Zero false positive program analysis in Java

with dynamic symbolic execution

Dmitry Ivanov

Huawei Saint Petersburg Research Center

Director of R&D Software Toolchain Laboratory

korifey@gmail.com, *@korifey_ad*

Dmitry Mordvinov

Huawei Saint Petersburg Research Center

Team leader of symbolic execution research group

Associate professor at SpbU

mordvinov.dmitry@gmail.com

What is plan for next 50 minutes?

- **[Episode I, Survey]** – What kinds of analysis exist?
- **[Episode II, Theory]** – How symbolic execution works?
- **[Episode III, Practice]** – How to use SMT-solver?
- **[Epilogue, Product]** – How to get value for products?

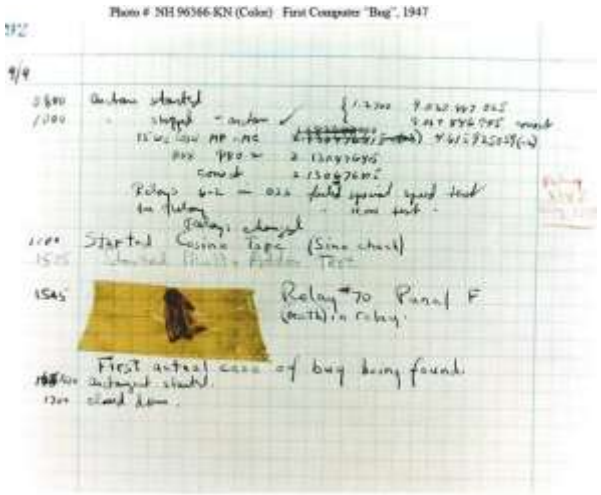
EPISODE I : ANALYSIS

Program analysis: Why?

- Conformance to specification
- **Error detection**
- **Security vulnerability detection**
- Coding standards checks
- Metrics calculation
- Architecture extraction & analysis

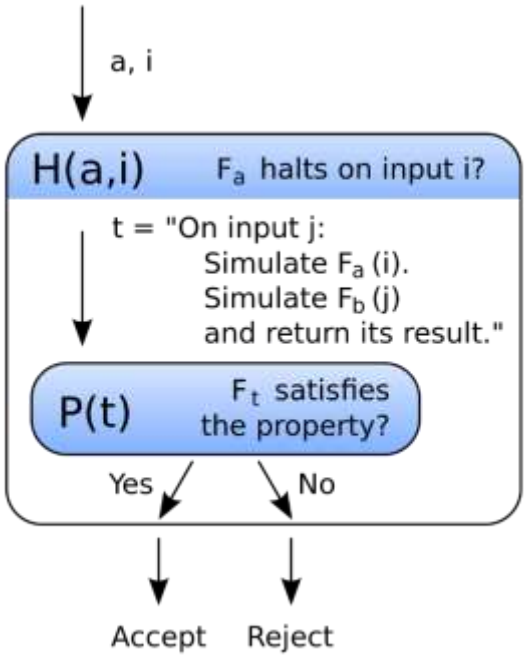
Program analysis: History

- 9 September 1947 – physical moth removing (debugging)



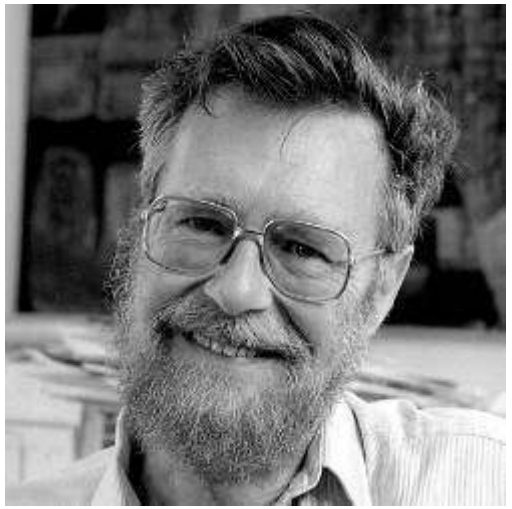
Program analysis: History

- 9 September 1947 – physical moth removing (debugging)
- 1950th – testing to specification conformance
- 1951st Henry Gordon Rice's Theorem: All non-trivial semantic properties of programs behavior are undecidable ☹



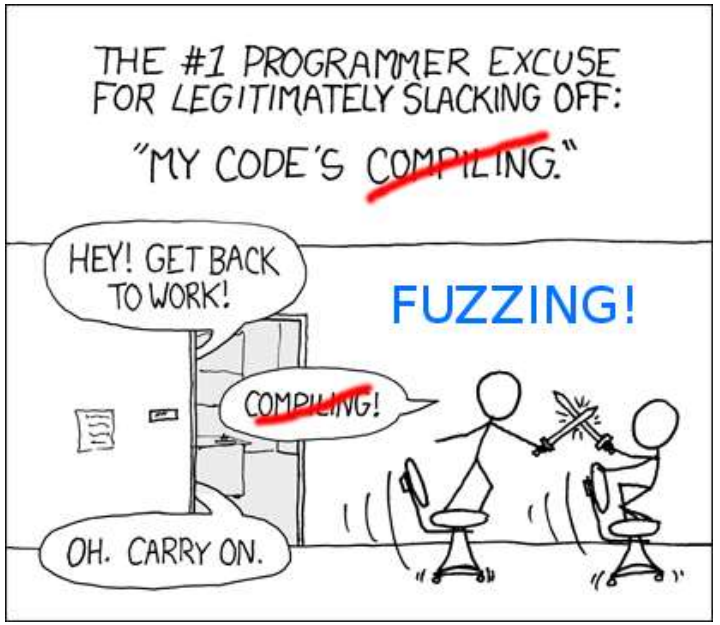
Program analysis: History

- 9 September 1947 – physical moth removing (debugging)
- 1950th – testing to specification conformance
- 1951st Henry Gordon Rice's Theorem: All non-trivial semantic properties of programs behavior are undecidable.
- 1970th – coding standards and first generation of source code static analysis
- 1971st – Edsger Wybe Dijkstra: Program testing can be used to show the presence of bugs, but never to show their absence! 😒



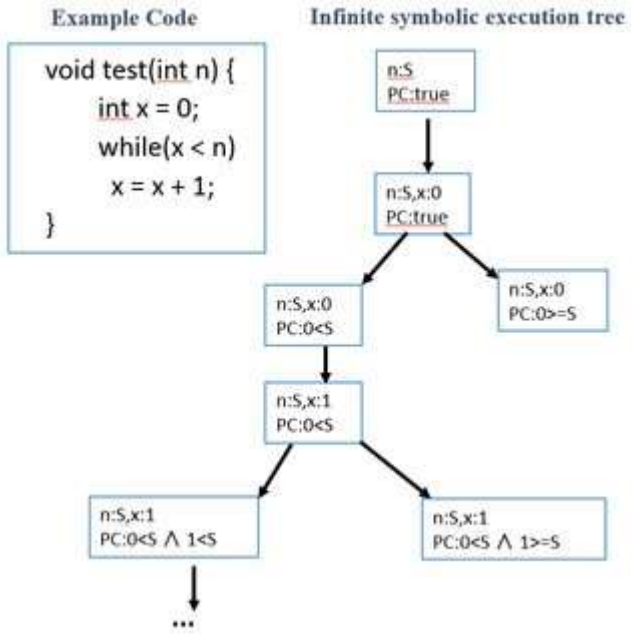
Program analysis: History

- 9 September 1947 – physical moth removing (debugging)
- 1950th – testing to specification conformance
- 1951st Henry Gordon Rice's Theorem: All non-trivial semantic properties of programs behavior are undecidable.
- 1970th – coding standards and first generation of source code static analysis
- 1971st – Edsger Wybe Dijkstra: Program testing can be used to show the presence of bugs, but never to show their absence!
- 1975th – Symbolic Execution idea and naïve implementation
- 1980th – randomized testing (Fuzzing)



Program analysis: History

- 9 September 1947 – physical moth removing (debugging)
- 1950th – testing to specification conformance
- 1951st Henry Gordon Rice's Theorem: All non-trivial semantic properties of programs behavior are undecidable.
- 1970th – coding standards and first generation of source code static analysis
- 1971st – Edsger Wybe Dijkstra: Program testing can be used to show the presence of bugs, but never to show their absence!
- 1975th – Symbolic Execution idea and naïve implementation
- 1980th – randomized testing (Fuzzing)
- 1990th – second generation of source code static analysis (data-flow analysis)
- 2000th – third generation of source code static analysis (IFDS + **SMT**)
- 2000th – **Symbolic Execution** engines (KLEE, S2E, Java Symbolic Pathfinder, …)
- 2010th – Hybrid analysis methods



Program analysis != Static code analysis

Method	+	-
Manual code inspection	Can detect complex error	Expert experience needed
Formal verification	Highest confidence	Lowest performance Lowest scalability
Static code analysis	High scalability High performance	False positives
Fuzzing	High performance High scalability No False Positives	Low control over analysis Low probability of error detection
Dynamic symbolic execution	High precision No False Positives	Low performance Low scalability

Program errors for source code static analysis

Plain text

Lexer based

AST based

Coding style guides for structuring source code

- Indentation error
- Naming rules violations
- Empty then-branch
- Lack of default-branch
- Assignment in conditional expression

checkstyle

PMD

Detekt

Path-sensitive

Condition-sensitive

Context-sensitive

Run-time errors, logical errors, security vulnerabilities

- Division by zero
- Resource leak/uncontrolled consumption
- NULL/uninitialized/dangling pointer dereference
- Buffer under/overflow
- Use after free
- SQL/Command injection
- …

SpotBugs

Find bugs in Java Programs

MICRO FOCUS Fortify

sonarqube

Infer

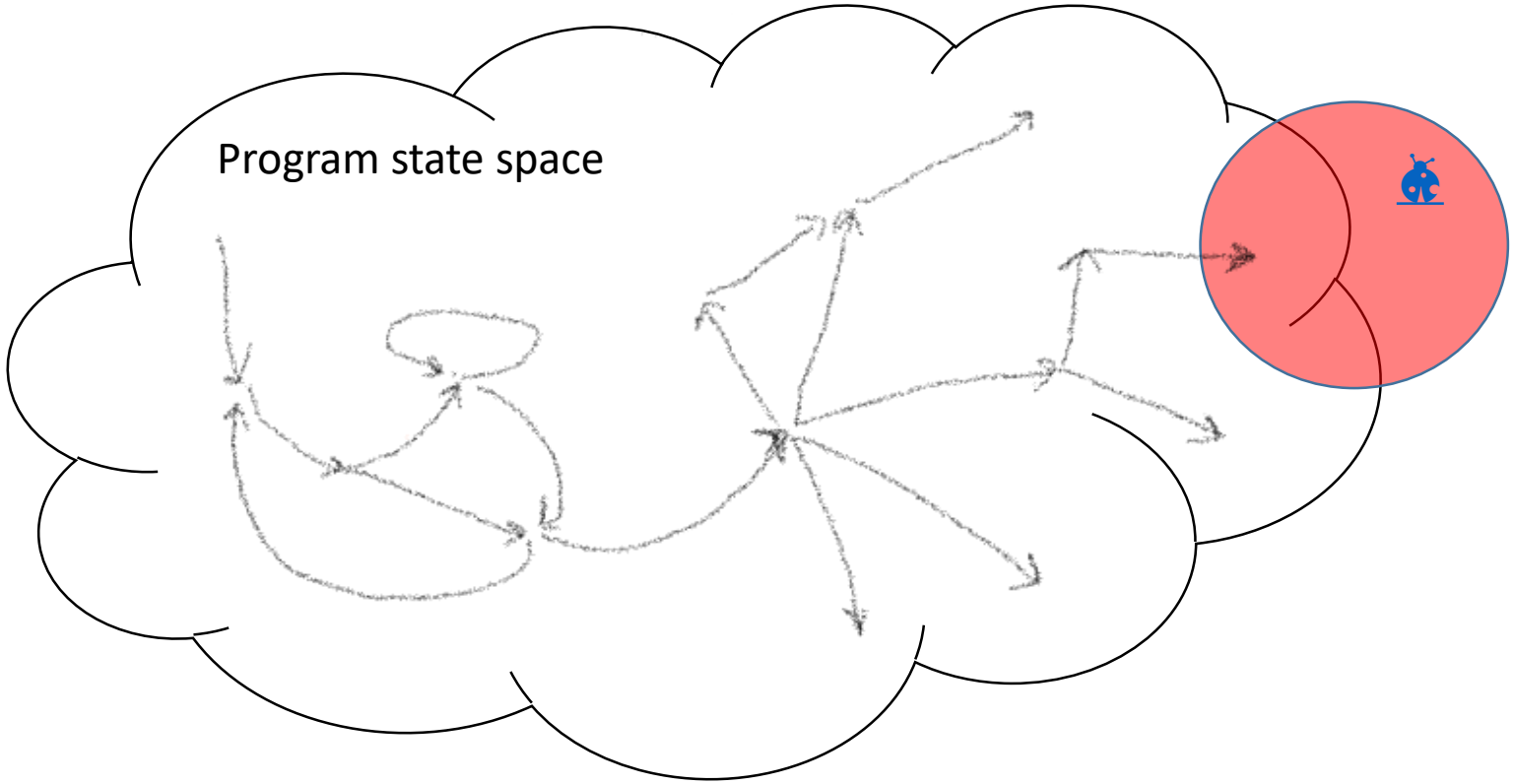
coverity

klocwork

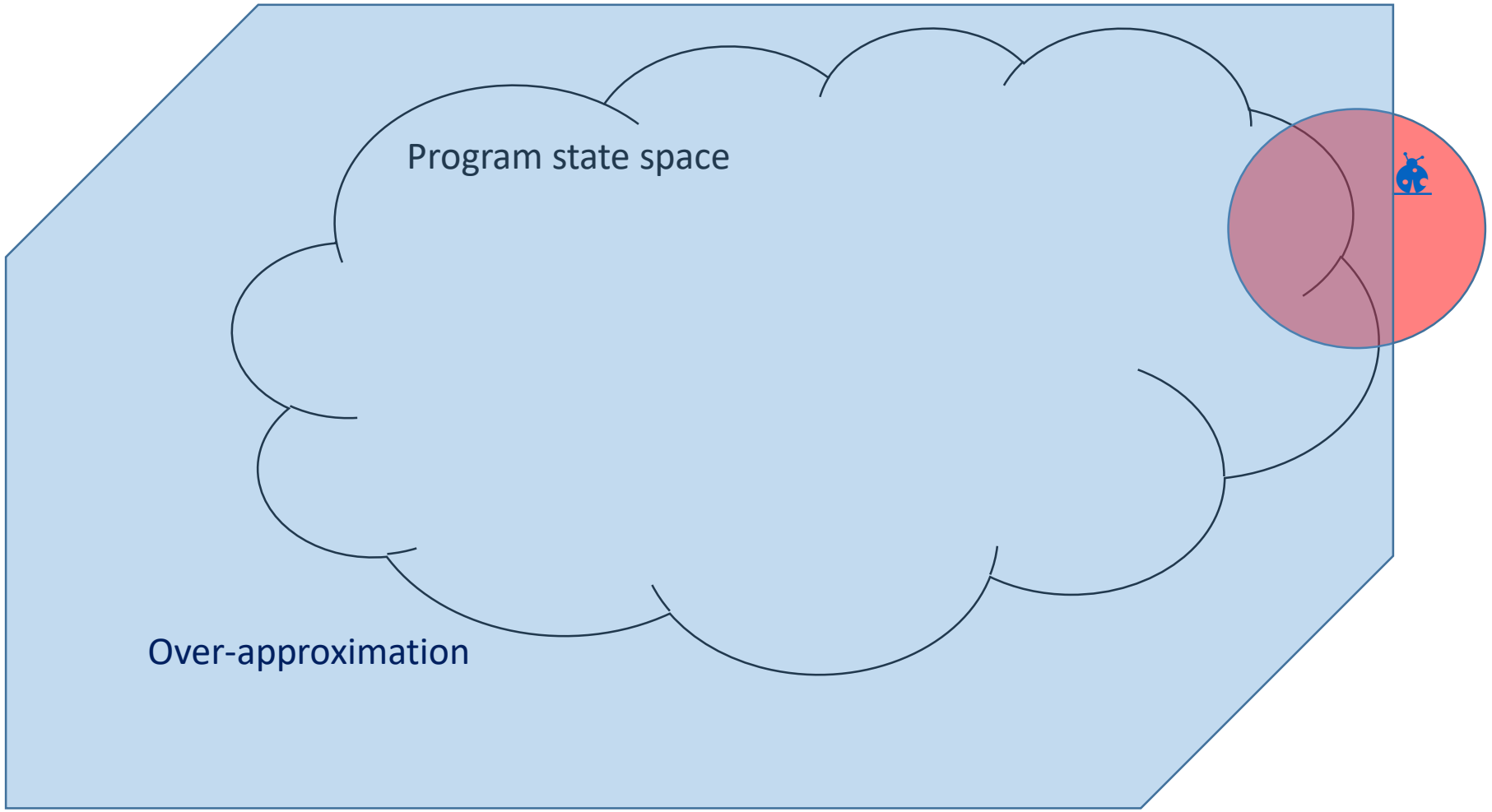
LIVE DEMO

IntellijIDEA

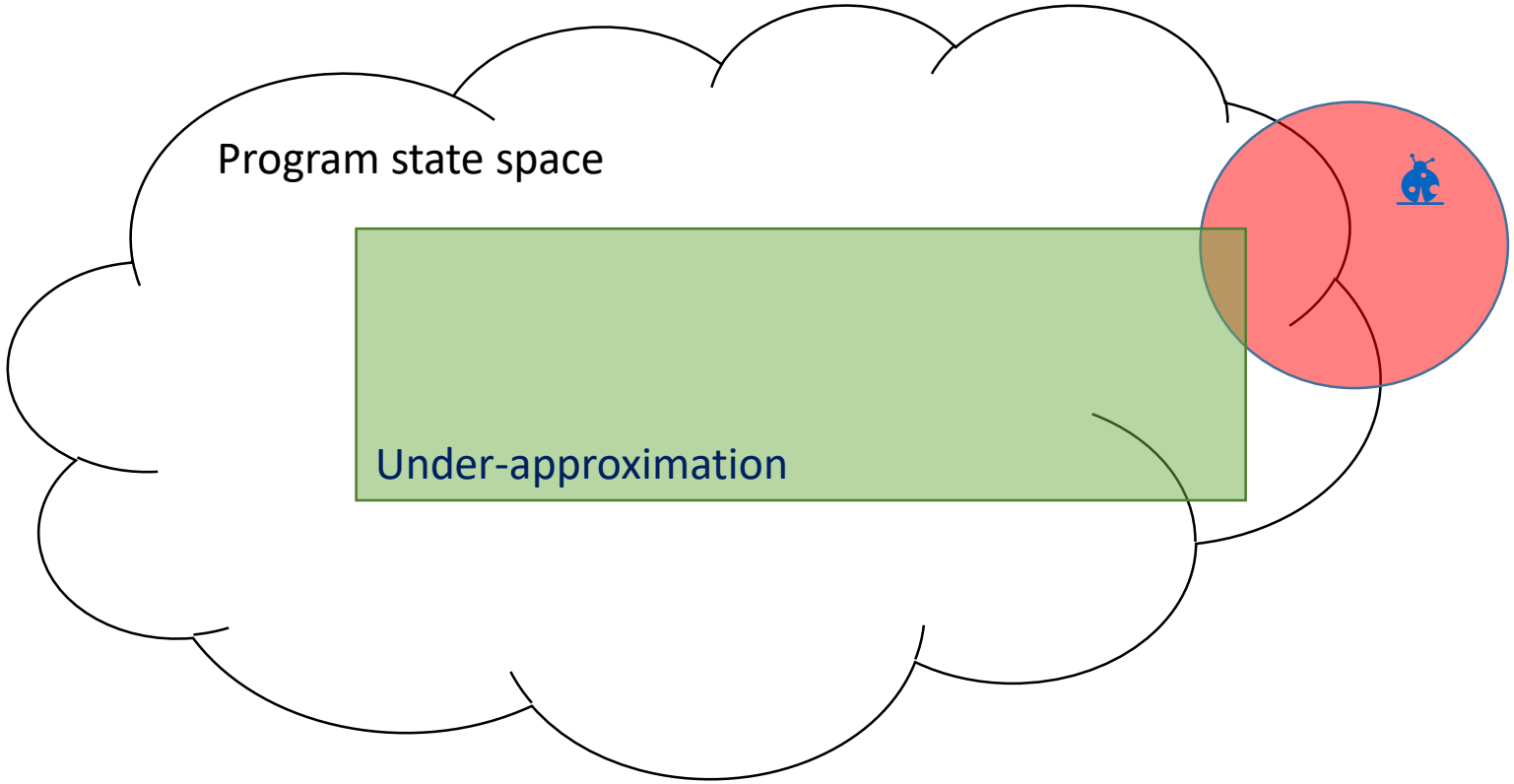
Program approximations



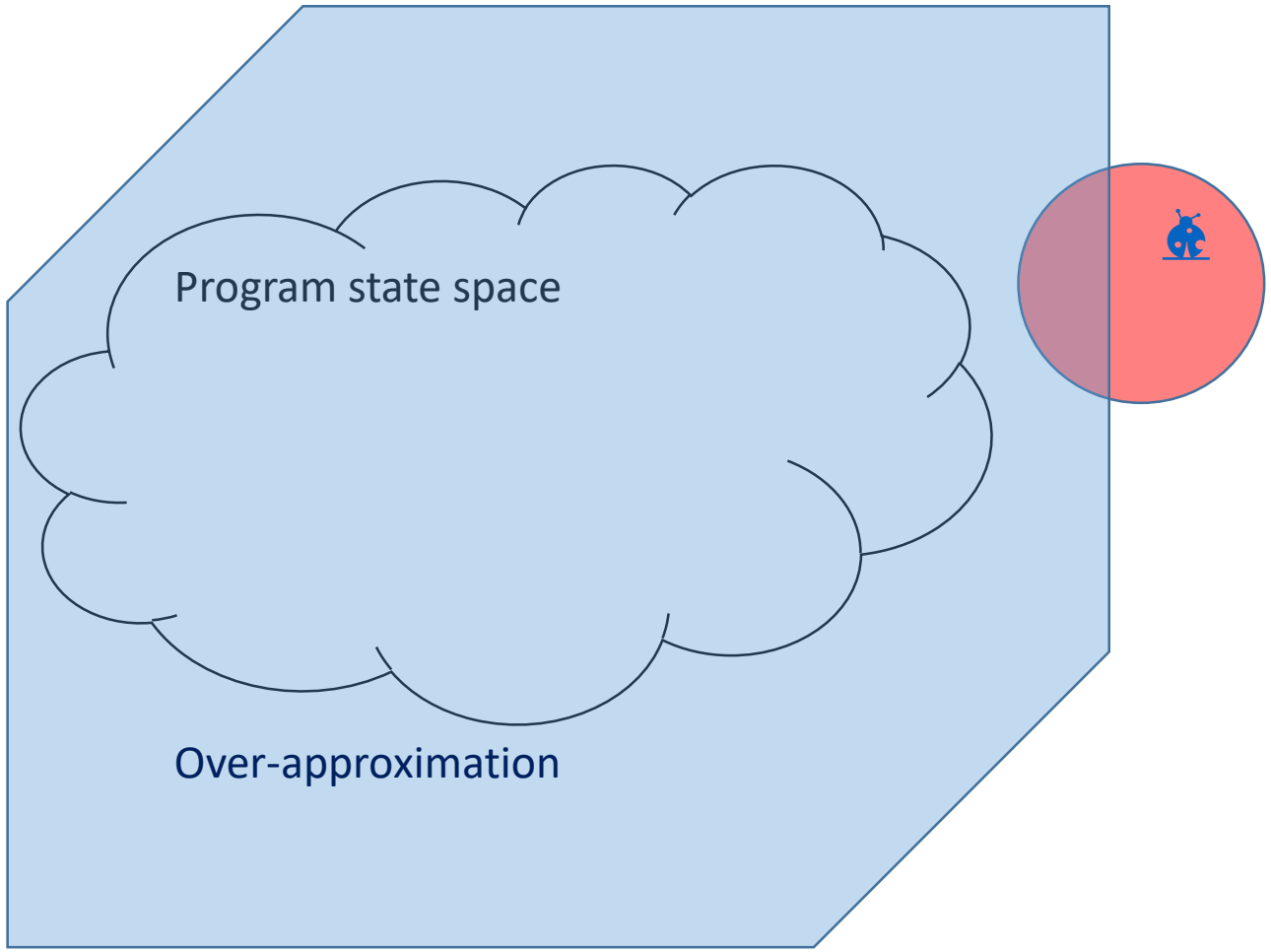
Program approximations: over-approximation



Program approximations: under-approximation

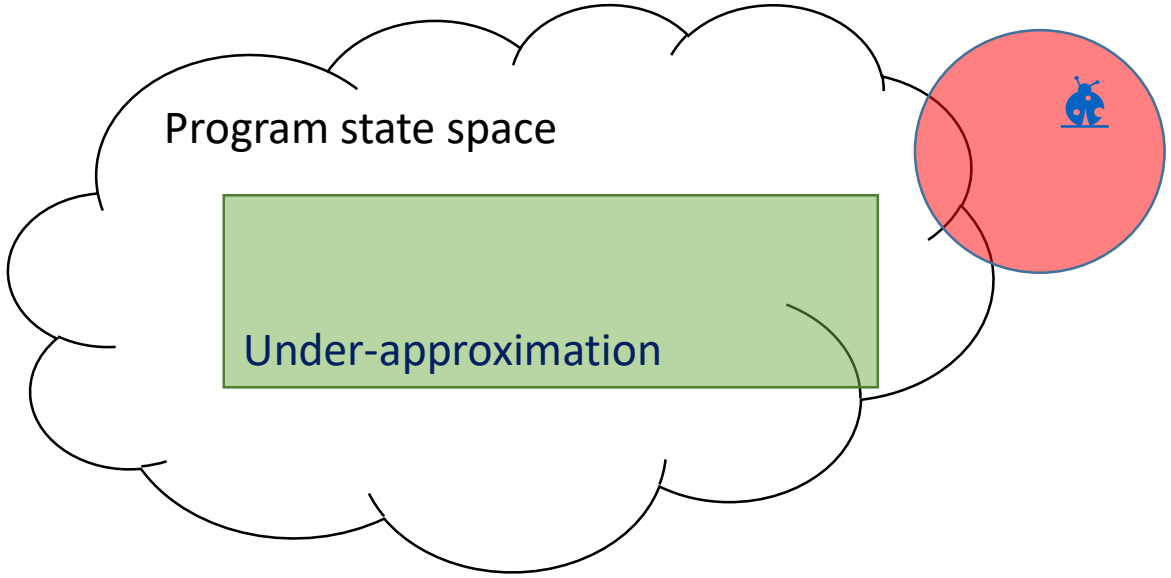


Over-approximation: false-positives



- Approximations can be too coarse
- It might lead to false positives
- In practice every static analyzer yield false positives
- False positives are frustrating and cause waste of time

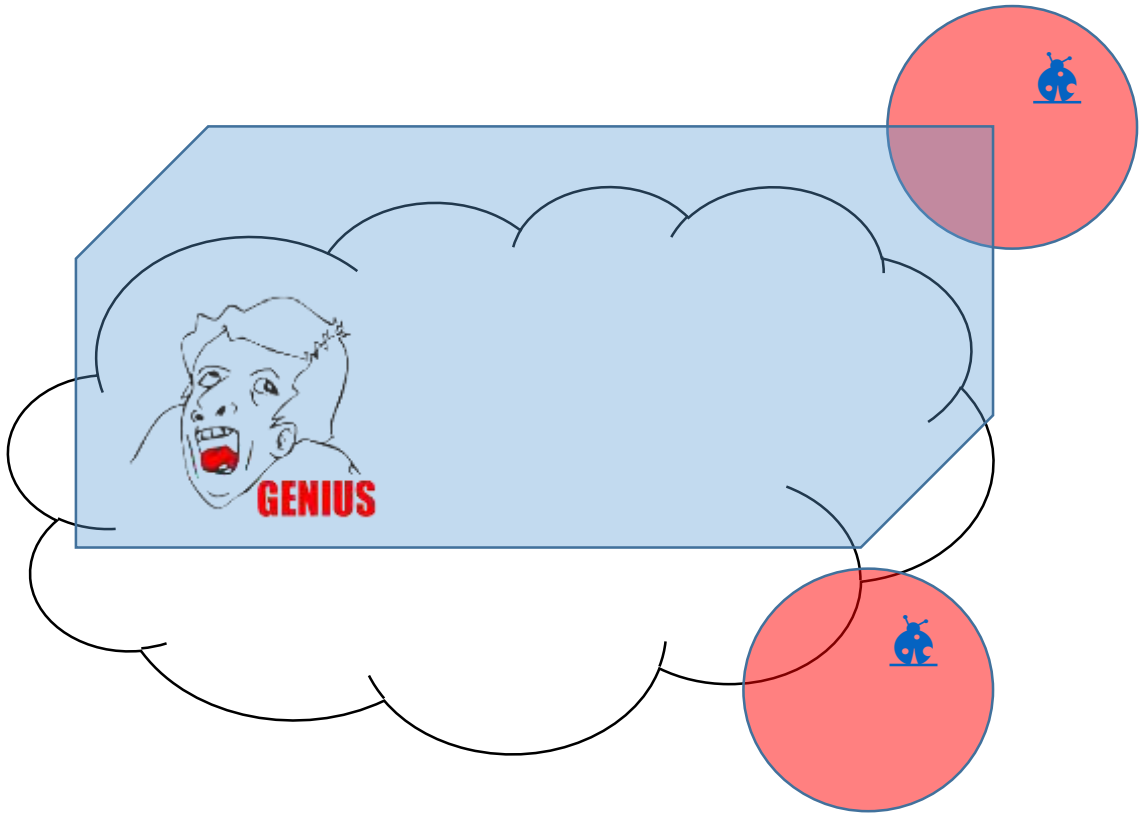
Under-approximation: false-negatives



How bad are false negatives?

- False negatives = missed errors
- Missing errors is fatal only for **safety-critical** systems
- In practice, most of over-approximating analyzers miss errors as well

Under-approximation: false-negatives



How bad are false negatives?

- False negatives = missed errors
- Missing errors is fatal only for **safety-critical** systems
- In practice, most of over-approximating analyzers miss errors as well
  - Avoiding too many false alarms
  - Intraprocedural analysis
  - Environment interactions
  - …

EPISODE II: THEORY

How to verify program is correct?

```
void absAndSum(int x, int y) {

  int abs;

  if (x > 0)
    abs = x;
  else
    abs = -x;

  if (y == 42)
    if (abs + y < 0)
      assert false;
  // else
  …
}
```

https://test-comp.sosy-lab.org/2021/

https://sv-comp.sosy-lab.org/2021/

Fuzzers

Random testing

Random inputs generation until crash

BLACK-BOX TECHNIQUE

Adaptive random testing (ART)

```
while (coverage is not enough) {
  generate new test()
  add to suite if coverage increases
}
```

Instrument program

GRAY-BOX TECHNIQUE

Evolutionary algorithm

- Generations (test suites)
- Cross-over existing tests
- Mutate existing tests

Tool	Score	Ranking
t3	145.27	2.30
evosuite	255.43	2.38
randoop	154.34	2.51
tardis	66.80	3.73
sushi	39.84	4.09

Symbolic execution

WHITE-BOX TECHNIQUE

Symbolic Virtual Machine State

Instruction: ***<Enter>***

Symbolic Memory(SM): x = xO, y = yO

Path Condition (PC): true

```
void absAndSum(int x, int y) {

  int abs;

  if (x > 0)
    abs = x;
  else
    abs = -x;

  if (y == 42)
    if (abs + y < 0)
      ERROR;
  // else
  …
}
```

Symbolic execution

Symbolic Virtual Machine State

Instruction: **if (x > 0)**

SM: x = $x0$, y = $y0$

PC: true && x0 > 0

```
void absAndSum(int x, int y) {

  int abs;

  if (x > 0)
    abs = x;
  else
    abs = -x;

  if (y == 42)
    if (abs + y < 0)
      ERROR;
  // else
  …
}
```

Symbolic execution

Symbolic Virtual Machine State

Instruction: **abs = x**

SM: x = $x0$, y = $y0$, abs = $x0$

PC: x0 > 0

```
void absAndSum(int x, int y) {

  int abs;

  if (x > 0)
    abs = x;
  else
    abs = -x;

  if (y == 42)
    if (abs + y < 0)
      ERROR;
  // else
  …
}
```

Symbolic execution

Symbolic Virtual Machine State

Instruction: **if (y == 42)**

SM: x = $x0$, y = $y0$, abs = $x0$

PC: x0 > 0 && y0 == 42

```
void absAndSum(int x, int y) {

  int abs;

  if (x > 0)
    abs = x;
  else
    abs = -x;

  if (y == 42)
    if (abs + y < 0)
      ERROR;
  // else
  …
}
```

Symbolic execution

Symbolic Virtual Machine State

Instruction: **if (abs + y < 0)**

SM: x = $x0$, y = $y0$, abs = $x0$

PC: x0 > 0 && y0 == 42 && x0 + y0 < 0

```
void absAndSum(int x, int y) {

  int abs;

  if (x > 0)
    abs = x;
  else
    abs = -x;

  if (y == 42)
    if (abs + y < 0)
      ERROR;
  // else
  …
}
```

Symbolic execution

Symbolic Virtual Machine State

Instruction: *ERROR*

SM: x = $x0$, y = $y0$, abs = $x0$

PC: x0 > 0 && y0 == 42 && x0 + y0 < 0

(Ask SMT Solver “Is PC satisfiable?”)

```
void absAndSum(int x, int y) {

  int abs;

  if (x > 0)
    abs = x;
  else
    abs = -x;

  if (y == 42)
    if (abs + y < 0)
      ERROR;
  // else
  …
}
```

Symbolic execution

Symbolic Virtual Machine State

Instruction: **if (abs + y < 0) //else**

SM: x = $x0$, y = $y0$, abs = $x0$

PC: x0 > 0 && y0 == 42 && ¬(x0+y0<0)

(Go to **else** branch: negate last condition)

```
void absAndSum(int x, int y) {

  int abs;

  if (x > 0)
    abs = x;
  else
    abs = -x;

  if (y == 42)
    if (abs + y < 0)
      ERROR;
  // else
  …
}
```

SMT solver

SMT = Satisfability modulo theories

```
PC:
x0 > 0
&&
y0 == 42
&&
x0 + y0 < 0
```

```
(declare-const x0 Int)
(declare-const y0 Int)

(assert (> x0 0))
(assert (= y0 42))
(assert (< (+ x0 y0) 0))

(check-sat)
```

SMT-LIB2 syntax

SMT solver: Z3

```
PC:
x0 > 0
&&
y0 == 42
&&
x0 + y0 < 0
```

```
(declare-const x0 Int)
(declare-const y0 Int)

(assert (> x0 0))
(assert (= y0 42))
(assert (< (+ x0 y0) 0))

(check-sat)  ;unsatisfiable
```

sample.smt

Try it here online:

https://compsys-tools.ens-lyon.fr/z3/index.php

Or use command line tool:

```
#> apt-get install z3

#> z3 –smt2 sample.smt
#unsat
```

SMT solver: theories

```
PC:
x0 > 0
&&
y0 == 42
&&
x0 + y0 < 0
```

Integer arithmetic theory

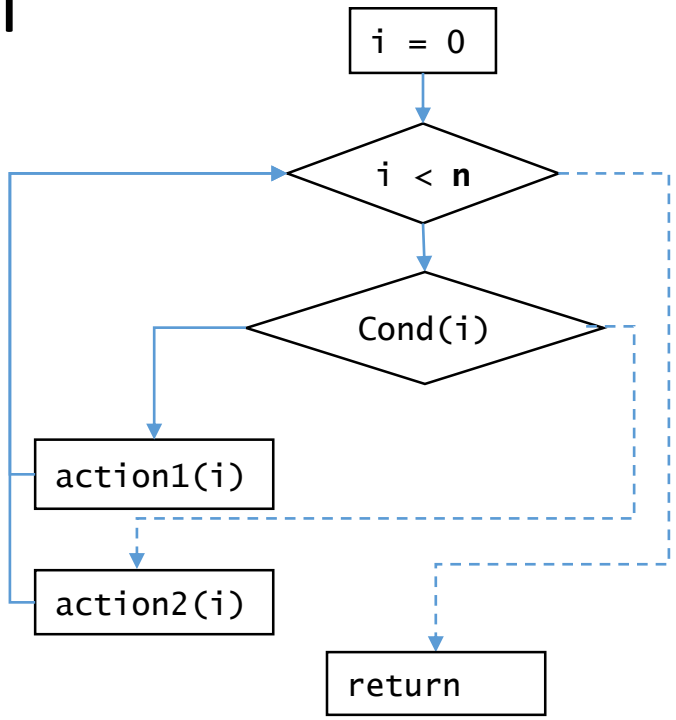
```
(declare-const x0 Int)
(declare-const y0 Int)

(assert (> x0 0))
(assert (= y0 42))
(assert (< (+ x0 y0) 0))

(check-sat)  ;unsatisfiable
```

Bitvector theory

```
(set-option :pp.bv-literals false)
(declare-const x0 (_ BitVec 32))
(declare-const y0 (_ BitVec 32))

(assert (bvsgt x0 (_ bv0 32)))
(assert (= y0 (_ bv42 32)))
(assert (bvslt (bvadd x0 y0) (_ bv0 32)))

(check-sat) ;satisfiable
(get-model) ;x0 = MAXINT-41, y0 = 42
```

Path Explosion

```
for (i=0; i<n; i++)
  if (cond(i))
    action1(i);
  else
    action2(i);

return;
```

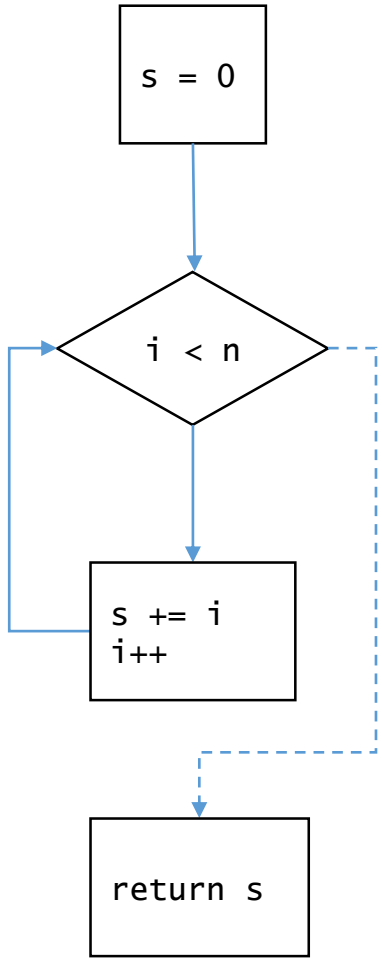


N	#paths
0	1
1	2
2	4
3	8
4	16
8	32

- Symbolic conditional statements fork the execution state
- N iterations of loop with conditional statement can fork 2^N times

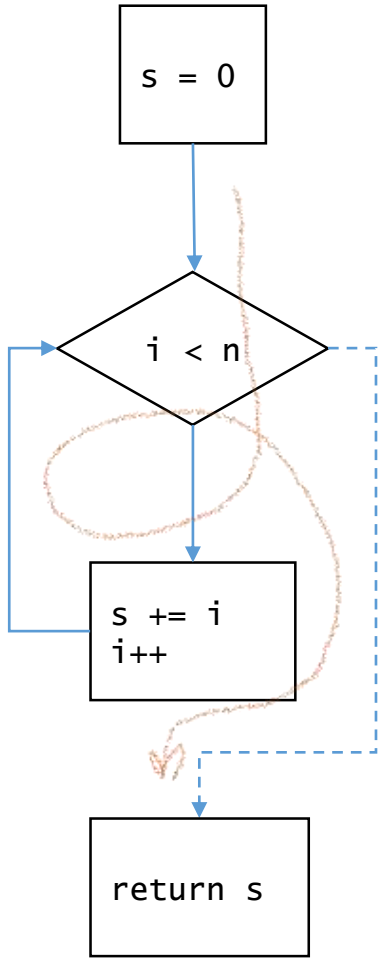
Path Selection

```
int s = 0;
for (i=0; i<n; i++)
    s += i;

return s;
```



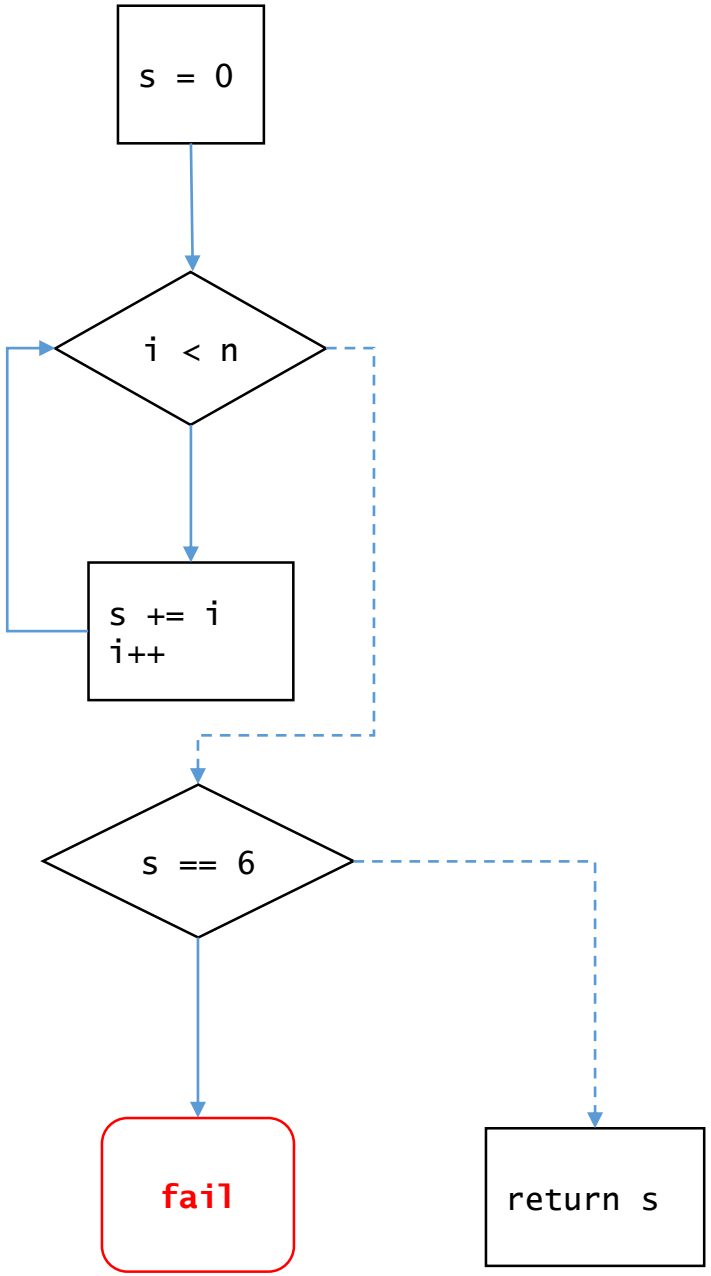
Path Selection

```
int s = 0;
for (i=0; i<n; i++)
    s += i;

return s;
```



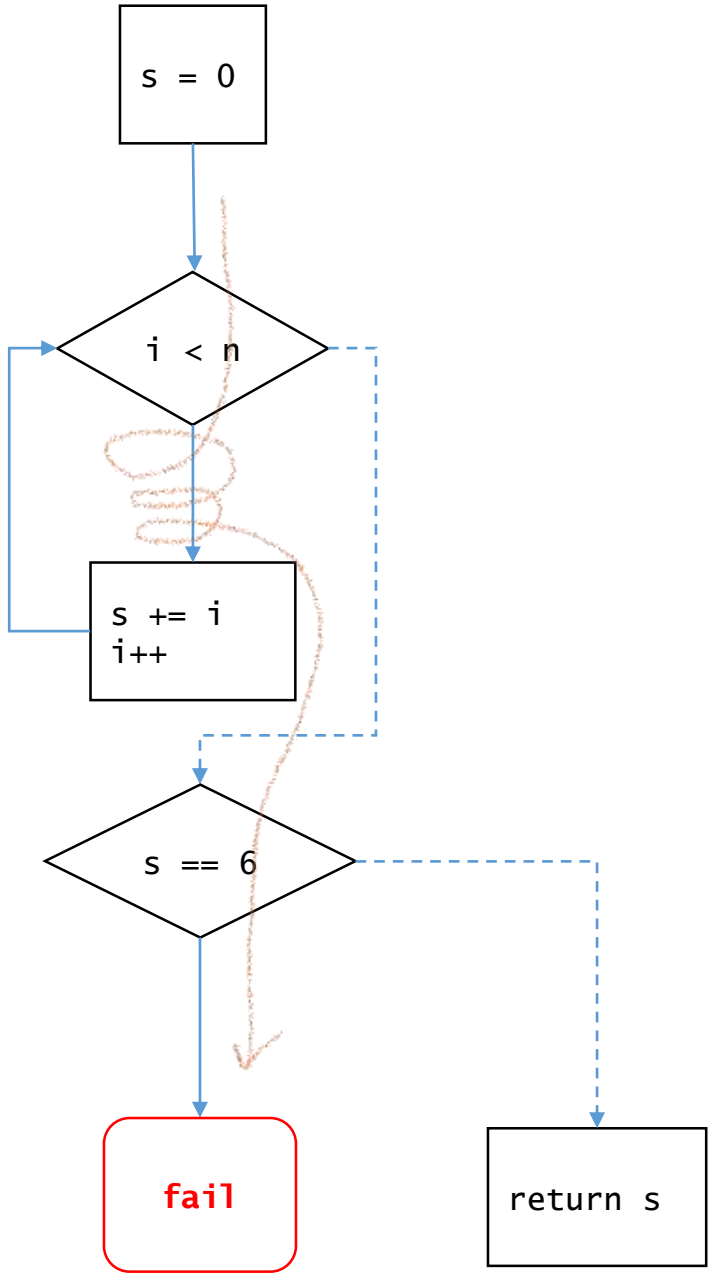
Path Selection: Heuristics

```
int s = 0;
for (i=0; i<n; i++)
    s += i;

if (s == 6)
  assert false;

return s;
```



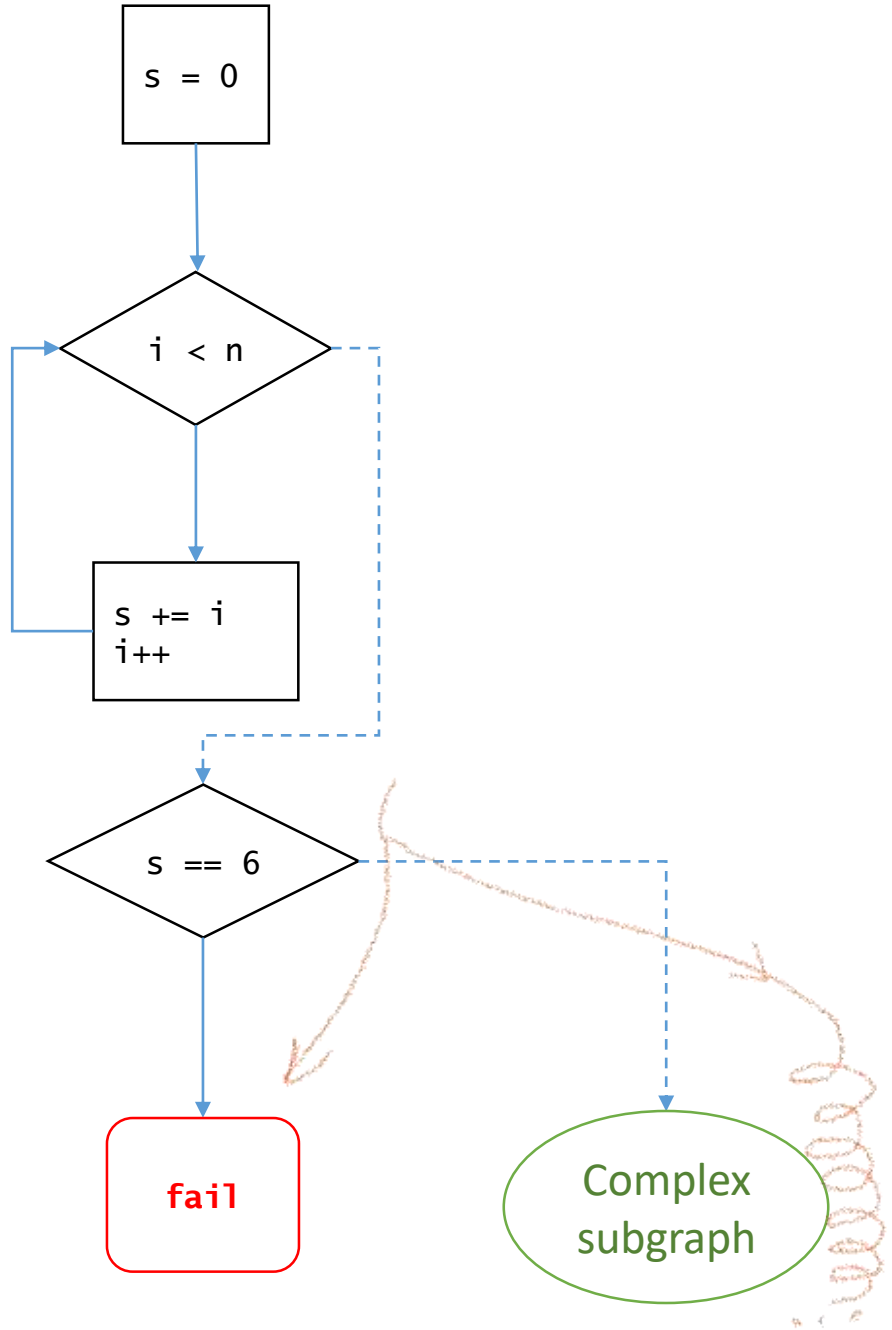
Path Selection: Heuristics

```
int s = 0;
for (i=0; i<n; i++)
    s += i;

if (s == 6)
  assert false;

return s;
```



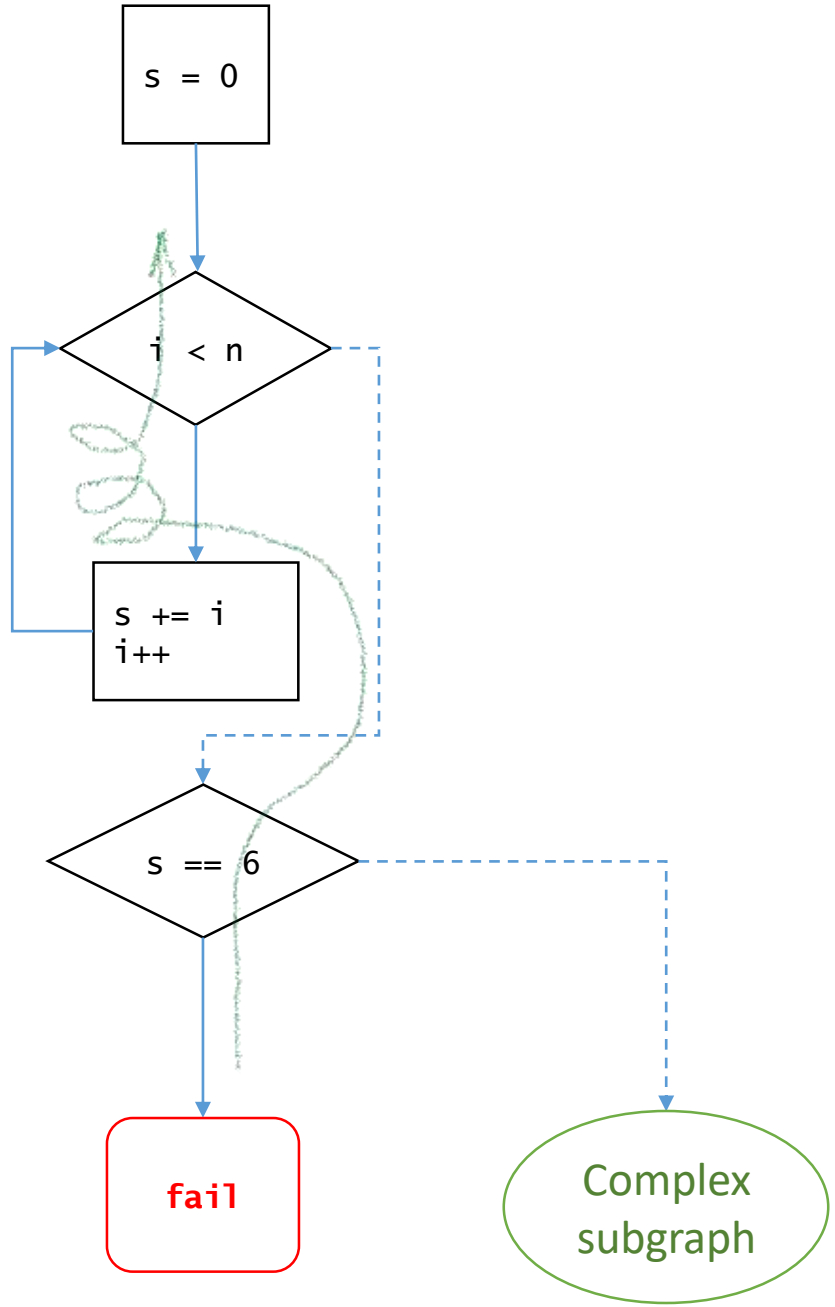
Path Selection

```
int s = 0;
for (i=0; i<n; i++)
    s += i;

if (s == 6)
  assert false;

complexSubgraph();
…
```



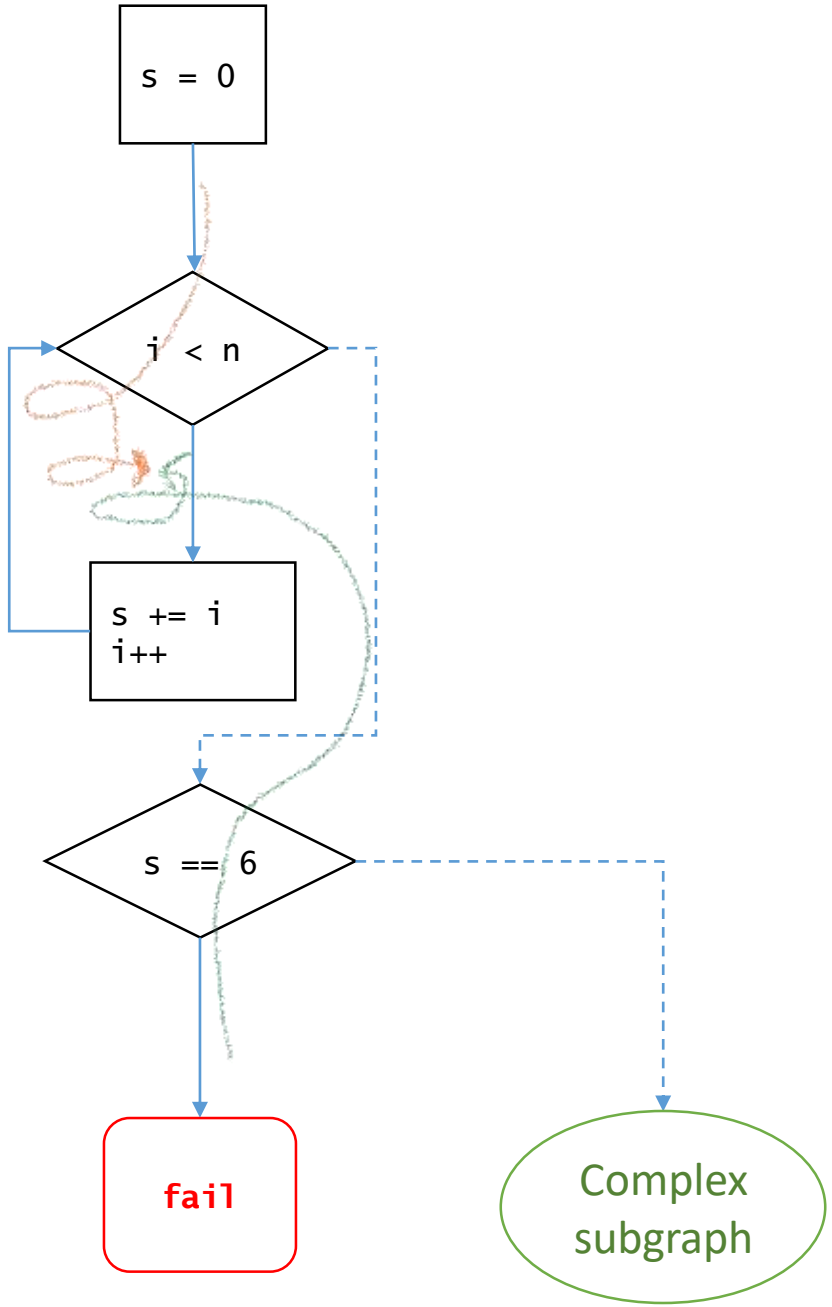
Path Selection: Backward

```
int s = 0;
for (i=0; i<n; i++)
    s += i;

if (s == 6)
  assert false;

complexSubgraph();
…
```



Path Selection: Bidirectional

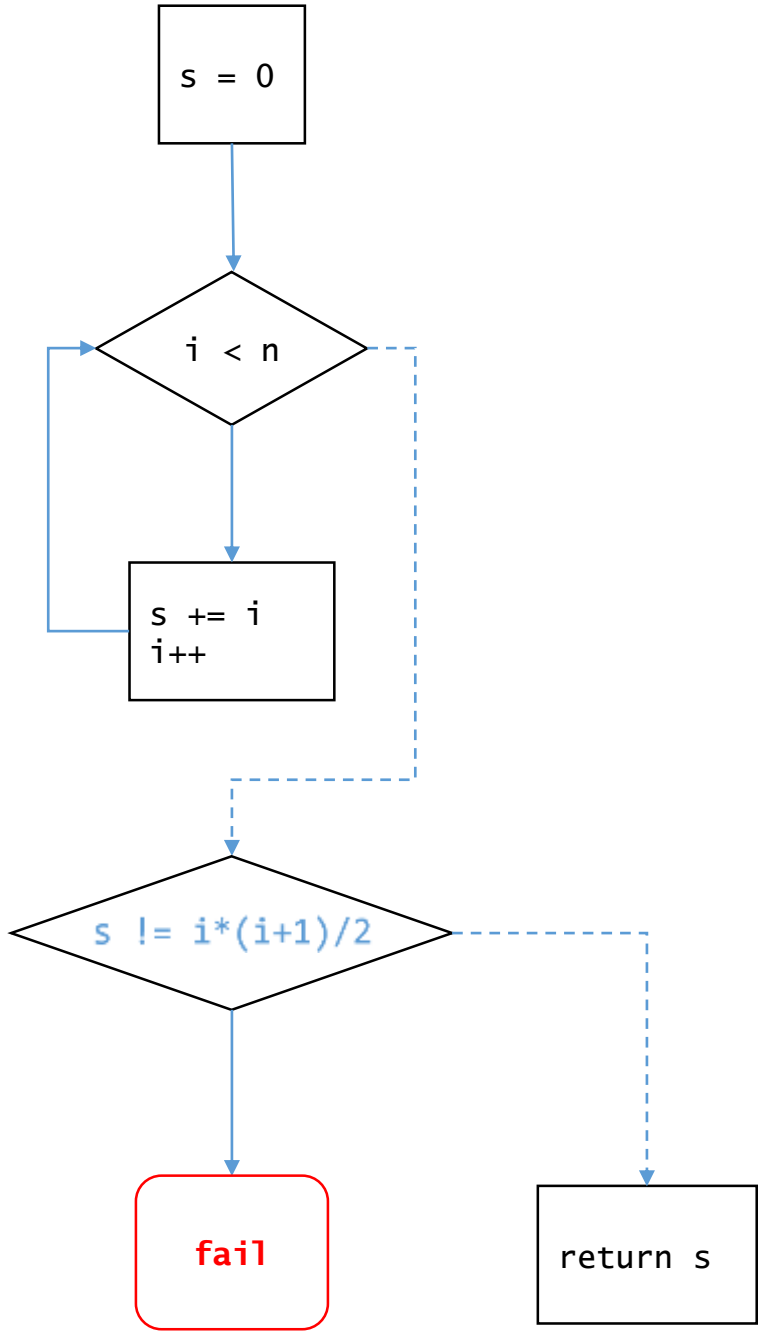
```
int s = 0;
for (i=0; i<n; i++)
    s += i;

if (s == 6)
  assert false;

complexSubgraph();
…
```



Path Selection: Invariants

```
int s = 0;
for (i=0; i<n; i++)
    s += i;

if (s != i*(i+1)/2)
  assert false;

return s;
```

Inductive invariant:
s == i*(i+1)/2



Code block invariants

- Loops and recursion can lead to the unbounded amount of different program behaviours
- Solution: **over-approximate** them!

```
int max = 0;

for (i=0; i<a.length; i++)
    max = Math.max(Math.abs(a[i], max));

if (max < 0)
  assert false;

return s;
```

Over-approximate the whole loop with:
max >= 0

Heap and Symbolic Execution

```
public void check(A x, A y)
{
    x.f = 1;
    y.f = 2;
    if (x.f == 2) {
        assert false;
    }
}
```

f = new HashMap<Object, Int>()

```
(declare-const x0 Addr)
(declare-const y0 Addr)
(declare-const f0 (Array Addr Int))
f := (store f0 x0 1)
f := (store (store f0 x0 1) y0 2)
(select (store (store f0 x0 1) y0 2) x0 == 2)
```

```
(check-sat)
x0 == y0
```

Theory of arrays

Symbolic execution: problems

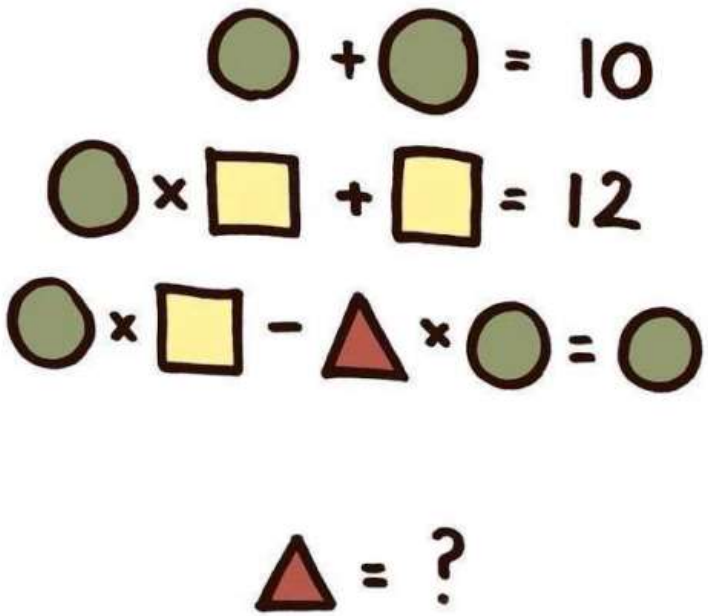
1. How to deal with *path explosion* ?
2. How to handle loops / recursion?
3. How to present Heap in symbolic memory?
4. How to invoke native functions/syscalls?
5. What to do with concurrency?
6. if (sha256(x) == “try to solve this!”)

1. Path selection strategy, bidirectional symbolic execution
2. Try calculate “Inductive invariant” – Horn clauses
3. SMM: Theory of Arrays + Theory of Bitvectors
4. Write mock / make value concrete and execute / forget
5. Hard: #concurrent_states=#states ^ #threads
6. Rare in real programs, bypass

A Survey of Symbolic Execution Techniques

EPISODE III: PRACTICE

SAT/SMT by Example




```
#!/usr/bin/python
from z3 import *

circle, square, triangle = Ints('circle square triangle')
s = Solver()
s.add(circle+circle==10)
s.add(circle*square+square==12)
s.add(circle*square-triangle*circle==circle)
print s.check()
print s.model()
```

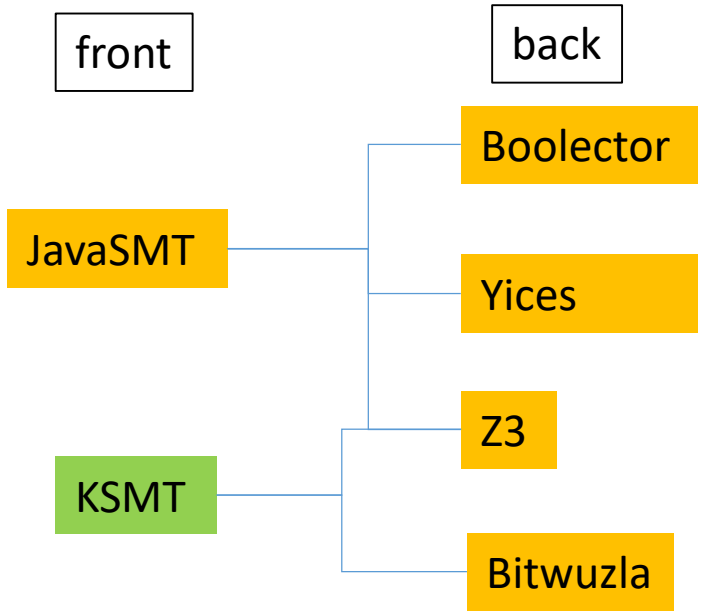
```
sat
[triangle = 1, square = 2, circle = 5]
```

SAT/SMT by Example

9		6		7		4		3
			4			2		
	7			2	3		1	
5						1		
	4		2		8		6	
		3						5
	3		7				5	
		7			5			
4		5		1		7		8

LIVE DEMO

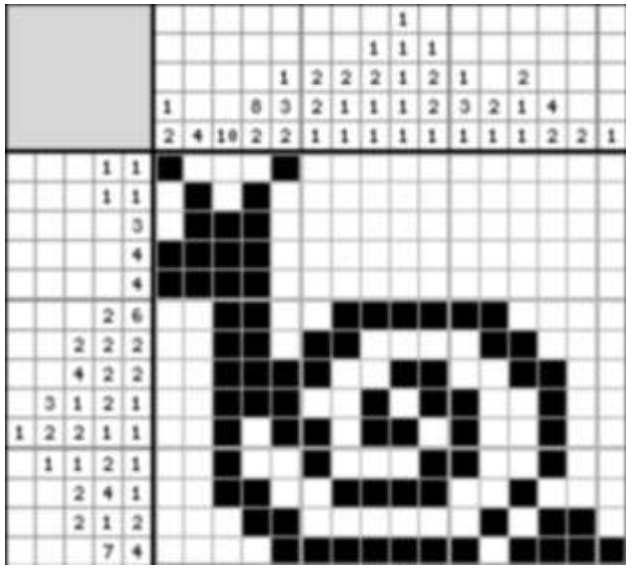
With KSMT

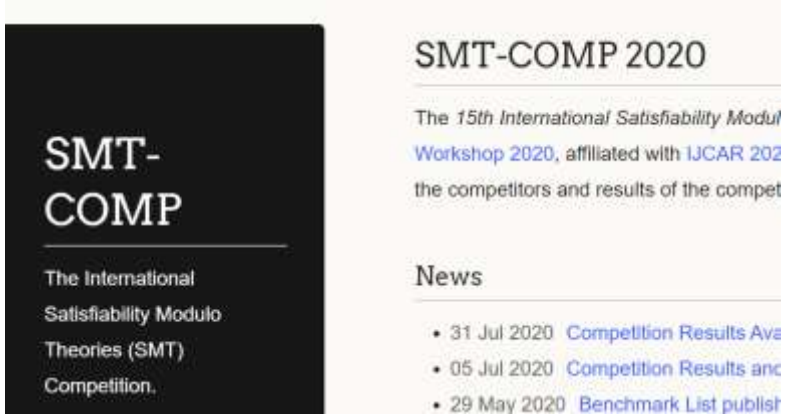


https://github.com/UnitTestBot/ksmt

Homework Problem: Nonograms

1. Solve Nonograms using SAT/SMT technique
   - https://webpbn.com/export.cgi
   - *Hint: Book "SAT/SMT by example"*
2. (*) Solve colored nonogram
3. (**) Experiment with solvers and choose the best





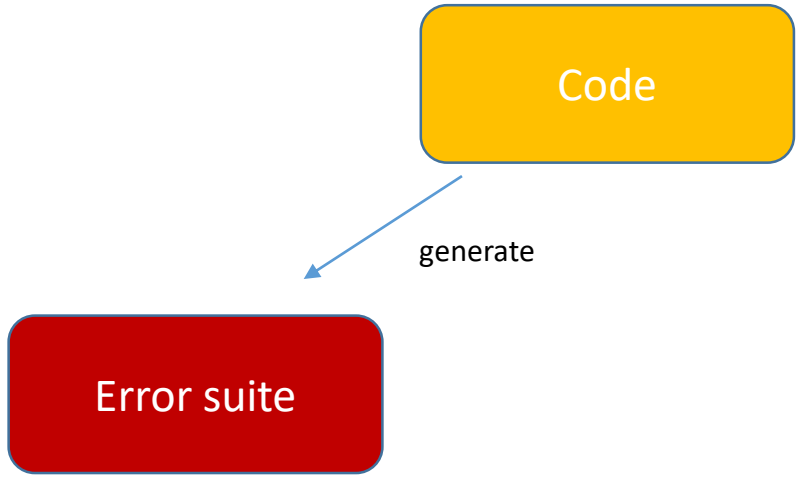
SMT-solvers becomes twice faster every 1.5 years

EPILOGUE : PRODUCT

How to reproduce deep bugs with auto-generated tests?

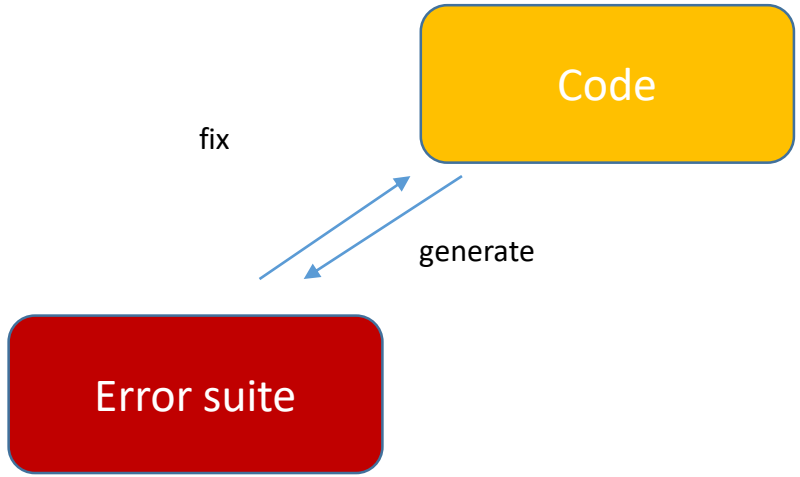
Code contains NPE,
StackOverflows and so on

Error suite



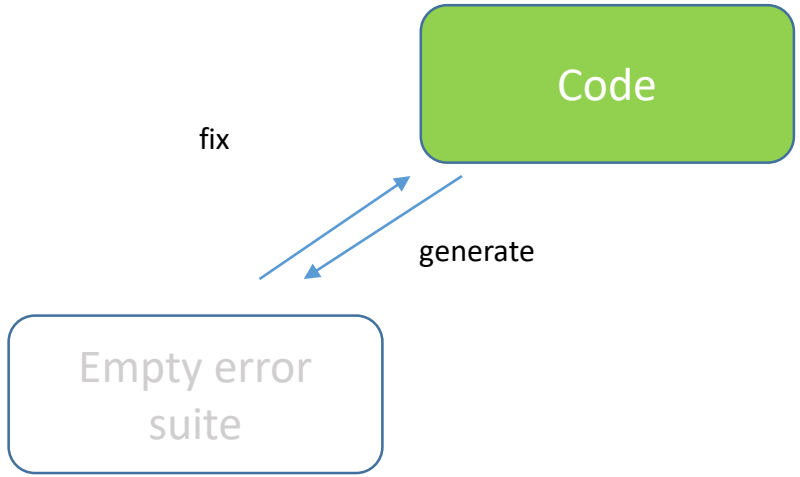
Code contains NPE,
StackOverflows and so on

Error suite



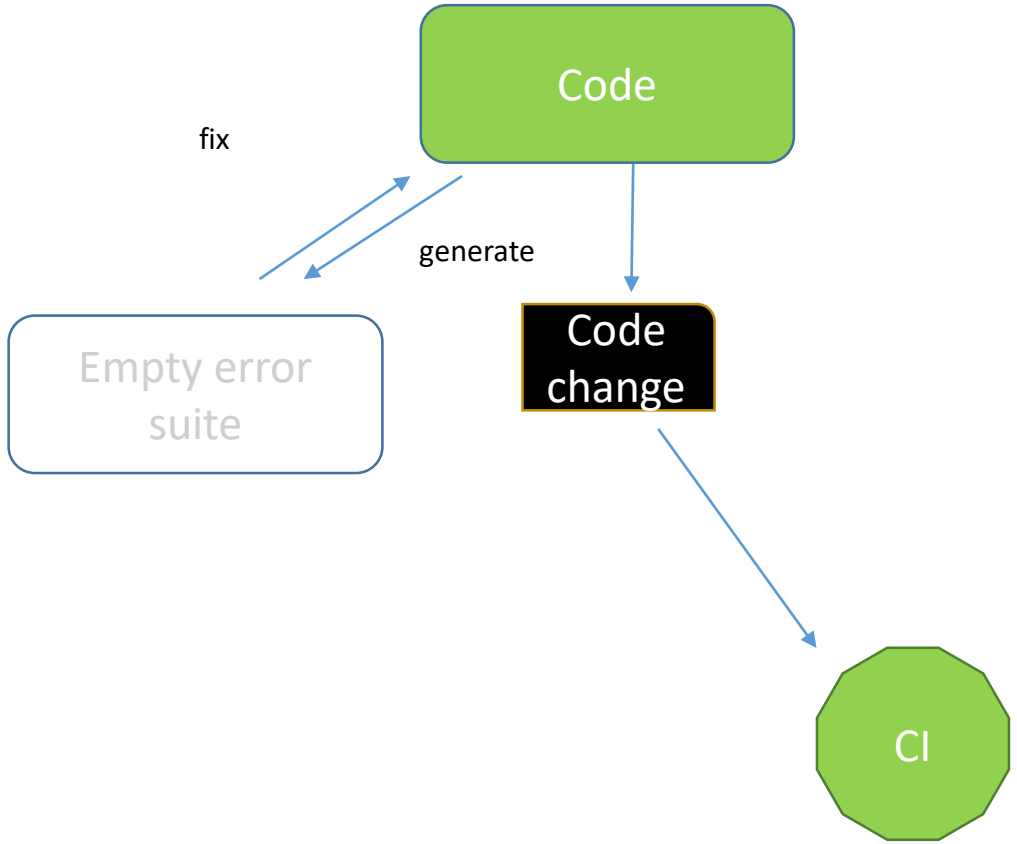
Code contains NPE,
StackOverflows and so on

Error suite



Code hasn’t NPE,
StackOverflows and so on

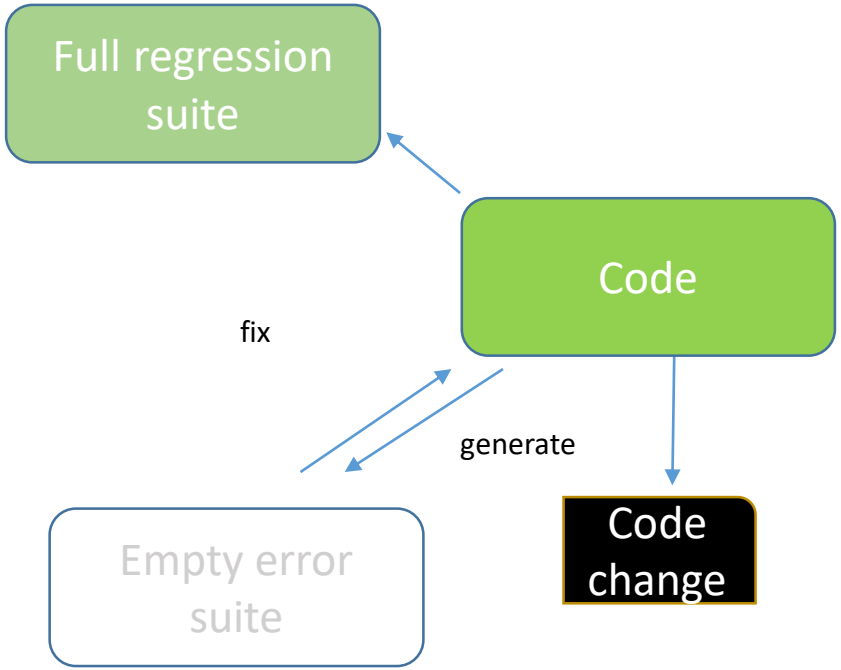
Regression



Code hasn’t NPE, StackOverflows and so on

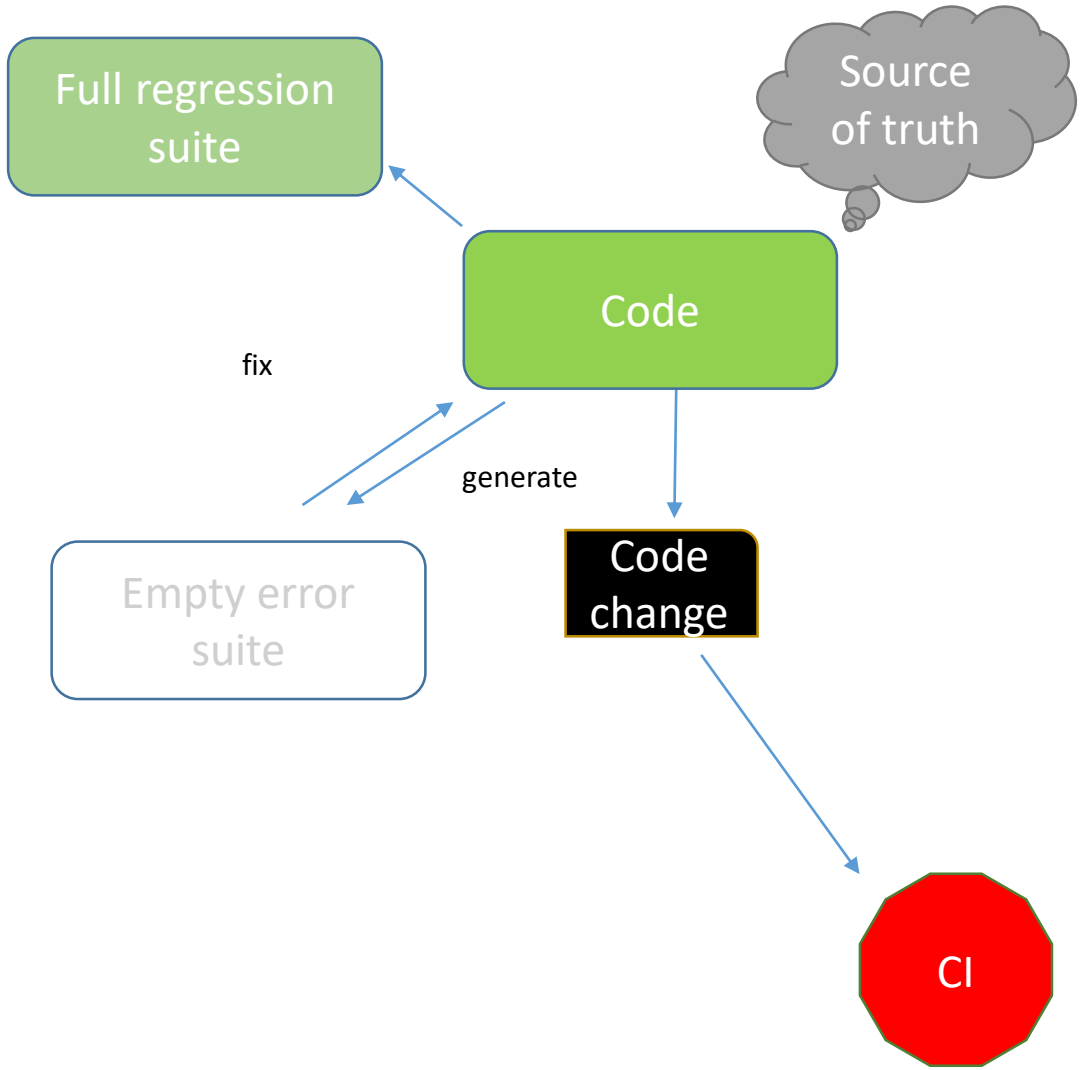
If developer commit change nobody will notice bug until it happens on production

Regression suite



Code hasn’t NPE, StackOverflows and so on

Regression suite



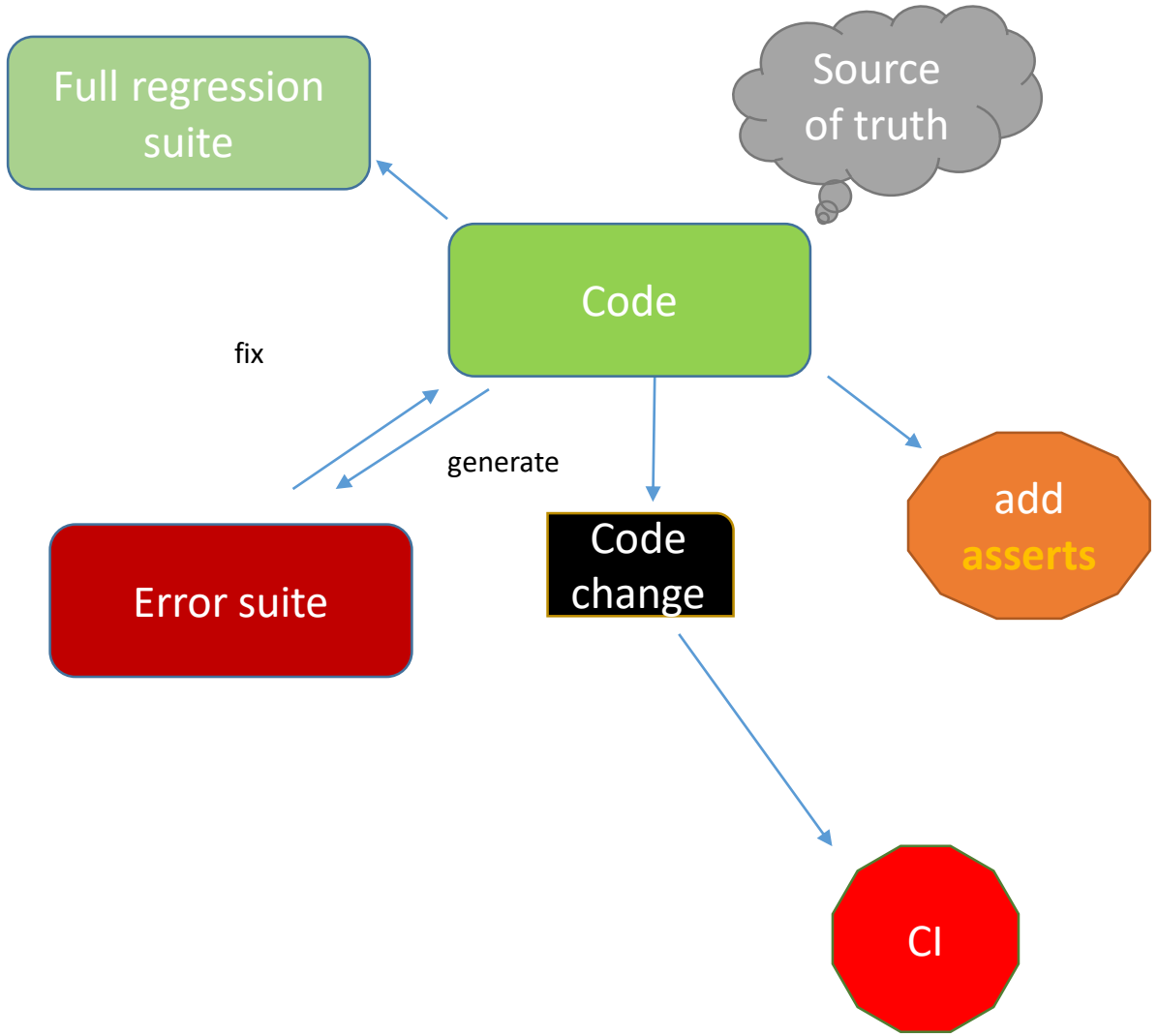
Code hasn't NPE, StackOverflows and so on

Now behavior is fixated.
Red CI status means one of two things:

- Code change breaks correct behavior
- Initial code behavior wasn't correct

Anyway it's *easy to localize* problem

Specification



Code hasn't NPE, StackOverflows and so on

Now behavior is fixated.
Red CI status means one of two things:

- Code change breaks correct behavior
- Initial code behavior wasn't correct

Anyway it's easy to localize problem

Code is tested against **specification** formalized by **asserts**

LIVE DEMO

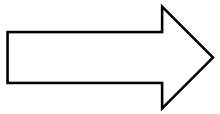
UnitTestBot

UnitTestBot

Own java symbolic engine

Soot

Z3



UTBot Java/Kt

Python/Go/JS

Own **universal** Symbolic engine

JCDB

KSMT

http://utbot.org

What are the key takeaways?

- **[Episode I**, **Survey]** – Now you know the motivation, history and layout of program analyzers
- **[Episode II, Theory]** – You can write your own simple symbolic execution engine (in theory ☺)
- **[Episode III, Practice]** – Try KSMT or Z3 now to encode and solve any combinatorial problem
- **[Epilogue, Product]** – If you convinced, you can apply program analyzer for your code right now

Thank you for your attention

- A Survey of Symbolic Execution Techniques – very good introduction into symbolic execution
- “SAT/SMT by Example” – lots of engineering examples how to use SAT and SMT solver
- https://theory.stanford.edu/~nikolaj/programmingz3.html - Programming Z3
- https://github.com/UnitTestBot/ksmt - Kotlin API for different SMT solvers
- http://soot-oss.github.io/soot/ - Soot framework for building statics analysis
- https://github.com/UnitTestBot/jcdb - Java Compilation Database
- https://github.com/SymbolicPathFinder/jpf-symbc - Mature symbolic execution framework for Java
- https://www.utbot.org/ – Error detection and test generation

Dmitry Ivanov, *Huawei Saint Petersburg Research Center*, *korifey@gmail.com*, *@korifey_ad*

Dmitry Mordvinov, *Huawei Saint Petersburg Research Center*, *mordvinov.dmitry@gmail.com*