CSCI426/CSCI926
Software Testing and Analysis

Symbolic Execution (Part 2)

Acknowledgement: Slides are adapted from Koushik Sen, Cristian Cadar, Omar Chowdhury, Jeff Foster, Suman Jana and Pezze & Young

Symbolic Execution Limitations

- **Loops and recursions** --- infinite execution tree
- **Path explosion** --- exponentially many paths
- **Heap modeling** --- symbolic data structures and pointers
- **SMT solver limitations** --- dealing with complex path constraints
- **Environment modeling** --- dealing with native/system/library calls/file operations/network events
- **Coverage Problem** --- may not reach deep into the execution tree, specially when encountering loops.

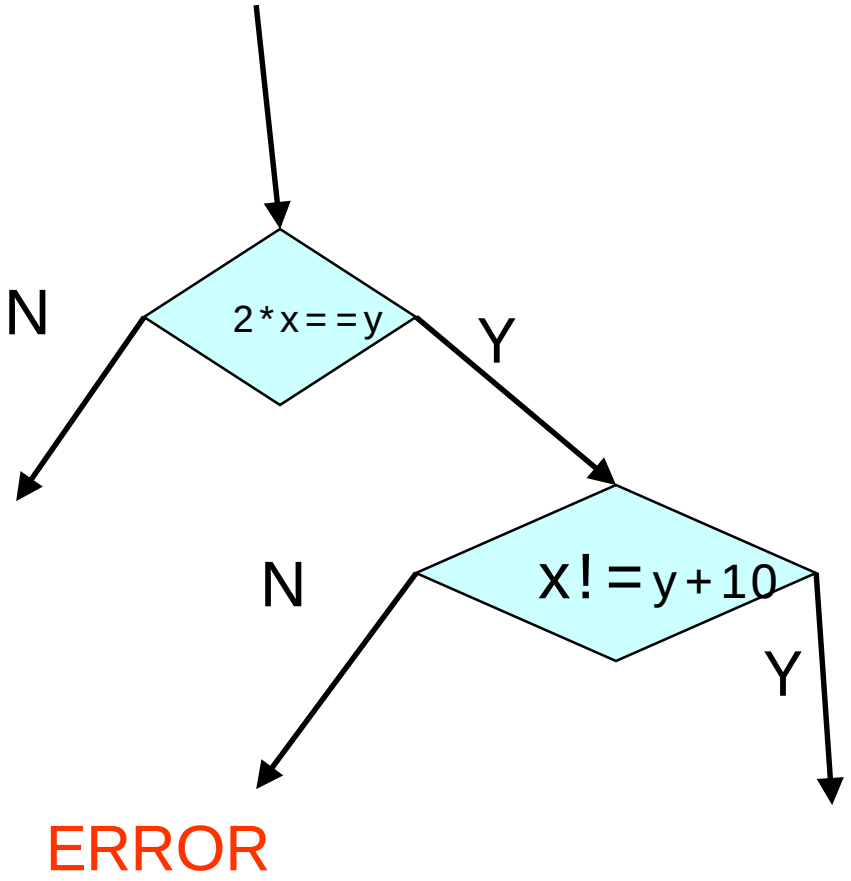
Symbolic Execution Limitations

```
1 void testme inf () {
2       int sum = 0;
3       int N = sym_input();
4       while (N > 0) {
5             sum = sum + N;
6             N = sym_input();
7       }
8       return;
9 }
```

Apply symbolic execution to the above code. How many execution paths are there?

Example of Execution Tree

```
void test_me(int x, int y) {
  if(2*x==y){
    if(x != y+10){
        printf("I am fine here");
    } else {
        printf("I should not reach
    here");
        ERROR;
    }
  }
}
```



Existing Approach I

- Random testing
  - generate random inputs
  - execute the program on generated inputs
- Probability of reaching an error can be astronomically less
  - What is the probability of hitting the ERROR path?

```
test_me(int x){
   if(x==94389){
        ERROR;
   }
}
```

Probability of hitting ERROR = $1/2^{32}$

Existing Approach II

- Symbolic Execution
  - use symbolic values for input variables
  - execute the program symbolically on symbolic input values
  - collect symbolic path constraints
  - use theorem prover to check if a branch can be taken
- Does not scale for large programs

```
test_me(int x){
  if(bbox(x)!=17){
      ERROR;
  } else {
      // OK
  }
}
```

Symbolic execution may not be able to determine whether the error is reachable.

Solution: Concolic Execution

Concolic = **Con**crete + Symb**olic**

Combining Classical Testing with Automatic Program Analysis

Also called **dynamic symbolic execution**

- The intention is to visit deep into the program execution tree
- Program is simultaneously executed with concrete and symbolic inputs
- Start off the execution with a random input
- Specially useful in cases of remote procedure call
- **Concolic execution implementations**: SAGE (Microsoft), CREST

Concolic Execution Steps

1. Generate a random seed input to start execution
2. Concretely execute the program with the random seed input and collect the path constraint - Example: **a && b && c**
3. In the next iteration, negate the last conjunct to obtain the constraint **a && b && !c**
4. Solve it to get input to the path which matches all the branch decisions except the last one

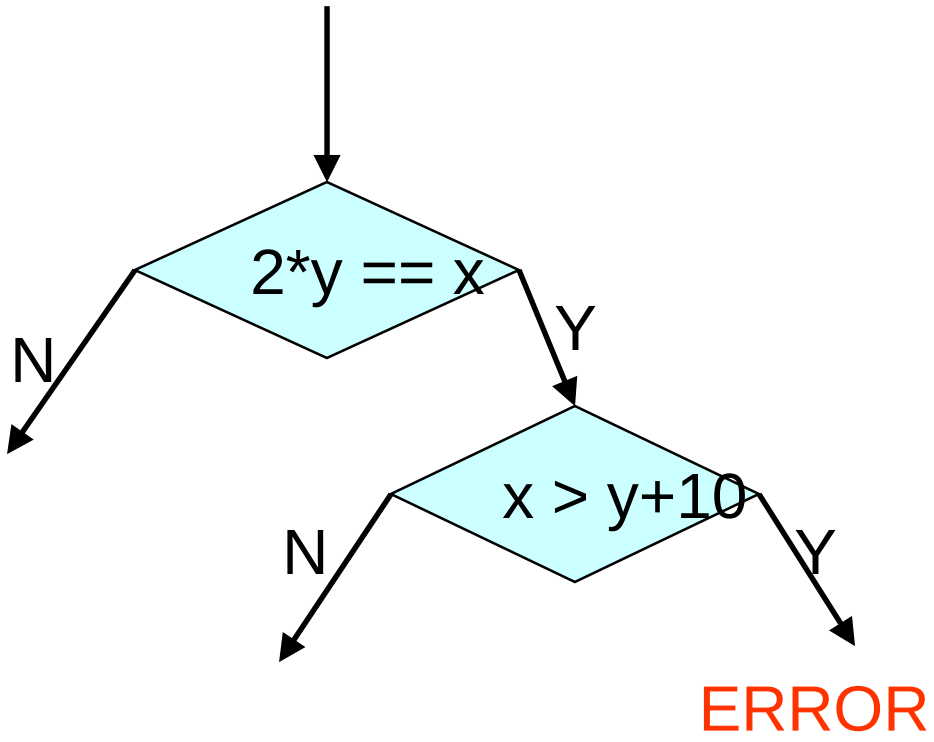
Concolic Testing Approach

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

    z = 2 * y;

    if (z == x) {

        if (x > y+10) {

            ERROR;
        }
    }

}
```

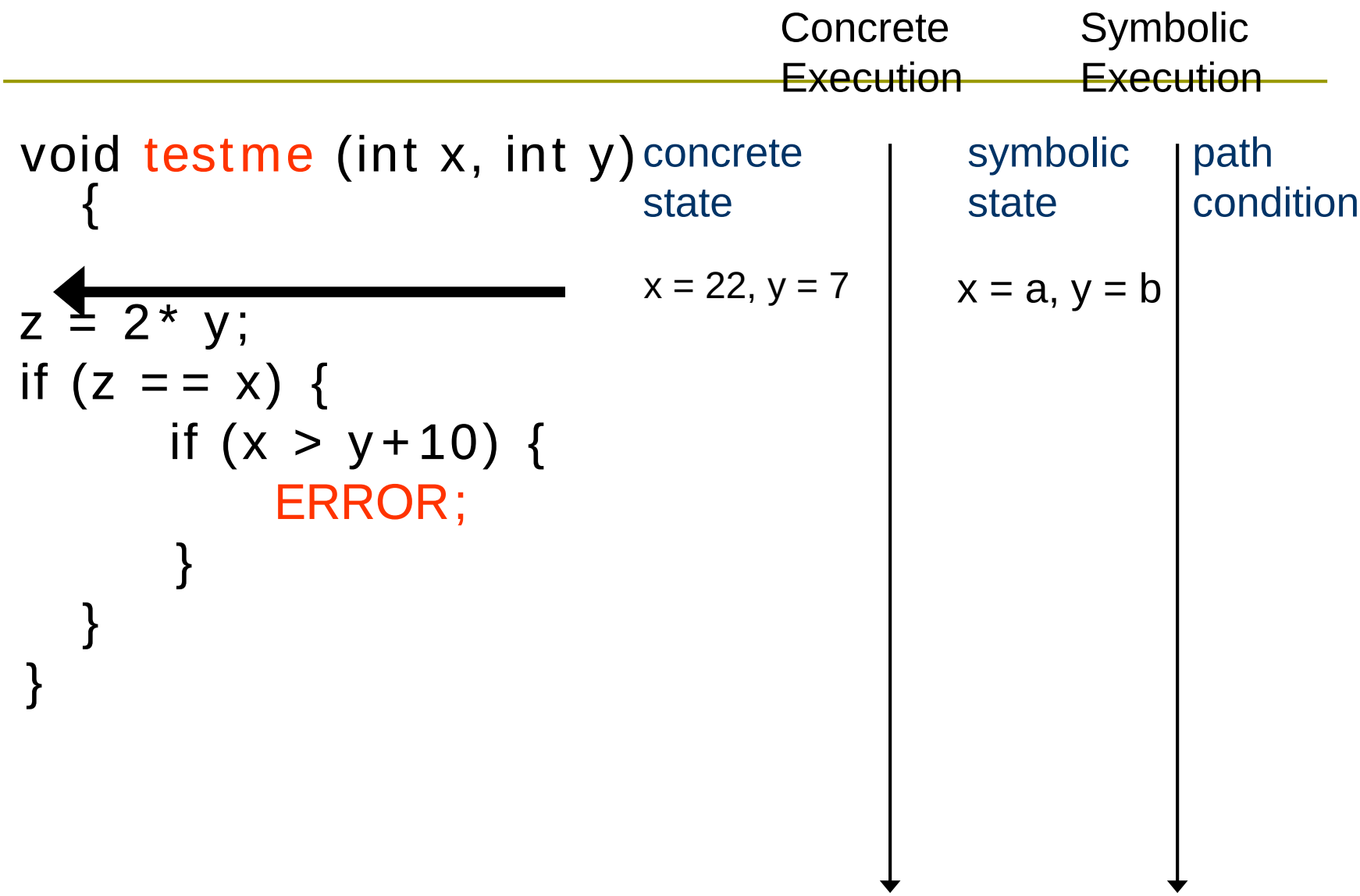
- Random Test Driver:
  - random value for x and y
- Probability of reaching ERROR is extremely low

Example

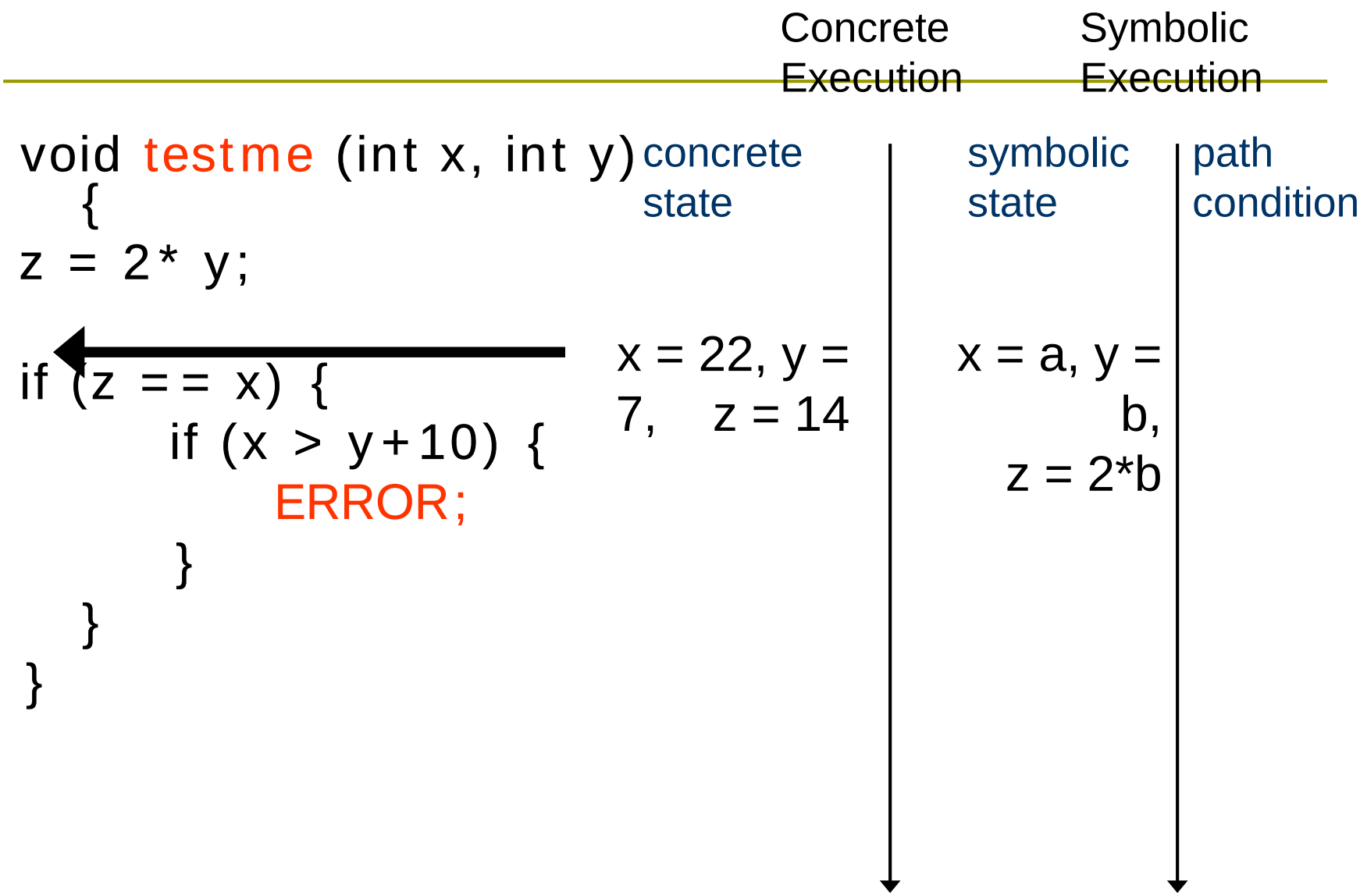
```
void testme (int x, int y)
{
   z = 2*y;
   if (z == x) {
        if (x > y+10) {
             ERROR;
        }
   }
}
```



Concolic execution example



Concolic execution example



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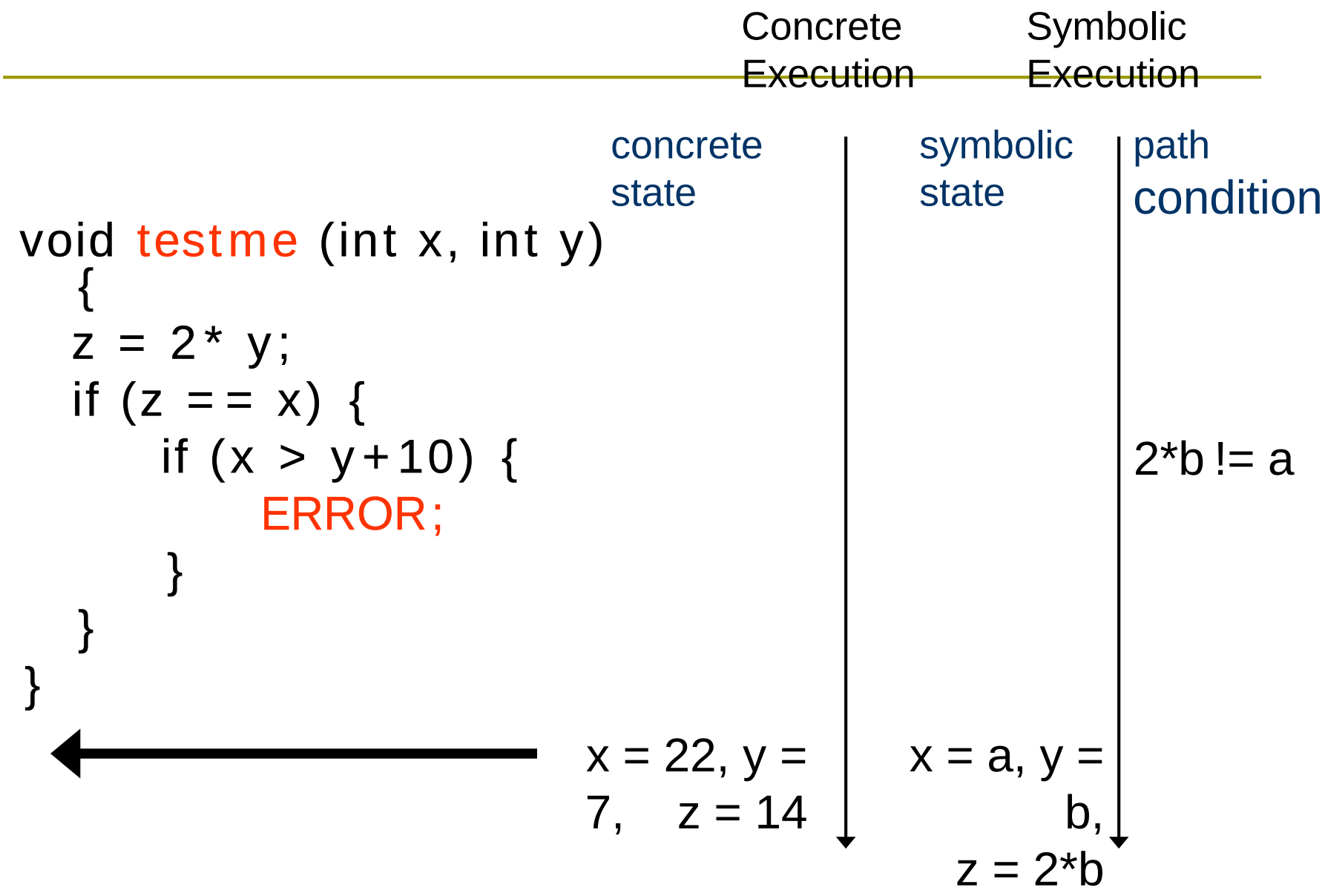

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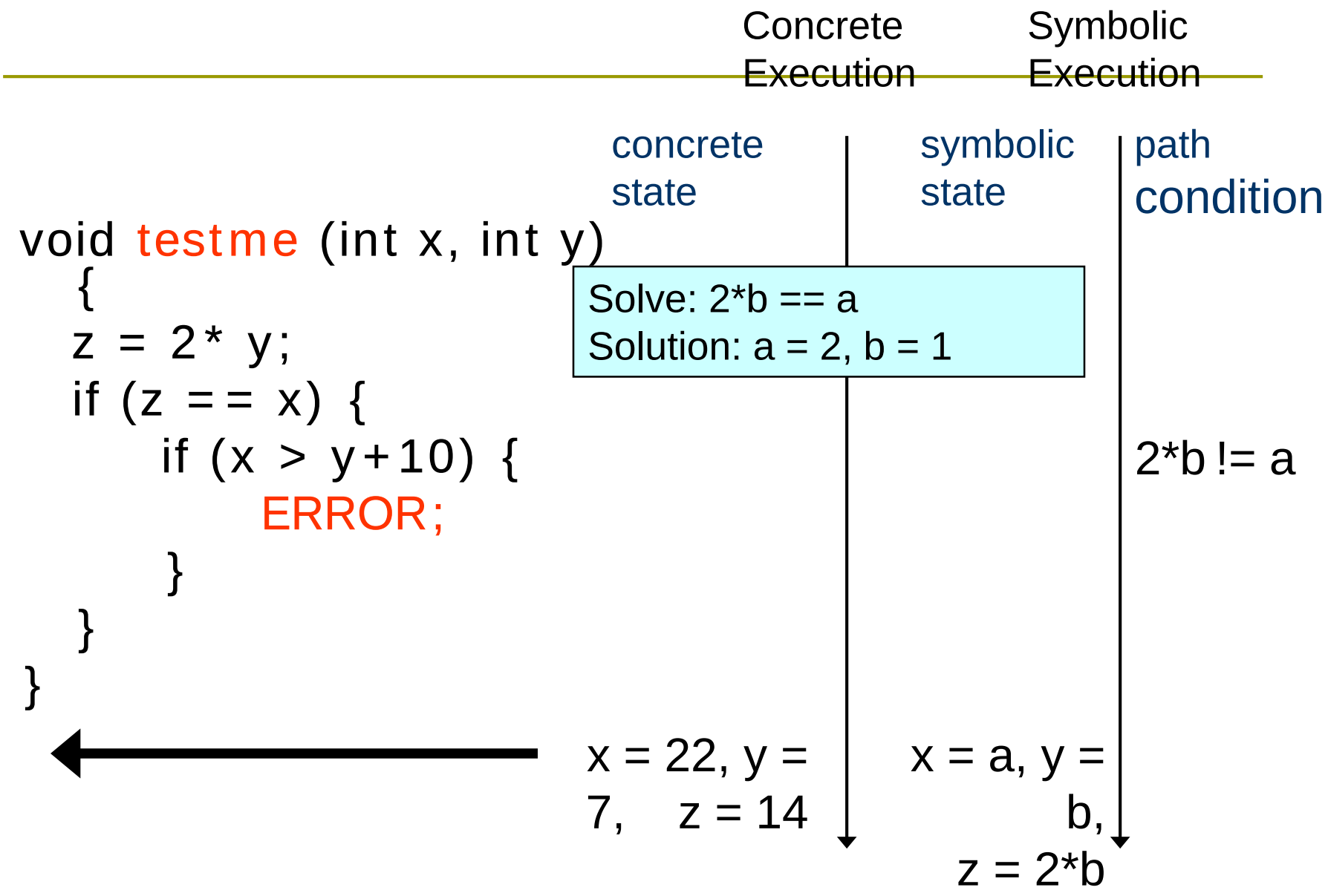

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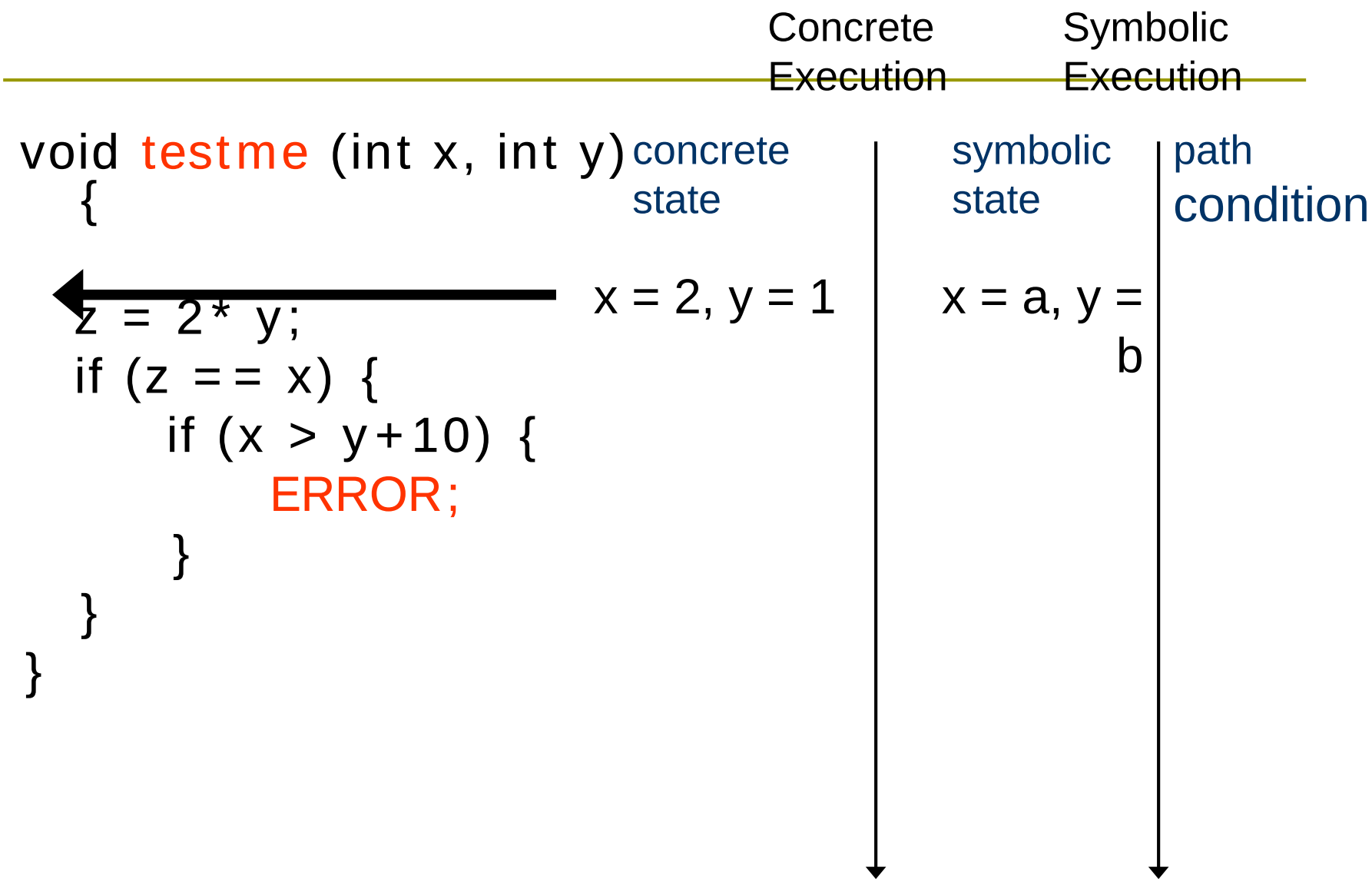

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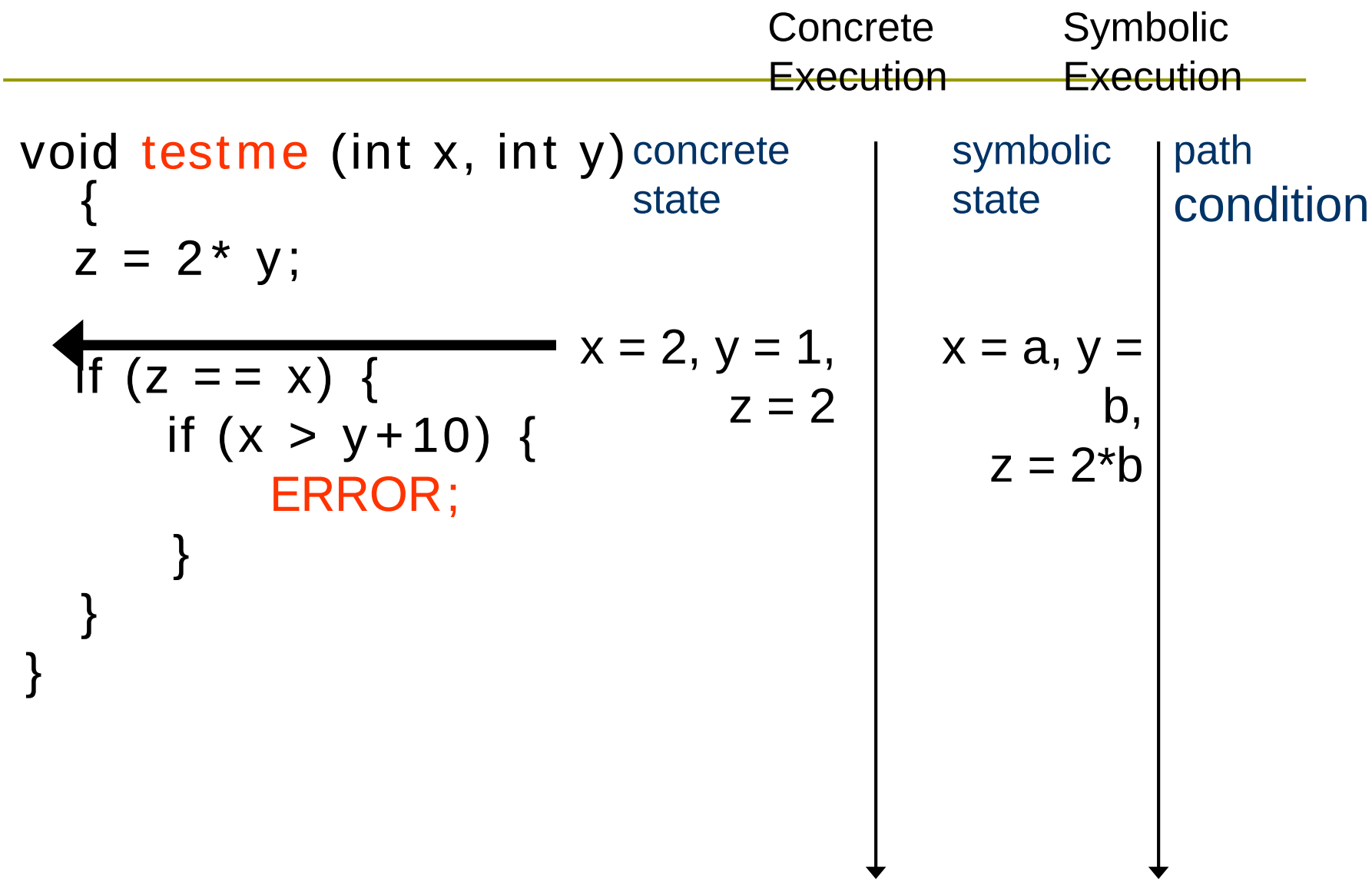

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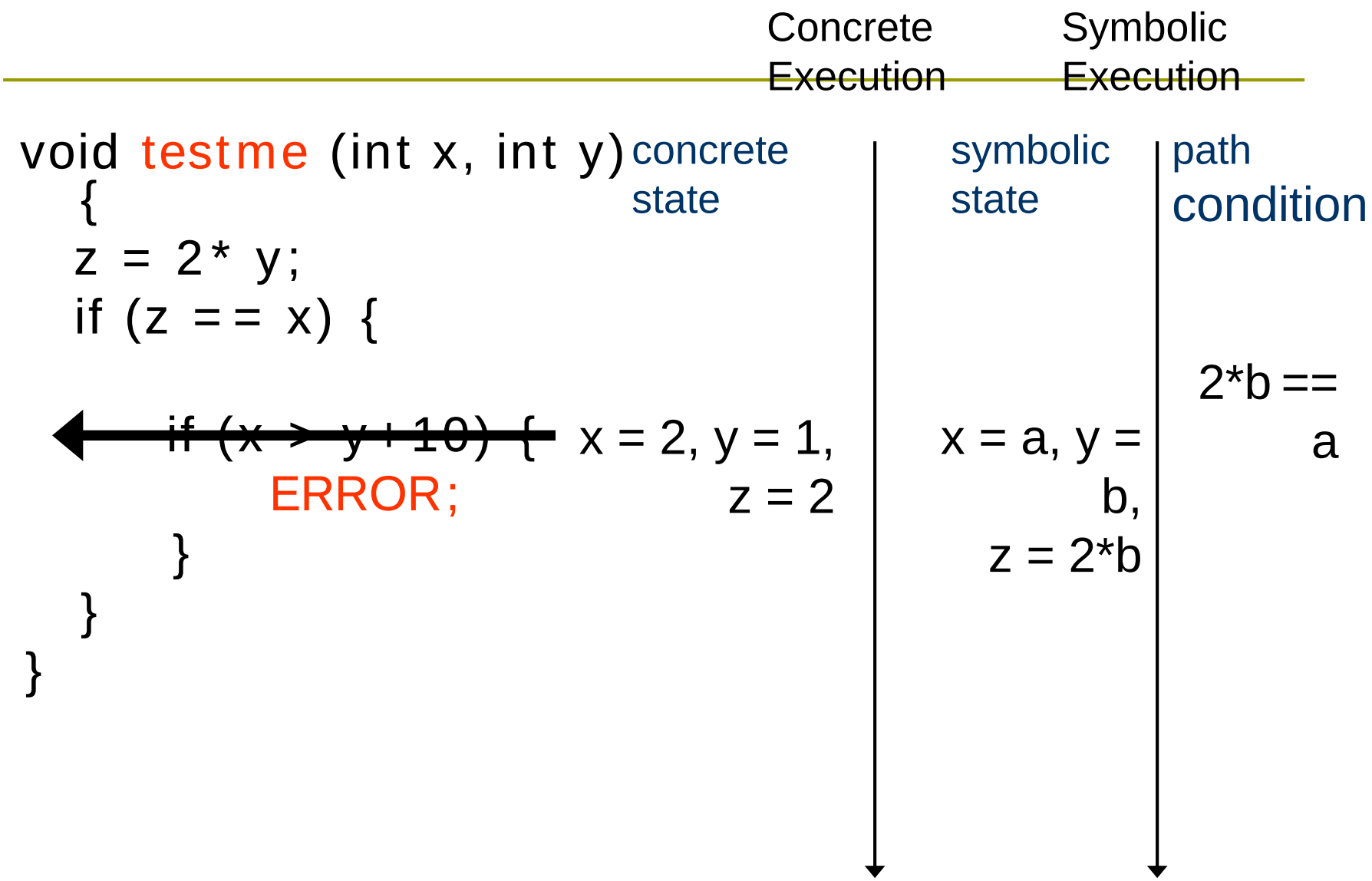
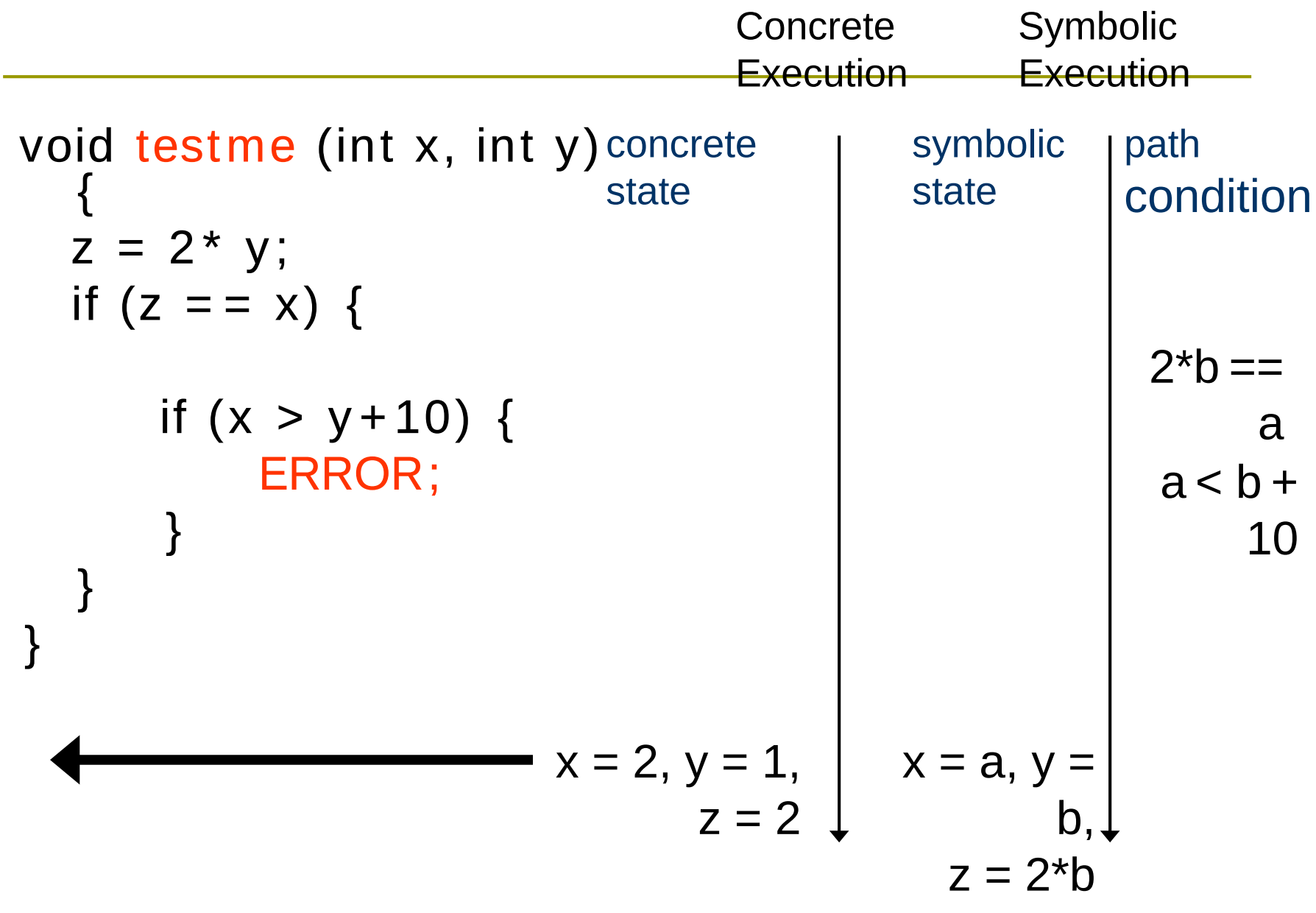
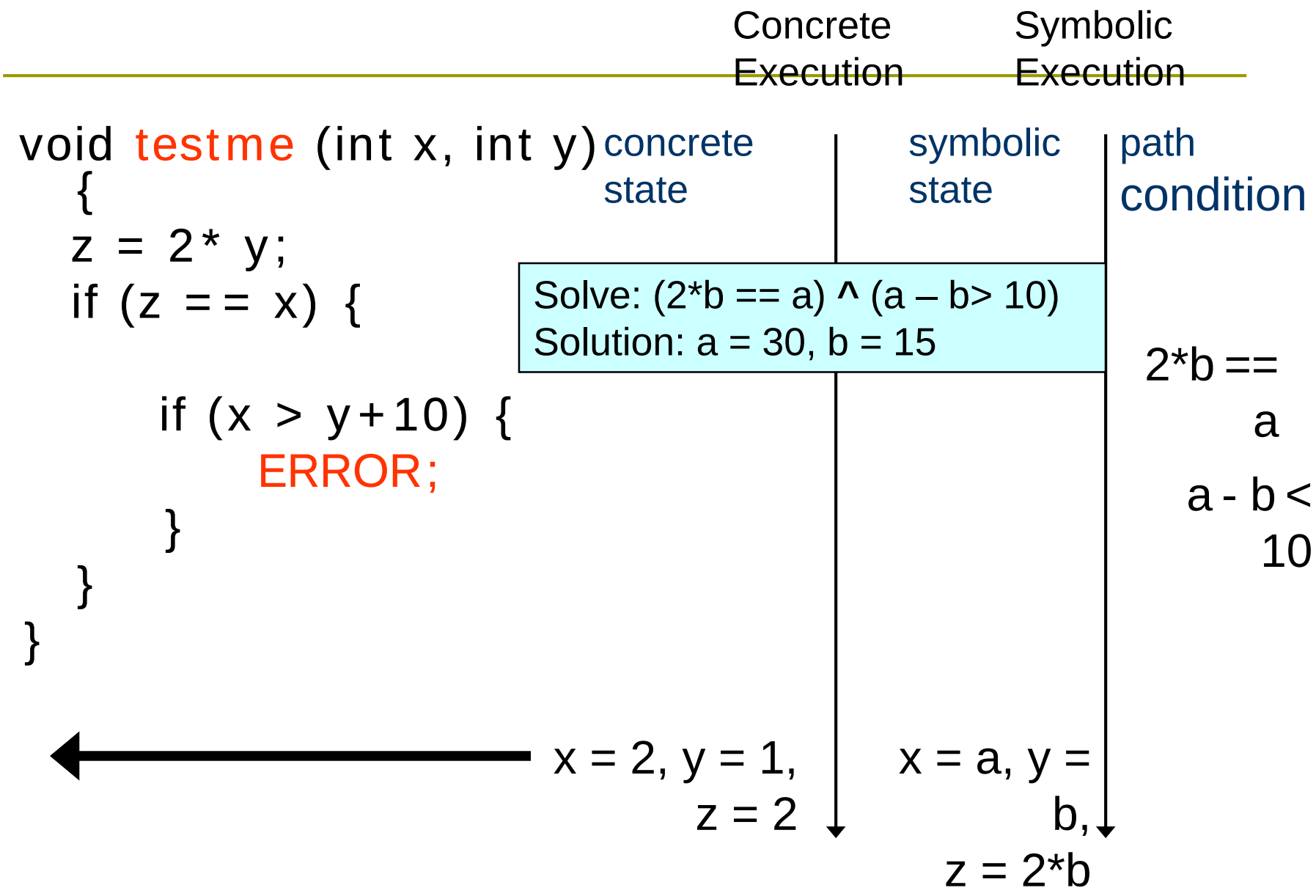


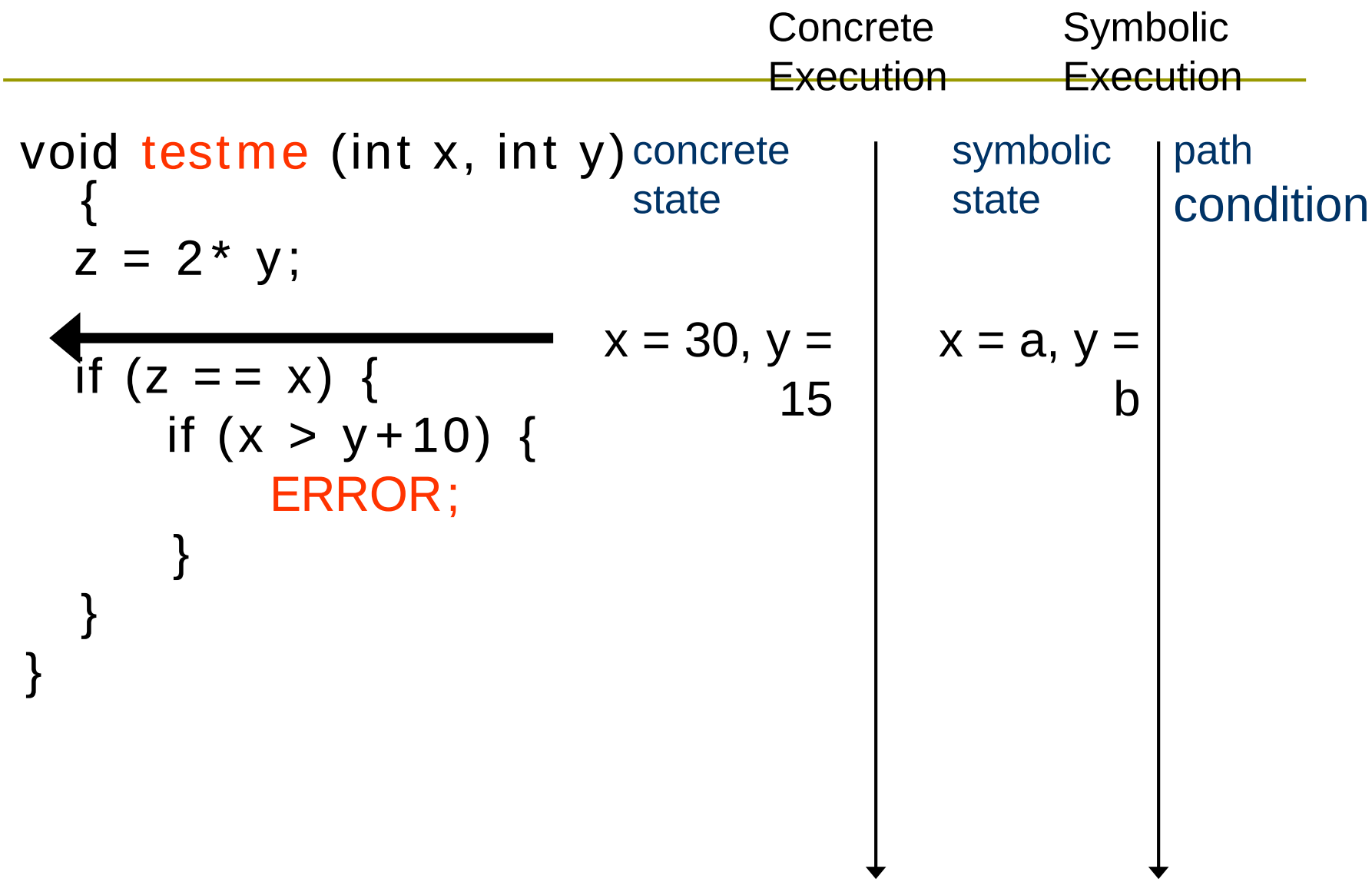
Concolic execution example



Concolic execution example



Concolic execution example



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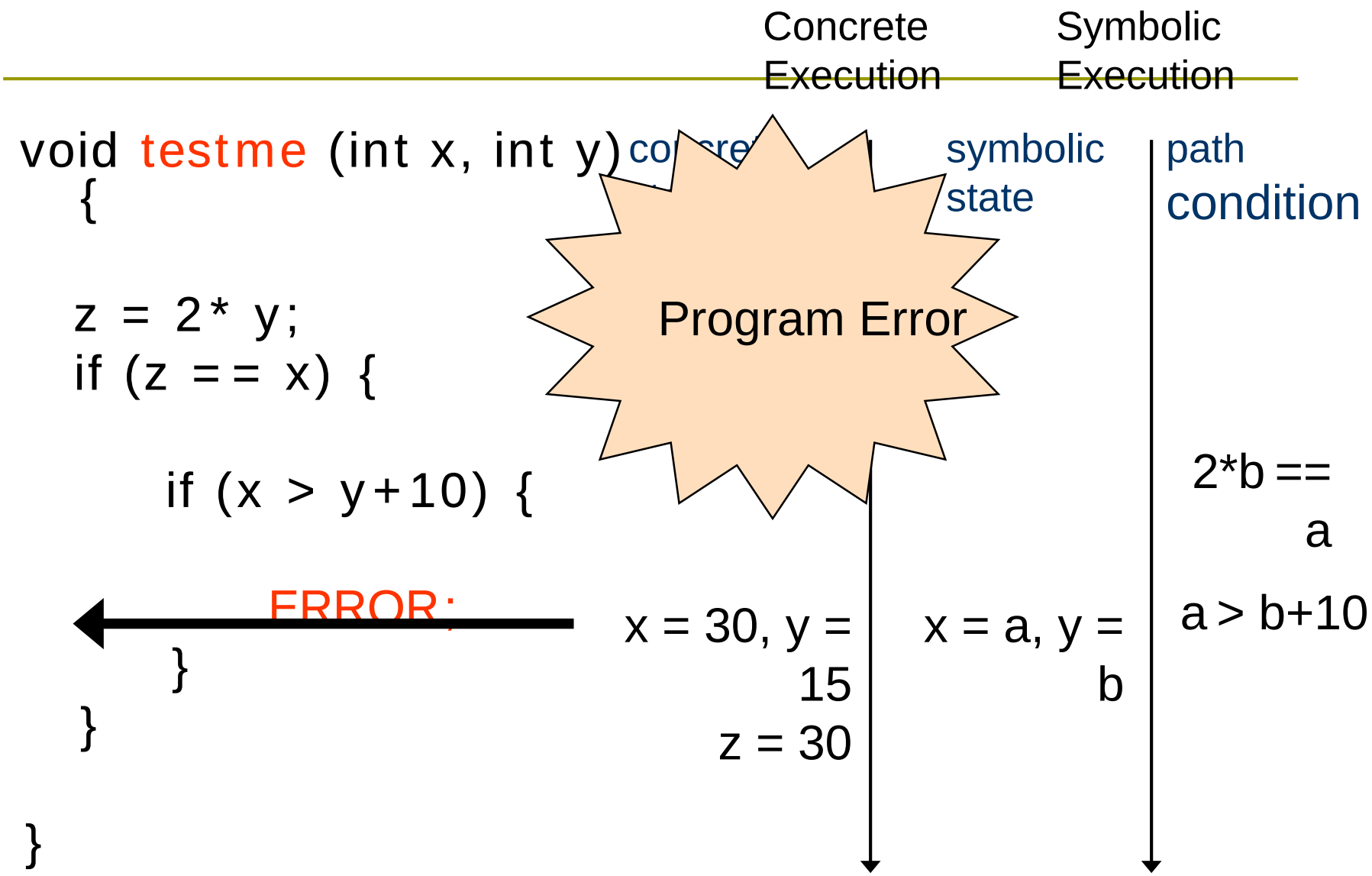
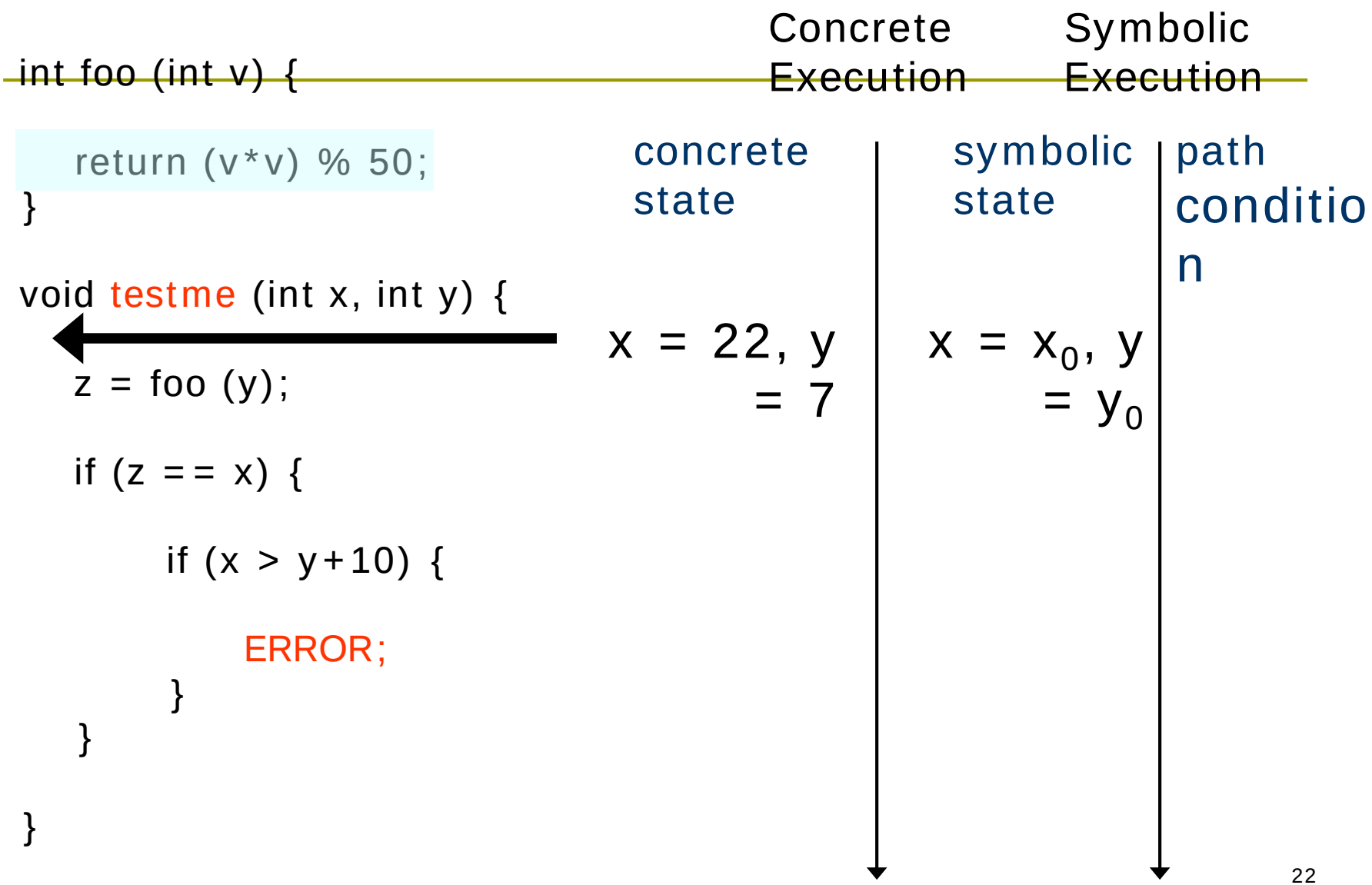


Novelty : Simultaneous Concrete and Symbolic Execution



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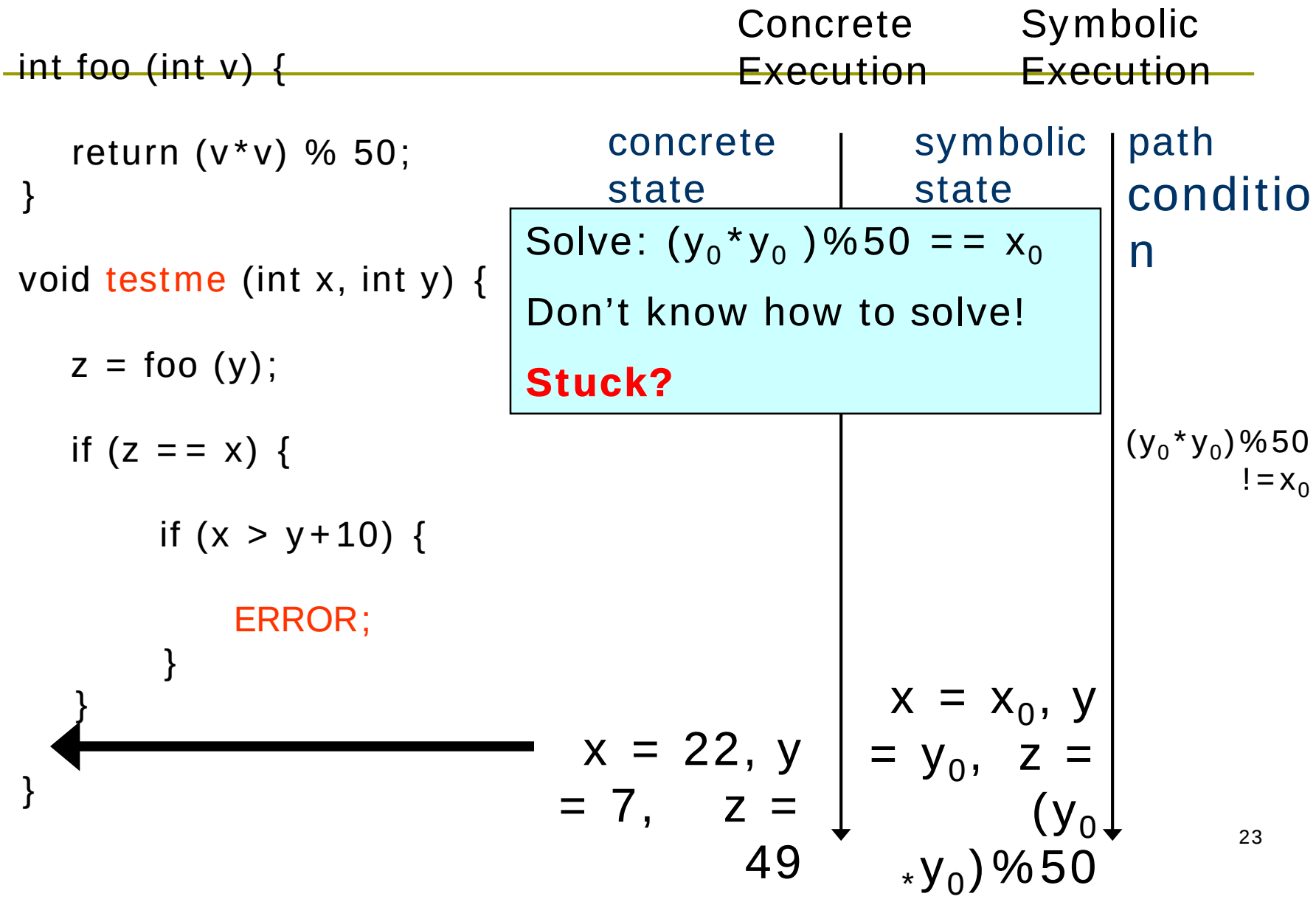

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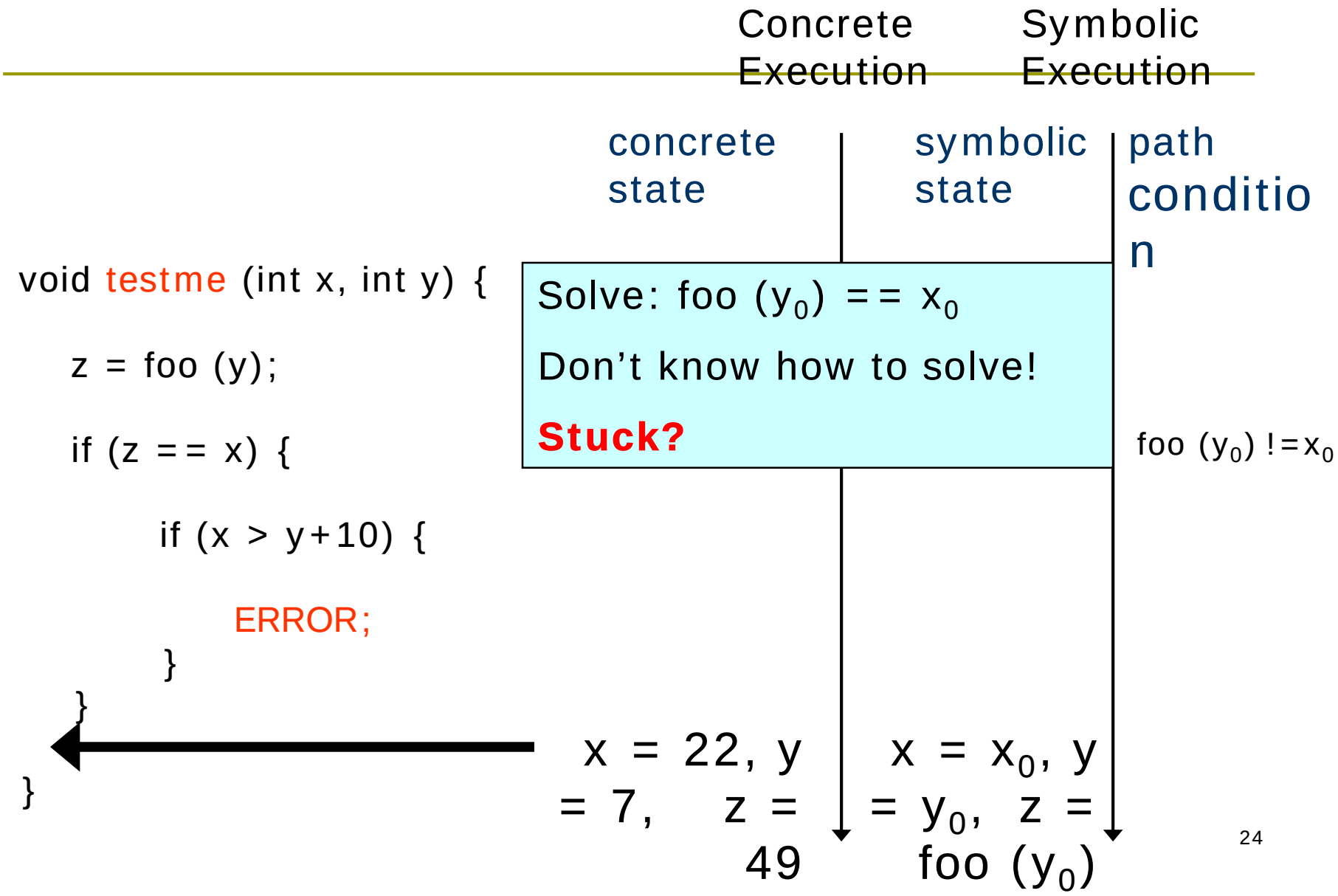

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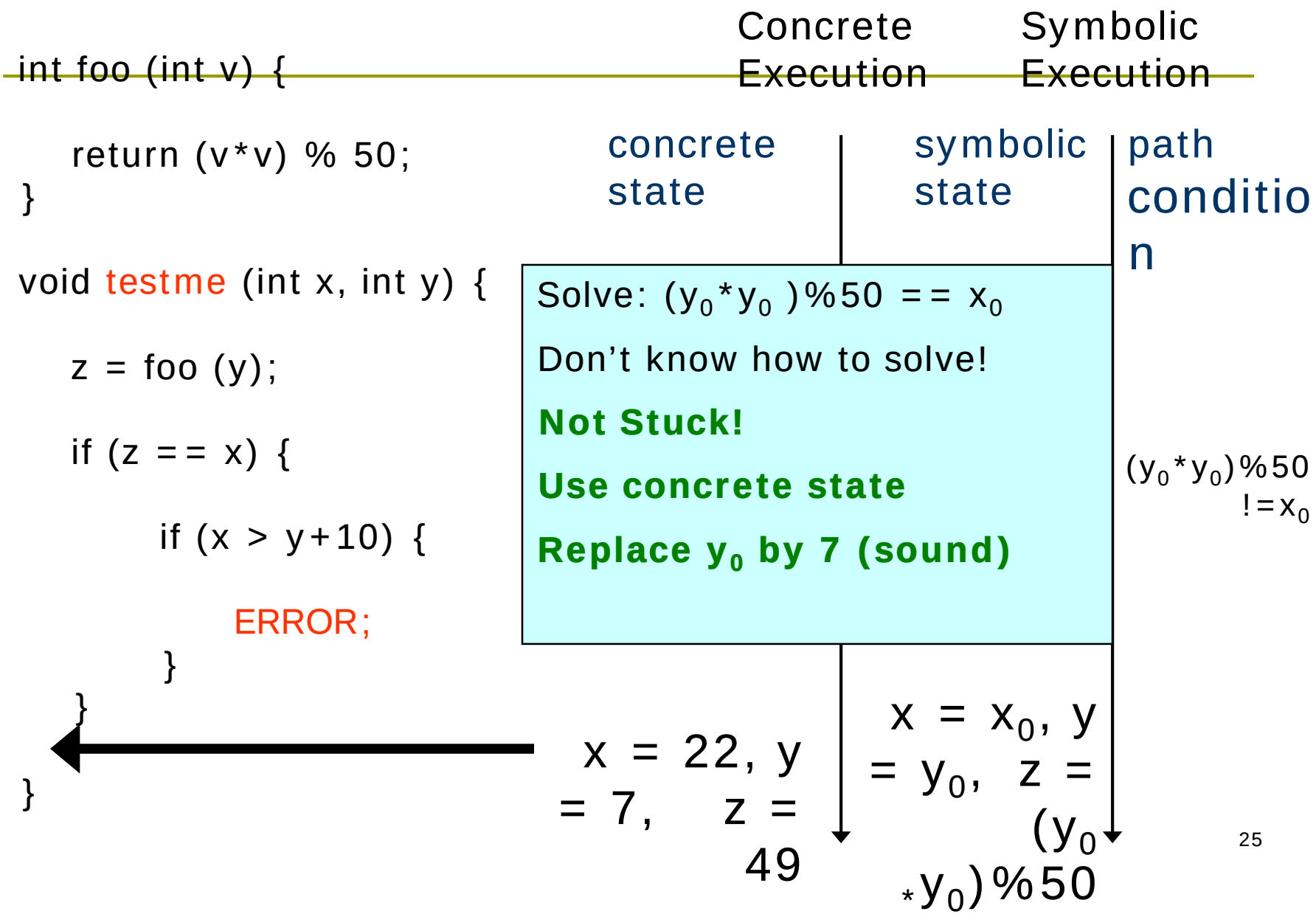

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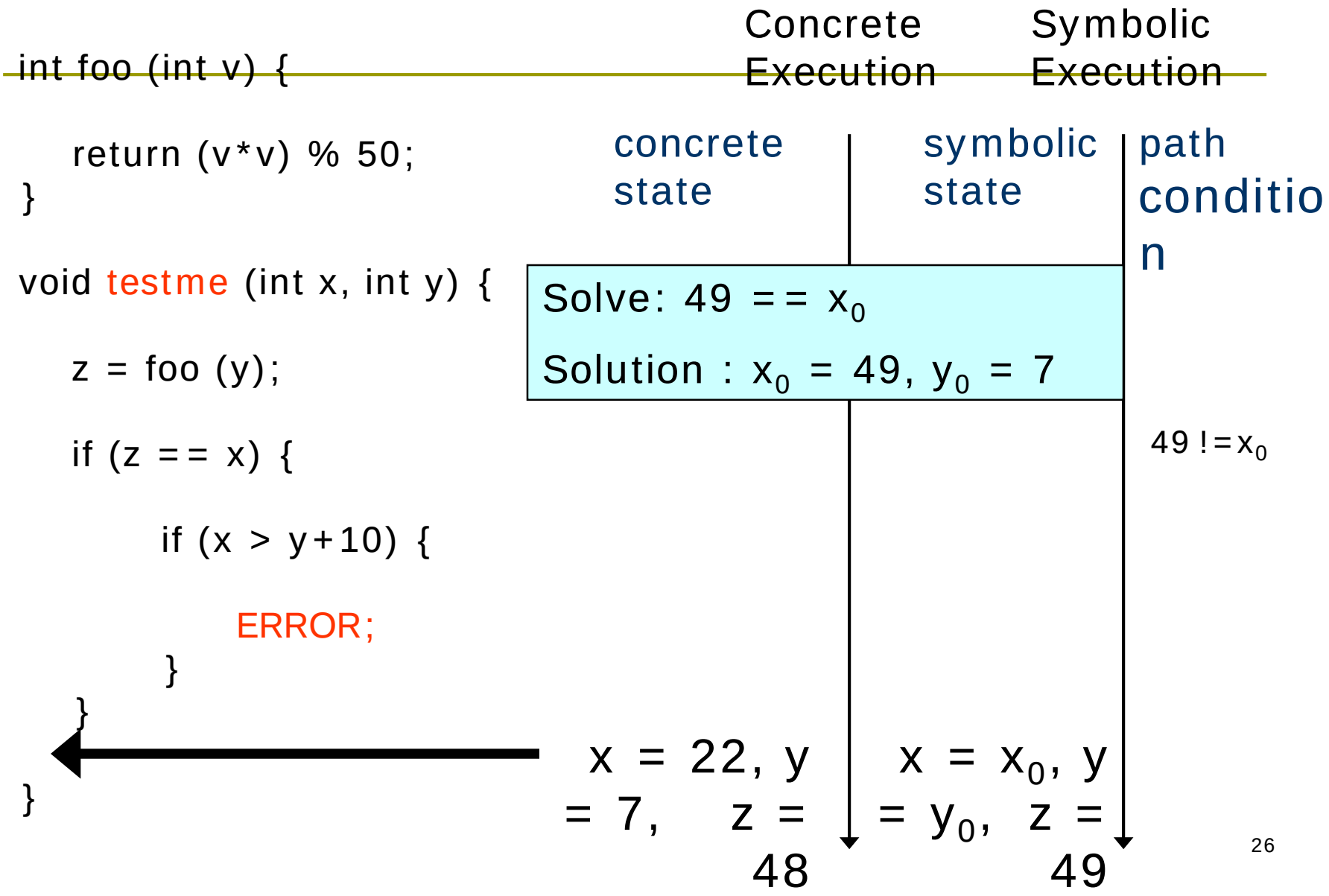

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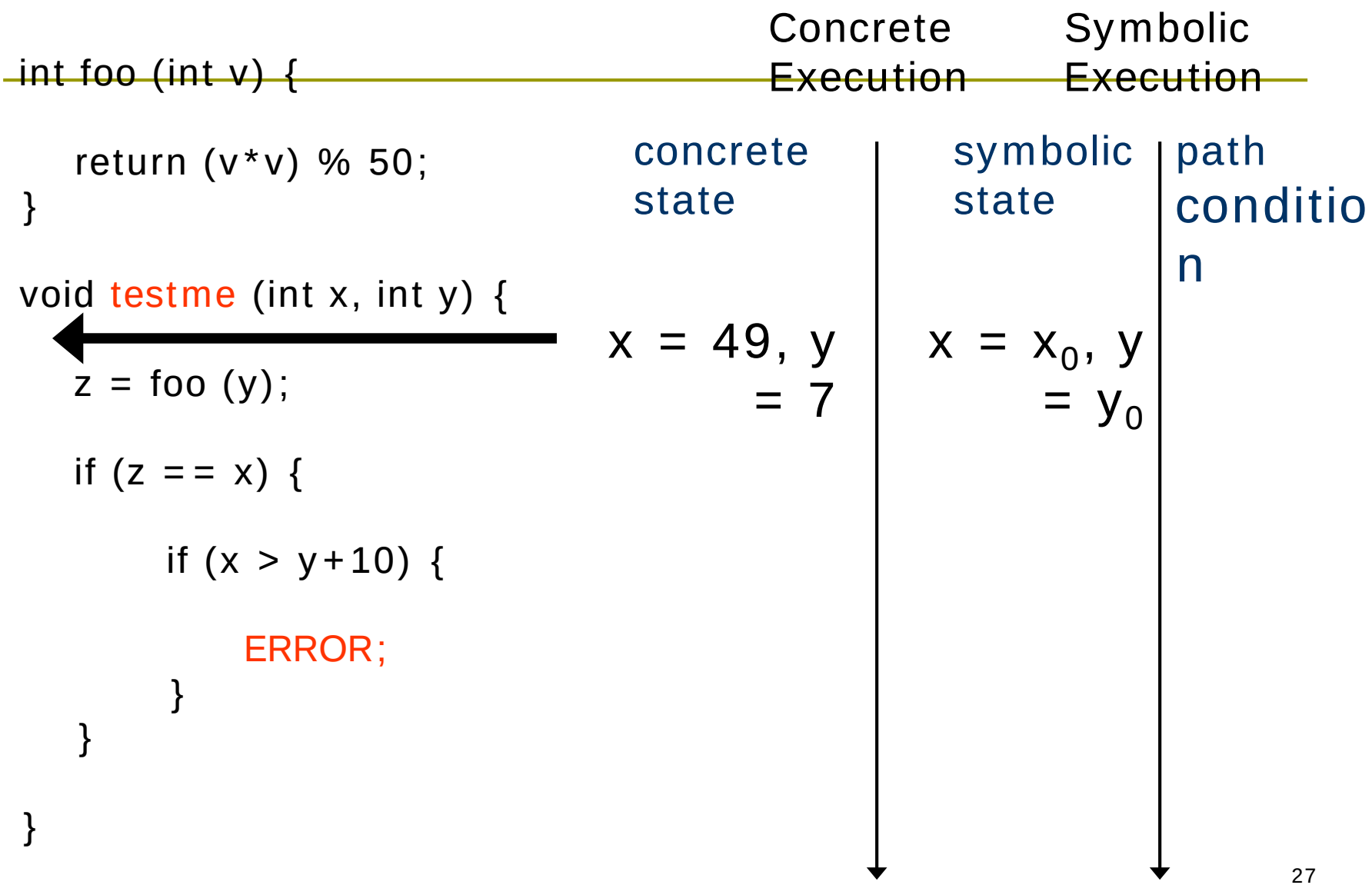

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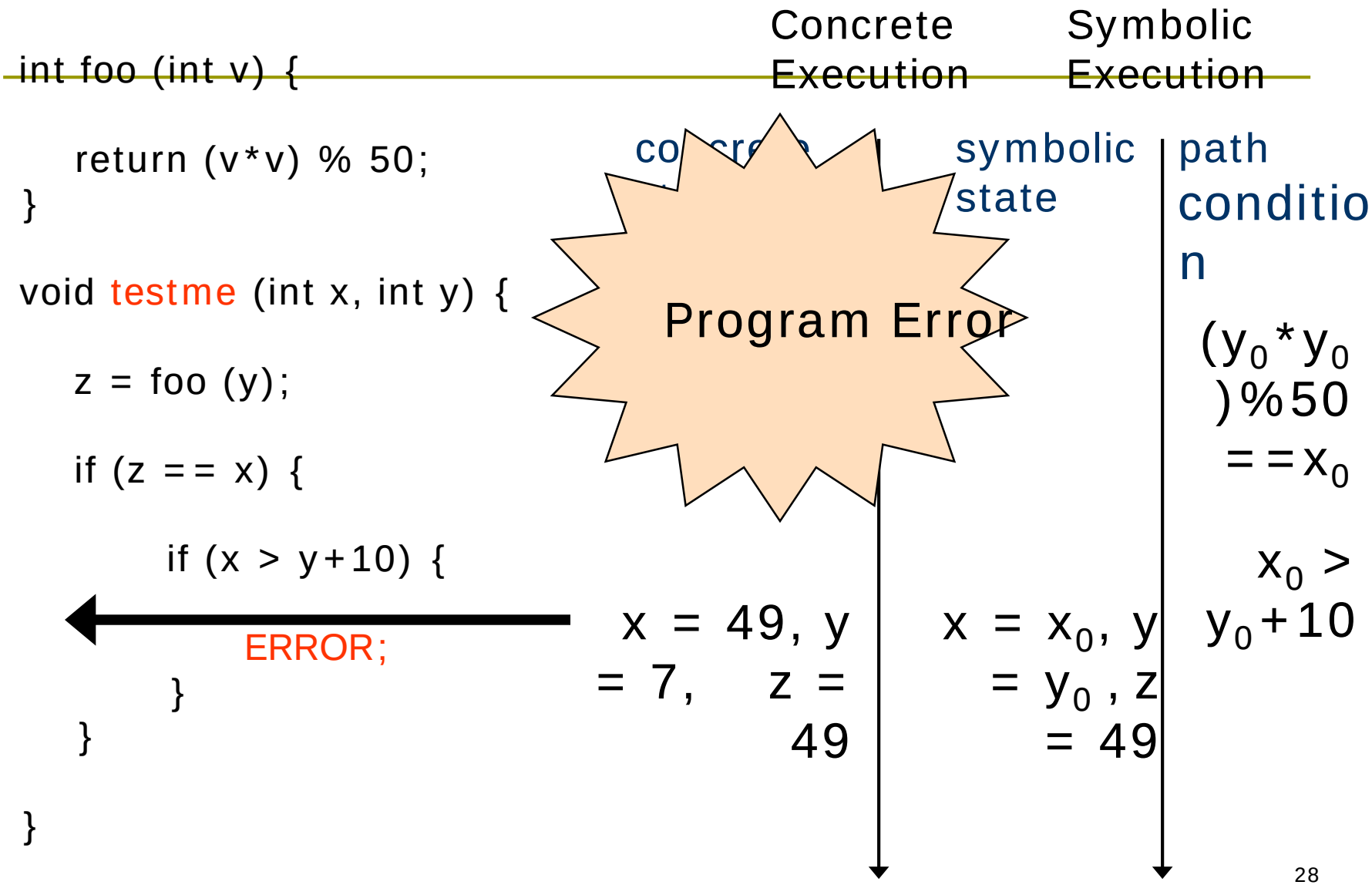
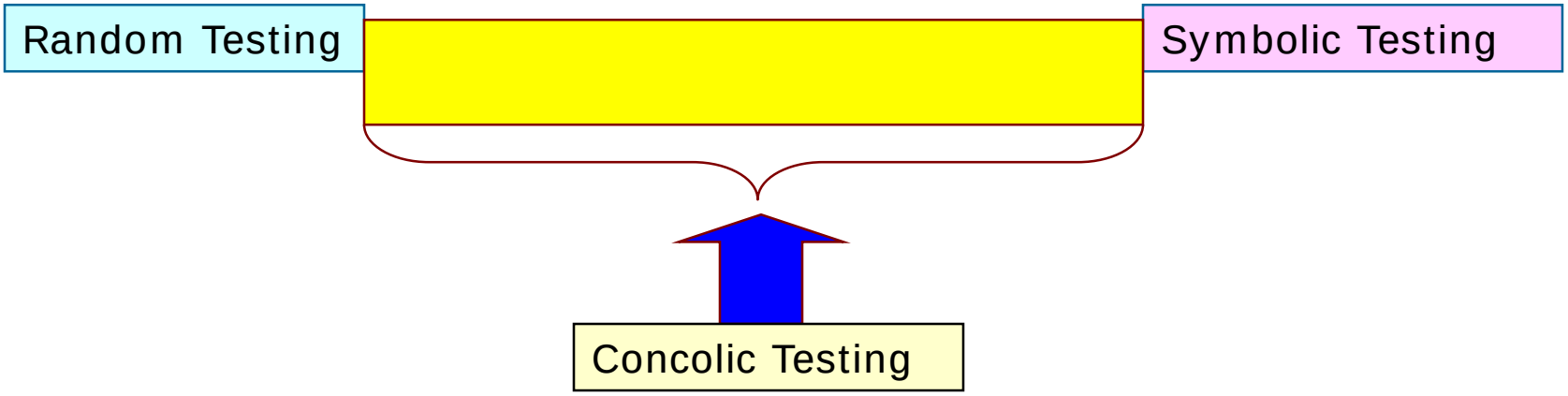


Concolic Testing: A Middle Approach



+ Complex programs
+ Efficient
- Less coverage
+ No false positive

+ Complex programs
+/- Somewhat efficient
+ High coverage
+ No false positive

- Simple programs
- Not efficient
+ High coverage
- False positive

Concolic Testing: Finding Security and Safety Bugs

Divide by 0 Error

```
x = 3 / i;
```

Buffer Overflow

```
a[i] = 4;
```

Concolic Testing: Finding Security and Safety Bugs

Key: Add Checks Automatically and Perform Concolic Testing

Divide by 0 Error

```
if (i !=0)
   x = 3 / i;
else
   ERROR;
```

Buffer Overflow

```
if (0<=i  &&  i <
   a.length)
   a[i] = 4;
else
   ERROR;
```

Implementations

- DART and CUTE for C programs
- jCUTE for Java programs
  - Goto http://srl.cs.berkeley.edu/~ksen/ for CUTE and jCUTE binaries
- MSR has four implementations
  - SAGE, PEX, YOGI, Vigilante
- Similar tool: EXE at Stanford
- Easiest way to use and to develop on top of CUTE
  - Implement concolic testing yourself

Pen and paper exercise

- Apply concolic execution on the following program

```
void hello(int x, int y) {
        int t = 0;
        if (x > y) {
                t = x * x - 3;
        } else {
                t = y;
        }

        if (t < x) {
                print("Hello World");
        }
}
```

Further reading

- Symbolic execution and program testing - James King
- KLEE: Unassisted and Automatic Generation of High-Coverage Tests for Complex Systems Programs - Cadar et. al.
- Symbolic Execution for Software Testing: Three Decades Later - Cadar and Sen
- DART: Directed Automated Random Testing - Godefroid et. al.
- CUTE: A Concolic Unit Testing Engine for C - Sen et. al.