Software Systems Verification and Validation

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Software Systems Verification and Validation

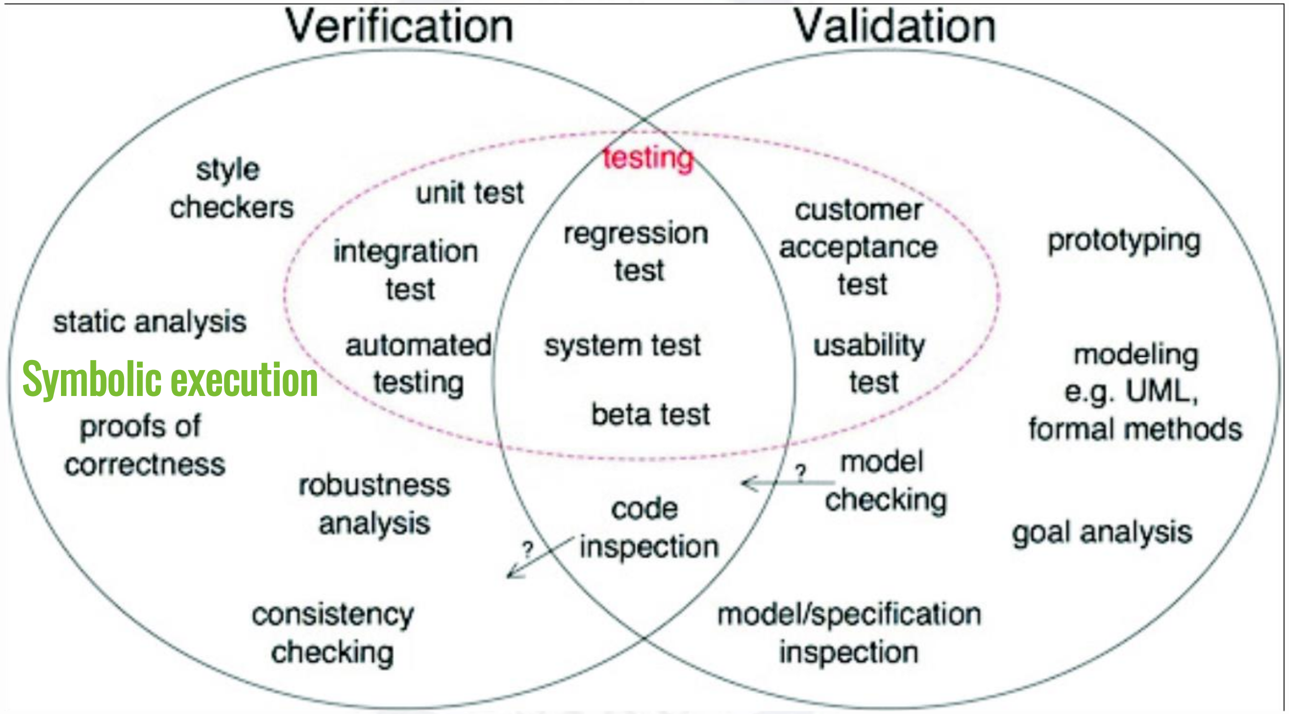
“Tell me and I forget, teach me and I may remember, involve me and I learn.”

(Benjamin Franklin)

(Next)/Today Lecture

- Symbolic execution
- Model checking

What we will learn!



- http://www.easterbrook.ca/steve/2010/11/the-difference-between-verification-and-validation/

Outline

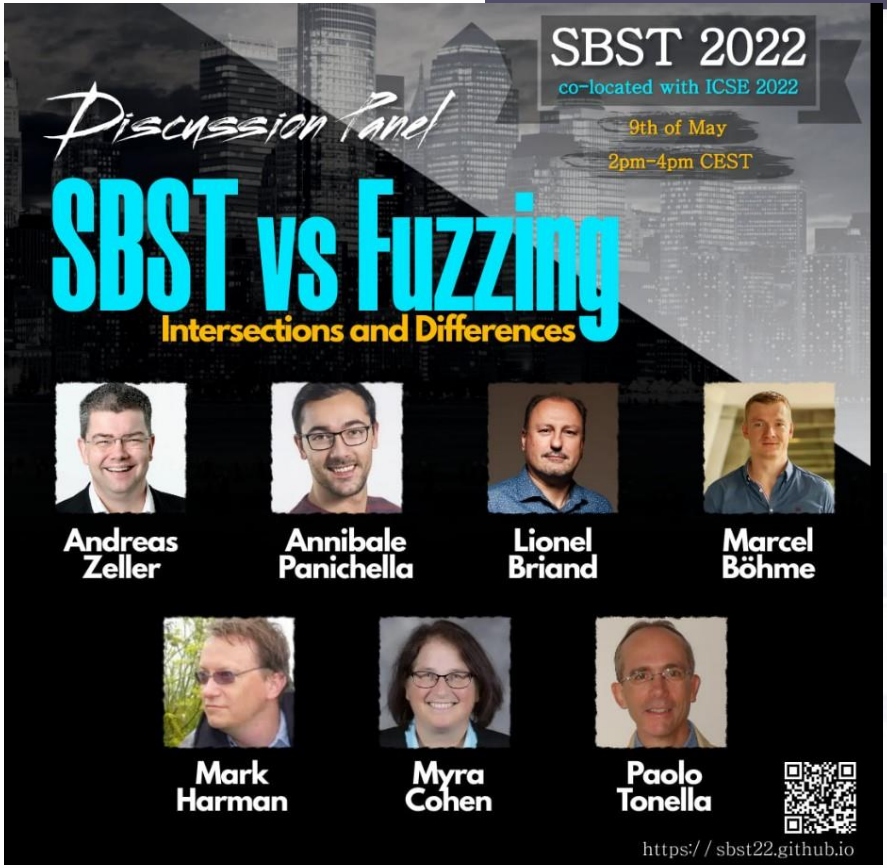
- Static analysis, Testing, Symbolic execution
- Conventional vs Symbolic execution
- Symbolic execution for sequential, alternative, repetitive structures
  - Sequential structure execution
  - Alternative structure execution
  - Repetitive structure execution
- Symbolic Execution Tree
  - Symbolic Execution Tree
  - Properties
- Questions

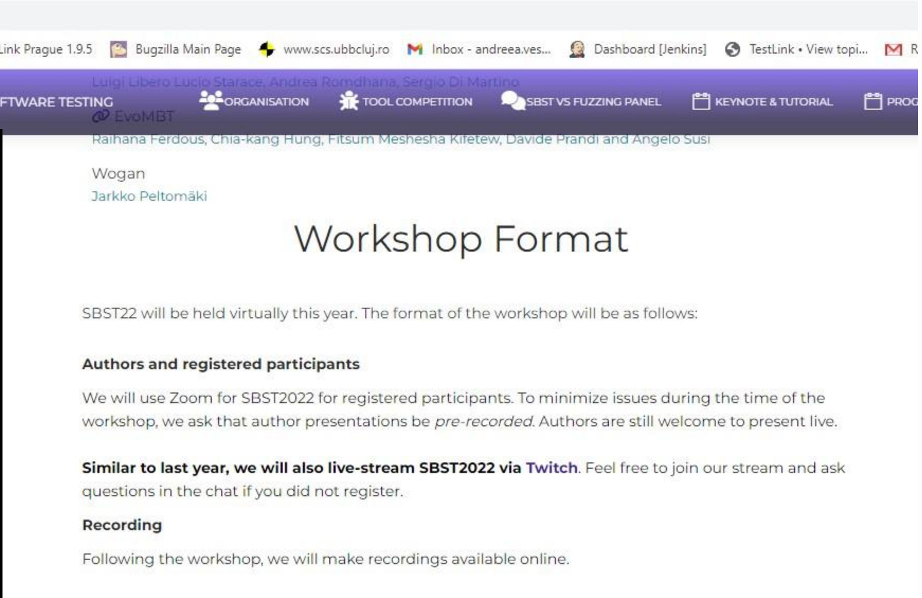
- Next lecture (still today)
  - Model checking

Static analysis
Symbolic execution

- Bugs that are missed by testing: rare features, rare circumstances, nondeterminism.
  - ➔ Static analysis
    - Can analyze all possible runs of a program
    - But can it find deep, difficult bugs?
      - Abstraction let us model all possible runs
      - Static analysis abstraction <> developer abstraction
- Testing works
  - reported bugs are real bugs, but each test only explores **one** possible execution. asssert (f(5)==6)
  - We ***hope*** test cases generalize, but no guarantees!
  - ➔Symbolic execution **generalizes** testing
    - ➔y=α, assert(f(y)==2*y+1)
- **Remarks**:
  - symbolic execution is not meant to inspect the quality of the code.
    - static analysis deals with issues of path feasibility,
    - dynamic analysis tends to deal with path coverage.
  - Symbolic analysis is sort of in between and deals with state space explosion by logically forking the analysis at branches and solving for a set of satisfiable constraints.

2022 - Fuzzing vs SBST Intersections and Differences





Luigi Libero Lucio Starace, Andrea Romdhana, Sergio Di Martino

EvoMBT

Raihana Ferdous, Chia-kang Hung, Fitsum Meshesha Kifetew, Davide Prandi and Angelo Susi

Wogan

Jarkko Peltomäki

Workshop Format

SBST22 will be held virtually this year. The format of the workshop will be as follows:

Authors and registered participants

We will use Zoom for SBST2022 for registered participants. To minimize issues during the time of the workshop, we ask that author presentations be *pre-recorded*. Authors are still welcome to present live.

Similar to last year, we will also live-stream SBST2022 via Twitch. Feel free to join our stream and ask questions in the chat if you did not register.

Recording

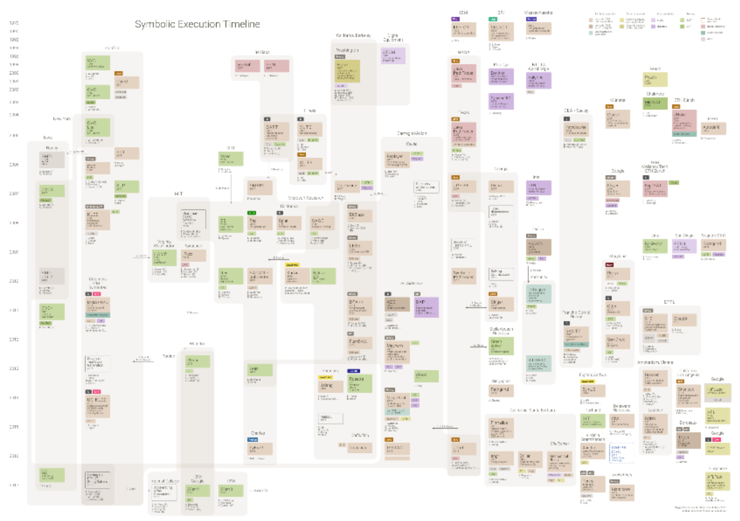
Following the workshop, we will make recordings available online.

Symbolic execution - research

- 1976 - King [Kin76], Clarke [Cla76]
- ....
- 2005 - Microsoft: DART [God05]
- 2006 - Univ. Stanford: EXE, Univ. Illinois: CUTE and jCUTE [SA06]
- ...
- 2008 - KLEE (Stanford) [CDE08]
- ...
- 1999 - 2016 - NASA: Symbolic (Java) Path Finder [PV09], [CS13]
  - http://javapathfinder.sourceforge.net/
  - http://babelfish.arc.nasa.gov/trac/jpf

- Modern Symbolic Execution Techniques
  - mix concrete and symbolic execution
  - Concolic testing (DART – Directed Automated Random Testing)
  - EGT (Execution-Generated Testing)
- 2017 -Learn&Fuzz: Machine Learning for Input Fuzzing
  - https://patricegodefroid.github.io/
- 2018
  - Chopped Symbolic Execution (ICSE) (2006 -EXE)
  - Shadow Symbolic Execution for Testing Software Patches
  - https://www.doc.ic.ac.uk/~cristic/
- 2018 -Deep Reinforcement Fuzzing, Konstantin Böttinger, Patrice Godefroid, Rishabh Singh

- SAGE (2005 -DART)
  - https://patricegodefroid.github.io/
  - https://channel9.msdn.com/blogs/peli/automated-whitebox-fuzz-testing-with-sage - video
- https://www.microsoft.com/en-us/security-risk-detection/
- PEX
  - https://www.microsoft.com/en-us/research/project/pex-and-moles-isolation-and-white-box-unit-testing-for-net/?from=http%3A%2F%2Fresearch.microsoft.com%2Fen-us%2Fprojects%2Fpex%2F
  - Symbolic execution timeline



Symbolic execution

What is symbolic execution ?

- Symbolic execution
  - Execution of program with symbols as argument.
  - Symbolic execution supplies symbols (as input to a program) representing arbitrary values.
  - int FunctionName(1, 2) ➔ int FunctionName(a1 , a2)

- The execution proceeds as in a normal execution except that values may be symbolic formulae over the input symbols.

- Symbolic execution
  - Produces a concrete input (a test case) on which the program will fail to meet the specification.
  - But it cannot, in general, prove the absence of errors

- Key idea
  - Evaluate the program on symbolic input values
  - Use an automated theorem prover to check whether there are corresponding concrete input values that make the program fail.

Symbolic execution

Symbolic state

- **Symbolic state**
  - Set of (particular) concrete states, yet not instantiated.
  - Symbolic states represent sets of concrete states.

- A **symbolic state** is described by:
  - **Variables**, i.e. symbolic values/expressions for variables;
  - **Path condition** - a conjunct of constraints on the symbolic input values;
  - **Program counter** - the statement that is executed.
- All paths in the program form its execution tree, in which some paths are feasible, and some are infeasible.
- Symbolic execution is a bug finding technique based on automated theorem proving:
  - Evaluates the program on symbolic inputs, and a solver finds concrete values for those inputs that lead to errors.

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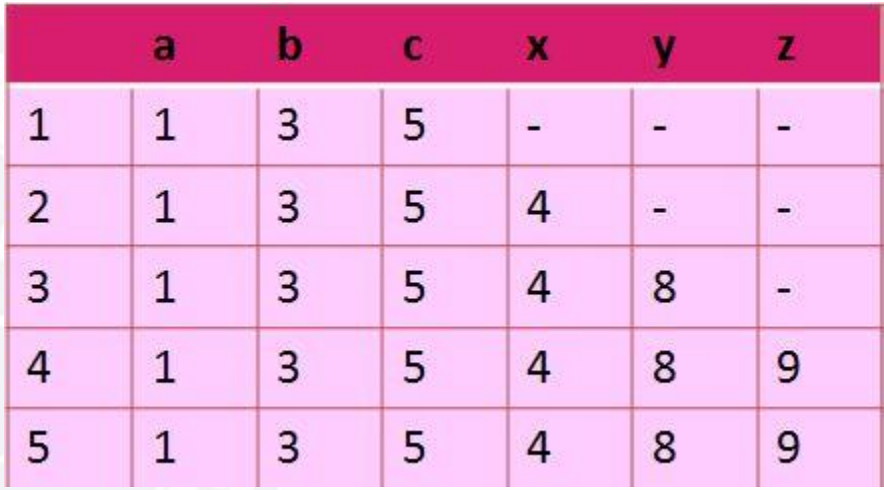
Conventional vs Symbolic execution

Conventional execution (CE)

- Function Sum
- Normal execution result of Sum(1,3,5)
- 1 : int Sum(int a, int b, int c)
- 2 : int x := a + b;
- 3: int y := b + c;
- 4: int z := x + y - b;
- 5: return z;
- 6:

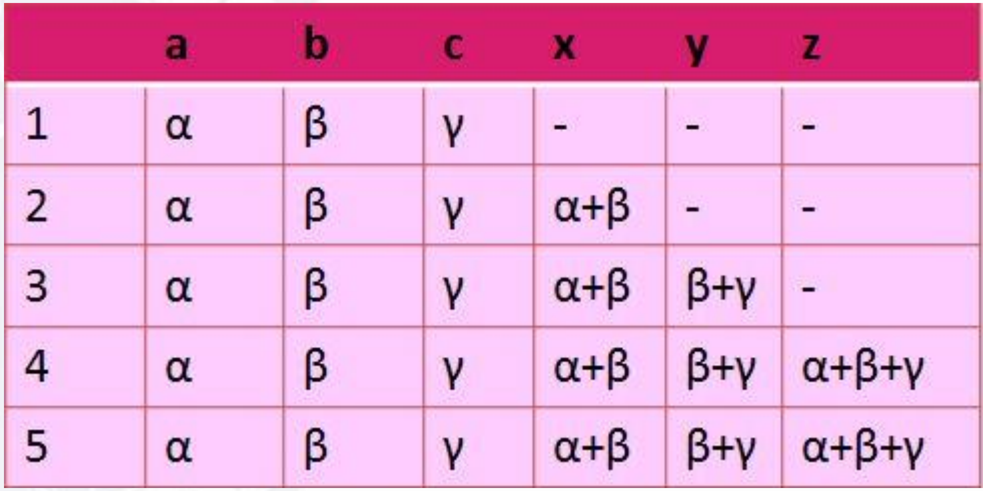


	a	b	c	x	y	z
1	1	3	5	-	-	-
2	1	3	5	4	-	-
3	1	3	5	4	8	-
4	1	3	5	4	8	9
5	1	3	5	4	8	9

Conventional vs Symbolic execution

Symbolic execution (SE)

- Function Sum
- Normal execution result of Sum(1,3,5)
- 1 : int Sum(int a, int b, int c)
- 2 : int x := a + b;
- 3: int y := b + c;
- 4: int z := x + y - b;
- 5: return z;
- 6:



	a	b	c	x	y	z
1	α	β	γ	-	-	-
2	α	β	γ	α+β	-	-
3	α	β	γ	α+β	β+γ	-
4	α	β	γ	α+β	β+γ	α+β+γ
5	α	β	γ	α+β	β+γ	α+β+γ

Symbolic execution

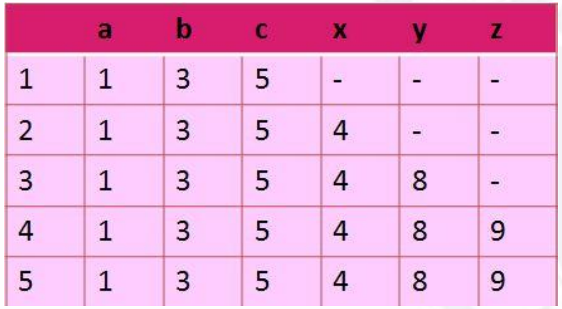
Symbolic execution for **sequential**, alternative, repetitive structures

- **Sequential structure execution**
  - path condition
    - condition to execute a statement;
  - when the symbolic execution starts, the value(pc) = true
  - the condition is updated from one statement to other
    - If τ represents the condition to execute statement < I > then pc′ = pc ^ τ(I)

Symbolic execution

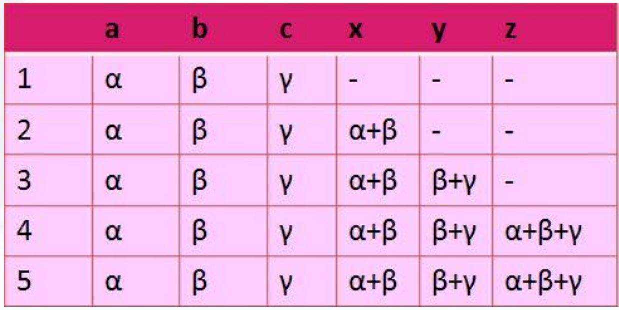
Symbolic execution for **sequential**, alternative, repetitive structures

Conventional - Sequential execution - Symbolic



	a	b	c	x	y	z
1	1	3	5	-	-	-
2	1	3	5	4	-	-
3	1	3	5	4	8	-
4	1	3	5	4	8	9
5	1	3	5	4	8	9

```
1 : int Sum(int a, int b, int c)
2 :      int x := a + b;
3:       int y := b + c;
4:       int z := x + y - b;
5: return z;
6:
```



	a	b	c	x	y	z
1	α	β	γ	-	-	-
2	α	β	γ	α+β	-	-
3	α	β	γ	α+β	β+γ	-
4	α	β	γ	α+β	β+γ	α+β+γ
5	α	β	γ	α+β	β+γ	α+β+γ

Symbolic execution

Symbolic execution for sequential, **alternative**, repetitive structures

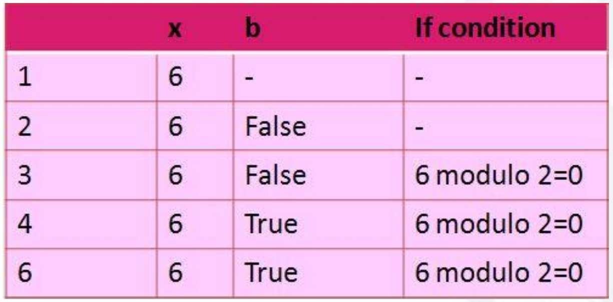
- **Alternative structure execution**
- Symbolic execution of an IF statement
  - **if (η) then**
    A
    else
    B.
- **During symbolic execution ➔** value(η) could be true, false, or some symbolic formula over the input symbols.

  ➔ "unresolved" execution of a conditional statement
- Path Condition (Initial value of pc is true)
  - pc → η
  - pc → $\neg\eta$

Symbolic execution

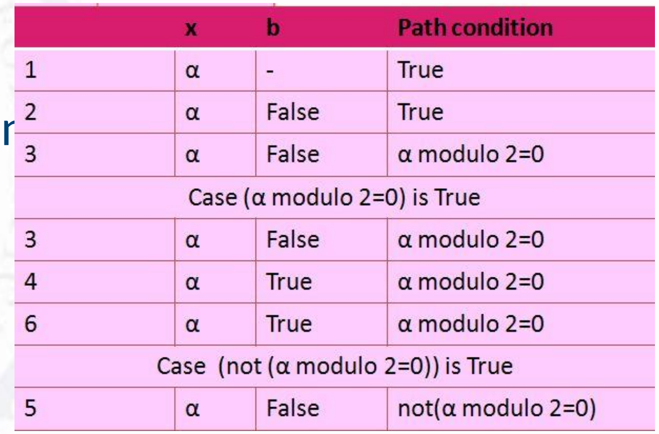
Symbolic execution for
sequential, **alternative**, repetitive structures

Conventional **- Alternative execution -** **Symbolic**



	x	b	If condition
1	6	-	-
2	6	False	-
3	6	False	6 modulo 2=0
4	6	True	6 modulo 2=0
6	6	True	6 modulo 2=0

```
1 : boolean IsEven(int x)
2 : boolean b := False;
3: If (x modulo 2 ==0) ther
4:        b:=true;
     else
5:        b:=false;
6: IsEven:=b;
```



	x	b	Path condition
1	α	-	True
2	α	False	True
3	α	False	α modulo 2=0
Case (α modulo 2=0) is True			
3	α	False	α modulo 2=0
4	α	True	α modulo 2=0
6	α	True	α modulo 2=0
Case (not (α modulo 2=0)) is True			
5	α	False	not(α modulo 2=0)

Symbolic execution

Symbolic execution for sequential, alternative, **repetitive** structures

- Symbolic execution of a WHILE statement

```
while (η)
    A
endWh;
B
```

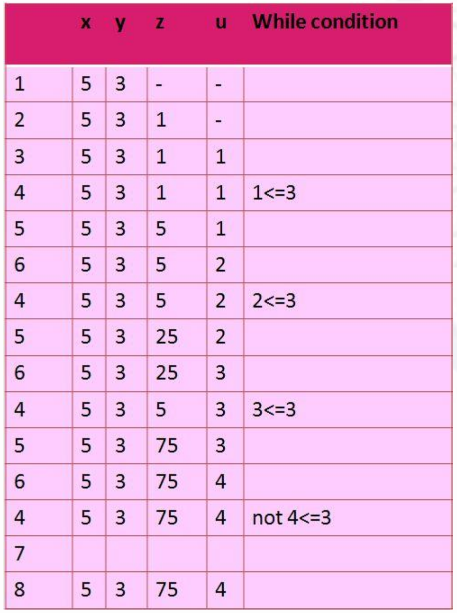
- During symbolic execution ➔ value(η) could be true, false, or some symbolic formula over the input symbols.

  ➔ "unresolved" execution of a conditional statement
- Condition to execute A: pc for executing "while" and η.
- Condition to execute B: pc for executing "while" and $\neg\ \eta$.

Symbolic execution

Symbolic execution for
sequential, alternative, **repetitive** struct

Conventional

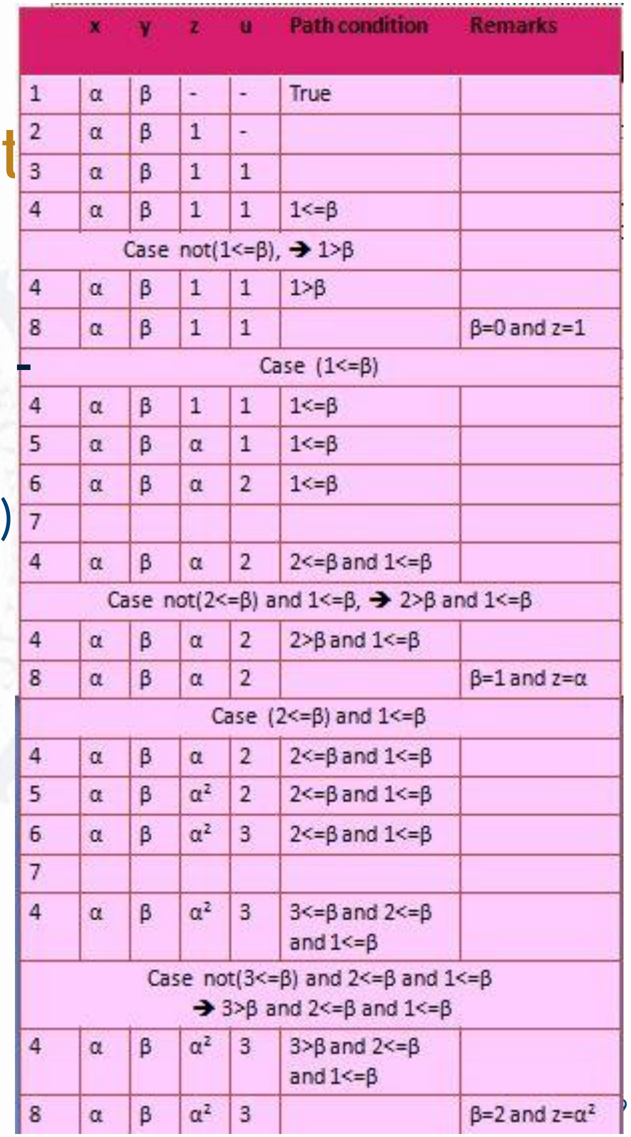


	x	y	z	u	While condition
1	5	3	-	-	
2	5	3	1	-	
3	5	3	1	1	
4	5	3	1	1	1<=3
5	5	3	5	1	
6	5	3	5	2	
4	5	3	5	2	2<=3
5	5	3	25	2	
6	5	3	25	3	
4	5	3	5	3	3<=3
5	5	3	75	3	
6	5	3	75	4	
4	5	3	75	4	not 4<=3
7					
8	5	3	75	4	

- Repetitive execution -

```
1 : Power(int x, int y, int z)
2 :     z := 1;
3:      u:=1
4:      while(u ≤ y)
5:          z:=z*x;
6:          u:=u+1
7:      endwh;
8:
```

Symbolic



	x	y	z	u	Path condition	Remarks
1	α	β	-	-	True	
2	α	β	1	-		
3	α	β	1	1		
4	α	β	1	1	1<=β	
Case not(1<=β), ➔ 1>β						
4	α	β	1	1	1>β	
8	α	β	1	1		β=0 and z=1
Case (1<=β)						
4	α	β	1	1	1<=β	
5	α	β	α	1	1<=β	
6	α	β	α	2	1<=β	
7						
4	α	β	α	2	2<=β and 1<=β	
Case not(2<=β) and 1<=β, ➔ 2>β and 1<=β						
4	α	β	α	2	2>β and 1<=β	
8	α	β	α	2		β=1 and z=α
Case (2<=β) and 1<=β						
4	α	β	α	2	2<=β and 1<=β	
5	α	β	α^2	2	2<=β and 1<=β	
6	α	β	α^2	3	2<=β and 1<=β	
7						
4	α	β	α^2	3	3<=β and 2<=β and 1<=β	
Case not(3<=β) and 2<=β and 1<=β ➔ 3>β and 2<=β and 1<=β						
4	α	β	α^2	3	3>β and 2<=β and 1<=β	
8	α	β	α^2	3		β=2 and z=α^2

Symbolic execution

Commutativity

- The same result is obtained using normal execution or using symbolic execution.
- Conventional execution (CE)
  - Sum(a, b, c) → Sum(1, 3, 5)
  - Sum(1, 3, 5) = 9
- Symbolic execution (SE)
  - Sum(a, b, c) = $\alpha + \beta + \gamma$
  - Instantiate the symbolic result
    - ➔$\alpha = 1, \beta = 3, \gamma = 5$
    - ➔1+3+5=9

$$\begin{tikzcd}
(P(X),K) \arrow[r, "\text{Symbolic execution}"] \arrow[d, "\text{Set parameters to integer values}"'] & (E(P(X)),K) \arrow[d, "\text{Substitute into result of symbolic execution}"] \\
P(K) \arrow[r, "\text{Conventional execution}"'] & E(P(K))
\end{tikzcd}$$

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Symbolic execution

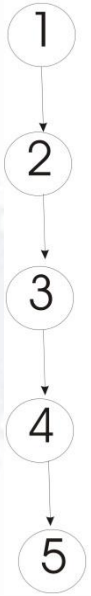
Symbolic Execution Tree

- We can generate symbolic execution tree characterizing the execution paths followed during the symbolic execution.
  - Associate a node with each statement executed.
  - Associate a directed arc connecting the associated nodes with each transition between statements.
  - For IF statement execution, the associated node has two arcs leaving the node which are labeled “T” and “F” for the true and false part, respectively.
  - Associate the complete current execution state, i.e. variable values, statement counter, and pc with each node.

Symbolic execution

Symbolic Execution Tree

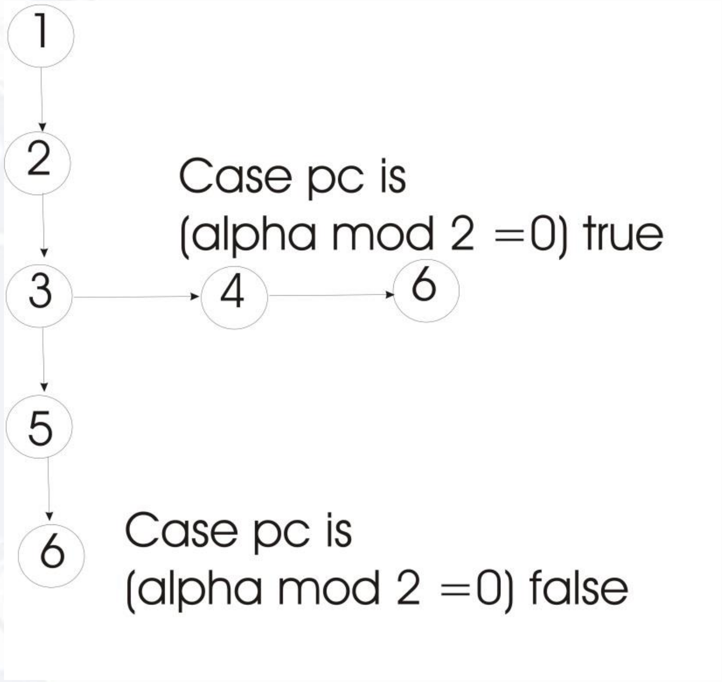
```
1 : int Sum(int a, int b, int c)
2 :      int x := a + b;
3:       int y := b + c;
4:       int z := x + y - b;
5: return z;
6:
```



Symbolic execution

Symbolic Execution Tree

```
1 : boolean IsEven(int a)
2 : boolean b := False;
3: If (x modulo 2 ==0) then
4:          b:=true;
      else
5:          b:=false;
6: IsEven:=b;
```



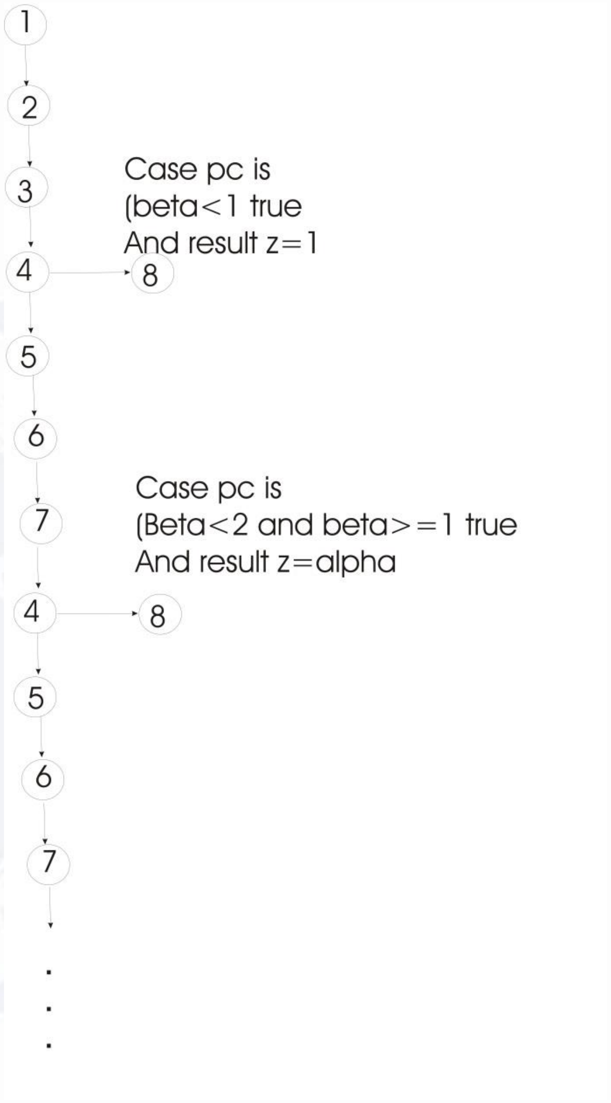
Case pc is
(alpha mod 2 =0) true

Case pc is
(alpha mod 2 =0) false

Symbolic execution

Symbolic Execution Tree

```
1 : Power(int x, int y, int z)
2 :     z := 1;
3:      u:=1
4:      while(u ≤ y)
5:          z:=z*x;
6:          u:=u+1
7:      endwh;
8:
```



Case pc is
(beta<1 true
And result z=1

Case pc is
(Beta<2 and beta>=1 true
And result z=alpha

Symbolic execution

Properties of the Symbolic Execution Tree

- For each terminal leaf exists a particular non symbolic input.
- The pc associated with any two terminal leaves are distinct.
- Test case generation
  - to execute every statement at least once
  - to include execution of each branch both ways
  - finding input values to reach a particular point in a program

  Symbolic execution
  - Symbolic variables for input variables
  - Execute the program symbolically
  - Collect symbolic path constraints
  - Use constraint solver to generate test inputs for each execution path
- **Remaining problem** - to instantiate the pc with particular values.
- The **pc** specifies **a class of equivalent tests**, and any feasible solution to the constraints (represented by the pc) would be a representative member.
- The symbolic execution also provides expressions describing the program outputs for all inputs in this set.

Symbolic execution

Symbolic execution – research- revisited

- 1975 - First introduced
- 1976 - King [Kin76], Clarke [Cla76]
- 2005 - Microsoft: DART [God05]
- 2006 - Univ. Stanford: EXE, Univ. Illinois: CUTE and jCUTE [SA06]
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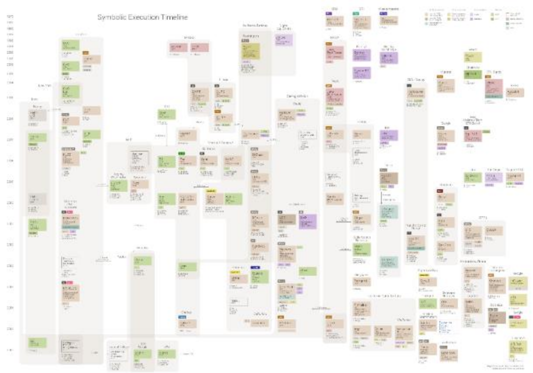
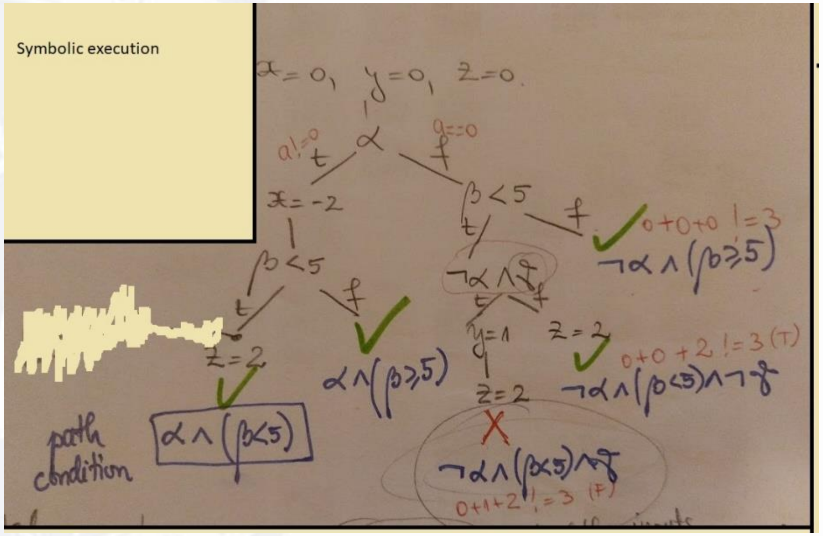
  - https://patricegodefroid.github.io/
  - https://channel9.msdn.com/blogs/peli/automated-whitebox-fuzz-testing-with-sage- **video**
- PEX
  - https://www.microsoft.com/en-us/research/project/pex-and-moles-isolation-and-white-box-unit-testing-for-net/?from=http%3A%2F%2Fresearch.microsoft.com%2Fen-



Symbolic execution

Symbolic Execution – example -http://klee.github.io/getting-started/
http://klee.github.io/tutorials/testing-function/

```
// Edit SymbolicExecutionExample.c

void SymbolicExecutionExample(int
a, int b, int c){

    int x=0, y=0, z=0;

    if (a!=0){

        x=-2;

     }

     if (b<5){

        if(!a && c){y=1;}

        z=2;

      }

     assert(x+y+z!=3);

}
```



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References

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- [Cla76] L. A. Clarke. A system to generate test data and symbolically execute programs.
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