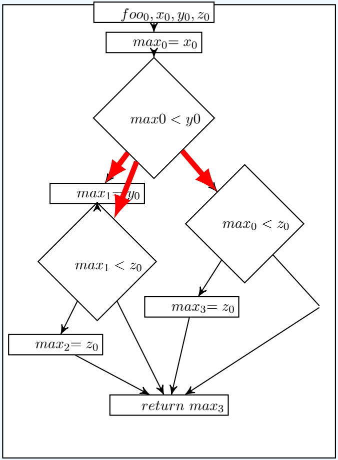

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$nD_0 = 1 \Leftrightarrow nS_1 \neq 0$
$nD_0 = 1 \Leftrightarrow nD_1 \neq 0$
$nD_0 = -1 \Leftrightarrow nD_2 \neq 0$

CPA-STDG

Results

Comparing CPA-STDG to a Dynamic SE approach (PathCrawler)

Program	k-path	# feasible Paths	CPA-STDG		PathCrawler	
			# T. D.	T. (s)	# T. D.	T. (s)
tri_type	-	10	10	0.001	14	0.010
Sample	3	240	240	0.060	241	0.270
Merge	5	321	321	0.148	337	0.780
Merge	10	20,481	20,481	28.640	20,993	116.000

CPA-STDG
Results

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CPA-STDG

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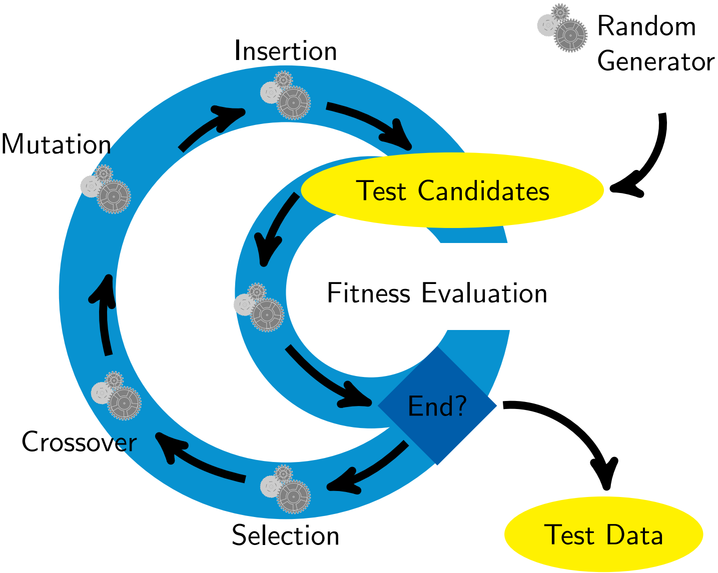
CPA-STDG is more efficient and effective than PathCrawler.

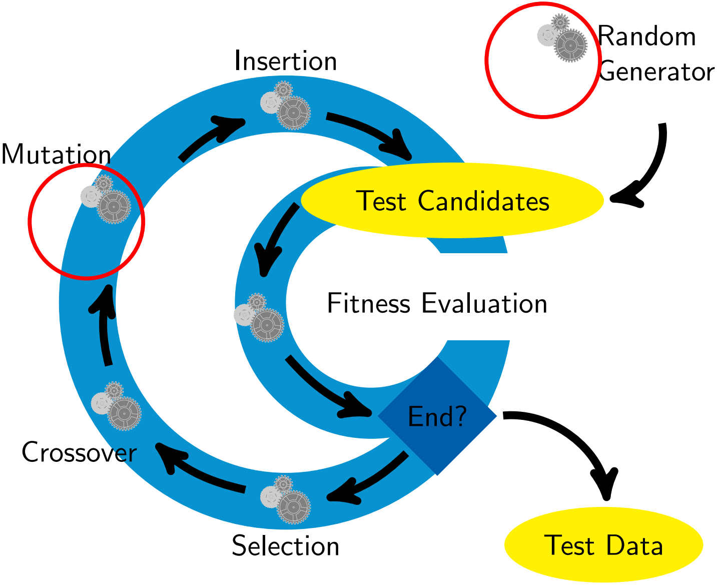
The scalability issue remains an open research question.

Constrained Search Based Software Test Data Generation (CSB-STDG).

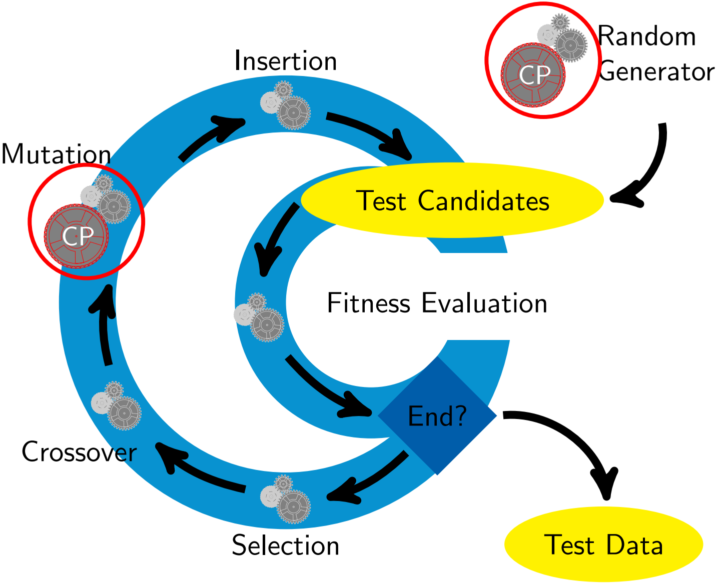
Search Based Software Test Data Generation



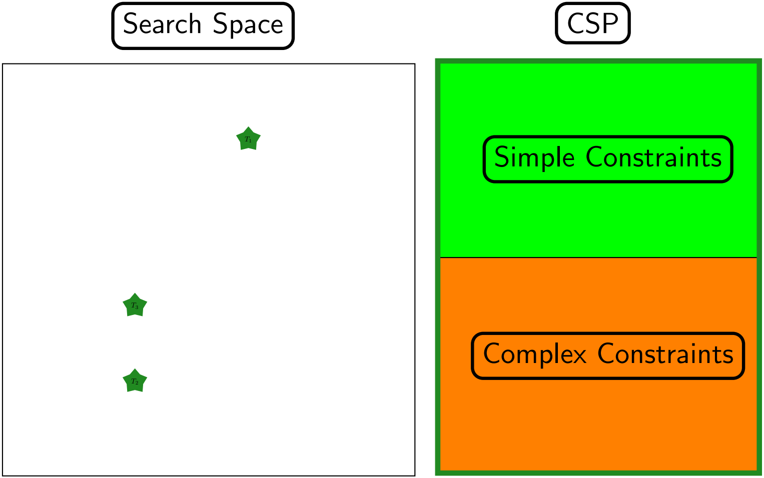
Search Based Software Test Data Generation



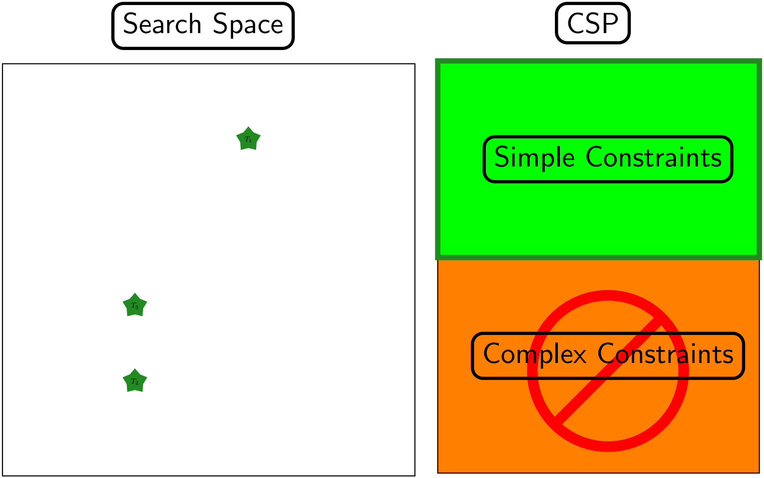
Search Based Software Test Data Generation



The Idea of CSB-STDG



The Idea of CSB-STDG



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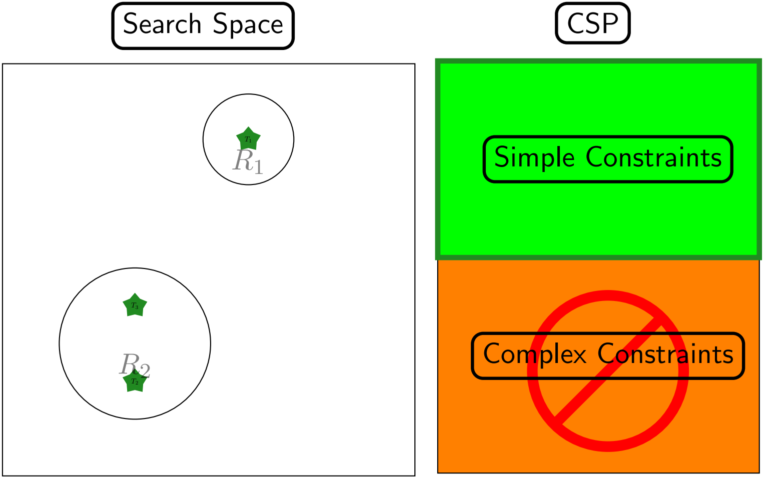

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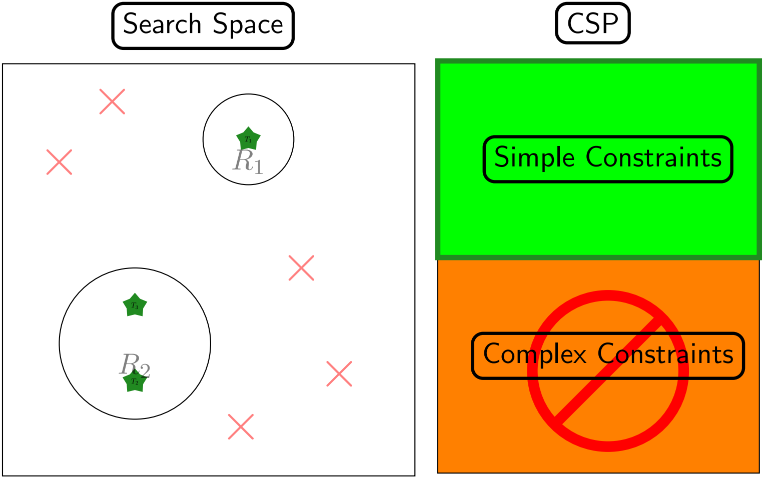
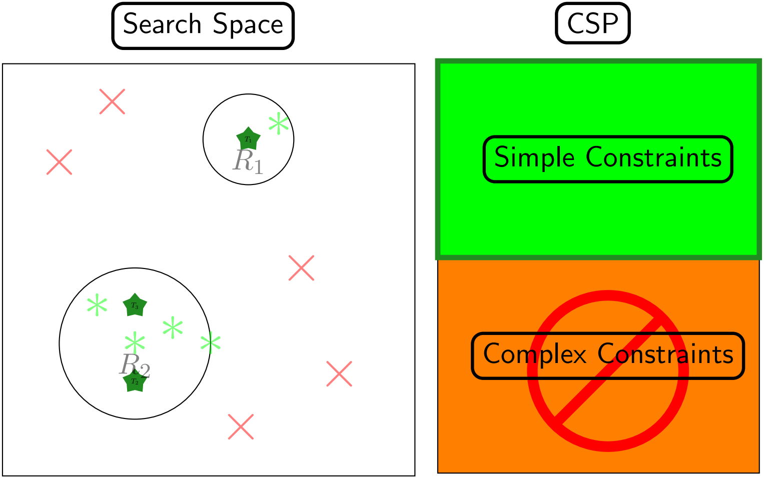


The Idea of CSB-STDG



Example: Unit Under Test Relaxation

```
int foo(int x,int y ~~, float z, String s1,String s2~~) {
    if(y==    ~~z~~)
        if(y>0)
            if(x==10)
                return     ~~s1.length()+s2.length()~~
     y= x<<y;
    x=y+x/y;
     ~~String s=s1+s2;~~
    if( (x>0) && R2>x)
          return y/    ~~s1.length()~~
    return 0;
 }
```

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    if( (x>0) && R2>x)
          return y/    s1.length()
    return 0;
 }
```

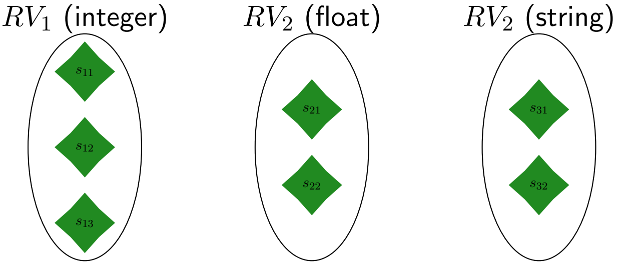
Abdelilah Sakti
Supervised by Gilles Pesant and Yann-Gaël Guéhéneuc

Example: Unit Under Test Relaxation

```
int foo(int x,int y                              ) {
  if(y==R0; )
    if(y>0)
      if(x==10)
        return R1;
   y= x<<y;
  x=y+x/y;

  if( (x>0) && R2>x)
      return y/R3;
  return 0;
 }
```

Constrained Population Generator(CPG)



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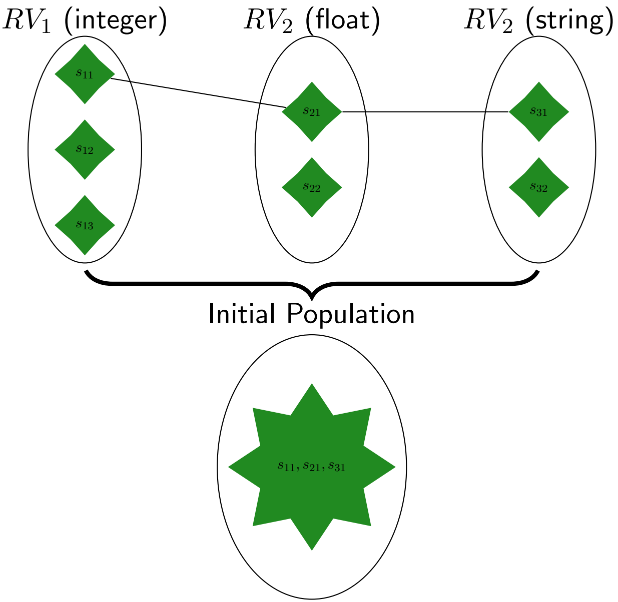

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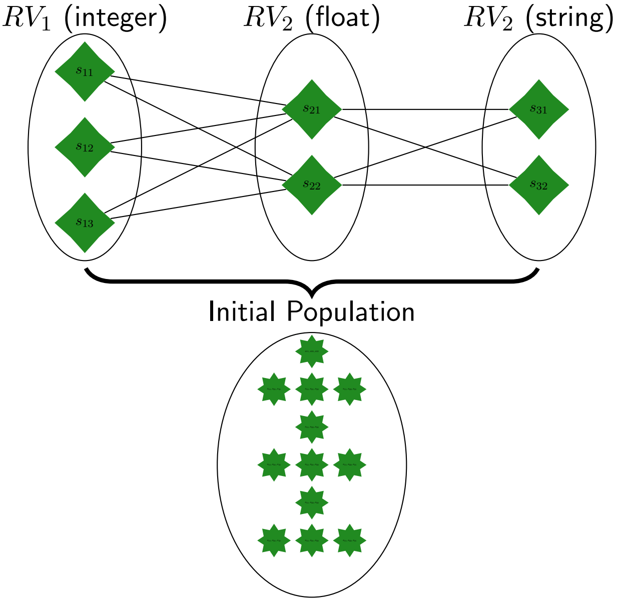
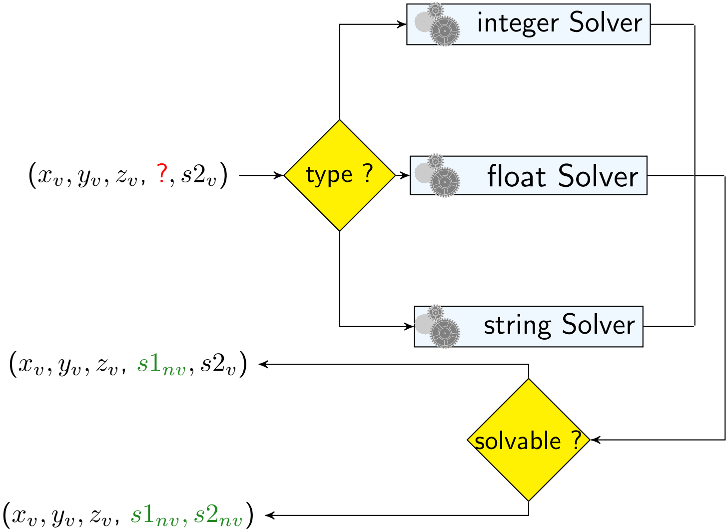


Constrained Evolution Operator (CEO)



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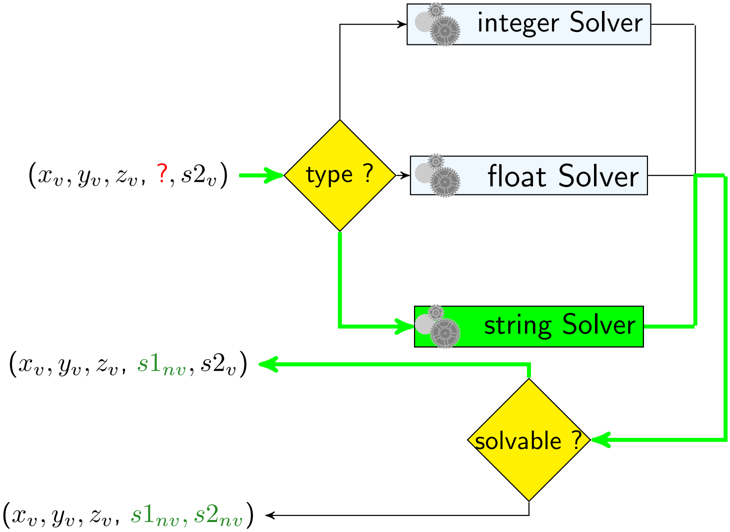


Evaluation

Subjects

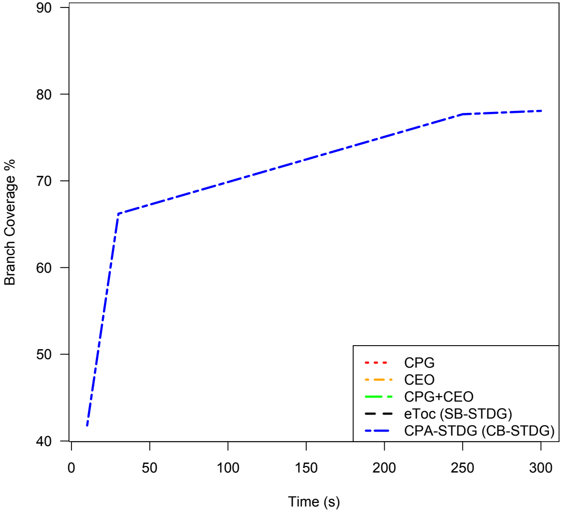
Subject	**# LOC**	**# Branches**
Integer	1244	38
BitSet	755	145
ArithmticUtils	959	102
All	**2958**	**285**

analysed approaches

- SB-STDG alone: eToc;
- CB-STDG alone: CPA-STDG;
- CSB-STDG: SB-STDG+CPG; SB-STDG+CEO.

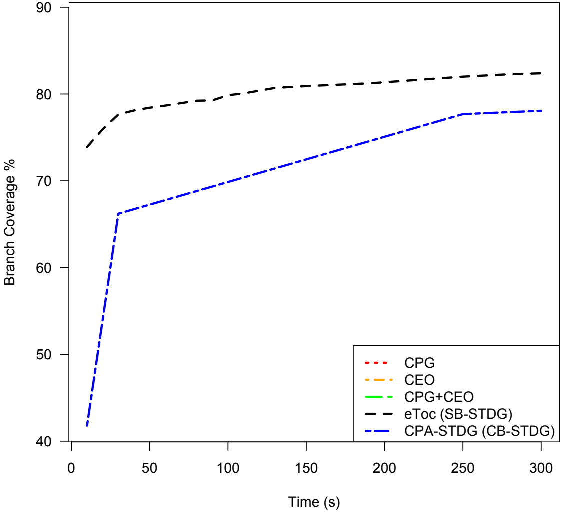
Evaluation

Results



Evaluation

Results



Evaluation

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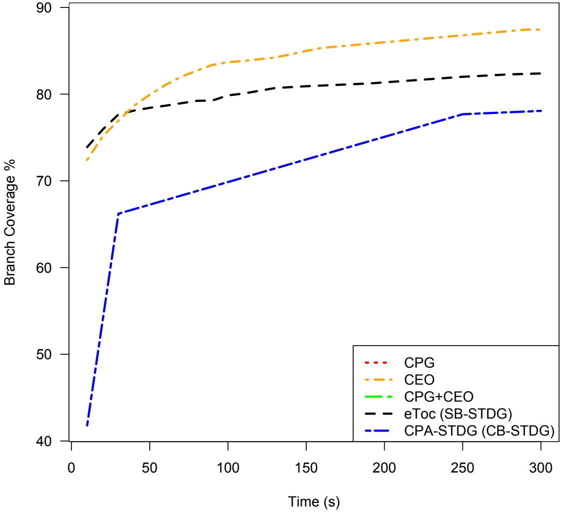
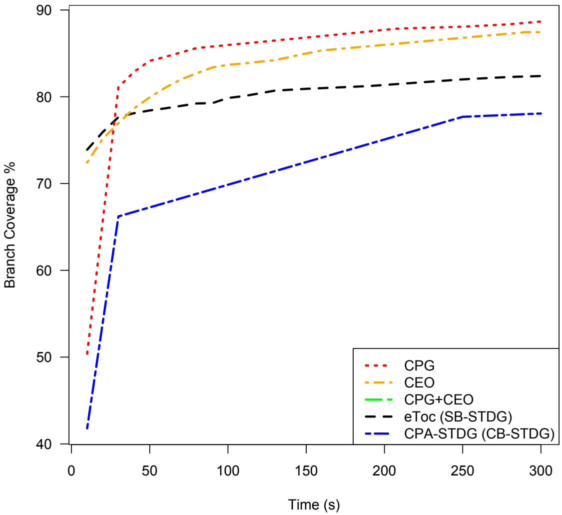
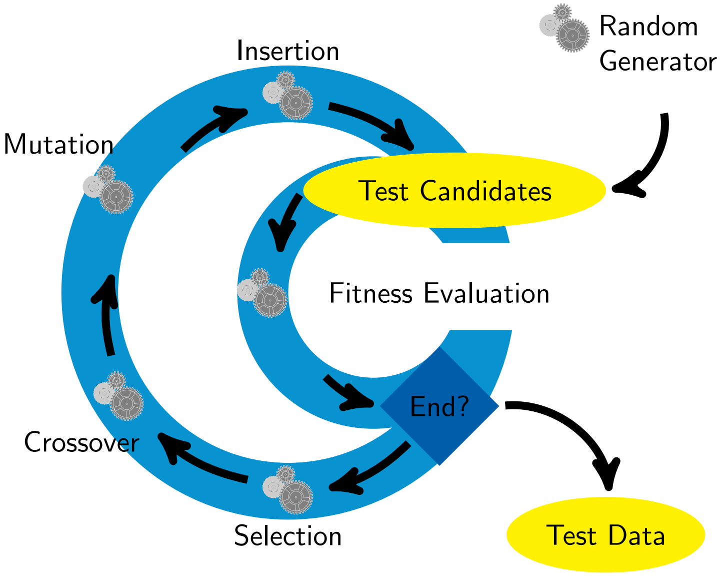


Evaluation

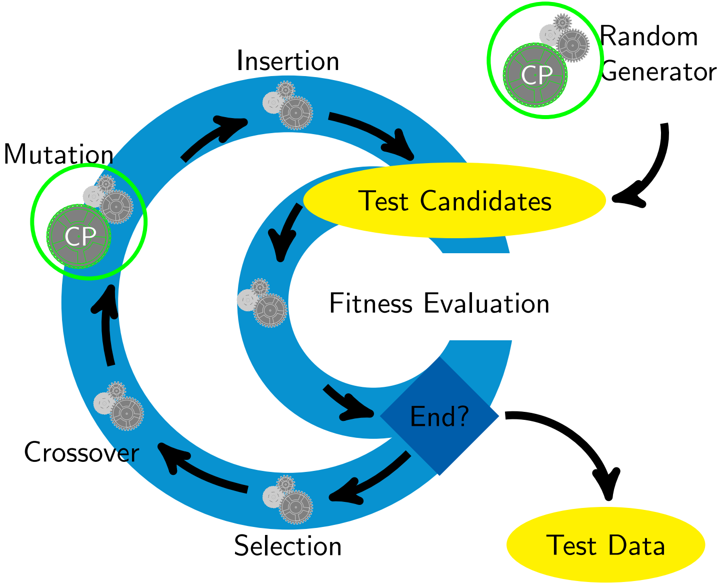
Results



CSB-STDG


Random Generator
Insertion
Mutation
Test Candidates
Fitness Evaluation
End?
Crossover
Selection
Test Data

CSB-STDG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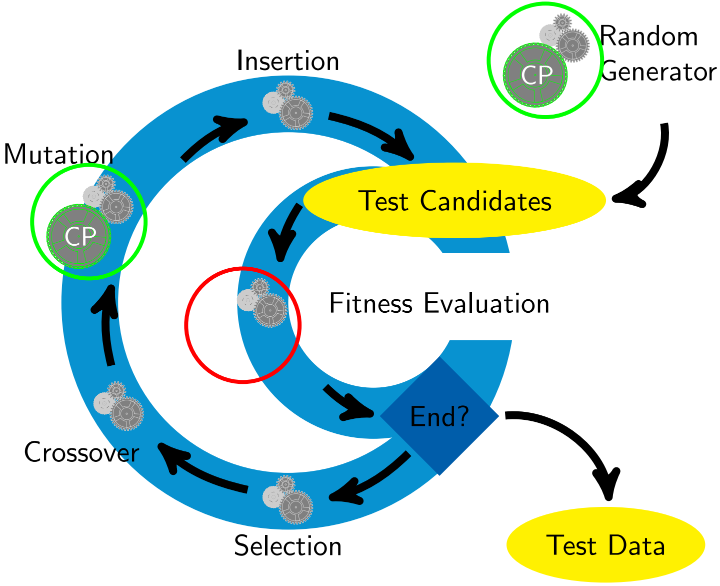
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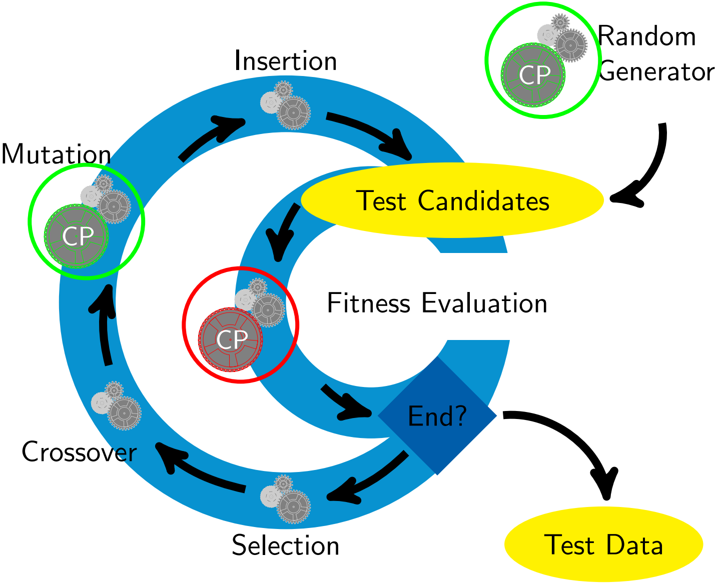
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Constraint Based Fitness Function (CB-FF).

The idea of CB-FF

- Prioritizing branches according to how **hard** it is to satisfy them.

The idea of CB-FF

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Hardness

- Defining the difficulty to satisfy a constraint in terms of its **arity** and its **projection tightness**;

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  1. The lower the arity of the constraint, the less freedom we have to choose some of its variables in order to evolve the test candidate.

The idea of CB-FF

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Hardness

- Defining the difficulty to satisfy a constraint in terms of its **arity** and its **projection tightness**;
  1. The lower the arity of the constraint, the less freedom we have to choose some of its variables in order to evolve the test candidate.
  2. A projection tightness close to 0 will indicate high constrainedness and hardness to satisfy a constraint.

Branch-Hardness Metrics

Difficulty Coefficient (DC)

- DC is a possible representation of the hardness of a branch;
- $DC(c) = B^2 \cdot \frac{1}{arity_c} + B \cdot (1 - tightness) + 1$.

Branch-Hardness Metrics

Difficulty Coefficient (DC)

- DC is a possible representation of the hardness of a branch;
- $DC(c) = B^2 \cdot \frac{1}{arity_c} + B \cdot (1 - tightness) + 1$.

Difficulty Level (DL)

- DL is based on DC ranking (r);
- DL is a representation of a relative hardness level of a constraint in a set of constraints;
- $DL(c, C) = \begin{cases} |C|, & \text{if } r = 0 \\ 2^{r-1} \cdot (|C| + 1), & \text{if } r > 0 \end{cases}$.

Branch-Hardness Fitness Functions

DC Fitness Function (f_{DC})

- DC is used as a penalty coefficient for breaking a constraint;
- The target of this fitness function is determining a standard-branch-distance.
- $f_{DC}(i, C) = \sum_{c \in C} DC(c) \cdot \eta(i, c)$.

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DL Fitness Function (f_{DL})

- DL is used as a constant penalty for breaking a constraint in a set of constraints to satisfy;
- $f_{DL}(i, C) = \sum_{c \in C} \ell(i, c) + \eta(i, c)$,

  where $\ell(i, c) = \begin{cases} 0, & \text{if } \eta(i, c) = 0 \\ DL(c, C), & \text{if } \eta(i, c) \neq 0 \end{cases}$.

Evaluation

Subjects and configuration

analyzed meta-heuristics and fitness functions

- Two widely used meta-heuristic algorithms are analyzed: Simulated Annealing (SA) and Evolutionary Algorithm (EA).
- f_{AL} and f_{SE} from the literature;
- Our fitness functions f_{DC} and f_{DL}.

Evaluation

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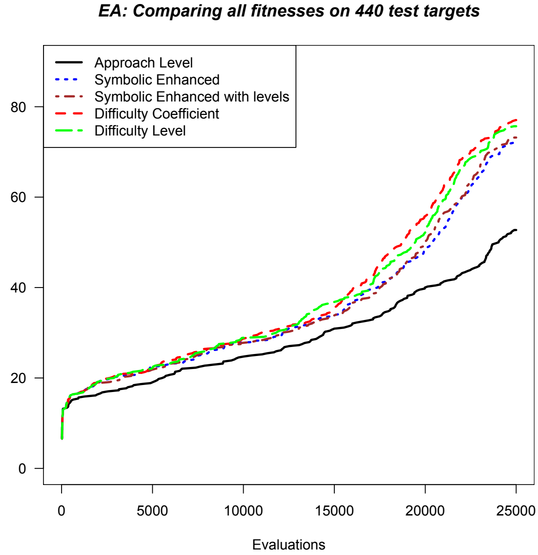
- Our fitness functions f_{DC} and f_{DL}.

Subjects

- 440 synthetic test targets that were randomly generated.
- 20 executions for every combination of fitness function and meta-heuristic algorithm.
- If test data was not found after 25,000 (respectively 100,000) fitness evaluations for EA (respectively SA), the search was terminated.

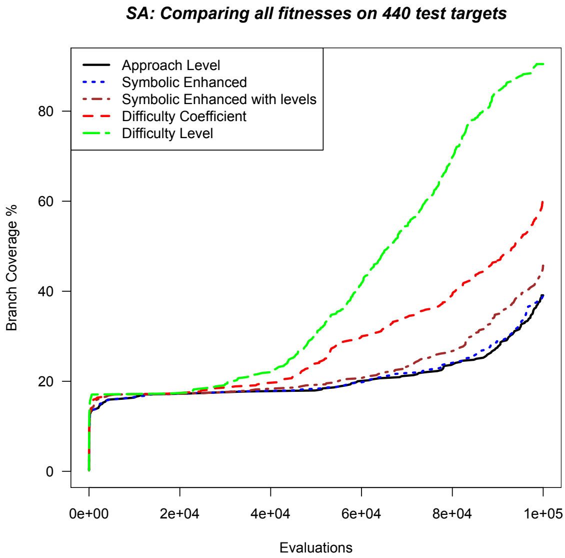
Evaluation

EA Results

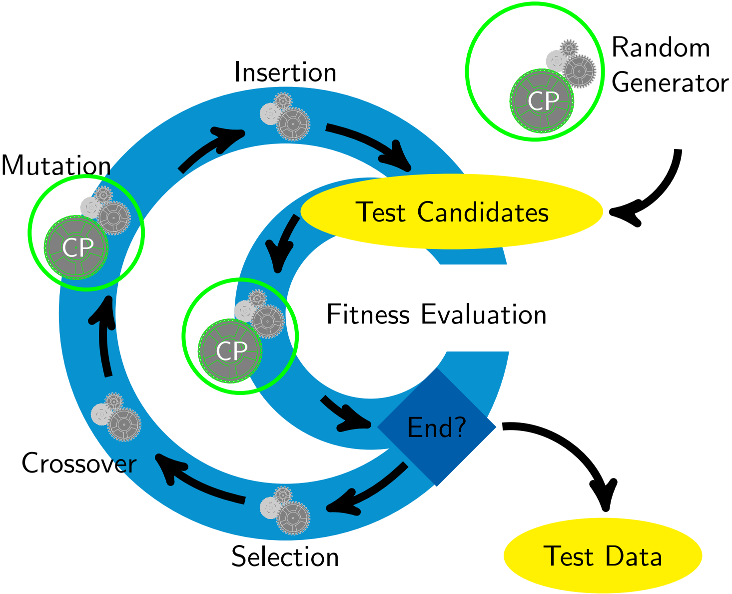


Evaluation

SA Results



CB-FF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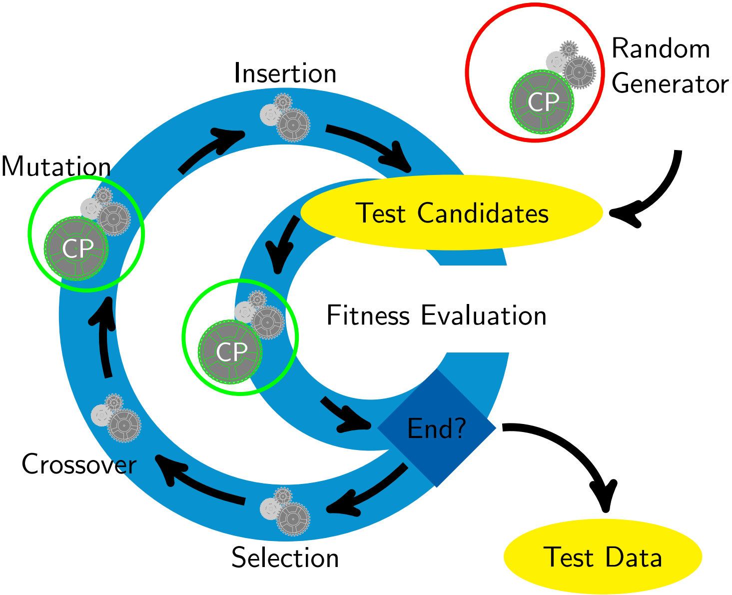
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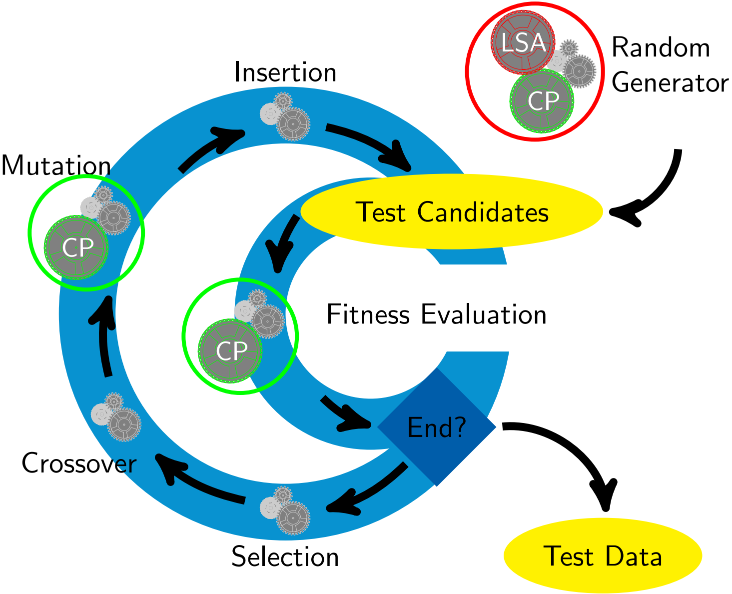
Insertion
LSA
CP
Random Generator
Mutation
CP
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CP
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Further Static Analyses to Improve SB-STDG (IG-PR-IOOCC).

IG-PR-IOOCC

The idea of IG-PR-IOOCC

Exploring relevant sequences

- Methods that may modify a data member or can reach the test target;
- A static analysis can determine the relevant methods.

Efficiently generate, diversify, and enrich instances of classes

- Instantiate a class with a minimum cost;
- Diversify instances of classes by using different means-of-instantiation;
- Seed instances of classes by using the constants existing in the source code.

IG-PR-IOOCC

The idea of IG-PR-IOOCC

	Requirements	To analyze	To extract
(I)	A means-of-instantiation of the class under test and each required argument	▶ Constructors; ▶ Factory methods; ▶ Data Members; ▶ Derived Classes (SubClasses).	Set of means-of-instantiation.
(II)	A sequence of method calls to make the class under test in a relevant state.	Data Member$_1$ Data Member$_2$ ⋮ Data Member$_m$	State Modifier$_1$ State Modifier$_2$ ⋮ State Modifier$_m$
(III)	A method that can reach the test target.	Method Under Test	Public Methods caller

IG-PR-IOOCC

Example

Source Code

```
public class FooClass{
private int y;
private float z;
private String s2;
public void setY(int y1) {y=y1};
public void setZ(float z1) {z=z1};
public void setS2(String s) {s2=s};
public int fooCaller(int a, String str){
      ...
      foo(a,str);
      ...
}
private int foo(int x, String s1){
      ...
}
      ...
}
```

IG-PR-IOOCC

Example

Source Code

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public class FooClass{
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    foo(a,str);
    ...
}
private int foo(int x, String s1){
    ...
}
    ...
}
```

Static Analyses

MIn

IG-PR-IOOCC

Example

Source Code

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public class FooClass{
private int y;
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Static Analyses

MIn FooClass()

IG-PR-IOOCC

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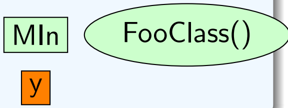
Static Analyses



IG-PR-IOOCC

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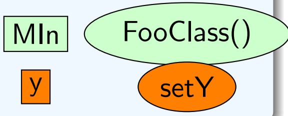

IG-PR-IOOCC

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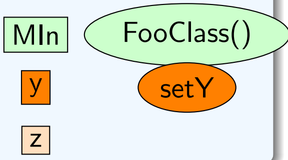

IG-PR-IOOCC

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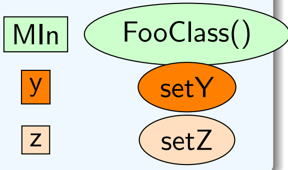

IG-PR-IOOCC

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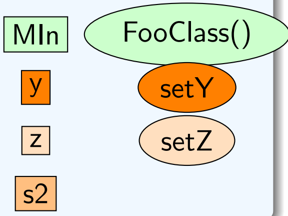

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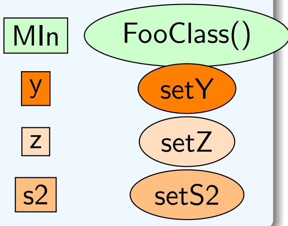

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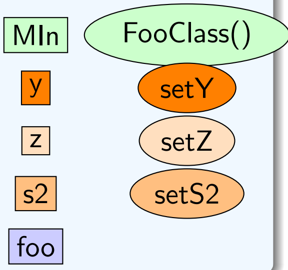

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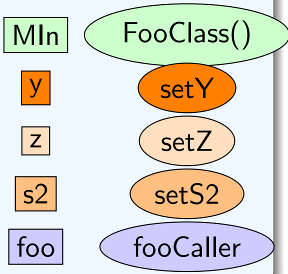


Evaluation I

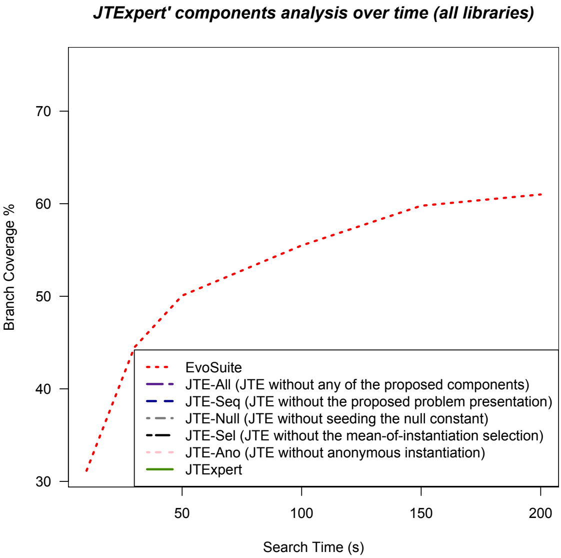
Subjects

Compared systems

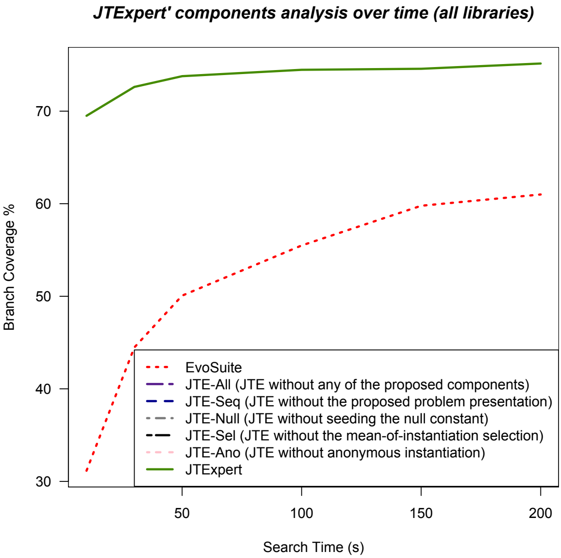
- EvoSuite;
- JTExpert.
  - Instance Generator;
  - Generator of sequences of method calls.

Libraries	Files	Classes	Methods	Branches	Lines	Instructions
Joda-Time	50	87	1,411	3,052	5,876	25,738
Barbecue	18	18	161	323	1,041	14,558
Commons-lang	5	6	366	1,942	2,134	9,139
Lucene	2	4	58	202	262	1,364
All	**75**	**115**	**1,998**	**5,519**	**9,313**	**50,799**

Results


JTExpert' components analysis over time (all libraries)
Branch Coverage %
Search Time (s)
30
40
50
60
70
50
100
150
200
EvoSuite
JTE-All (JTE without any of the proposed components)
JTE-Seq (JTE without the proposed problem presentation)
JTE-Null (JTE without seeding the null constant)
JTE-Sel (JTE without the mean-of-instantiation selection)
JTE-Ano (JTE without anonymous instantiation)
JTExpert

Results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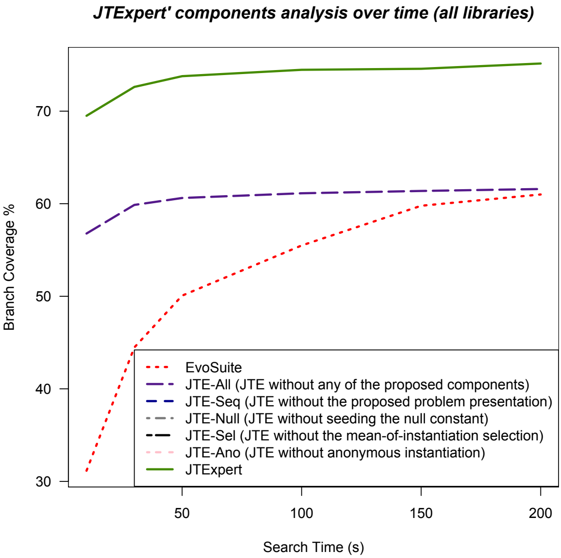
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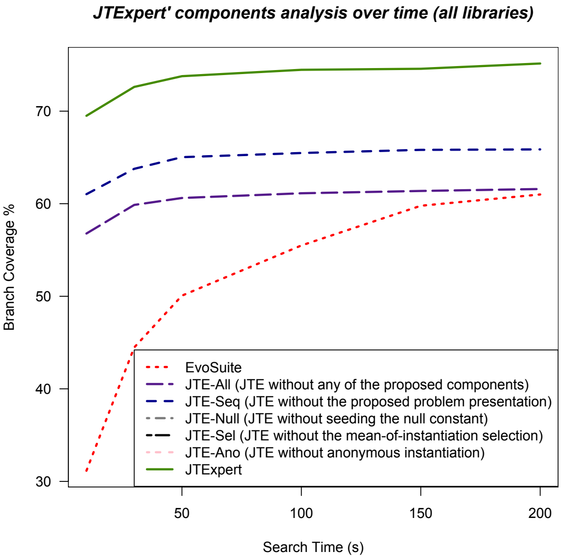
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JTExpert: A Large Scale Experimentation

Exceptions-oriented Test-data Generation

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public int fooCaller(int a, String str){
    foo(a,str);...
}
private int foo(int x, String s1){
   if(y==z)
      if(y>0)
         if(x==10)
            return s1.length()+s2.length();
   y= x<<y;
   x=y+x/y;
   String s=s1+s2;
   if((s.equals("OK") && (x>0) && s.length()>x)
      return y/s1.length();
   return 0;
}
}
```

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JTExpert: A Large Scale Experimentation

Subjects

The Apache Hadoop framework

The Apache Hadoop framework allows the distributed processing of large data sets across clusters of computers using simple programming models.

- 43 sub-modules;
- 3,545 Java files;
- 7,531 classes;
- 88,971 methods;
- 148,691 branches;
- 421,032 lines of code;
- 1,698,650 statements.

JTExpert: A Large Scale Experimentation

Results

Exception	Alerted	Alerted in different		
		Lines	Methods	Classes
`NullPointerException`	13,663	3,604	3,377	1,343
`ClassCastException`	658	213	206	165
`NoClassDefFoundError`	602	87	86	86
`IllegalArgumentException`	326	104	102	100
`ArrayIndexOutOfBoundsException`	296	119	108	71
`Fatal Errors`	9	2	2	2
`Other Exceptions`	492	193	180	153
All Exceptions	**16,046**	**4,322**	**4,061**	**1,920**

JTExpert: A Large Scale Experimentation

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JTExpert: A Large Scale Experimentation

Results

The source of Fatal Errors

- Package: `org.apache.hadoop.io`;
- Class: `WritableComparator`;
- Method: `compareBytes(byte[] b1, int s1, int l1,byte[] b2, int s2, int l2)`;
- How to reproduce it : use `b1=null` or `b2=null`;
- The root: The class `FastByteComparisons` uses reflection to get an instance of the private class `sun.misc.Unsafe`;
- Discussed at: `http://comments.gmane.org/gmane.comp.java.hadoop.hbase.devel/39017`.

JTExpert: A Large Scale Experimentation

- New instance generator;
- New representation of the test-data generation problem;
- Strategy of revealing bugs;
- JTExpert is available for download at `https://sites.google.com/site/saktiabdel/JTExpert`.

Conclusions

- CPA-STDG (**A. SAKTI et al. JFPC' 11**);
  - CP is a promising approach for automatic test-data generation.
- CSB-STDG (**A. SAKTI et al. SSBSE' 12**) and CB-FF (**A. SAKTI et al. CPAIOR' 13**);
  - CP is useful for SB-STDG;
- IG-PR-IOOCC (**A. SAKTI et al. TSE' 14**);
  - Lightweight static analyses is a way to improve SB-STDG.

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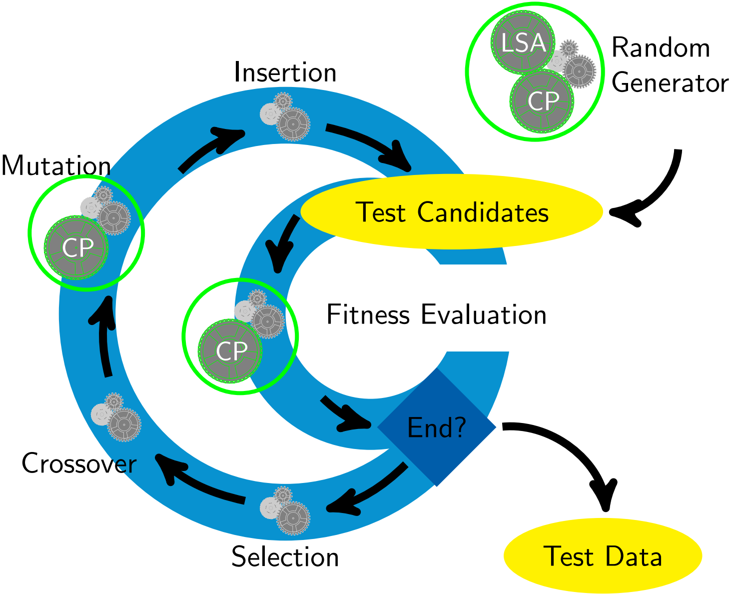
  - Lightweight static analyses is a way to improve SB-STDG.

Future work

- Further experiments;
- Broadening and enlarging internal static analyses;
- Statically analyzing new external sources to derive information that are relevant for test-cases generation.

Thank you, Questions?



Start fitter and finish better.