SEENG3320/6320: Software Verification and Validation

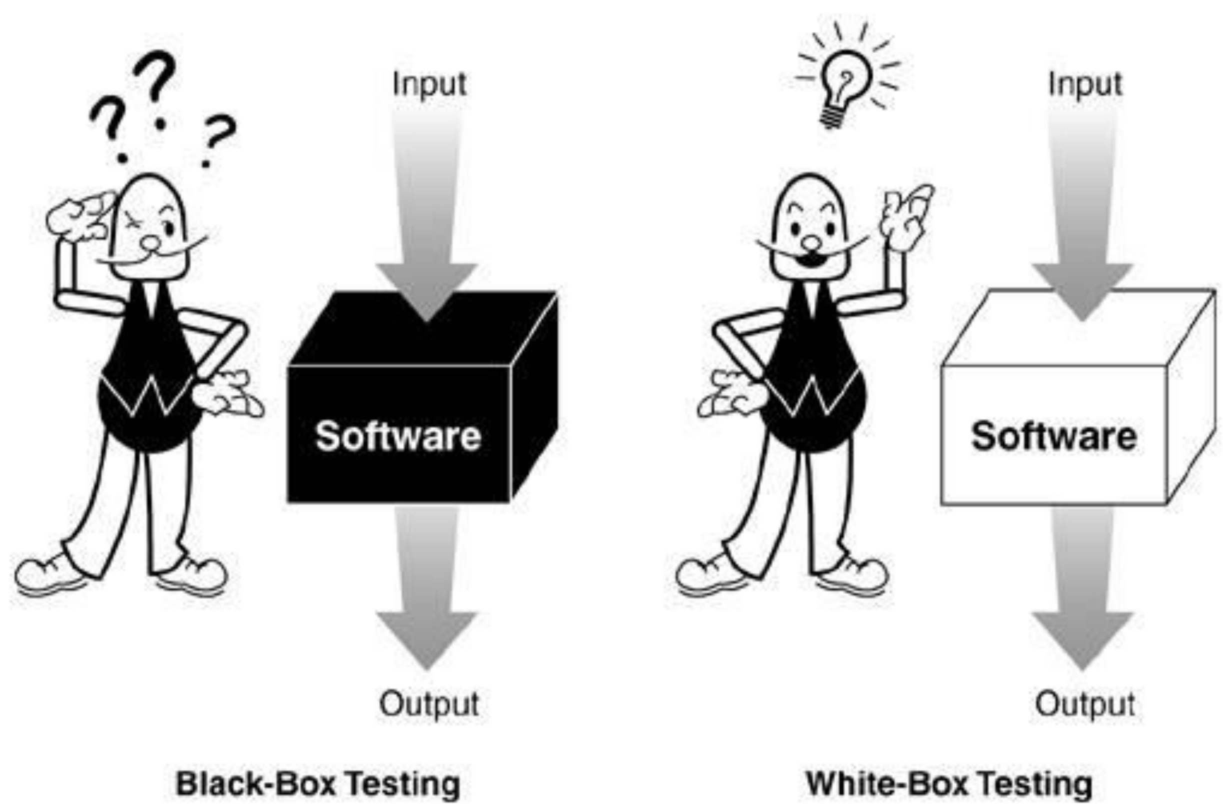
School of Electrical Engineering and Computing

Semester 1, 2020

Symbolic Execution

Types of test generation

- Black-box (functional) vs. white-box (structural) test generation
- Black-box test generation: Generating test cases based on the functionality of the software
- White-box test generation: Generating test cases based on the source-code structure of the program



Symbolic Execution

- **Symbolic execution** (also called **symbolic evaluation**) is a means of analyzing a program to determine what inputs cause each part of a program to execute.
- ’Execute’ programs with symbols: we track symbolic state rather than concrete input
- When ’execute’ one path, we actually simulate many test runs, since we are considering all the inputs that can exercise the same path.
- Firs proposed by James C King in 1975.

Concrete Execution Verse Symbolic Execution

During a concrete execution:

- The program would read a concrete input value (e.g., 5) and assign it to y.
- Execution would then proceed with the multiplication and the conditional branch.

During a symbolic execution:

- The program reads a symbolic value (e.g., `Y`) and assigns it to y.
- The program would then proceed with the multiplication and assign `Y * 2` to `z`. When reaching the `if` statement, it would evaluate `Y * 2 == 12`.

```
int f() {
  ...
  y = read();
  z = y * 2;
  if (z == 12) {
    fail();
  } else {
    printf("OK");
  }
}
```

Path Conditions:

```
Path 1: Y * 2 == 12
Path 2: Y * 2 != 12
```

Basic Concepts

- Consider the following code

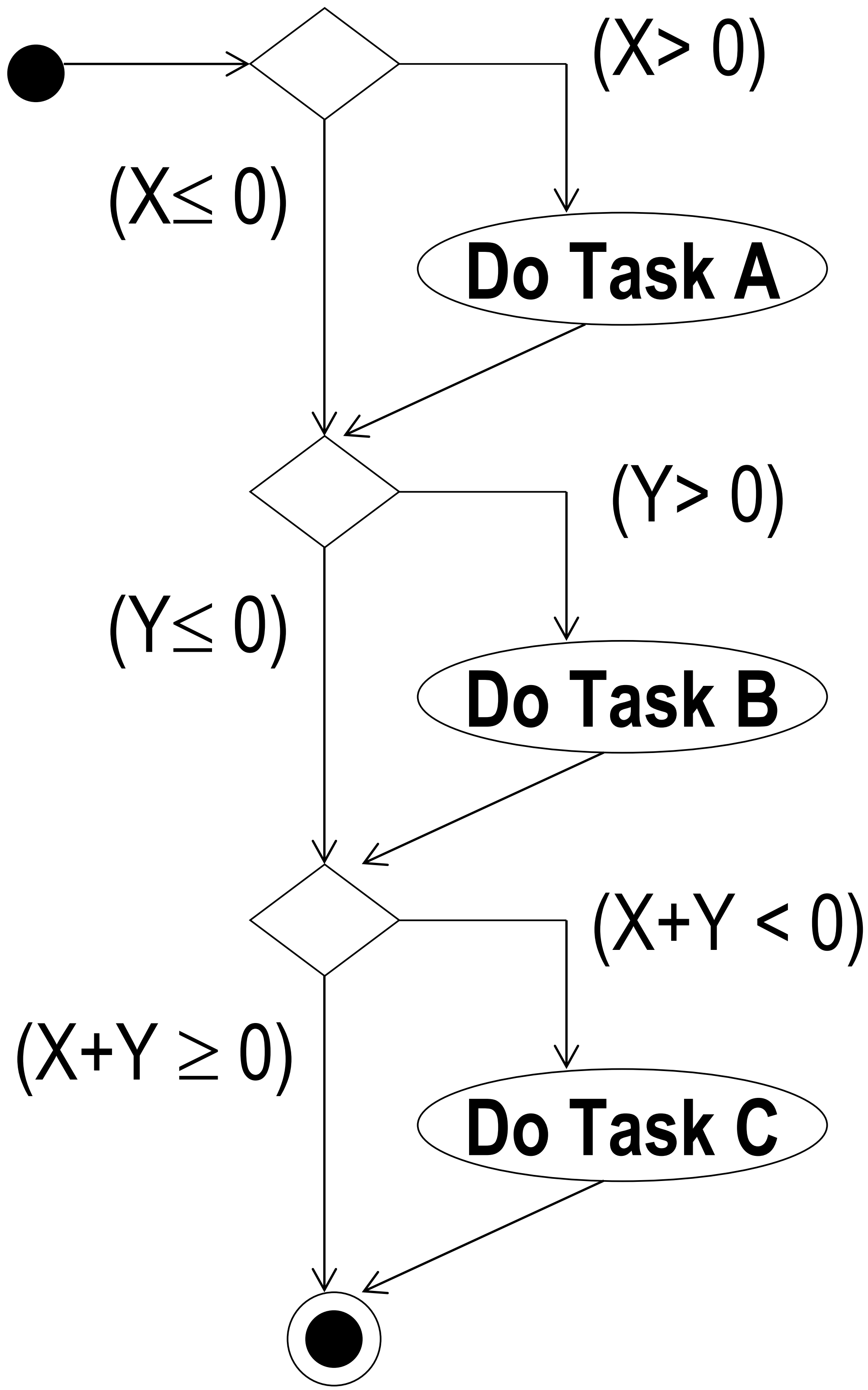
```
public void methodZ()
{
    INPUT 2 values of double type: X and Y
    Define Z = X+Y
    If (X> 0)      { /*do Task A*/ }
    If (Y>0)       { /*do Task B*/ }
    If (Z < 0)     { /*do Task C*/ }
}
```

Convert (**Z** < 0) to (**X**+**Y** <0).
This process is called "***predicate interpretation***" , which ensures that the **predicate** is made up by the **input variables**.

Basic Concepts (cont.)

- Path condition: conjunction of predicate interpretations along a path
- Executable (feasible) path
  - If a **path** can be executed by at least one **input**, the path is called executable path
- Infeasible path
  - The *path condition* can never be **satisfied**.
    - NO test cases can be generated for an infeasible path

Basic Concepts (cont.)



Path 1: $(X > 0)$ and $(Y>0)$ and $(X+Y < 0)$ **Infeasible**
Path 2: $(X > 0)$ and $(Y>0)$ and $(X+Y \geq 0)$ Feasible
Path 3: $(X > 0)$ and $(Y\leq 0)$ and $(X+Y < 0)$ Feasible
Path 4: $(X > 0)$ and $(Y\leq 0)$ and $(X+Y \geq 0)$ Feasible
Path 5: $(X\leq 0)$ and $(Y>0)$ and $(X+Y < 0)$ Feasible
Path 6: $(X\leq 0)$ and $(Y>0)$ and $(X+Y \geq 0)$ Feasible
Path 7: $(X\leq 0)$ and $(Y\leq 0)$ and $(X+Y < 0)$ Feasible
Path 8: $(X\leq 0)$ and $(Y\leq 0)$ and $(X+Y \geq 0)$ Feasible

7 paths are feasible because they can be executed by at least **ONE input**

Basic Concepts (cont.)

- We can refine the path conditions for Paths 2-8 as follows:

Path 2: $(X > 0)$ and $(Y > 0)$ and $(X+Y > 0)$	Feasible
Path 3: $(X > 0)$ and $(Y < 0)$ and $(X+Y < 0)$	Feasible
Path 4: $(X > 0)$ and $(Y \leq 0)$ and $(X+Y \geq 0)$	Feasible
Path 5: $(X < 0)$ and $(Y > 0)$ and $(X+Y < 0)$	Feasible
Path 6: $(X \leq 0)$ and $(Y > 0)$ and $(X+Y \geq 0)$	Feasible
Path 7: $(X \leq 0)$ and $(Y \leq 0)$ and $(X+Y < 0)$ and $(x \neq y = 0)$	Feasible
Path 8: $X = Y = 0$	Feasible

Basic Concepts (cont.)

- Input sub-domain
    - A set of inputs satisfying a path condition
- "**Searching** an input to execute a path" **is equivalent** to "**solving** the associated path condition"

Searching = Solving

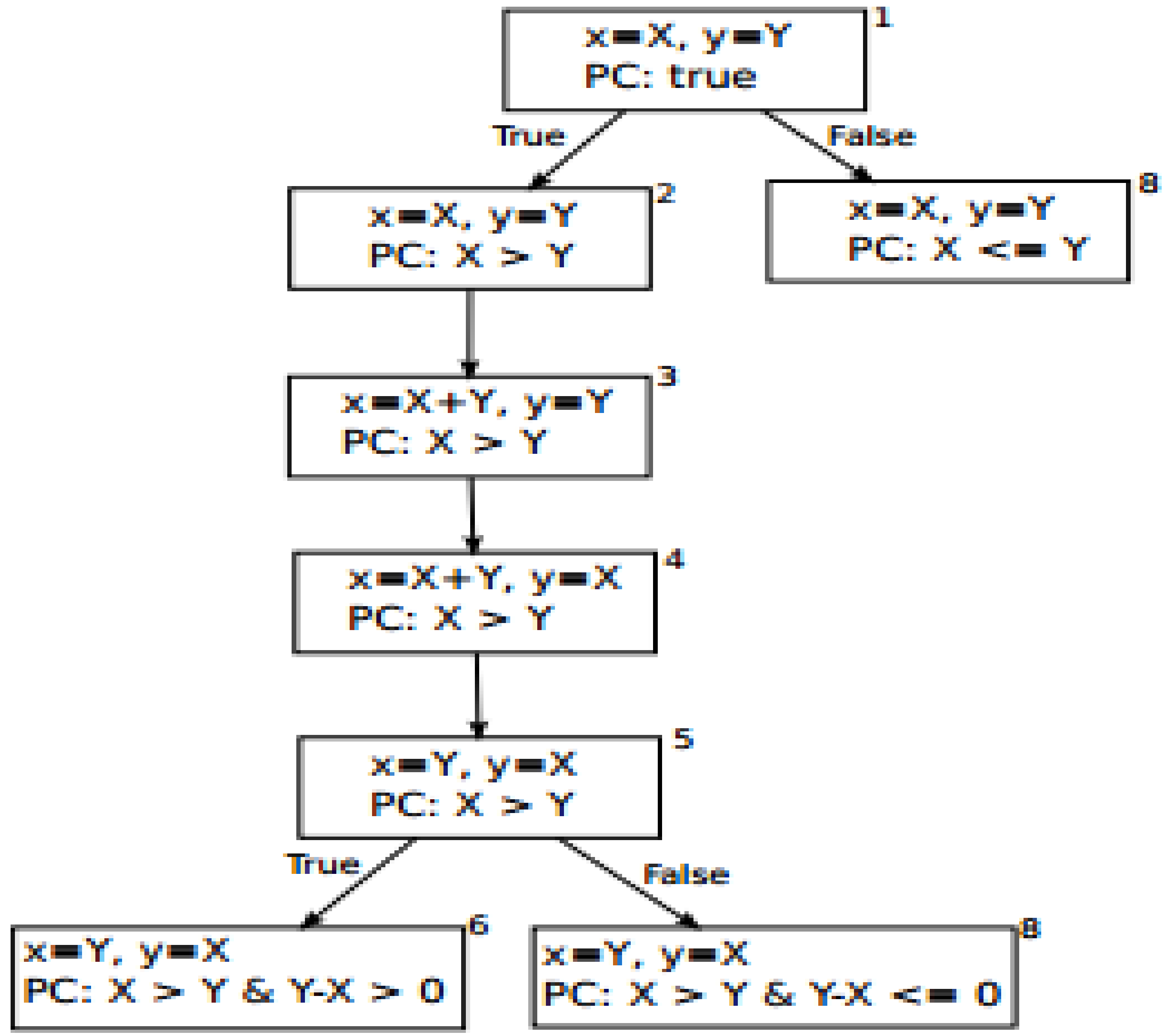
Test Case Generation based on Symbolic Execution

```
    int x, y;
1   if(x > y){
2     x = x+y;
3     y = x-y;
4     x = x-y;
5     if(x - y > 0)
6       assert false;
7   }
8   print(x, y)
```

(a)

Path	PC	Program Input
1,8	X <= Y	X=1 Y=1
1,2,3,4,5,8	X>Y & Y-X<=0	X=2 Y=1
1,2,3,4,5,6	X>Y & Y-X>0	none

(c)

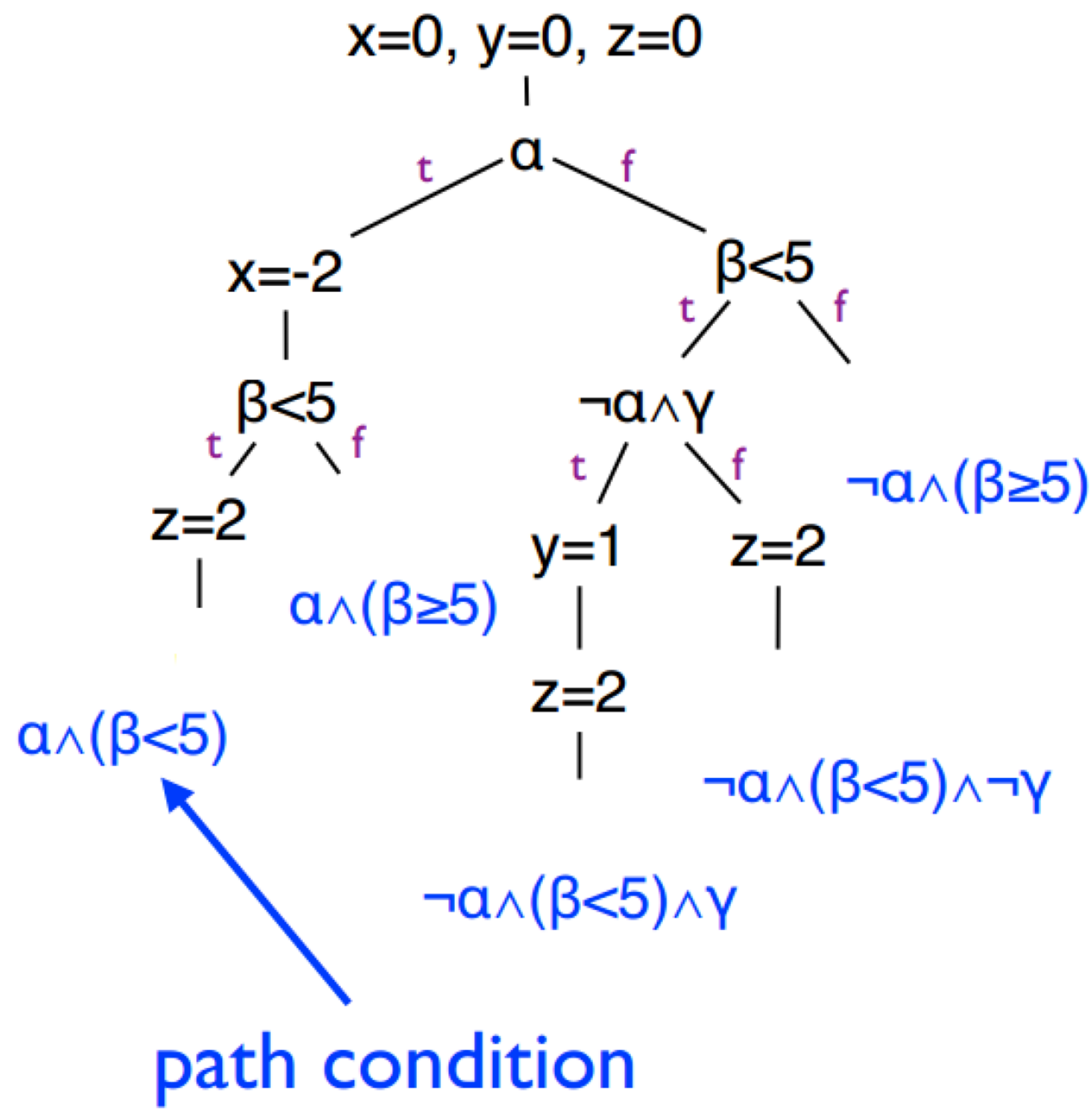


(b)

Test Case Generation based on Symbolic Execution

```
bool a= α;
int b = β; bool c = γ;
                    // symbolic
```

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



Test case 1: α = true; $\beta = 1$

Test case 2: α = true; $\beta = 6$

…

Example

`y = read();`	y=s, s is a symbolic variable for input
`p = 1;`	$p = 1, y = s$
`while(y < 10){`	$p = 1, y = s$
`    y = y + 1;`	$s<10, y = s + 1, p = 1$
`    if y >2`	
`      p = p + 1;`	$2 < s + 1< 10, y = s + 1, p = 2$
`    else`	
`      p = p + 2;`	$s + 1<=2, y = s + 1, p = 3$
`}`	
`print (p);`	

Quiz

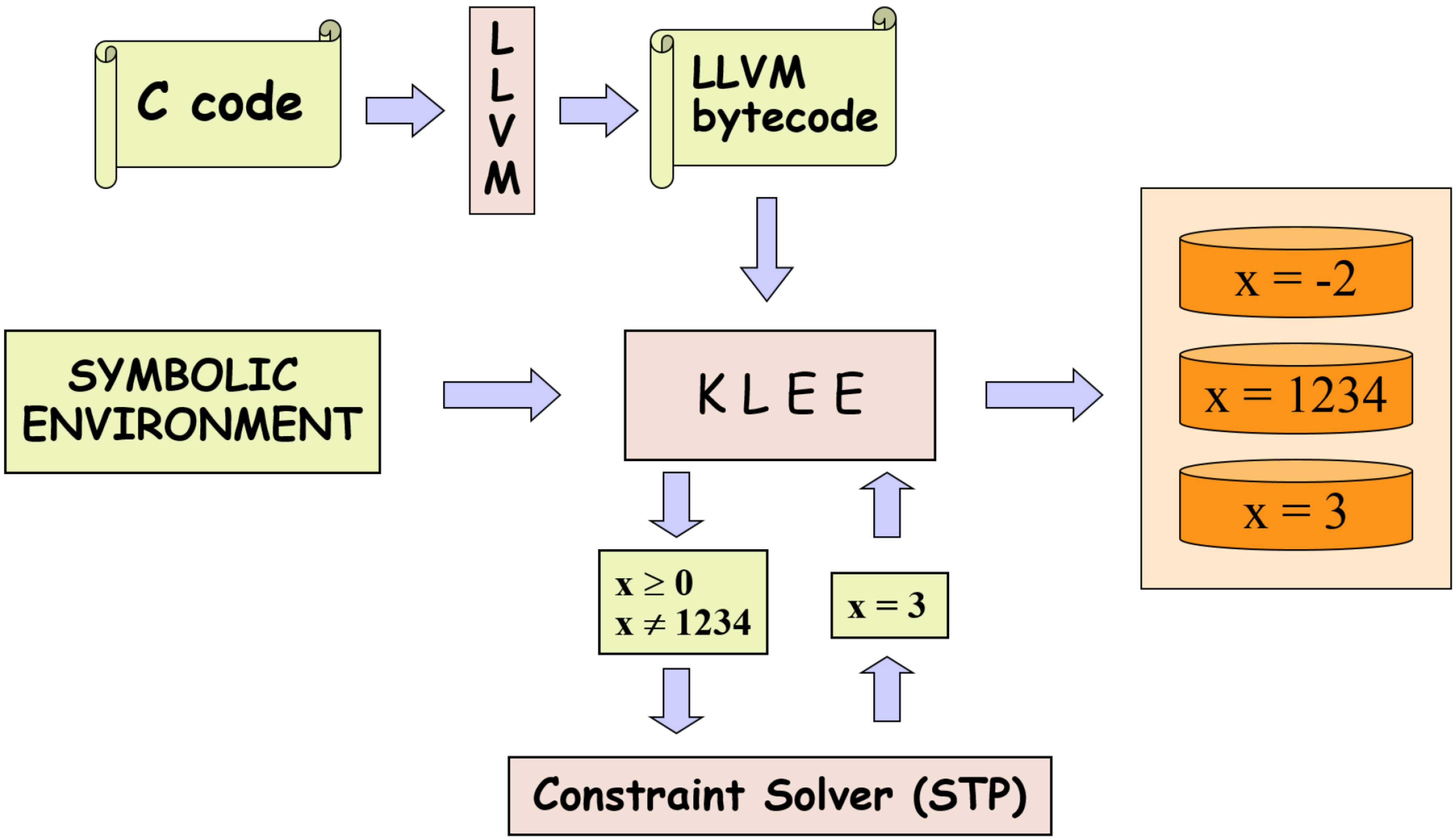
```
int foo(int i){
        int j = 2*i;
        i = i++;
        i = i * j;
        if ( i < 1 )
                i =   -i;
        return i;
}
```

- Perform symbolic execution of this code:
  - What are the path conditions ?
  - Generate test cases for each path

Tool Support

- Java：
  - Java PathFinder: http://babelfish.arc.nasa.gov/trac/jpf
  - JCUTE: https://github.com/osl/jcute
- C：
  - CUTE/S2E/Crest
  - KLEE: http://klee.github.io/
- .Net:
  - Pex: http://research.microsoft.com/en-us/projects/pex/
- ……

KLEE



- Using the LLVM compiler infrastructure to compile C code to bytecode.
- Modelling program environment.
- Using STP, an efficient constraint solver, to solve path conditions.

Constraint Solver

SAT: find an assignment to a set of Boolean variables that makes the Boolean formula true

Complexity: NP-Complete

https://en.wikipedia.org/wiki/Boolean_satisfiability_problem

SMT (Satisfiability Modulo Theories) = SAT++
An SMT formula is a Boolean combination of formulas over first-order theories

https://en.wikipedia.org/wiki/Satisfiability_modulo_theories

Problems of static symbolic execution

- Path explosion
  - Remember n branches will cause 2^n paths
  - Infinite paths for unbounded loops
  - Calculate constraints on all paths is infeasible for real software
- Too complex constraint
  - The constraint gets very complex for large programs
  - Not to mention the resolving part is NPC

Further Reading

- R. G. Hamlet, “Testing programs with the aid of a compiler,” TSE, vol. 3, 1977.
- R. A. DeMillo, R. J. Lipton, and F. G. Sayward, “Hints on test data selection: Help for the practicing programmer,” Computer, vol. 11, 1978.
- A. J. Offutt, A. Lee, G. Rothermel, R. Untch, and C. Zapf, “An experimental determination of sufficient mutation operators,” ACM TOSEM, vol. 5, no. 2, pp. 99–118, 1996.
- James C. King, Symbolic execution and program testing, Communications of the ACM, volume 19, number 7, 1976, 385—394.
- Cadar, Cristian; Dunbar, Daniel; Engler, Dawson, "KLEE: Unassisted and Automatic Generation of High-coverage Tests for Complex Systems Programs". Proceedings of the 8th USENIX Conference on Operating Systems Design and Implementation. OSDI'08. Berkeley, CA, USA, USENIX Association, pp. 209–224.

Thanks!


Testing
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