SOFT620020.01
Advanced Software Engineering

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Course Outline

Date	Topic
Sep. 09	Introduction
Sep. 16	Testing Overview
Sep. 23	Guided Random Testing
Sep. 30	Search-Based Testing
Oct. 12	Performance Analysis
Oct. 14	Presentation 1
Oct. 21	Security Testing
Oct. 28	Compiler Testing

Date	Topic
Nov. 04	Mobile Testing
Nov. 11	Delta Debugging
Nov. 18	Bug Localization
Nov. 25	Presentation 2
Dec. 02	Automatic Repair
Dec. 09	**Symbolic Execution**
Dec. 16	Big Code Analysis
Dec. 23	Presentation 3

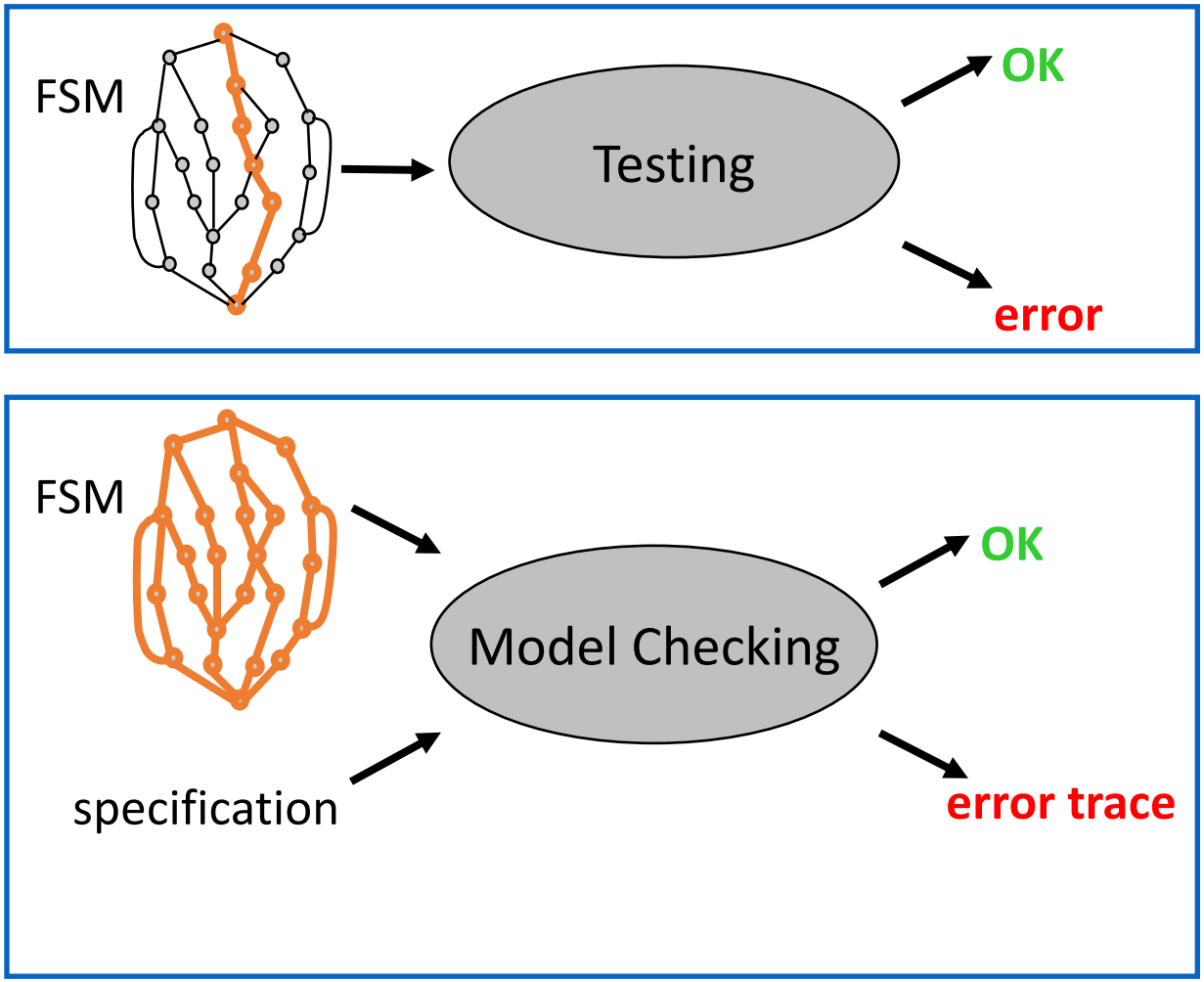
Discussion – Will the Assertion Fail?

```
0. int x, y;
1. if (x>0) {
2.         assert(x>=0);
3. }
```

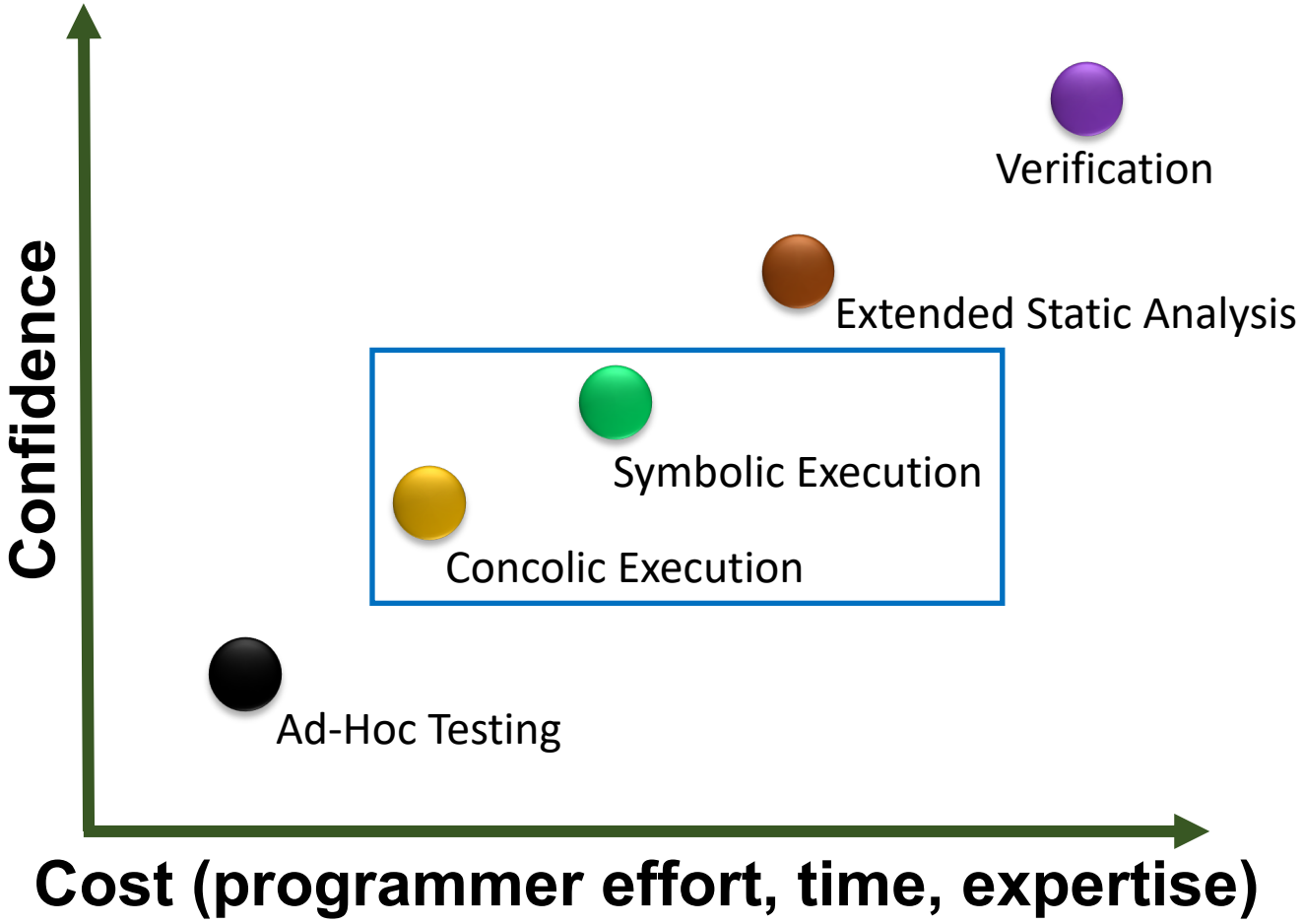
```
0. int x, y;
1. if (x>y) {
2.         x = x + y;
3.         y = x – y;
4.         x = x – y;
5.         if (x-y>0) {
6.             assert(false);
7.         }
8. }
```

- Can automatic testing prove whether the assertion fails?
  - No! Why?
- Can we automatically prove whether the assertion fails?
  - Partially Yes. How?

Testing vs. Model Checking



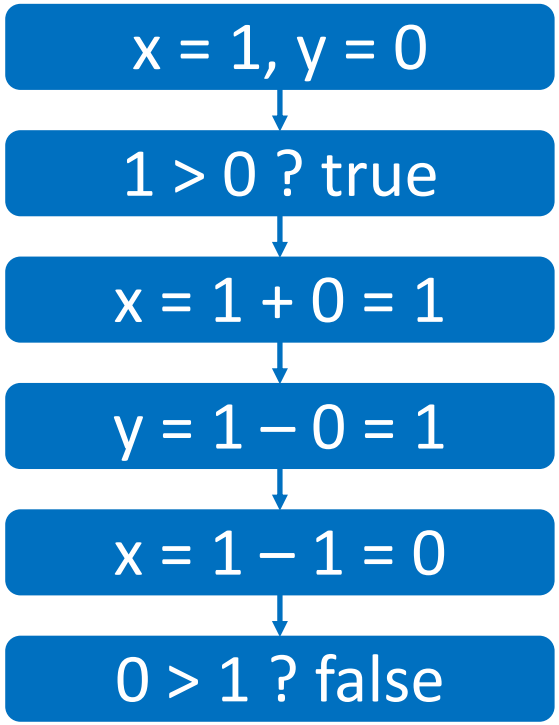
Program Validation Approaches



Symbolic Execution

Example of Standard (Concrete) Execution

```
int x, y;
if (x > y) {
  x = x + y;
  y = x – y;
  x = x – y;
  if (x > y)
    assert (false);
}
```

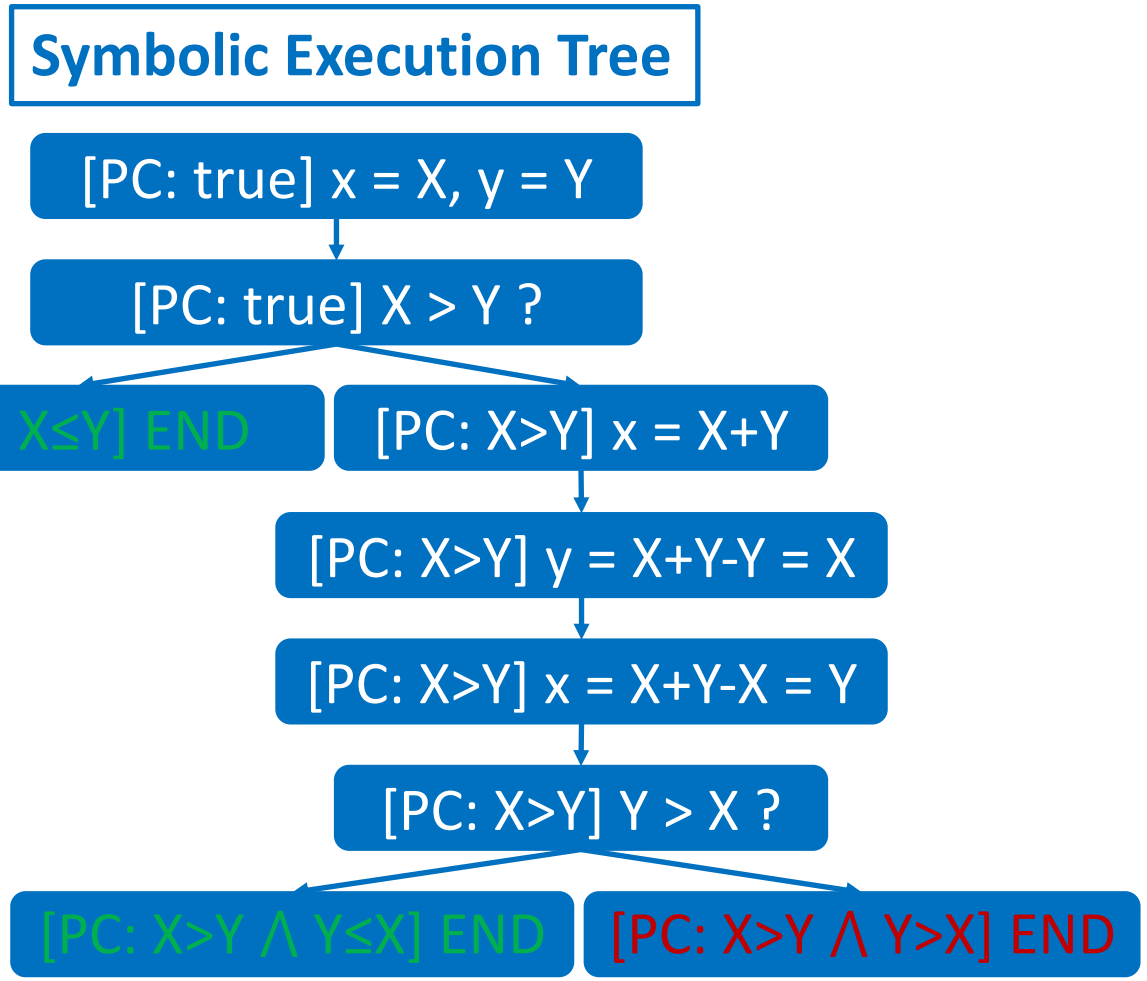


Symbolic Execution

- Analysis of programs with unspecified inputs
  - Execute a program on symbolic inputs
- Symbolic states represent sets of concrete states
- For each path, build a path condition
  - Condition on inputs – for the execution to follow that path
  - Check path condition satisfiability – explore only feasible paths
- Symbolic state
  - Symbolic expressions for variables
  - Path condition
  - Program counter
- Tools: KLEE (C), JavaPath Finder (Java), …

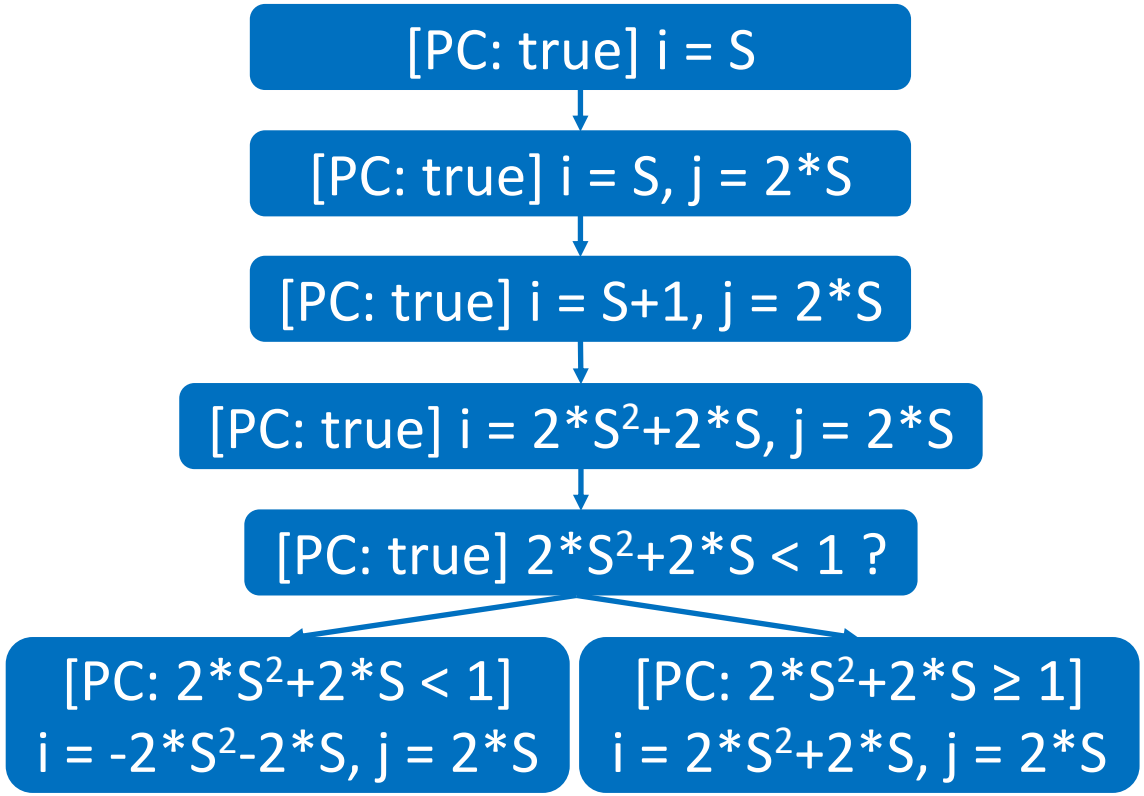
Example of Symbolic Execution

```
int x, y;
if (x > y) {
  x = x + y;
  y = x – y;
  x = x – y;
  if (x > y)
    assert (false);
}
```



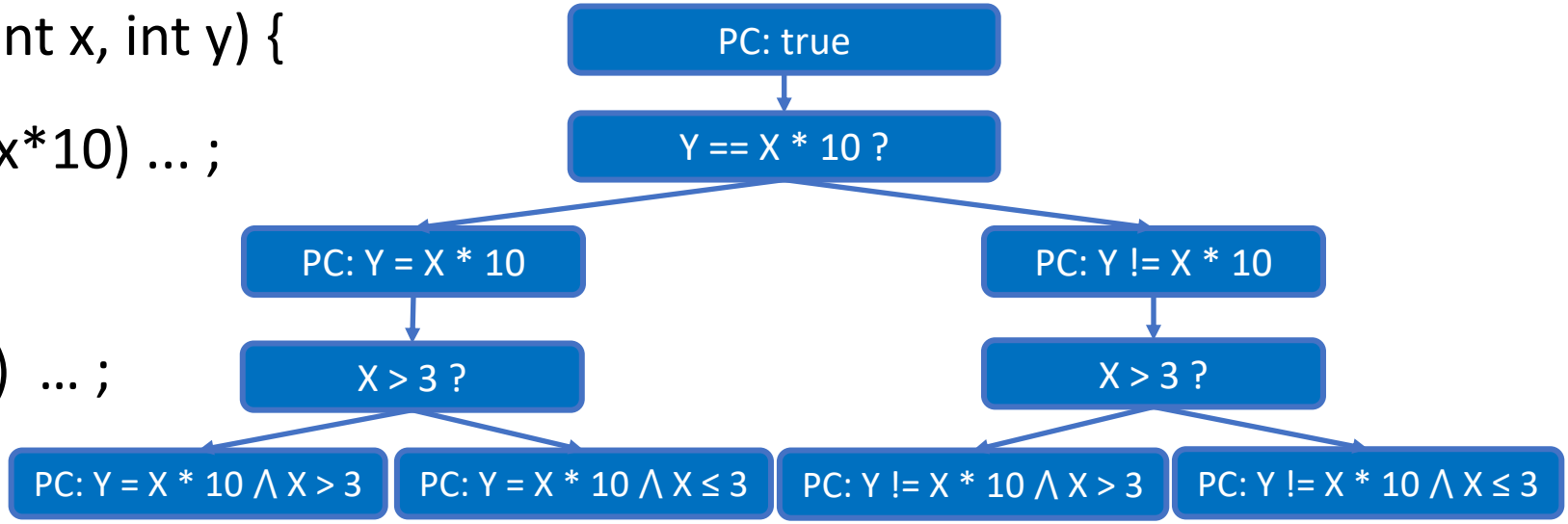
Exercise: Symbolically Execute the Program

```
int i;
int j = 2 * i;
i = i++;
i = i * j
if (i < 1)
    i = -i;
```



Exercise: Symbolically Execute the Program

```
void test(int x, int y) {
    if (y == x*10) ... ;
    else ... ;
    if (x > 3)  ... ;
    else ... ;
}
```



- How can we check the satisfiability of path conditions?
  - Constraint Solving
- How can we explore the large space of symbolic execution tree?
  - Searching Strategy

Constraint Solving

- Symbolic execution was proposed in 1976
  - L. A. Clarke, “A System to Generate Test Data and Symbolically Execute Programs”, IEEE Transactions on Software Engineering
- Become popular only in recent years due to advancement in constraint solving techniques
  - SAT Solver
  - SMT Solver
  - …

Boolean Satisfiability Problem

- **Boolean Satisfiability** (often abbreviated **SAT**) is the problem of determining if there exists an assignment that satisfies a given Boolean formula
- Consider the formula $(a \vee b) \wedge (\neg a \vee \neg c)$
  - The assignment b = true and c = false satisfies the formula
- History
  - SAT is shown to be NP-complete in 1971 (Stephen Cook)
  - Breakthrough occurred in 1990s
  - Advanced SAT solver handles problem instances with millions of Boolean variables
  - Annual competition: http://www.satcompetition.org/

SAT Solver Progress

Solvers have continually improved over time

Instance	Posit' 94
ssa2670-136	40.66s
bf1355-638	1805.21s
pret150_25	>3000s
dubois100	>3000s
aim200-2_0-no-1	>3000s
2dlx_..._bug005	>3000s
c6288	>3000s

Source: Marques-Silva 2002

Exercise: Applying SAT Solving

- Consider the following constraints
  - John can only meet either on Monday, Wednesday or Thursday; Catherine cannot meet on Wednesday; Anne cannot meet on Friday; Peter cannot meet neither on Tuesday nor on Thursday
- Question: when can the meeting take place?
  - John = (Mon ∨ Wed ∨ Thu) ∧ ¬Tue ∧ ¬Fri
  - Catherine = (Mon ∨ Tue ∨ Thu ∨ Fri) ∧ ¬Wed
  - Anne = (Mon ∨ Tue ∨ Wed ∨ Thu) ∧ ¬Fri
  - Peter = (Mon ∨ Wed ∨ Fri) ∧ ¬Tue ∧ ¬Thu
  - John ∧ Catherine ∧ Anne ∧ Peter ?
  - Monday!

SAT Extension: SMT

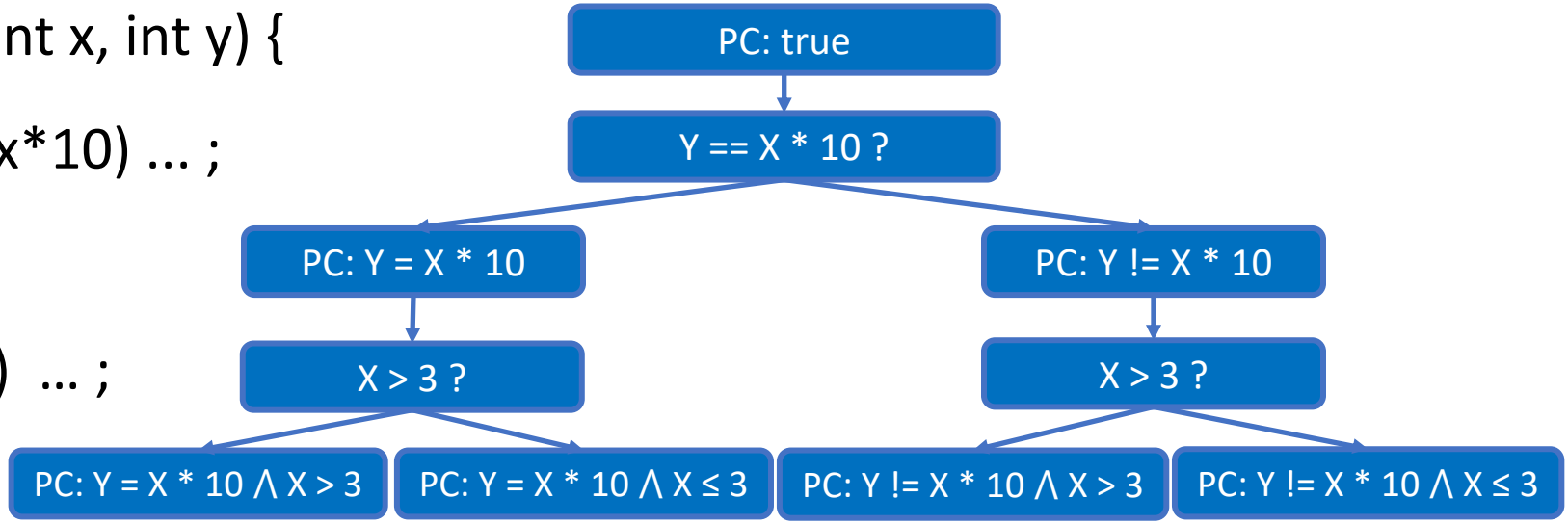
- **Satisfiability Modulo Theories** (**SMT**) enrich quantified Boolean formulas (QBF) with linear constraints, uninterpreted functions, etc.
  - QBF: Is there a solution {x, y, z} satisfying $\forall x \, \forall y \, \exists z \, (x \vee y \vee z) \wedge (\neg x \vee \neg y \vee \neg z)$?
  - Linear constraints: Is there a solution {x, y, z} satisfying $3x+2y >= 5z \wedge 5z = 2x$?
- Very efficient SMT solvers are now available that can handle many such kinds of constraints.
- Annual competition: http://www.smtcomp.org/

Optimizing SMT Queries

- Expression rewriting
  - Simple arithmetic simplifications (x * 0 --> 0)
  - Linear simplification (2 * x - x --> x)
- Constraint set simplification
  - $x < 10 \wedge x = 5$ --> $x = 5$
- Implied value concretization
  - $x + 1 = 10$ --> $x = 9$
- Constraint independence
  - $c > a \wedge b <= 5 \wedge a >= d + 10$ --> $c > a \wedge a >= d + 10, b <= 5$

Search Strategy – Breadth First Search

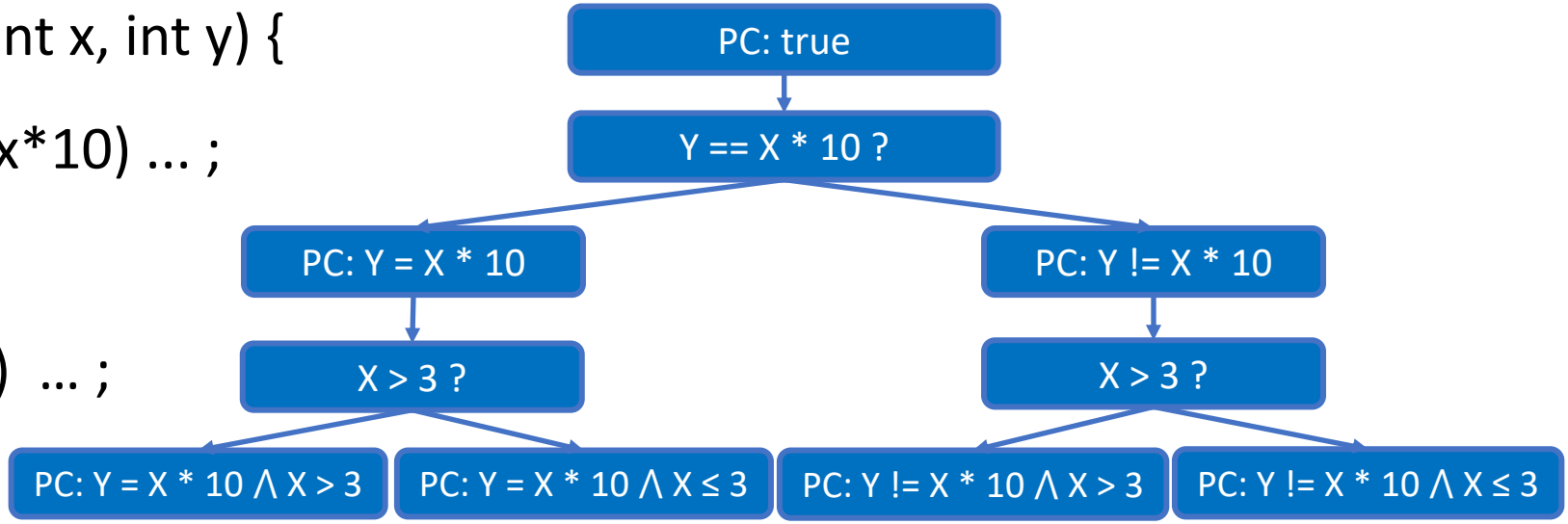
```
void test(int x, int y) {
    if (y == x*10) ... ;
    else ... ;
    if (x > 3)  ... ;
    else ... ;
}
```



Breadth first search is very slow to determine properties for a path if there are many branches

Search Strategy – Depth First Search

```
void test(int x, int y) {
    if (y == x*10) ... ;
    else ... ;
    if (x > 3)  ... ;
    else ... ;
}
```



Depth first search can stuck at somewhere in a loop

More Search Strategies

- Random Search
  - Pick next path to explore uniformly at random
  - Hard to reproduce, probably good to use pseudo-randomness based on seed
- Coverage Guided Search
  - Select paths likely to hit the new statements
  - Favor paths on recently covering new statements
  - Errors are often in hard-to-reach parts of the program, this strategy tries to reach everywhere
- Generational Search
  - Generation 0: pick one path at random, run to completion
  - Generation 1: take the path from generation 0, negate one branch condition on the path to yield a new path prefix, find a solution for that path prefix, and then take the resulting path
  - …

Applications of Symbolic Execution

- Generating test inputs
- Detecting infeasible paths
- Finding bugs and vulnerabilities
  - E.g., divide by zero bugs
- Proving two code segments are equivalent
- Generating program invariants
- Debugging
- Repairing programs
- …

Challenges – Path Explosion

- Exponential in branch structures

```
1. int a = input(), b = input();
2. Int c = input(), d = input();
2. if (a) {…} else {…}
3. if (b) {…} else {…}
4. if (c) {…} else {…}
4. if (d) {…} else {…}
```

4 variables and $2^4 = 16$ program paths!

- Even worse, loops on symbolic variables

```
1. int x = input();
2. while (x > 0) {
3.       x++;
4.       assert(…);
5. }
```

Potentially 2^{31} paths through the loop!

Challenges – Constraint Solving

- The state-of-the-art: support theories on linear integer arithmetic, bit vectors, string, etc., but have limited support for complex constraints and are not particularly scalable
  - Non-linear constraints, e.g., sin(), cos()
  - Float-point constraints, e.g., 2.5 * x – 2.9 * y > 1.1
  - …

```
1. int x = input(), y = input(), z = input();
2. if (5x^63 + 7x^12 = 78y^2 + z) {
3.       assert(false);
4. }
```

Challenges – Complex Code and Environment Dependencies

- Complex code
  - Data structures and pointers
- Environment dependencies
  - Native calls
  - System calls
  - Library calls
  - File operations
  - Network events
  - …

Potential Solutions

- Path explosion
  - Heuristic-based search strategies
  - Limit the exploration depth (but lead to incompleteness)
  - …
- Constraint solving
  - Meta-heuristic-based solvers (but lead to imprecise)
  - …
- Complex code and environment dependencies
  - Build simple versions of library calls
  - Simulate system calls
  - Concretization
  - …

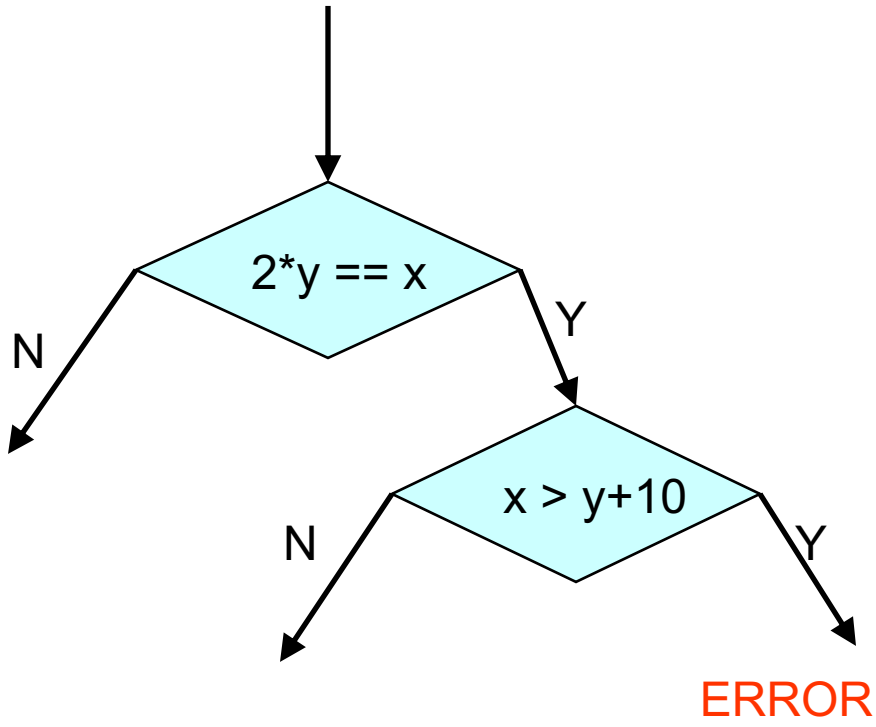
Concolic Execution

Concolic (Concrete + Symbolic) Execution

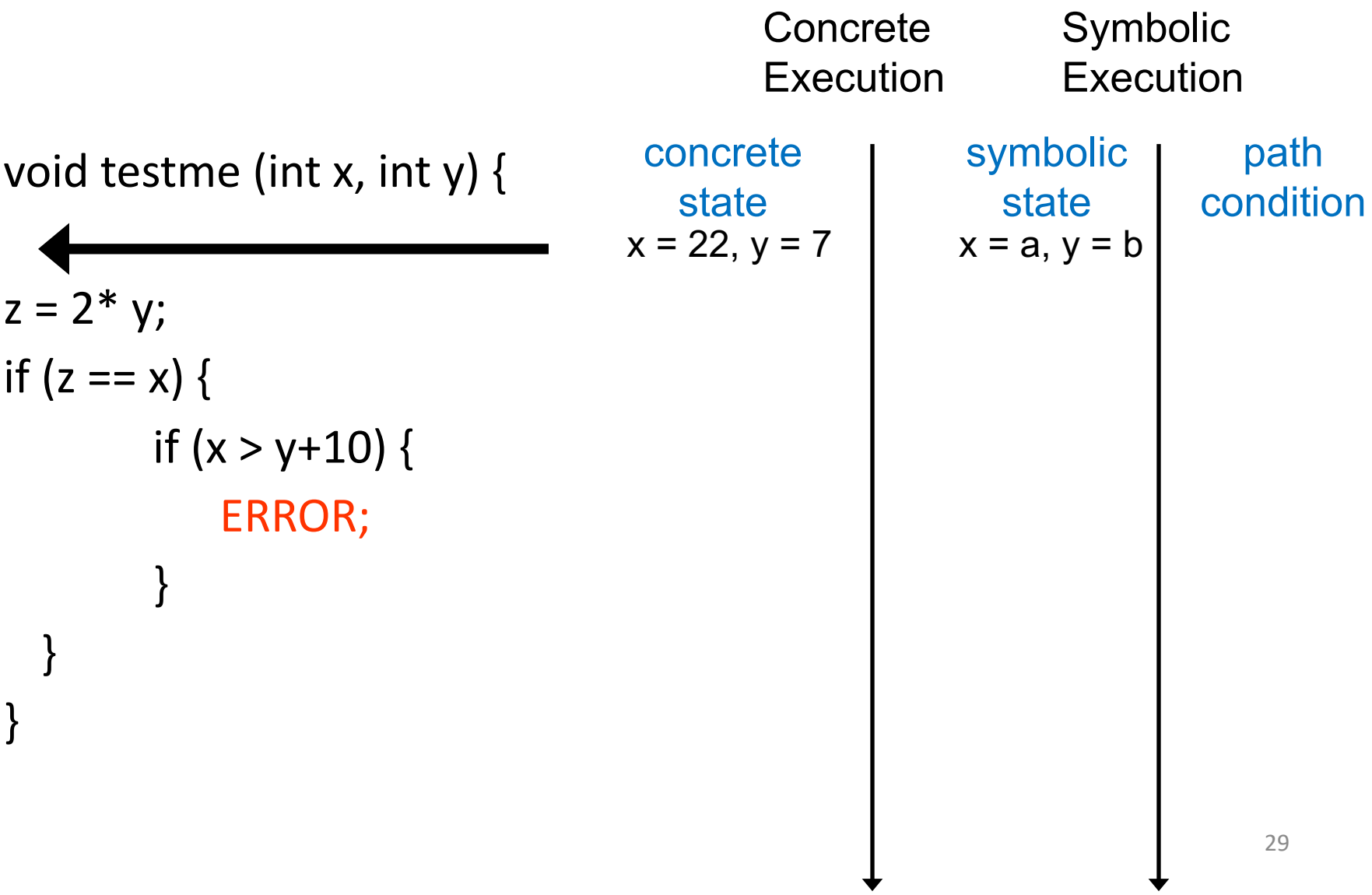
- Execute program with both concrete and symbolic inputs (also known as dynamic symbolic execution)
- The intention is to visit deep into the program execution tree
- Steps
  - Generate a random test input
  - Execute the program with the random test input and the symbolic input to collect the path constraint
  - Negate the last conjunct to obtain a constraint
  - Solve it to get test input to another path and execute the input

Example

```
void testme (int x, int y)
{
      z = 2*y;
      if (z == x) {
            if (x > y+10) {
                  ERROR;
            }
      }
}
```



Example of Concolic Execution



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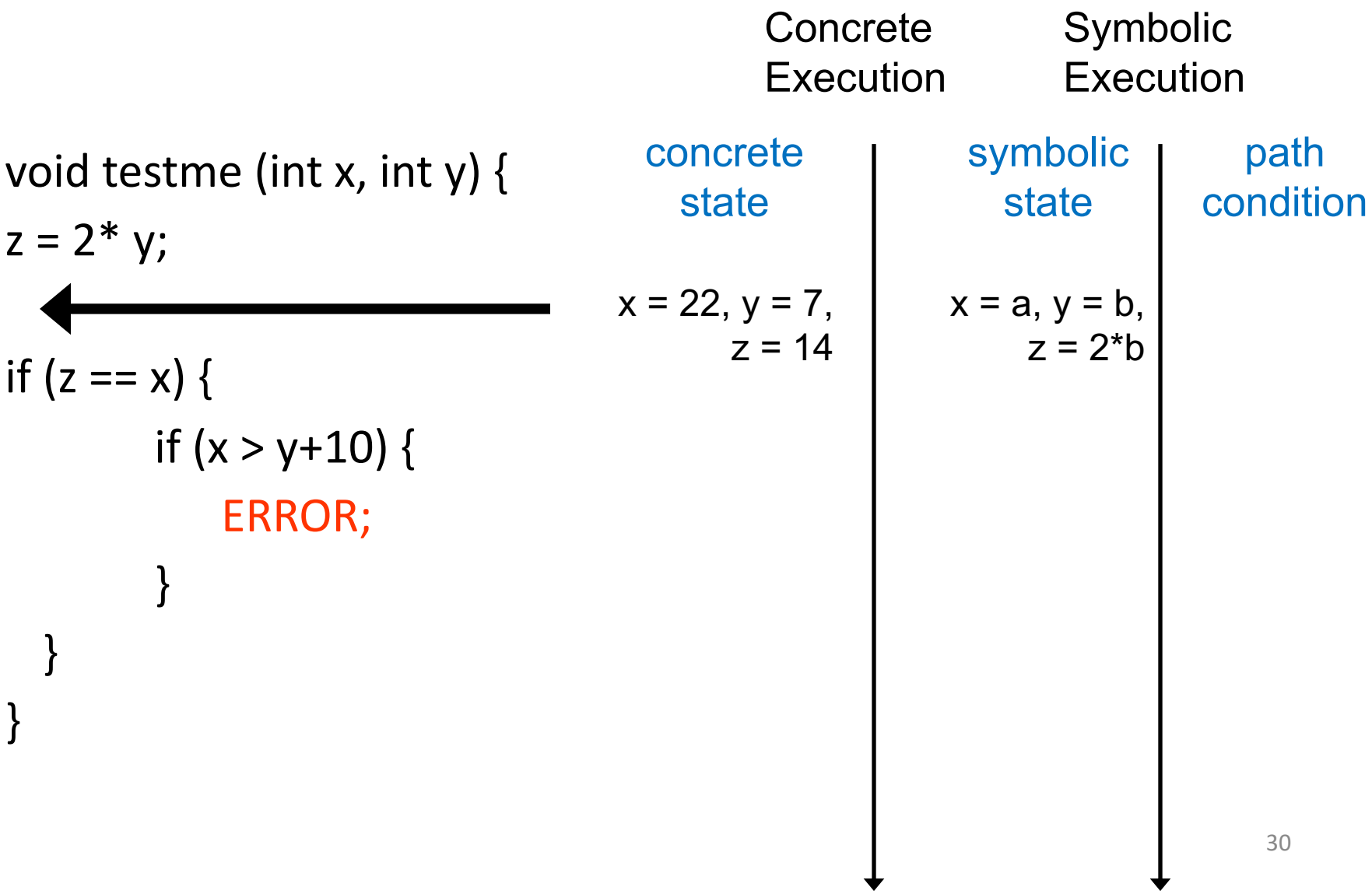

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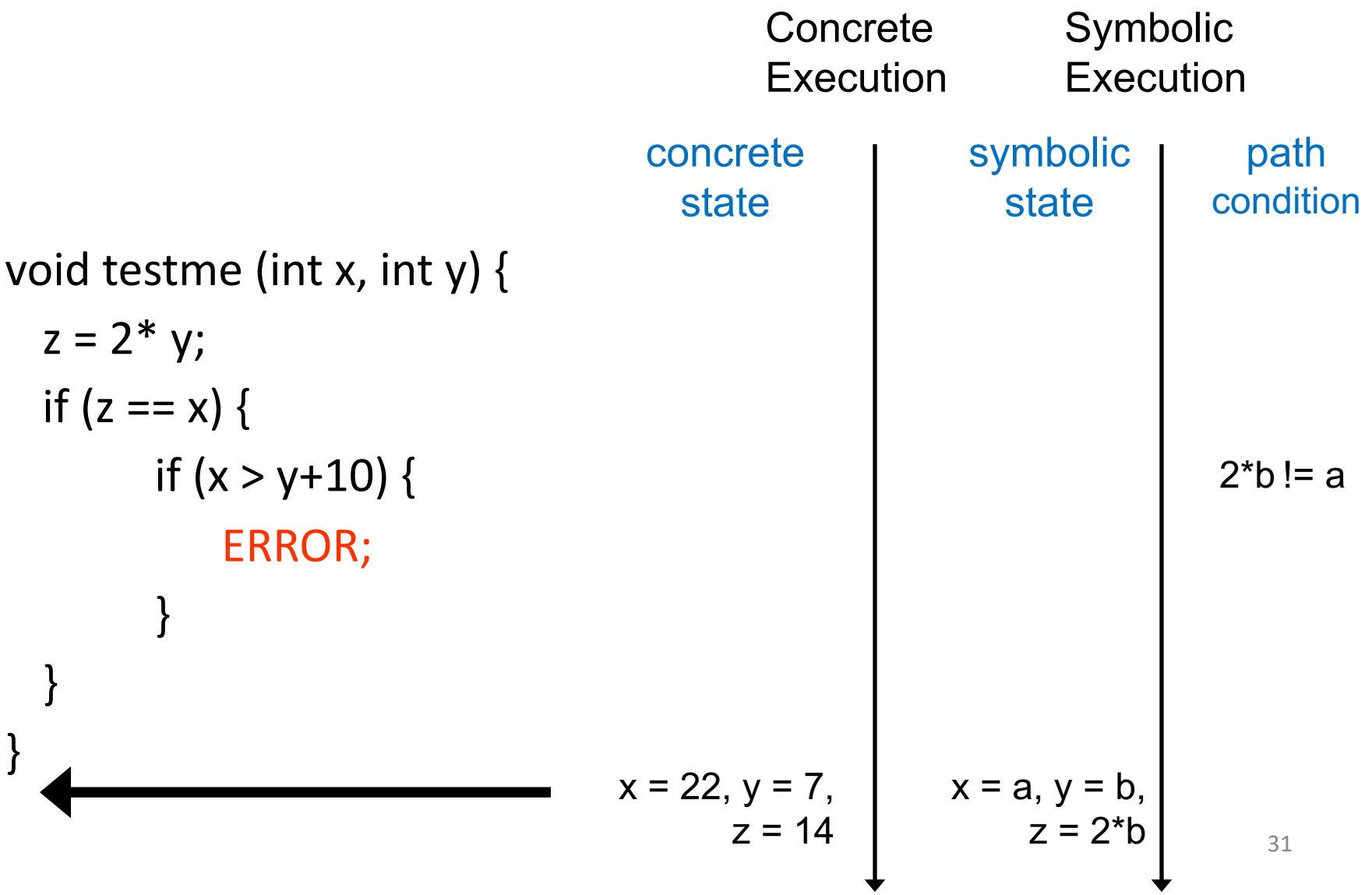
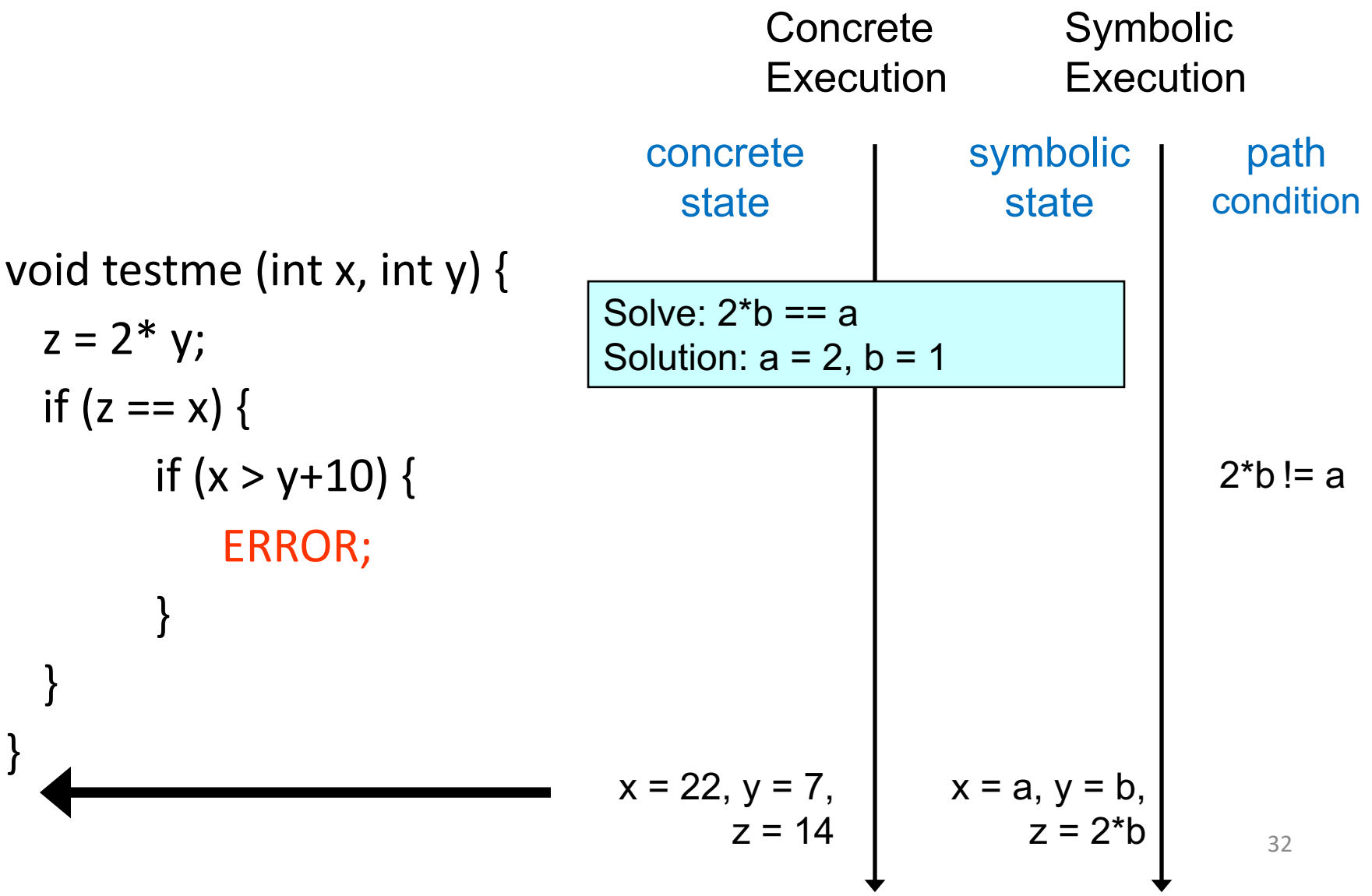
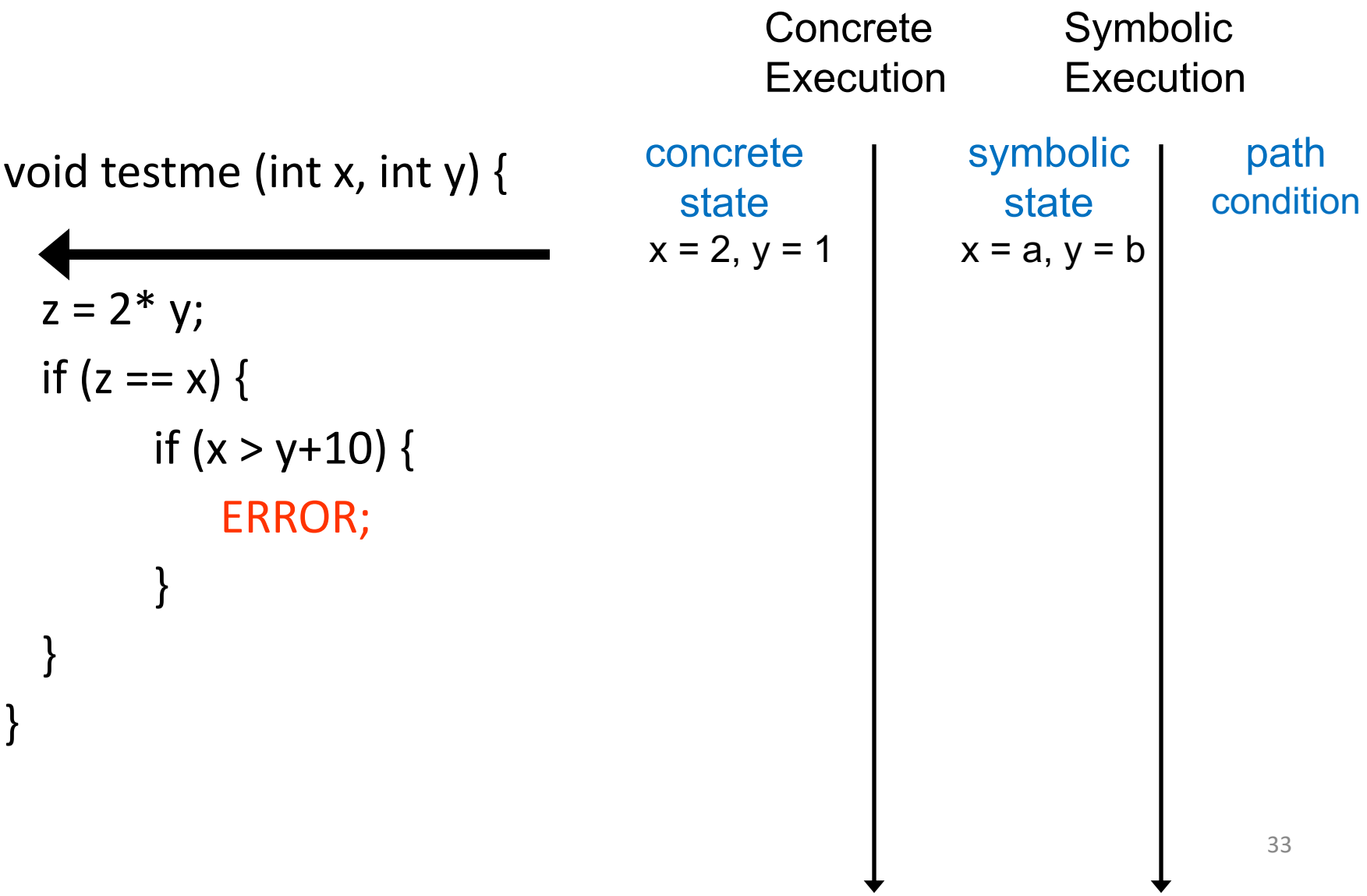


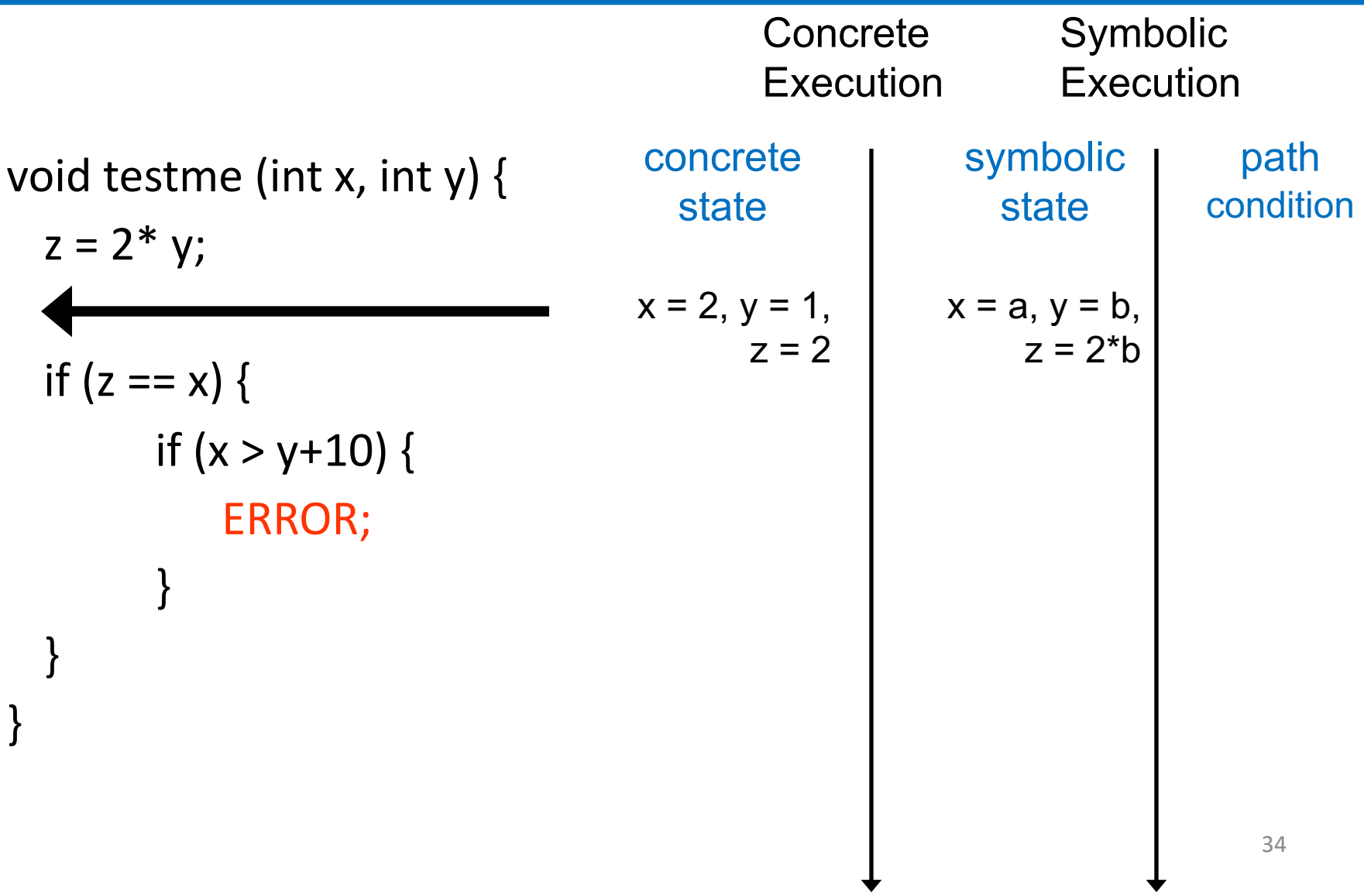
Example of Concolic Execution



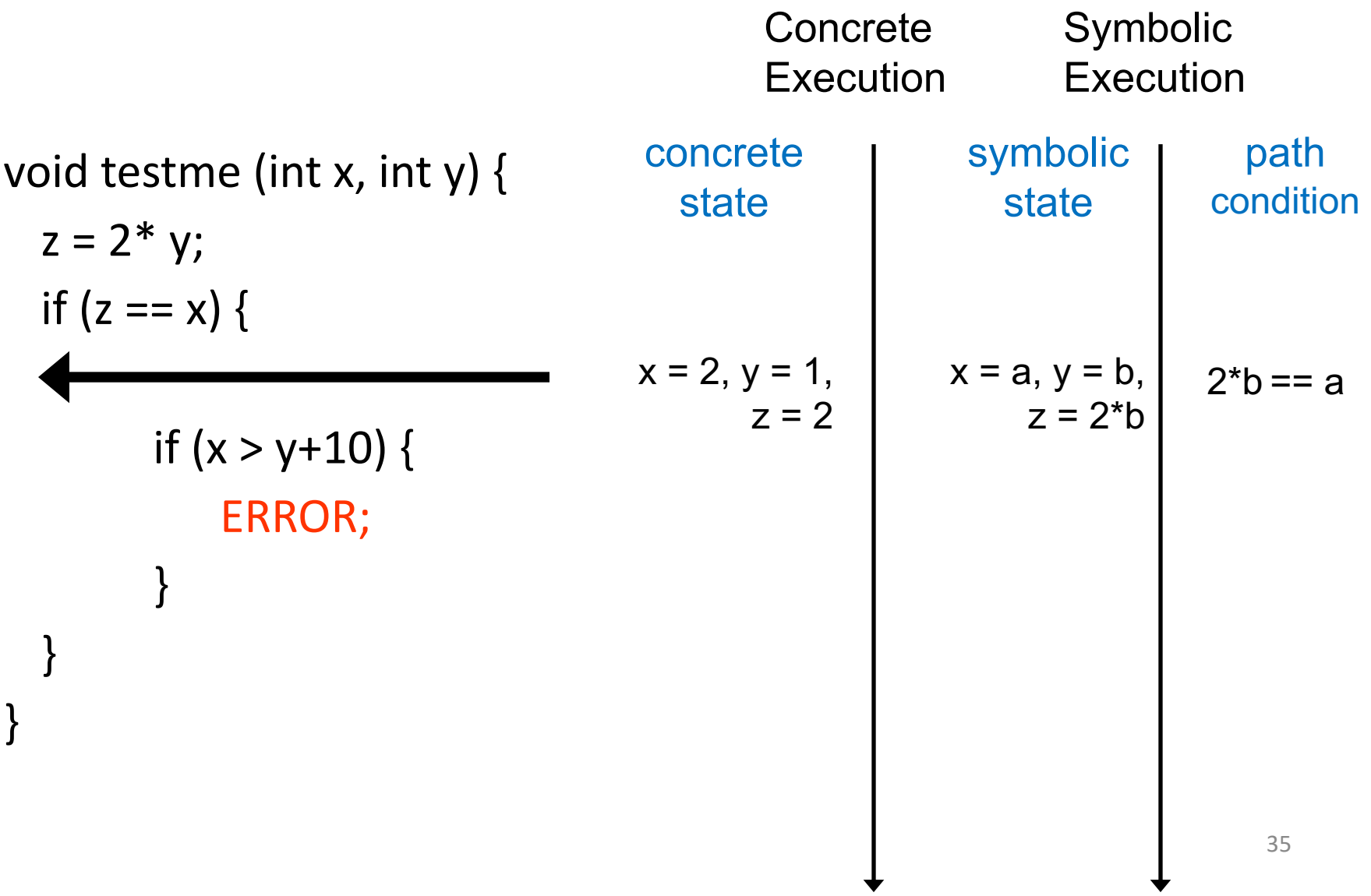
Example of Concolic Execution



Example of Concolic Execution



Example of Concolic Execution



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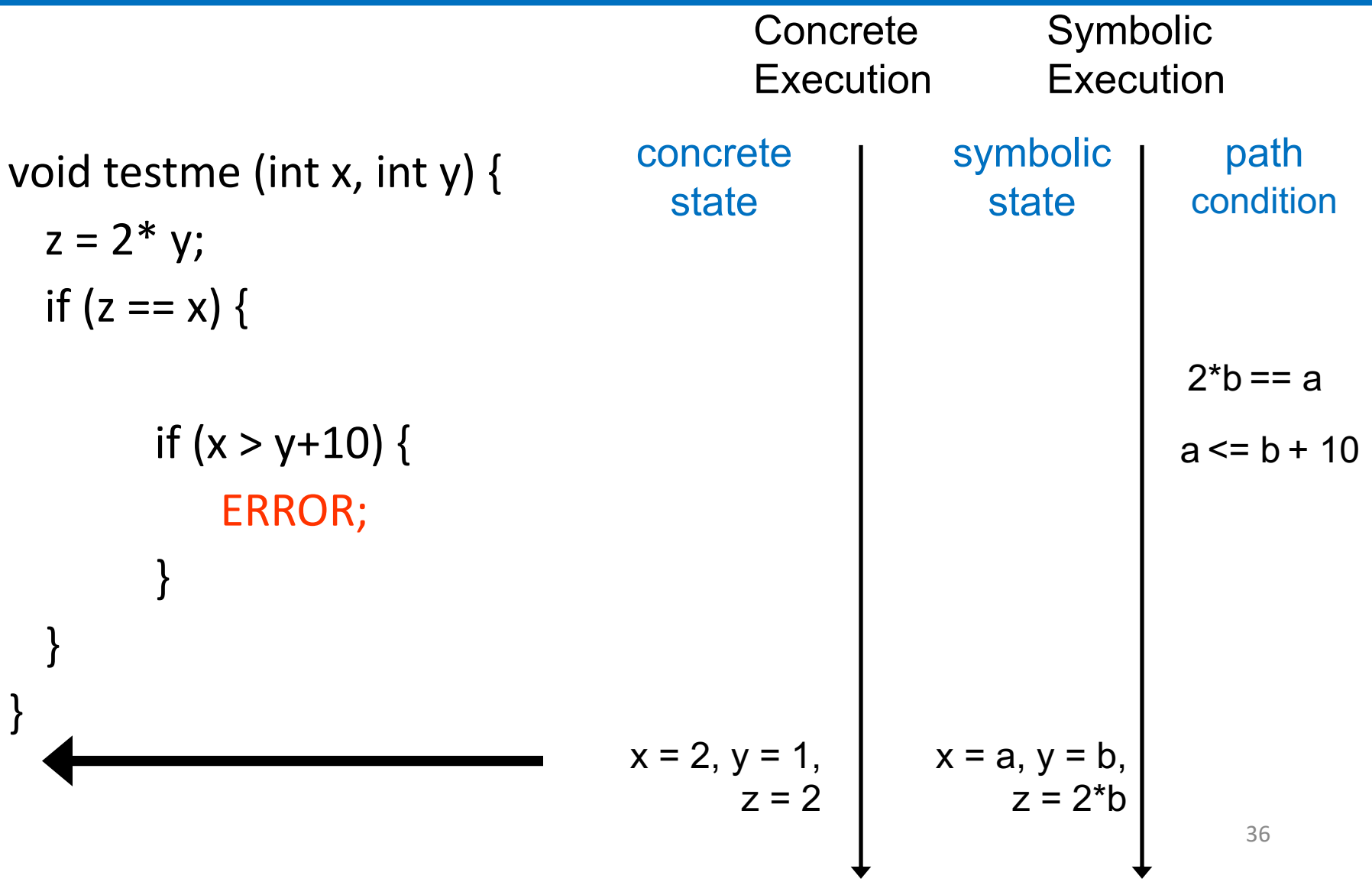
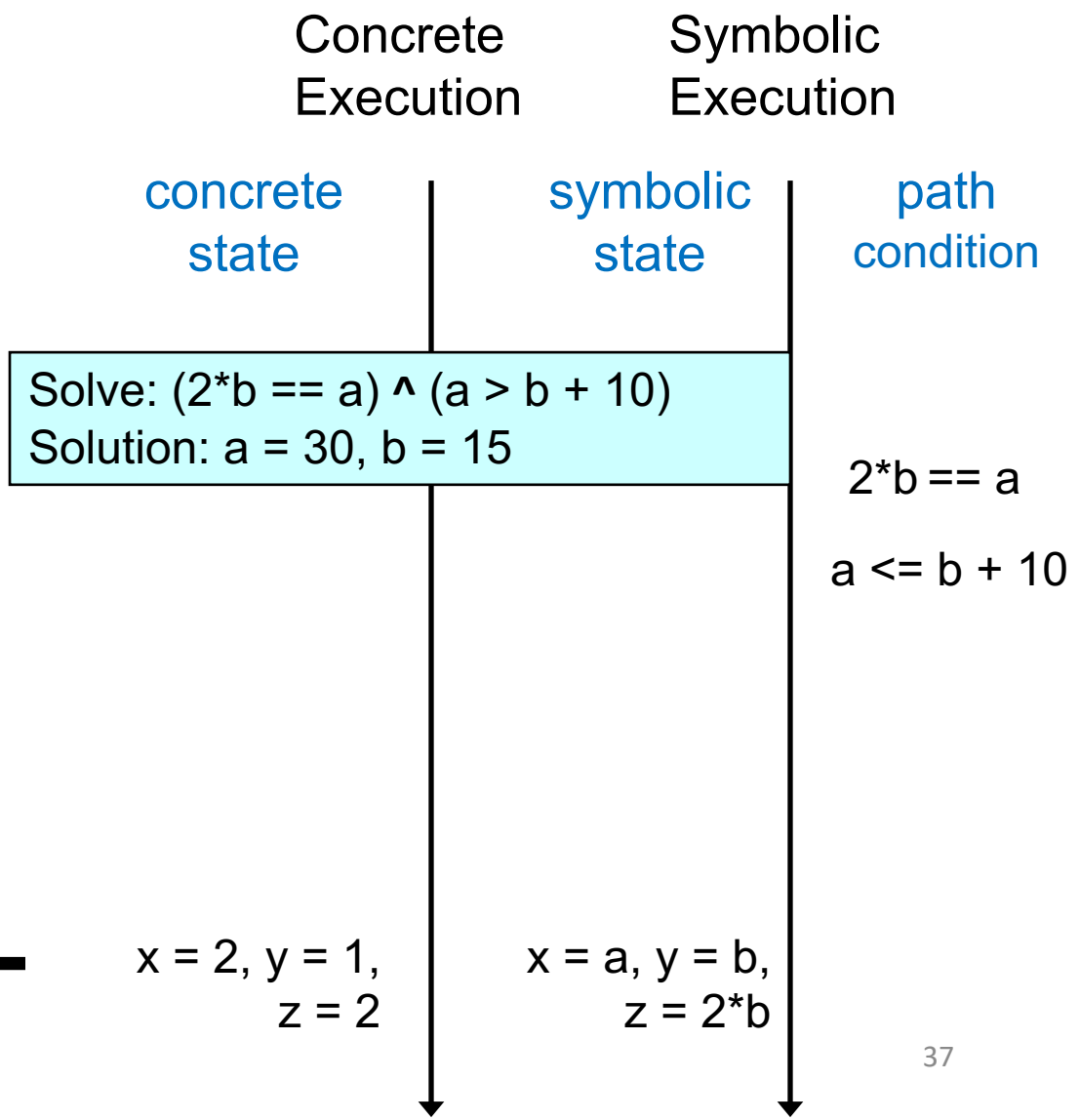


Example of Concolic Execution

```
void testme (int x, int y) {
   z = 2* y;
   if (z == x) {

         if (x > y+10) {
            ERROR;
         }
   }
}
```



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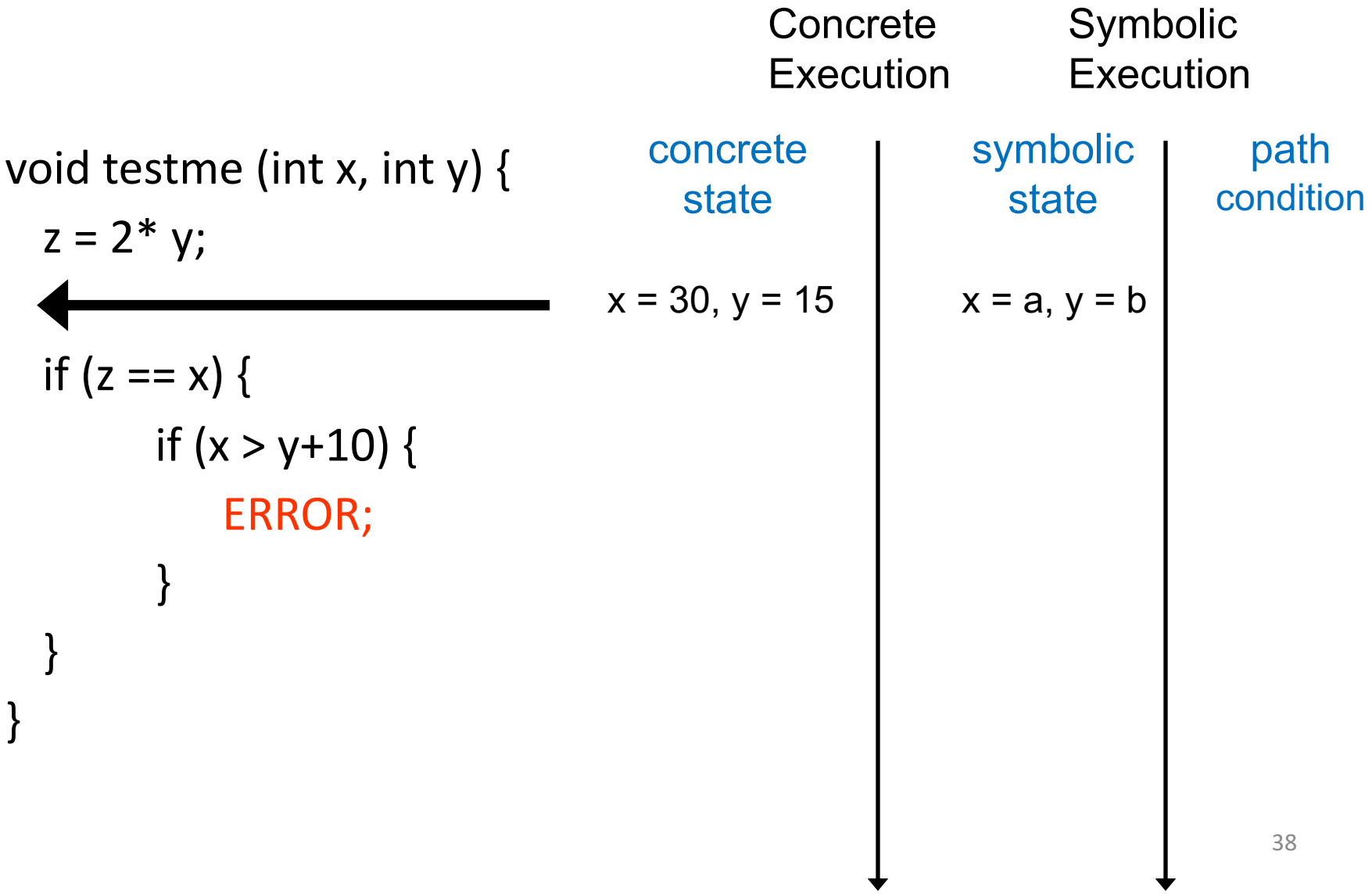
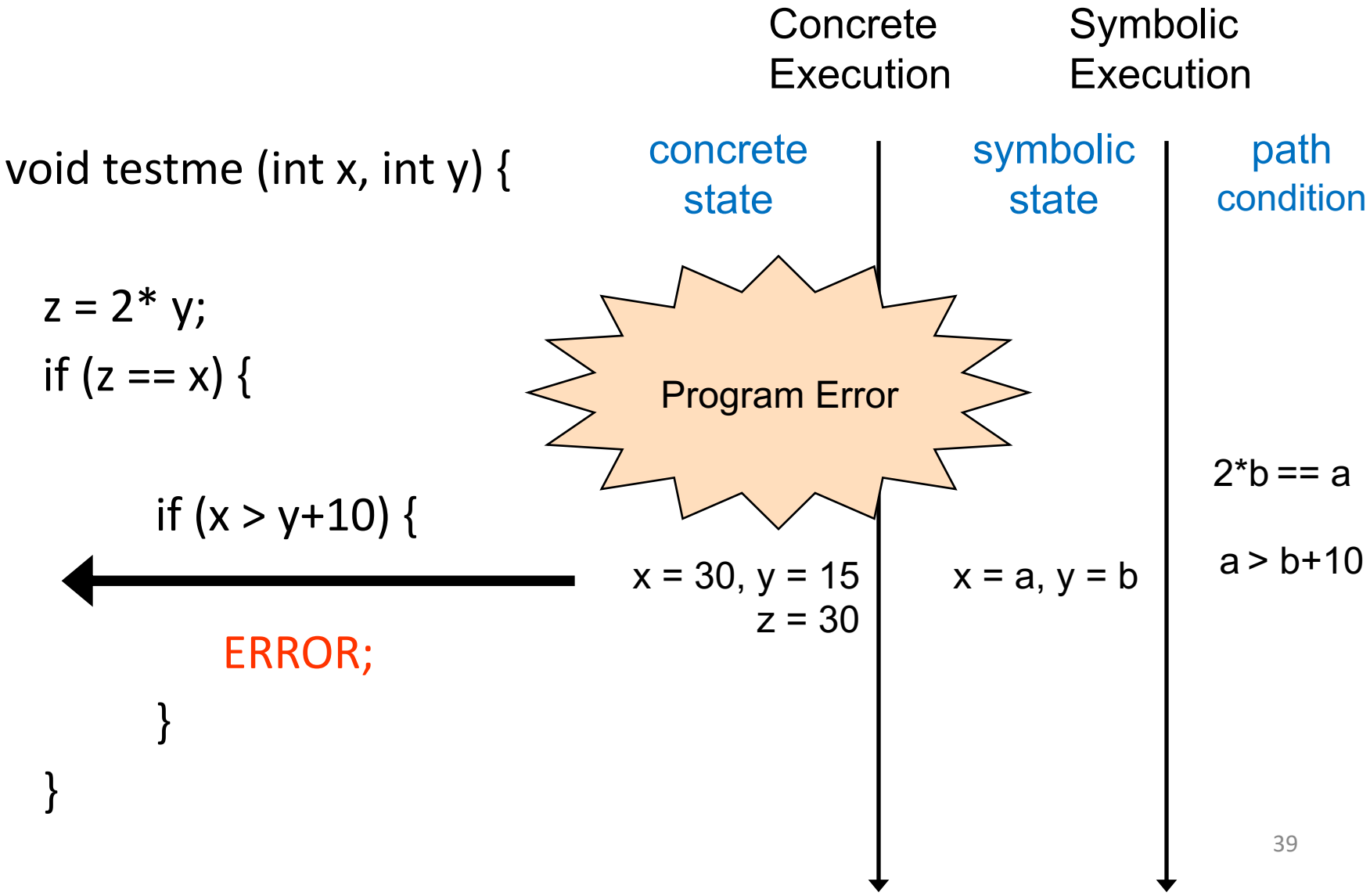
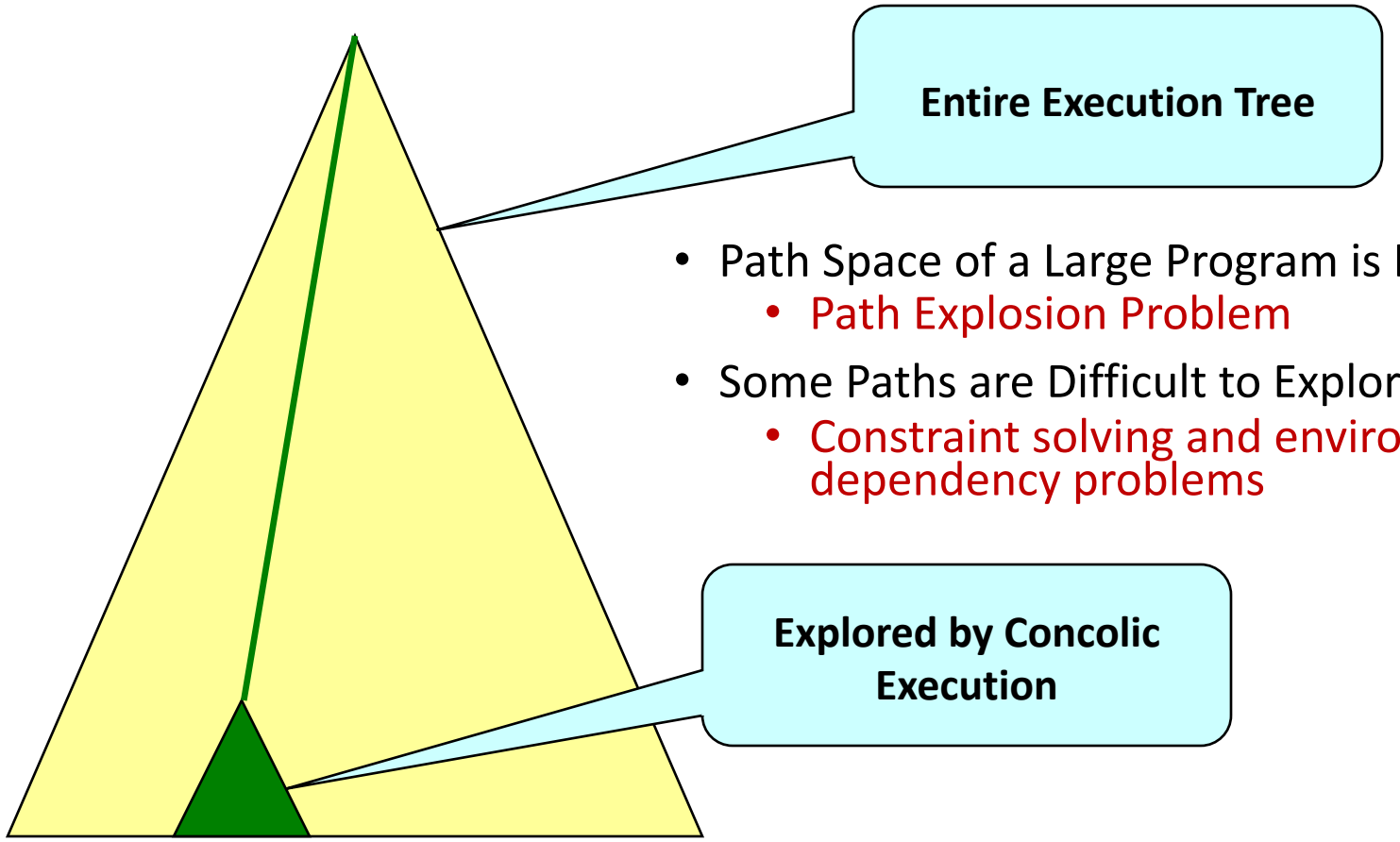


Example of Concolic Execution



Bird's View



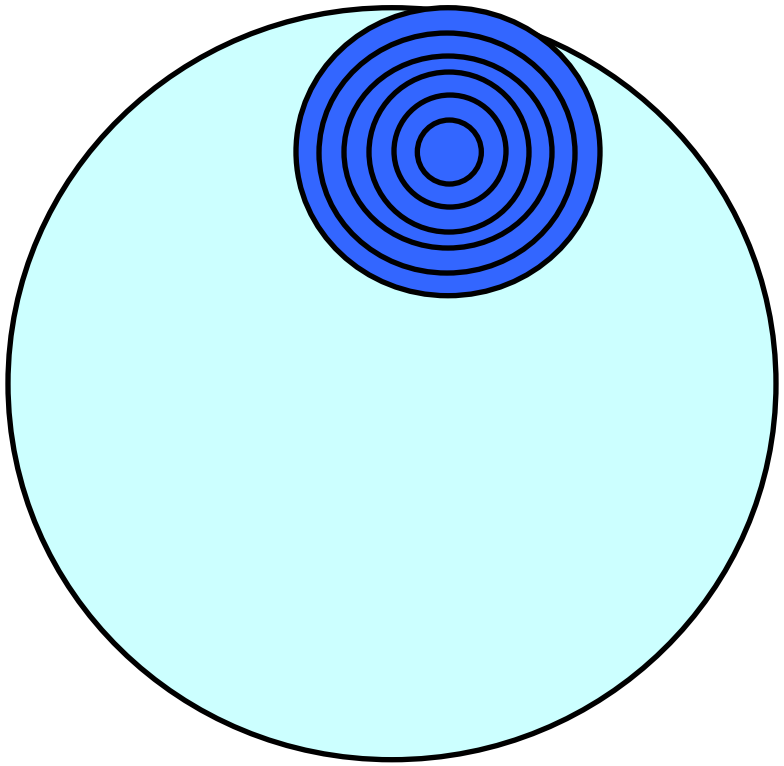
- Path Space of a Large Program is Huge
  - Path Explosion Problem
- Some Paths are Difficult to Explore
  - Constraint solving and environment dependency problems

An Example

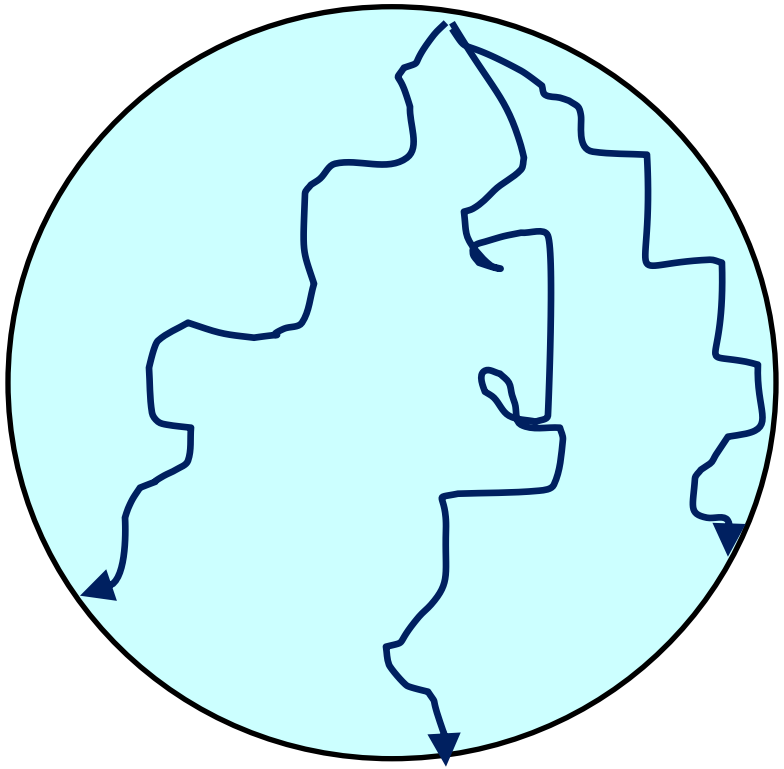
```
1.  foobar(int x, int y){
2.    if (x*x*x > 0){
3.      if (x>0 && y==10){
4.        abort();
5.      }
6.    } else {
7.      if (x>0 && y==20){
8.        abort();
9.      }
10.   }
11. }
```

- Random testing gets stuck at line 3
- Symbolic execution gets stuck at line 2
- Concolic execution finds the only error at line 4
  - Use concrete value for x

Concolic Execution vs. Random Testing



Concolic: Broad, Shallow



Random: Narrow, Deep

An Example

```
Example ( ) {
1: state = 0;
2: while(1) {
3:   s = input();
4:   c = input();
5:   if(c==':' && state==0)
       state=1;
6:   else if(c=='\n' && state==1)
       state=2;
7:   else if (s[0]=='I' &&
       s[1]=='C' &&
       s[2]=='S' &&
       s[3]=='E' &&
       state==2) {
         COVER_ME;
    }
  }
}
```

COVER_ME can be hit on an input

- s = "ICSE"
- c = ':' '\n'

Similar code in

- Text editors (vi)
- Parsers (lexer)
- Event-driven programs (GUI)

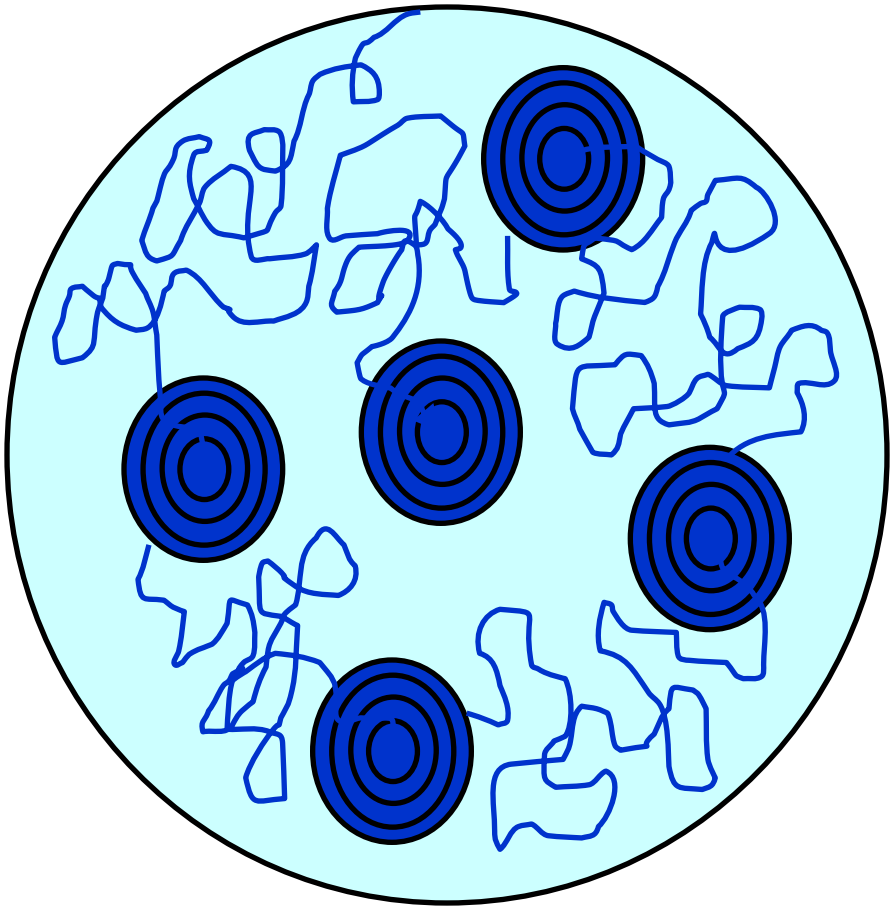
An Example

```
Example ( ) {
1: state = 0;
2: while(1) {
3:   s = input();
4:   c = input();
5:   if(c==':' && state==0)
       state=1;
6:   else if(c=='\n' && state==1)
       state=2;
7:   else if (s[0]=='I' &&
       s[1]=='C' &&
       s[2]=='S' &&
       s[3]=='E' &&
       state==2) {
         COVER_ME;
    }
  }
}
```

- **Pure random testing** can get to state = 2, but difficult to get 'ICSE'
- Probability $1/(2^8)^6 = 3*10^{-15}$

- **Concolic testing** can generate 'ICSE' but explores many paths to get to state = 2

Hybrid Concolic Testing



```
while (not required coverage) {
    while (not saturation)
        perform random testing;
    Checkpoint;
    while (not increase in coverage)
        perform concolic testing;
    Restore;
}
```

Interleave random testing and concolic testing to increase coverage

Deep and broad search

Hybrid Concolic Testing

```
Example ( ) {
1: state = 0;
2: while(1) {
3:   s = input();
4:   c = input();
5:   if(c==':' && state==0)
       state=1;
6:   else if(c=='\n' && state==1)
       state=2;
7:   else if (s[0]=='I' &&
       s[1]=='C' &&
       s[2]=='S' &&
       s[3]=='E' &&
       state==2) {
         COVER_ME;
    }
  }
}
```

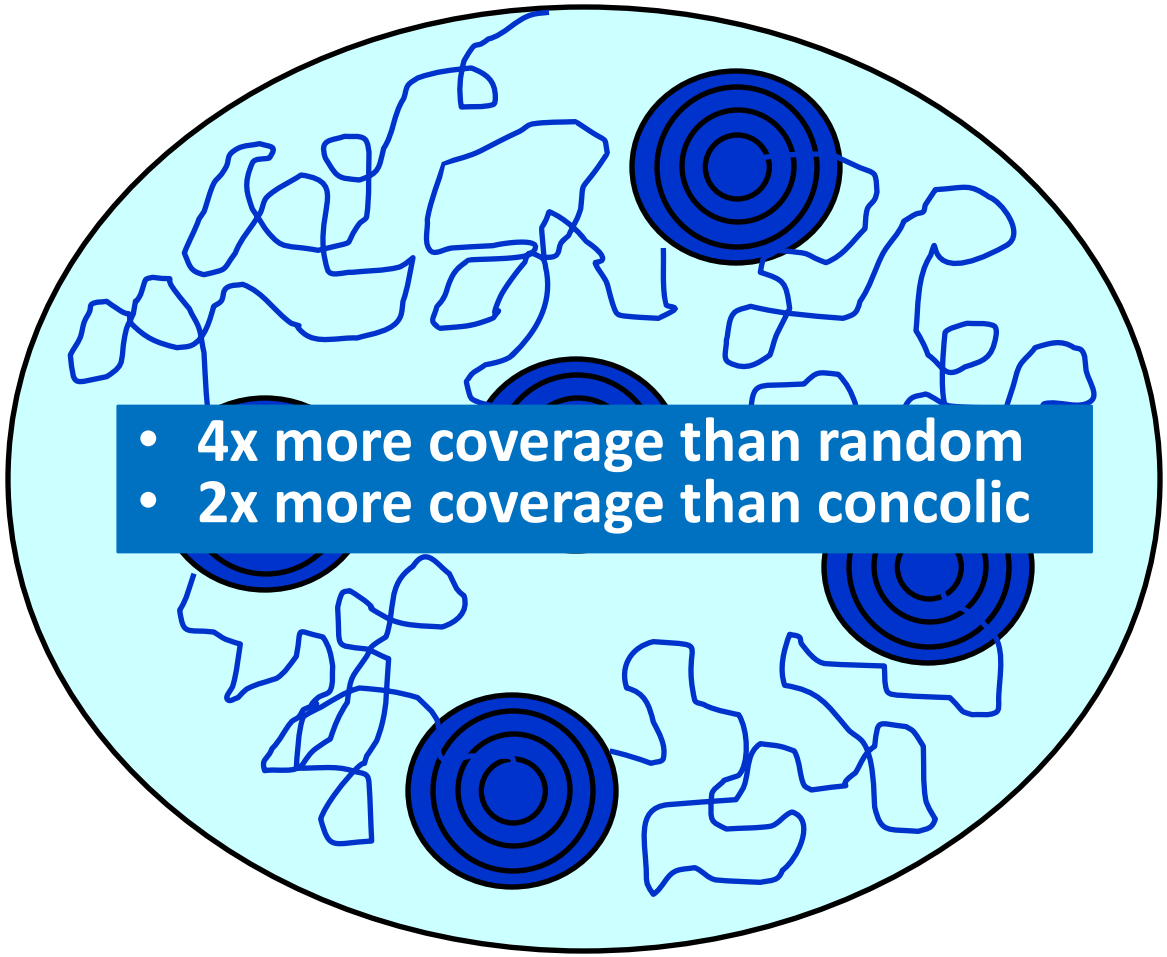
Random Testing Phase

- '$', '&', '-', '6', ':', '%', '^', '\n', 'x', '~' …
- Saturate after many (~10000) iterations
- In less than 1 second
- **COVER_ME** is not reached

Concolic Testing Phase

- s[0]='I', s[1]='C', s[2]='S', s[3]='E'
- Reach **COVER_ME**

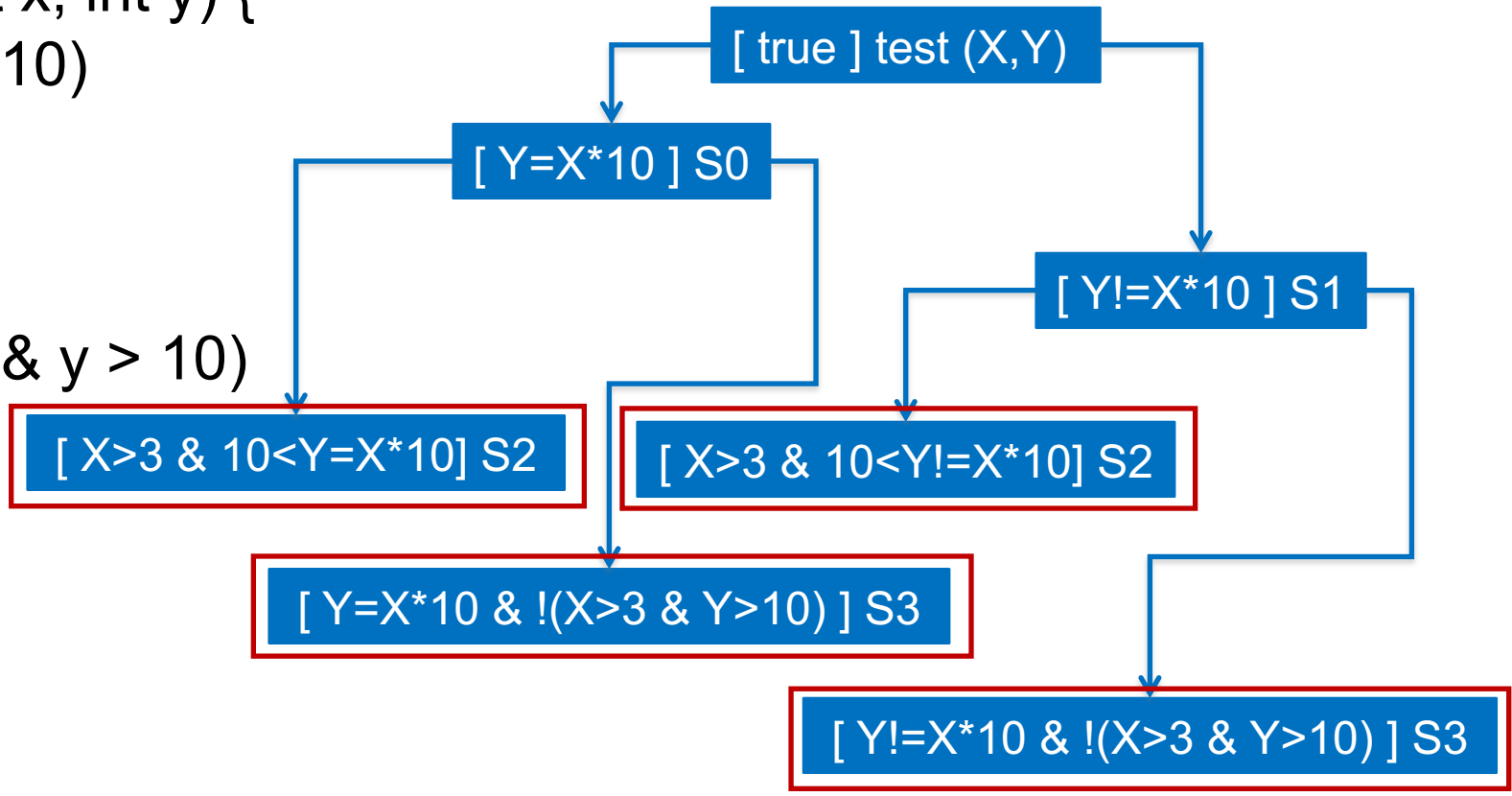
Hybrid Concolic Testing



Probabilistic Symbolic Execution

Symbolic Execution

```
void test(int x, int y) {
   if (y == x*10)
     S0;
   else
     S1;
   if (x > 3 && y > 10)
     S2;
   else
     S3;
}
```



What is the probability of reaching these state?

Probabilistic Symbolic Execution

>=

$$PC = C_1 \,\&\, C_2 \,\&\, \ldots \,\&\, C_n$$

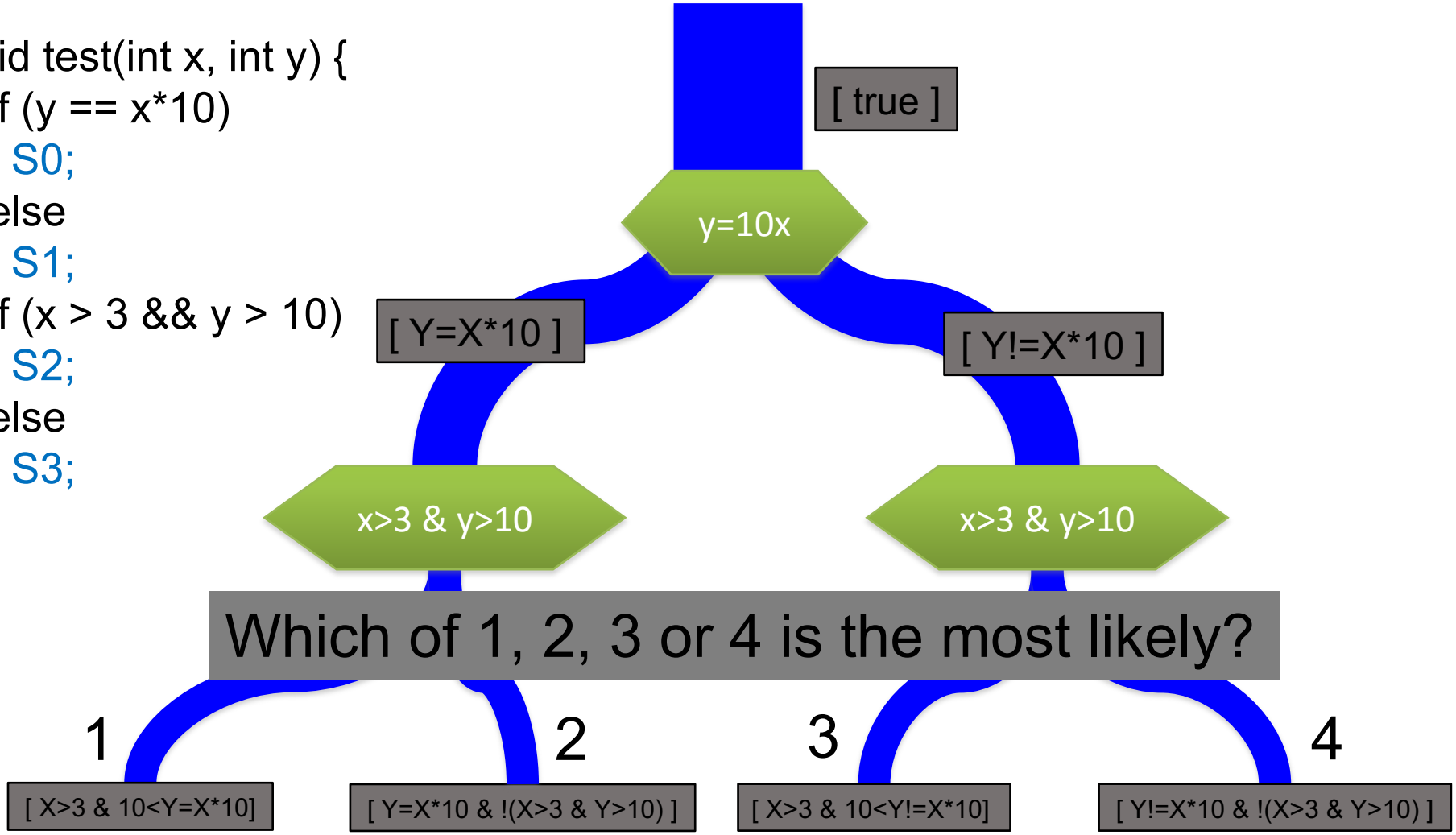
PC solutions

PC feasibility

>0

Paths and Rivers

```
void test(int x, int y) {
   if (y == x*10)
     S0;
   else
     S1;
   if (x > 3 && y > 10)
     S2;
   else
     S3;
}
```



Paths and Rivers

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void test(int x, int y) {
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     S0;
   else
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   if (x > 3 && y > 10)
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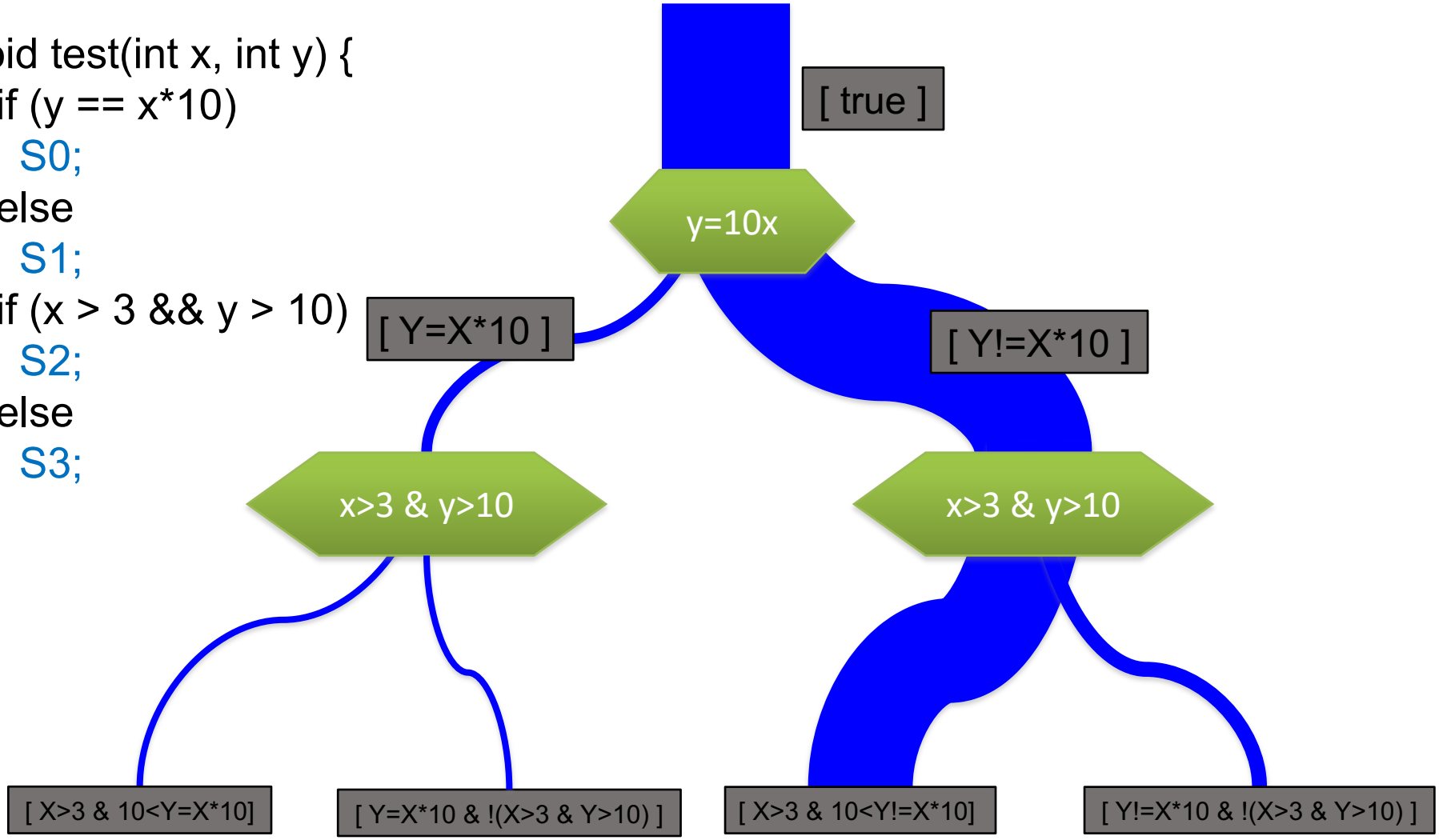
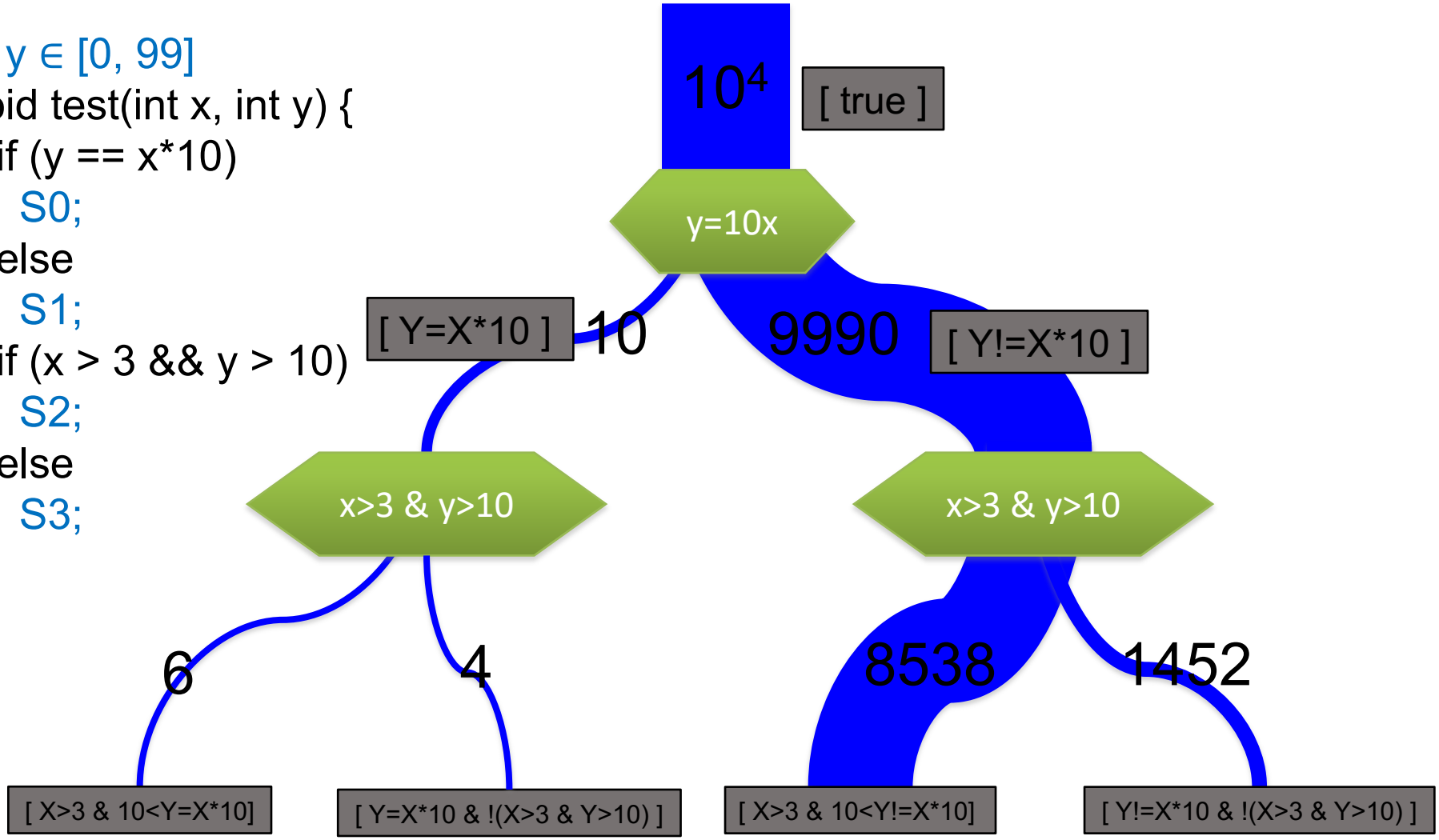


Model Counting (e.g., LattE)

```
x, y ∈ [0, 99]
void test(int x, int y) {
   if (y == x*10)
     S0;
   else
     S1;
   if (x > 3 && y > 10)
     S2;
   else
     S3;
}
```



Probabilities

x, y ∈ [0, 99], uniform distribution

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void test(int x, int y) {
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   else
     S1;
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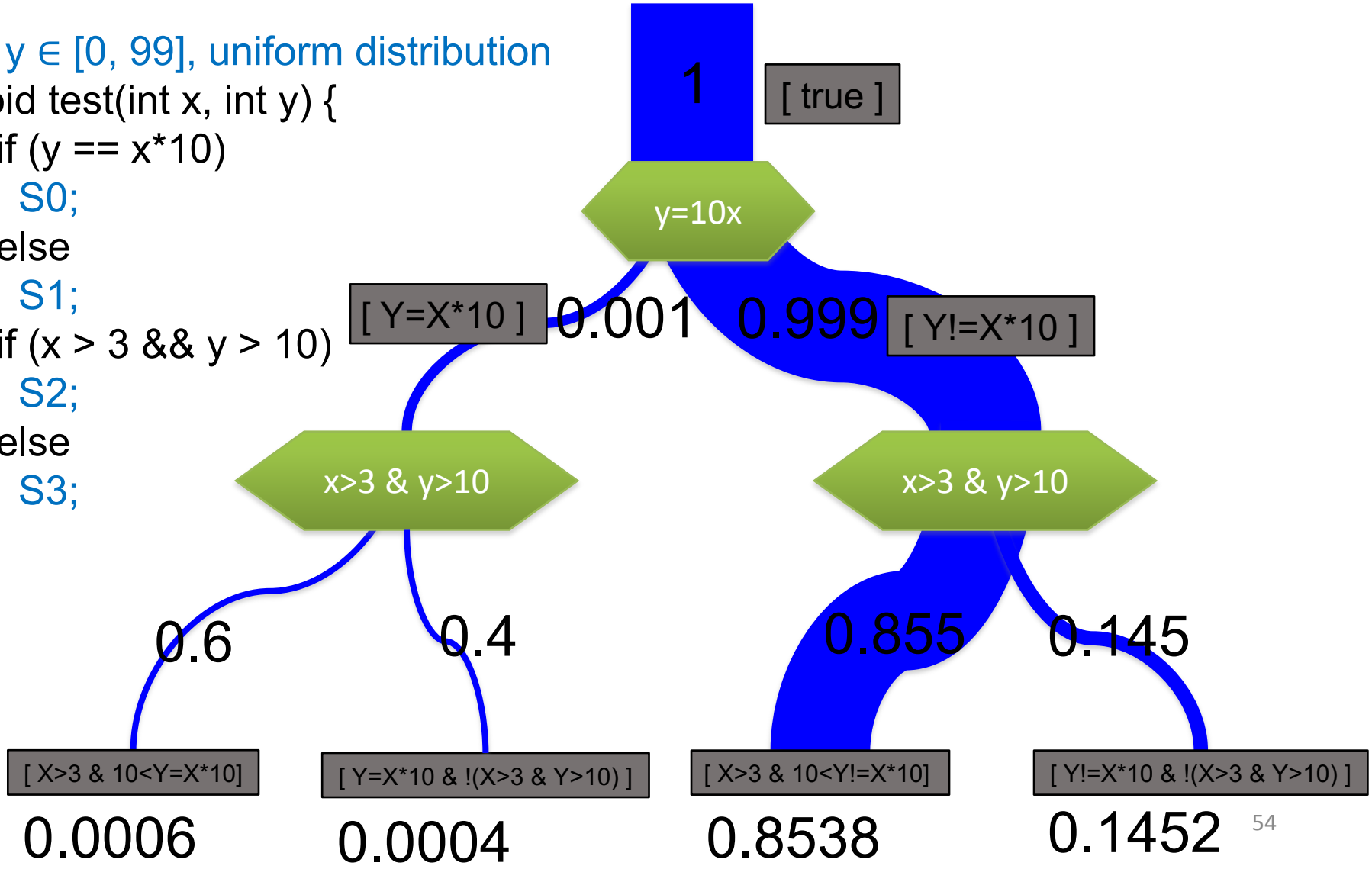
     S2;
   else
     S3;
}
```



Probabilities

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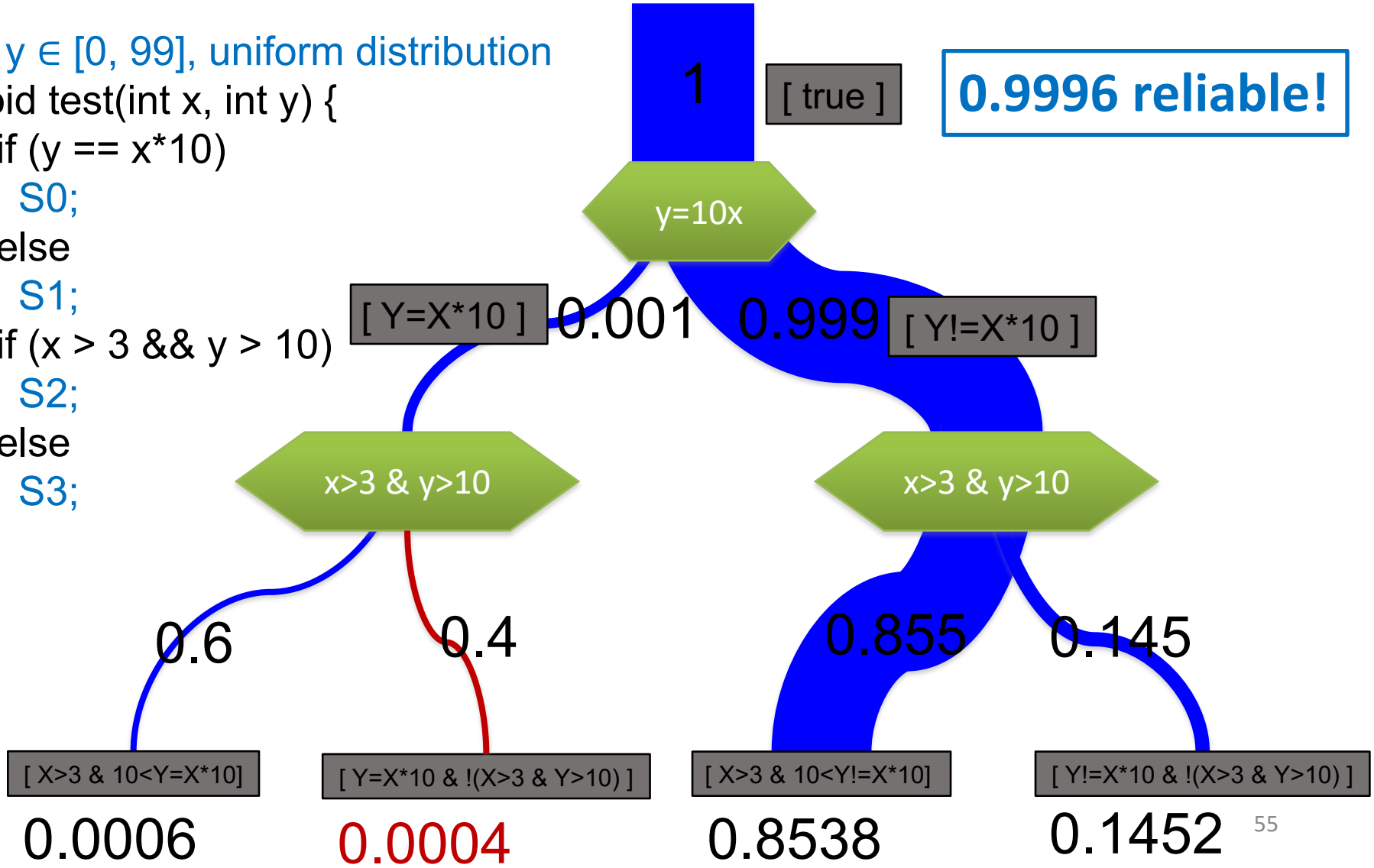
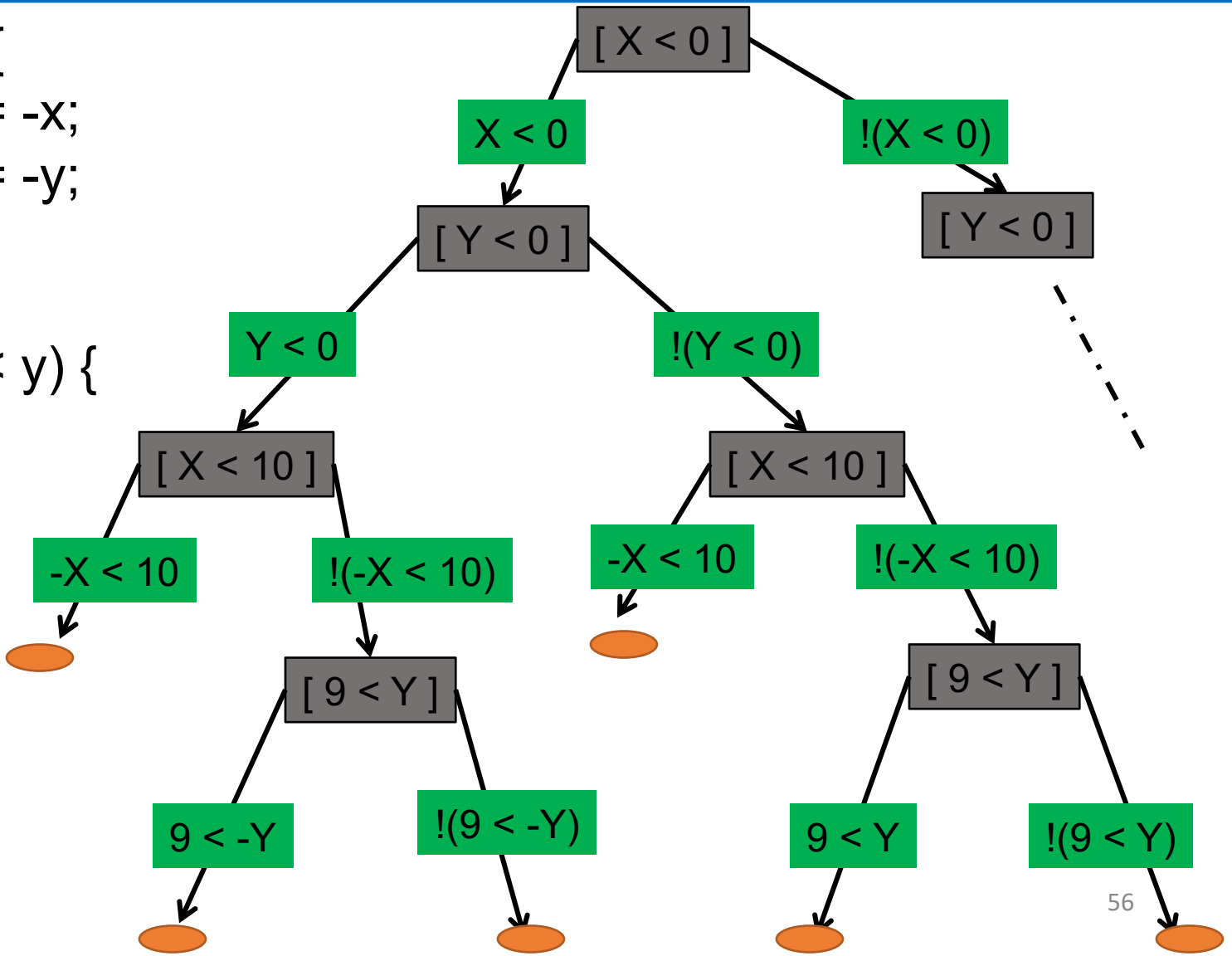
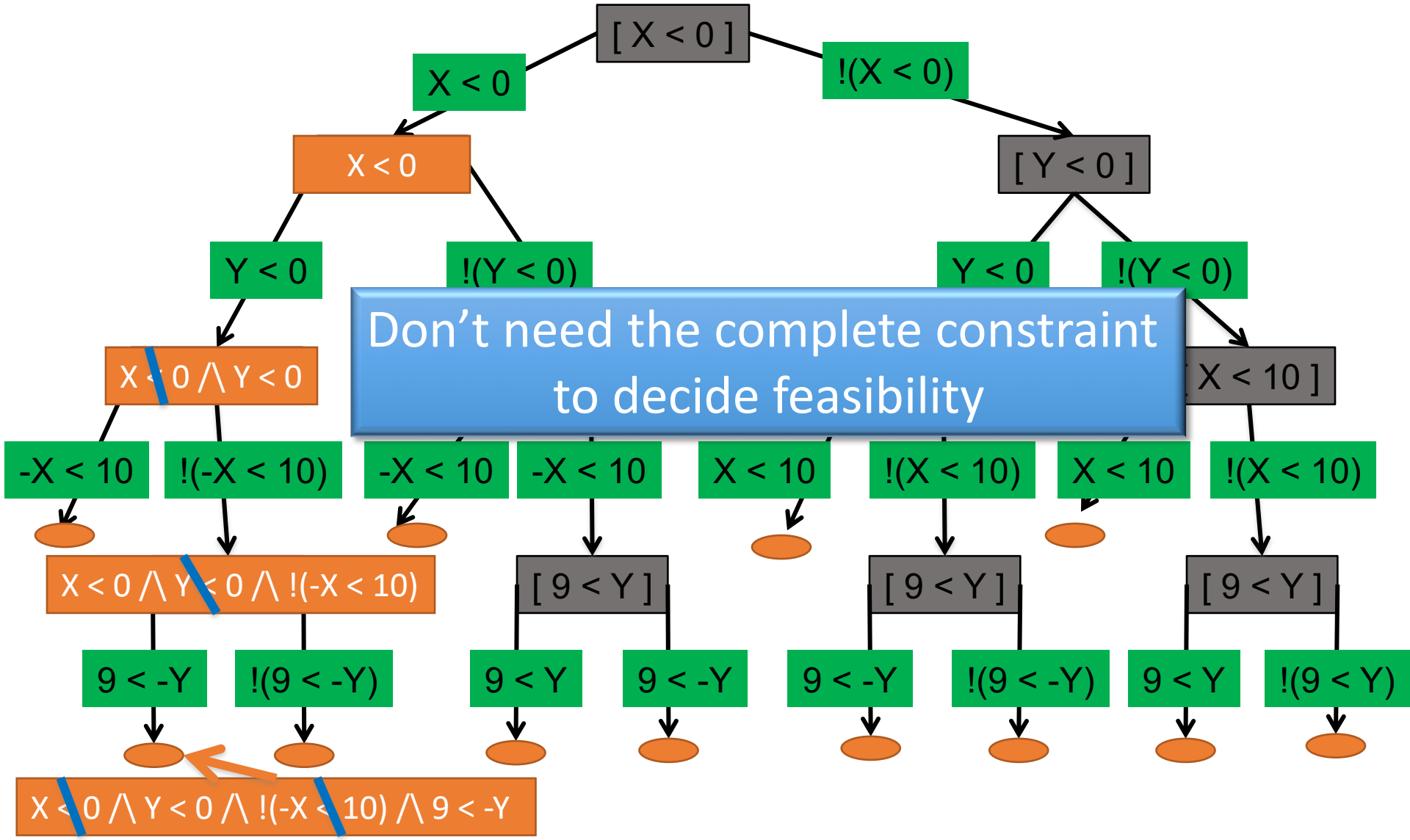


Reduce, Reuse and Recycle Constraints

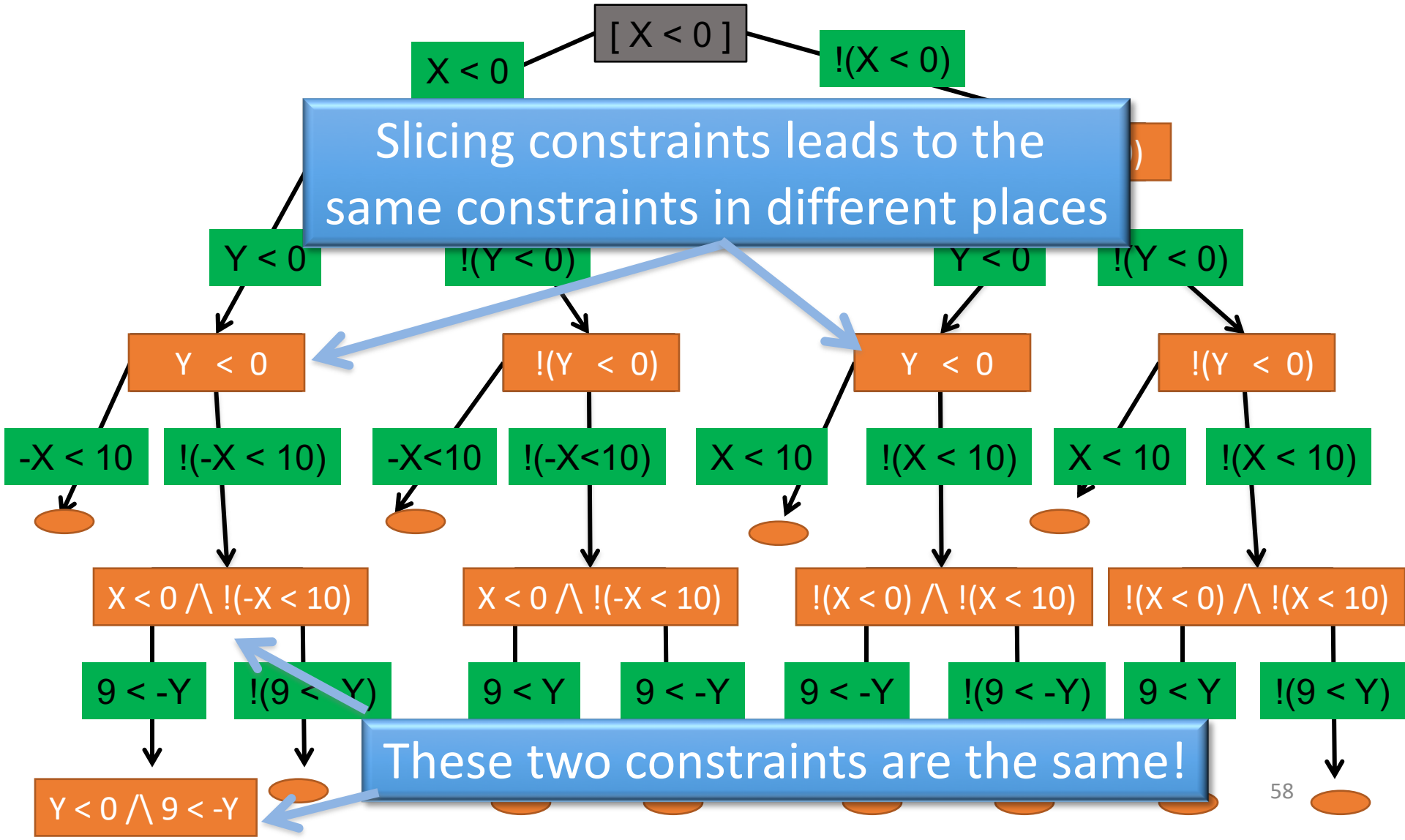
```
int m(int x,y) {
   if (x < 0) x = -x;
   if (y < 0) y = -y;
   if (x < 10) {
      return 1;
   } else if (9 < y) {
      return -1;
   } else {
      return 0;
   }
}
```



Reduce, Reuse and Recycle Constraints



Reduce, Reuse and Recycle Constraints



Canonization of Constraints

$X < 0 \wedge !(-X < 10)$

$X < 0 \wedge -X >= 10$

$X < 0 \wedge X <= -10$

$X + 1 <= 0 \wedge X + 10 <= 0$

$Y < 0 \wedge 9 < -Y$

$Y < 0 \wedge Y < -9$

$Y < 0 \wedge Y + 9 < 0$

$Y + 1 <= 0 \wedge Y + 10 <= 0$

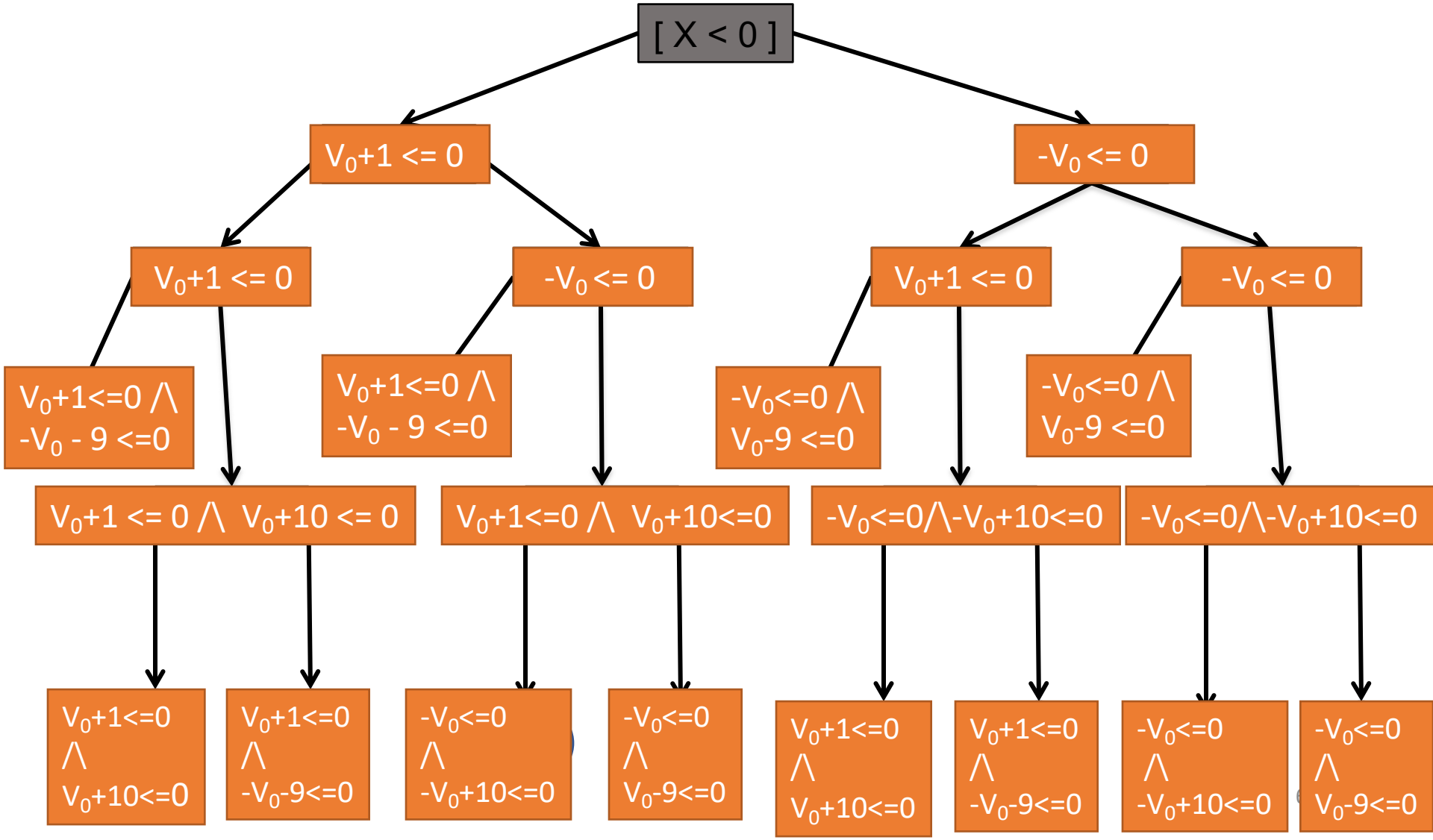
$V_0 + 1 <= 0 \wedge V_0 + 10 <= 0$

Canonical Form

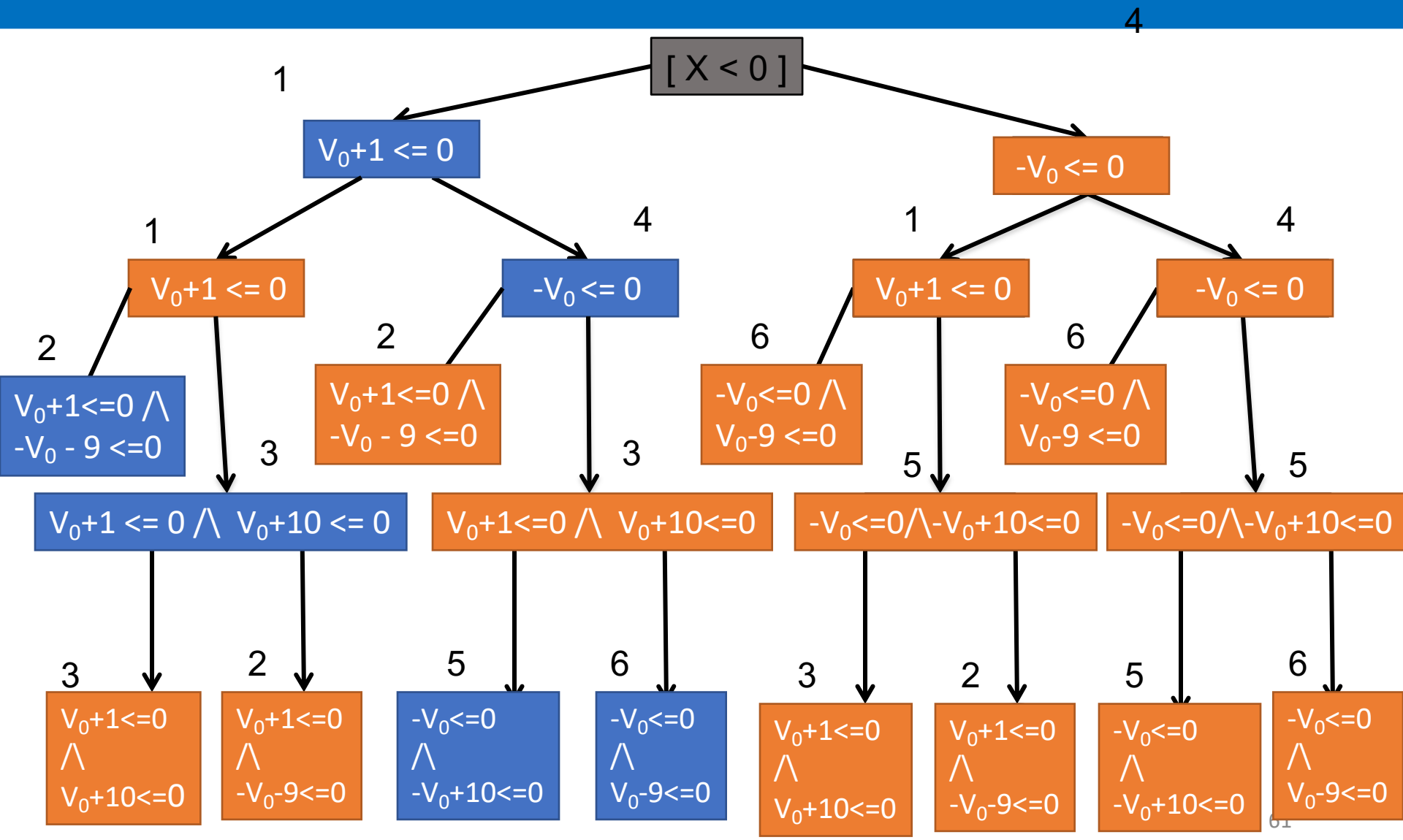
$$ax + by + cz + \ldots + k \{<=, =, !=\} 0$$

- Scale by -1 to transform > and >= to < and <=
- Add 1 to transform < to <=

Canonization of Constraints



Reduce, Reuse and Recycle Constraints



Reduce, Reuse and Recycle Constraints

```
int m(int x,y) {
   if (x < 0) x = -x;
   if (y < 0) y = -y;
   if (x < 10) {
      return 1;
   } else if (10 < y) {
      return -1;
   } else {
      return 0;
   }
}
```

Only the last 8 constraints are changed in the symbolic execution tree and 4 of them are reused!

Reusing the stored results from the first analysis eliminates 14 decision procedure calls!

Reading Materials

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Q&A?

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https://chenbihuan.github.io