Software Systems Verification and Validation

Lecture 8: Symbolic execution

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Surprise!

Floyd, Dijkstra, Hoare (25XP)

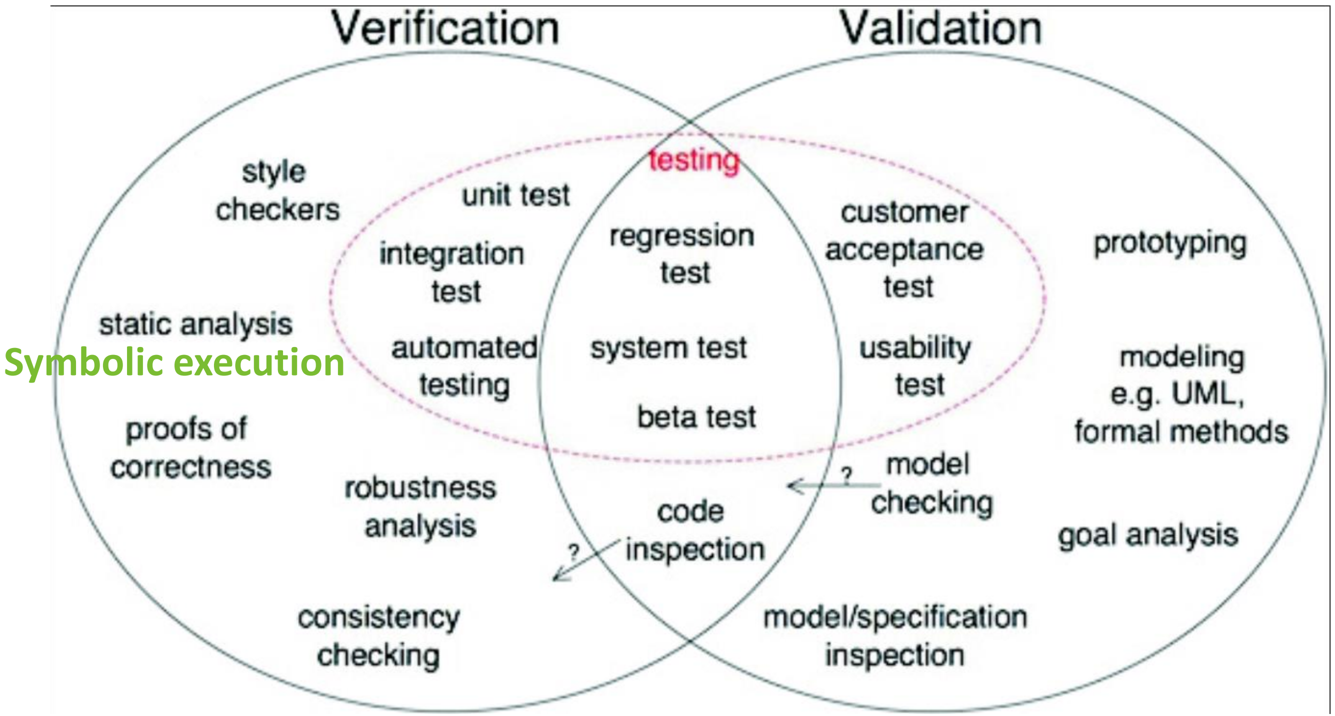
- **Robert Floyd** OR **Edsger Wybe Dijkstra** OR **Charles Antony Richard Hoare**

- 1 page A4 information (electronic format and printed format)
  - short bio
  - profession
  - Institution
  - known by…
  - awards
  - interesting facts

- Feel free to select a format: plain text, mindmap, other
- Delivery: Lecture 8

Sales paradigm - SSVV

- Motivate the STUDENT - what you 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 (in L09 (free on 26 April 2019) but still today)
  - Model checking

- Next next Lecture (L10)
  - **ENDAVA** Presentation, topic: **Verification and Validation during the Software Development Life Cycle**
  - **When:** Friday, May 10, 2019, hours 14:00-16:00;
  - **Where:** Room A2 (FSEGA Building)

Static analysis
Symbolic execution

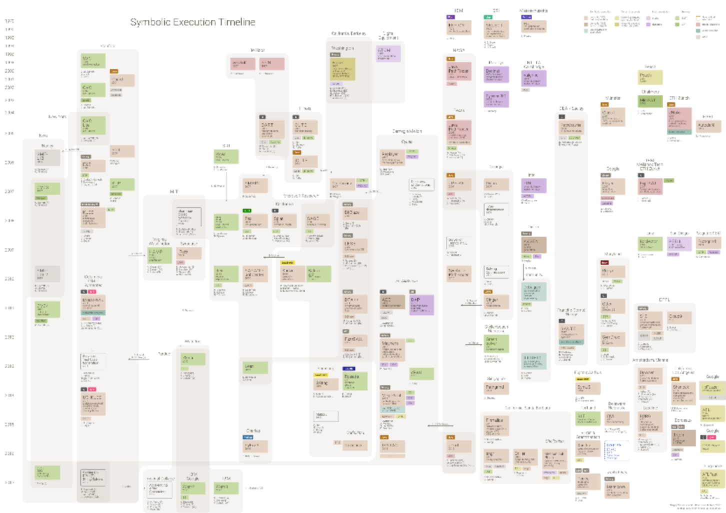
- Bugs that are missed by testing: rare features, rare circumstances, nondeterminism.
  - ➔ Static analysis
    - Can analyze all possible runs of a program
    - But, can it finds deep, difficult bugs?
      - – Abstraction let us model all possible runs
      - – Static analysis abstraction <> developer 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.

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
- 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

- 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

- 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.

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
- Symbolic execution result of Sum
- 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	$\alpha+\beta$	-	-
3	α	β	γ	$\alpha+\beta$	$\beta+\gamma$	-
4	α	β	γ	$\alpha+\beta$	$\beta+\gamma$	$\alpha+\beta+\gamma$
5	α	β	γ	$\alpha+\beta$	$\beta+\gamma$	$\alpha+\beta+\gamma$

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 ($\boldsymbol{\eta}$) 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 $\rightarrow \eta$
  - pc $\rightarrow \neg\eta$

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) then
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 an 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 structures

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:
```

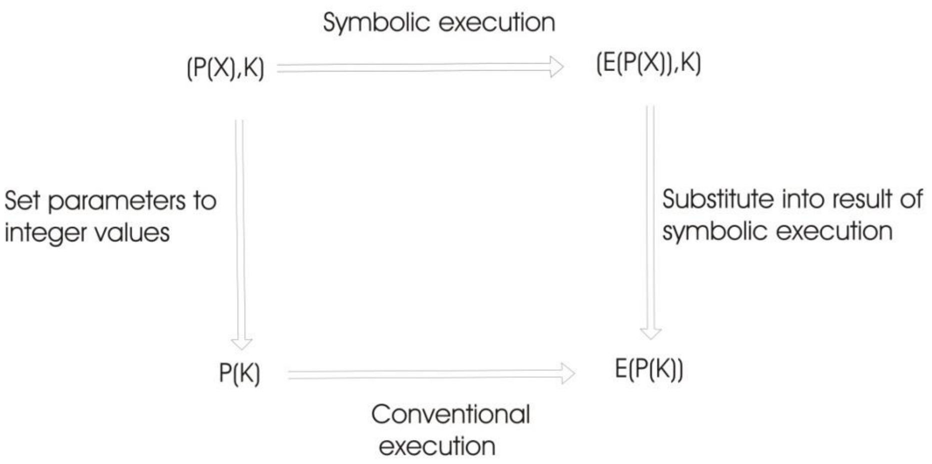
Symbolic

	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



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

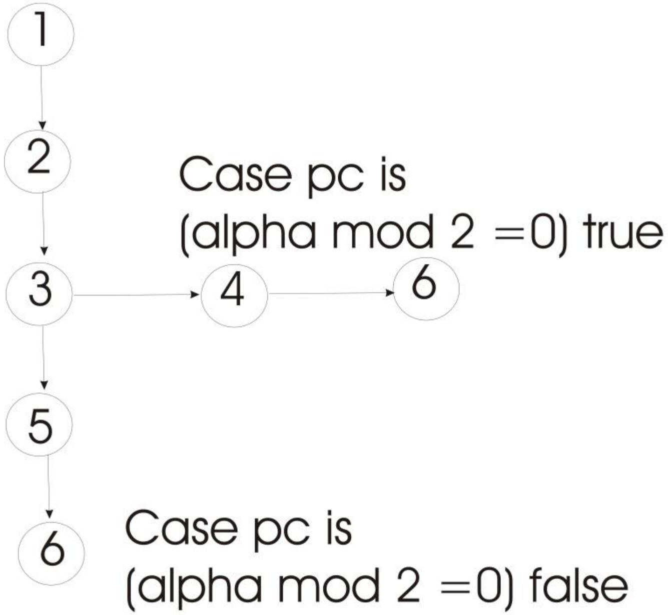
Symbolic Execution Tree

```
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;



Symbolic execution

Symbolic Execution Tree

```
1 : Power(int x, int y, int z)
2 :     z := 1;
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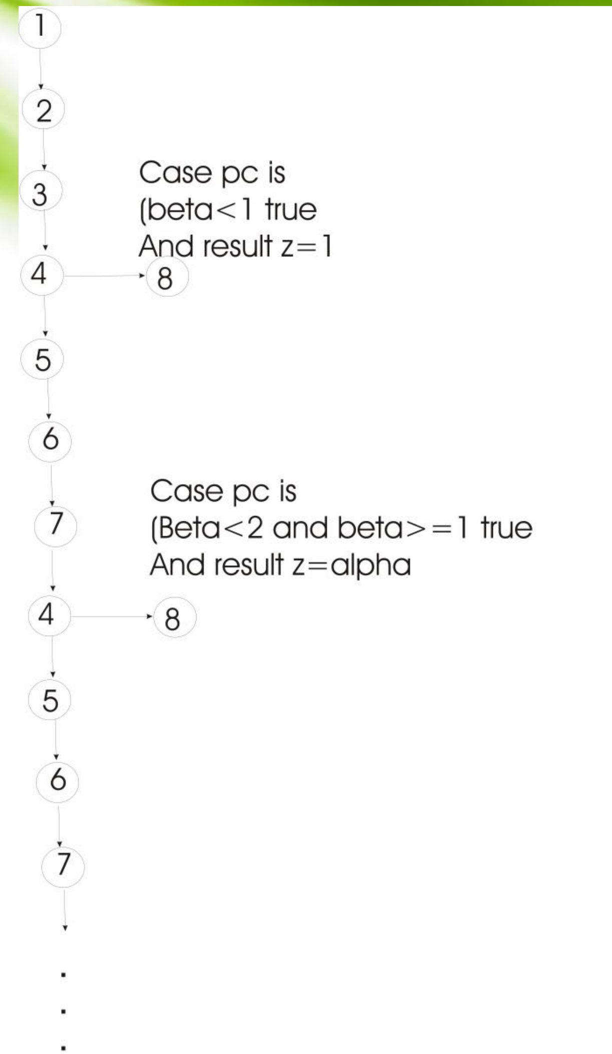

Symbolic execution

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 – research- **revisited**

- 1975 - First introduced
- 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

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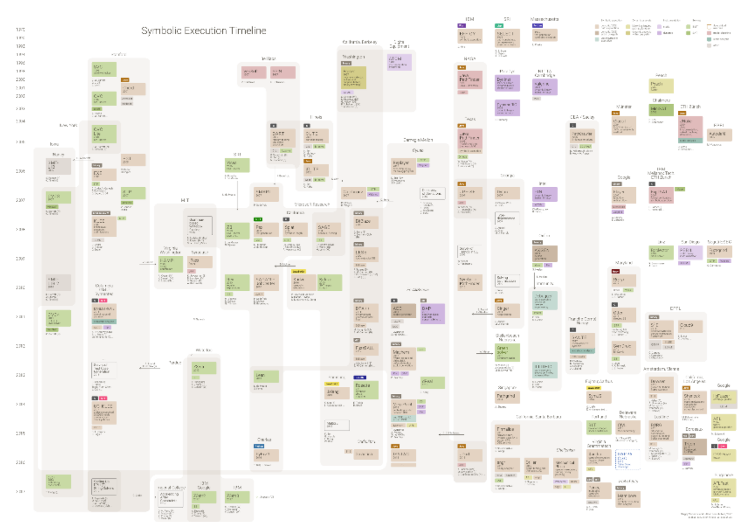
- 2018 -Chopped Symbolic Execution (ICSE) (2006 -EXE)
  - https://www.doc.ic.ac.uk/~cristic/
- 2018 -Deep Reinforcement Fuzzing, Konstantin Böttinger, Patrice Godefroid, Rishabh Singh

- SAGE (2005 -DART)
  - https://patricegodefroid.github.io/
  - https://channel9.msdn.com/blogs/peli/automated-whitebox-fuzz-testing-with-sage- **video**
- 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



Surprise!

Symbolic execution

3-5 minutes

Formative Assessment

Anonymous voting

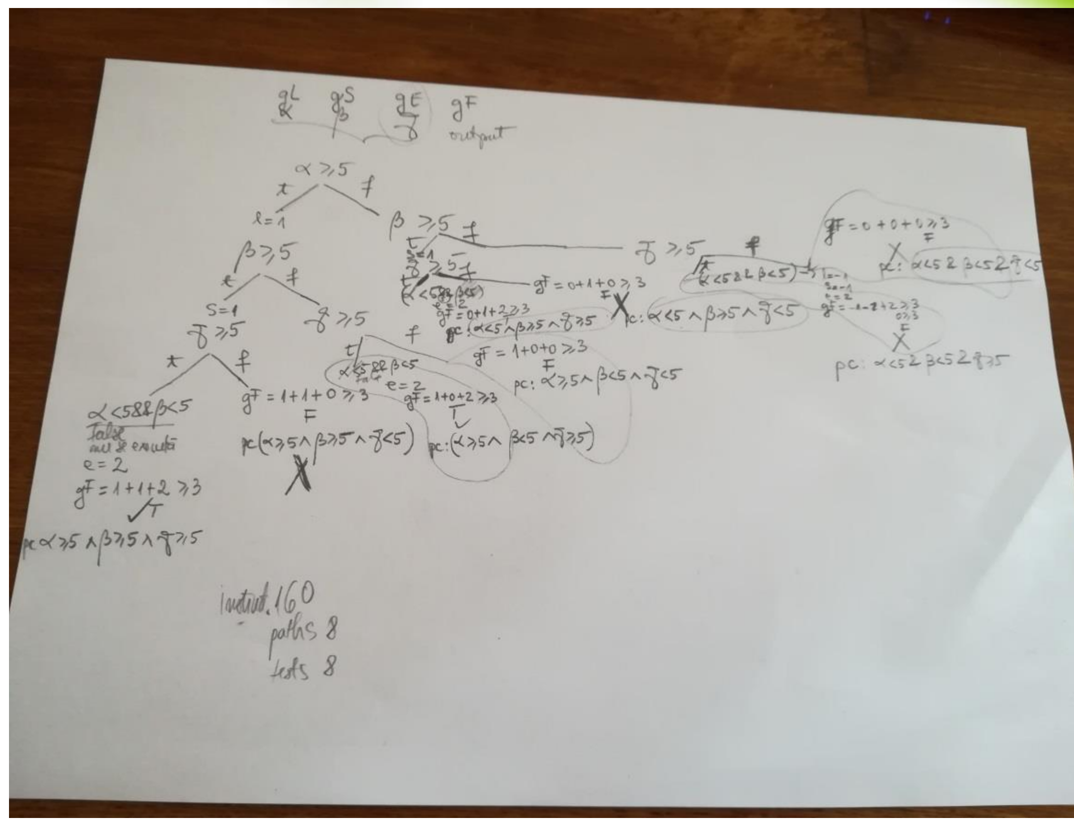
Symbolic execution

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

- Subalgorithm FinalGrade (gL, gS, gE, gF)is

```
int l=0, s=0, e=0;
if (gL>=5)
        l=1
if (gS>=5)
        s=1
if (gE>=5){
  if(gL<5 && gS<5)
        l=-1, s=-1
  e = 2
}
gF= l +s +e
assert (gF>=3)
```

EndSubalgorithm



Surprise!

Surprise!

```
int get_sum(int a, int b, int c) {
    int x=0, y=0, z=0,d=0;
    if (a >=3 )
        x=-2;
    if (b<5){
        if (a<3 && c>0){
            y=1;
        }
        z=2;
    }
    d=x+y+z;
   // assert(d!=3);
    return d;}
```

Symbolic execution tree

5 minutes

25 XP

In class lecture assessments (bonus points)
Take Home – Lecture 11

Questions

- Thank You For Your Attention!

References

- [Kin76] James C. King. Symbolic execution and program testing. Commun. ACM, 19(7):385–394, 1976.
- [Cla76] L. A. Clarke. A system to generate test data and symbolically execute programs.
- IEEE Transactions on Software Engineering, SE-2(3):215–222, 1976.
- [God05] P. Godefroid. Dart: directed automated random testing. pages 213–223, 2005.
- [SA06] Koushik Sen and Gul Agha. Cute and jcute: Concolic unit testing and explicit path model-checking tools. In Proceedings of the 18th International Conference on Computer Aided Verification, pages 419–423, 2006.
- [CDE08] Cristian Cadar, Daniel Dunbar, and Dawson Engler. Klee: Unassisted and automatic generation of high-coverage tests for complex systems programs. In Proceedings of the 8th USENIX Conference on Operating Systems Design and Implementation, pages 209–224, 2008.
- [PV09] Corina S. Pasareanu and Willem Visser. A survey of new trends in symbolic execution for software testing and analysis. Int. J. Softw. Tools Technol. Transf., 11(4):339–353, 2009.
- [CS13] Cristian Cadar and Koushik Sen. Symbolic execution for software testing: Three decades later. Commun. ACM, 56(2):82–90, 2013.