Symbolic Execution

Testing, Quality Assurance, and Maintenance
Fall 2023

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based on slides by Prof. Johannes Kinder and others

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How would you test this program?

Remember this little program Foo()?

Is it possible to **automatically** generate a test-suite that

- achieves full branch coverage
- discovers weather division by 0 is possible
- identifies all infeasible test requirements (i.e., dead code)

Remarkably, the answer is YES

```
def Foo(x, y):
""" requires: x and y are int
    ensures: returns floor(max(x,y)/min(x, y))"""
   if x > y:
      return x / y
   else
      return y / x
```

`floor(z)` is the largest integer not greater than z

Symbolic execution in a nutshell

- to identify division by 0, add explicit tests (i.e., oracles)
- **traverse** the program to compute each program path
  - path1: `x > y, y == 0` ; path2: `x > y, y != 0, return x / y` ; …
- **solve** constraints for each path using a constraint (or logic) solver
  - path1: `x=10, y=0`; path2: `x=10, y=1`; …
- **run** the program on tests generated by previous step
- all testing is now automatic

```
def Foo(x, y):
""" requires: x and y are int
    ensures: returns floor(max(x,y)/min(x, y))"""
   if x > y:
      assert y != 0
      return x / y
   else
      assert x != 0
      return y / x
```

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Symbolic Execution is a Combination of

Automatically explore program paths

- Execute program on “symbolic” input values
- “Fork” execution at each branch
- Record branching conditions

Constraint solver

- Decides path feasibility
- Generates test cases for paths and bugs

History

Int. Conference on Reliable Software 1975

James C. King:
A new approach to program testing

Robert S. Boyer, Bernard Elspas, Karl N. Levitt:
SELECT—a formal system for testing and debugging programs by symbolic execution

Recent work on proving the correctness of programs by formal analysis [5] shows great promise and appears to be the ultimate technique for producing reliable programs. However, the practical accomplishments in this area fall short of a tool for routine use. Fundamental problems in reducing the theory to practice are not likely to be solved in the immediate future.

History (2)

SAT / SMT solvers lead to boom in 2000s

- Constraint solving becomes a commodity
- Makes classic algorithms viable in practice

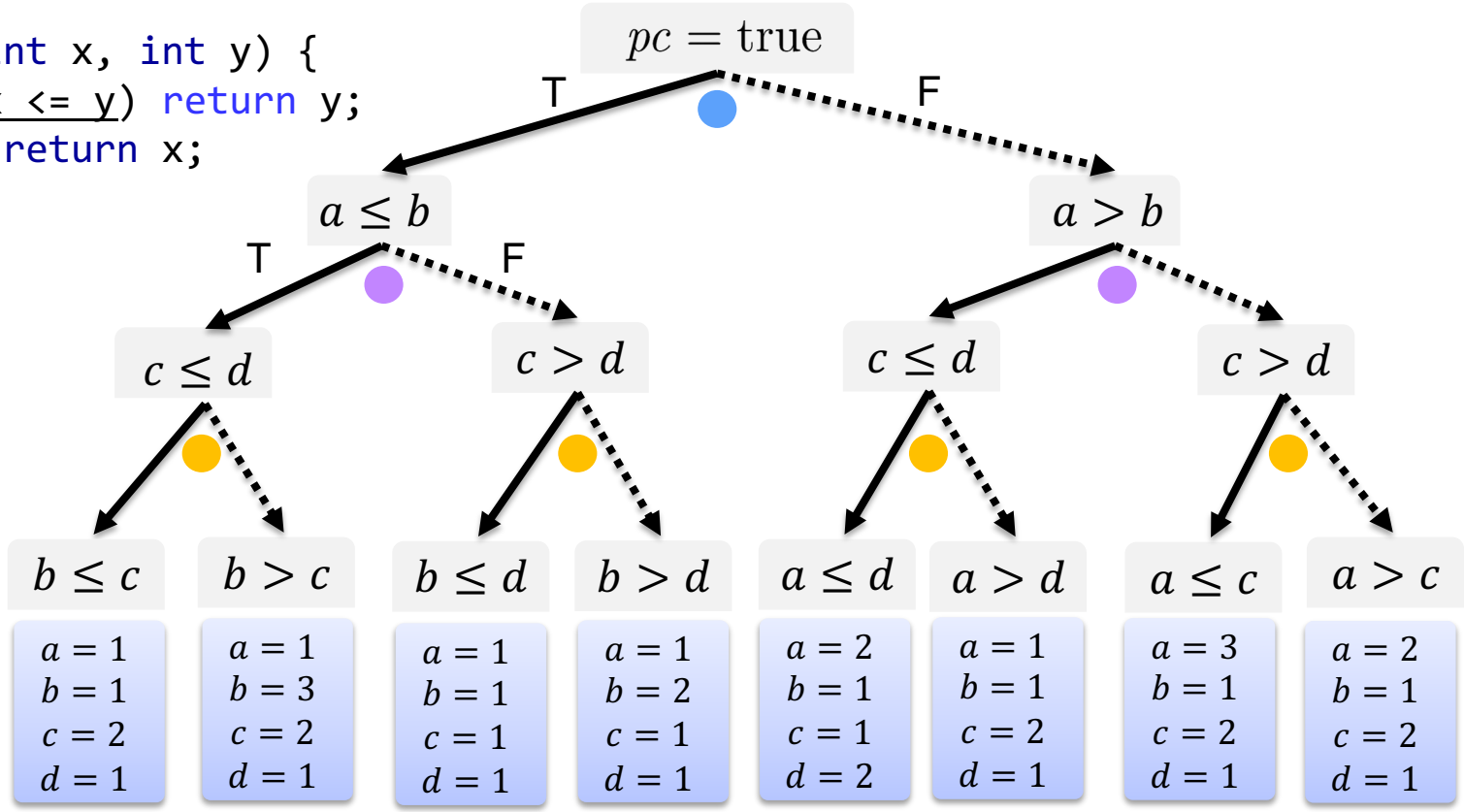
Conceptual breakthroughs (Dynamic Symbolic Execution)

- Patrice Godefroid, Nils Klarlund, Koushik Sen: *DART: directed automated random testing*. PLDI 2005
- Cristian Cadar, **Vijay Ganesh**, Peter M. Pawlowski, David L. Dill, Dawson R. Engler: *EXE: automatically generating inputs of death*. CCS 2006

Symbolic Execution Illustrated

```
int Max(int a, int b, int c, int d) {
    return Max(Max(a, b ●), Max(c, d ●) ●);
}
```

```
int Max(int x, int y) {
    if (x <= y) return y;
    else return x;
}
```



$pc = \text{true}$

$\mathtt{x} = X$

$\mathtt{r} = 0$

```
1  int proc(int x) {
2
3    int r = 0
4
5    if (x > 8) {
6      r = x - 7
7    }
8
9    if (x < 5) {
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13   return r
   }
```
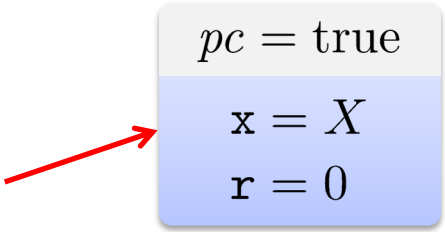

Symbolic program state

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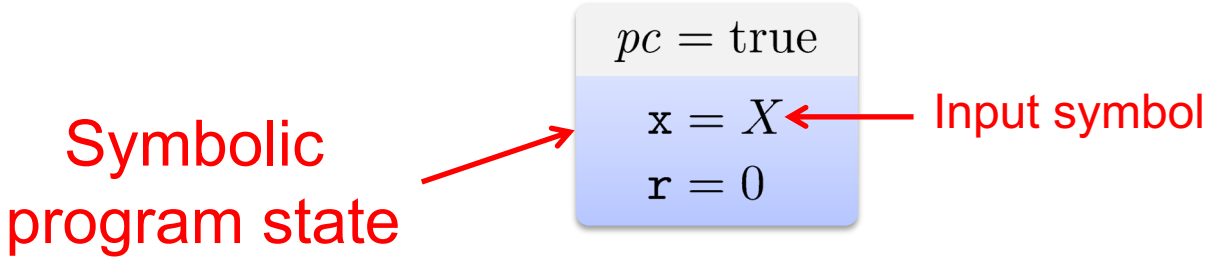


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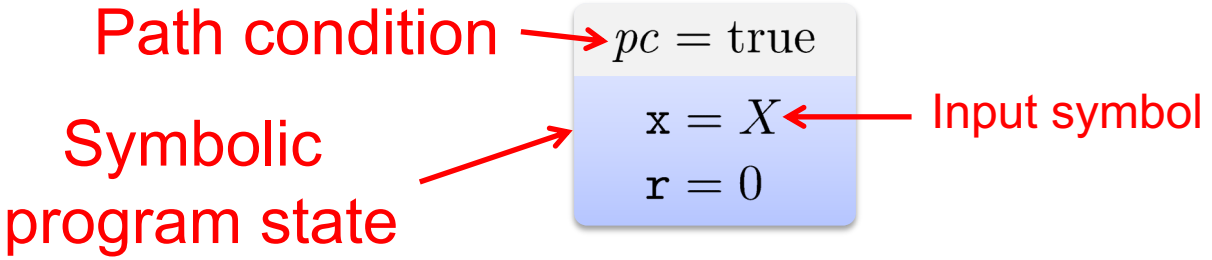


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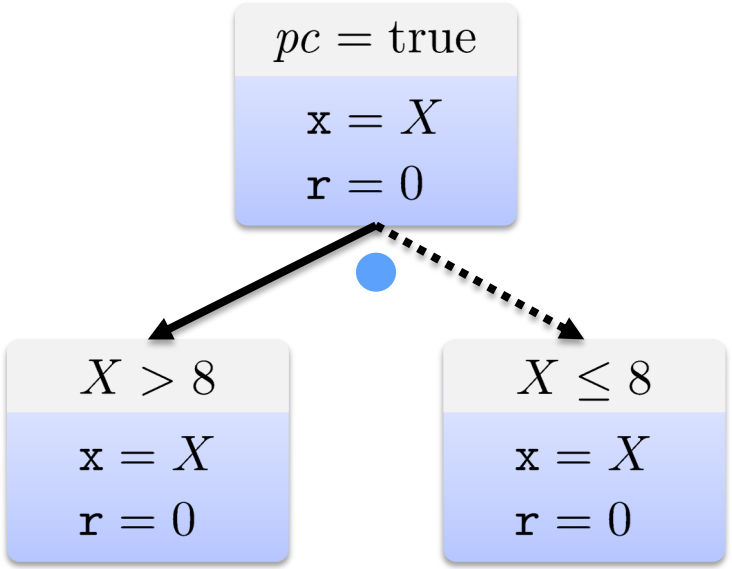

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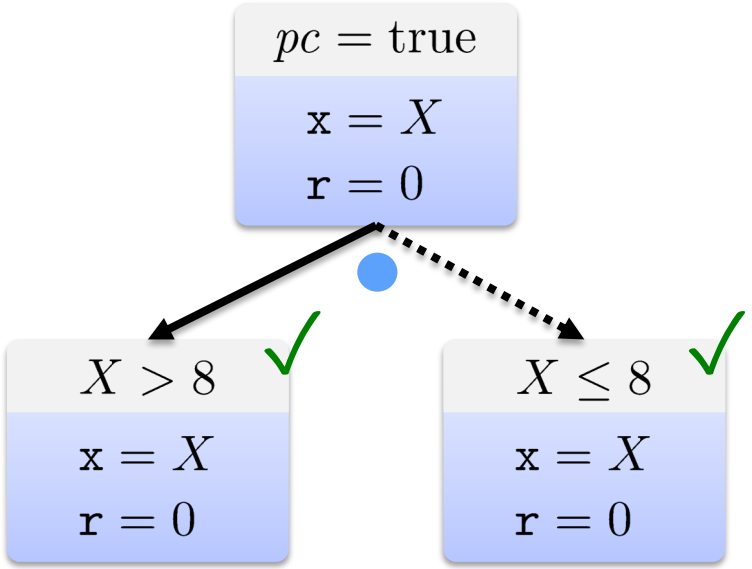

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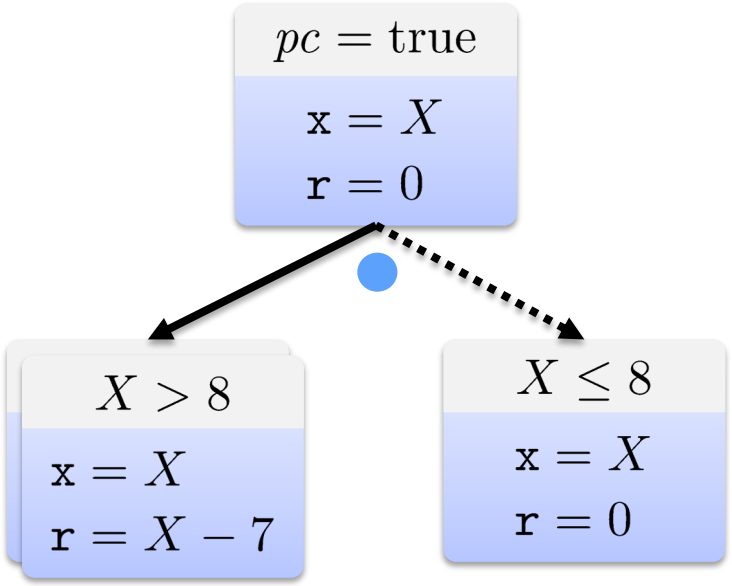

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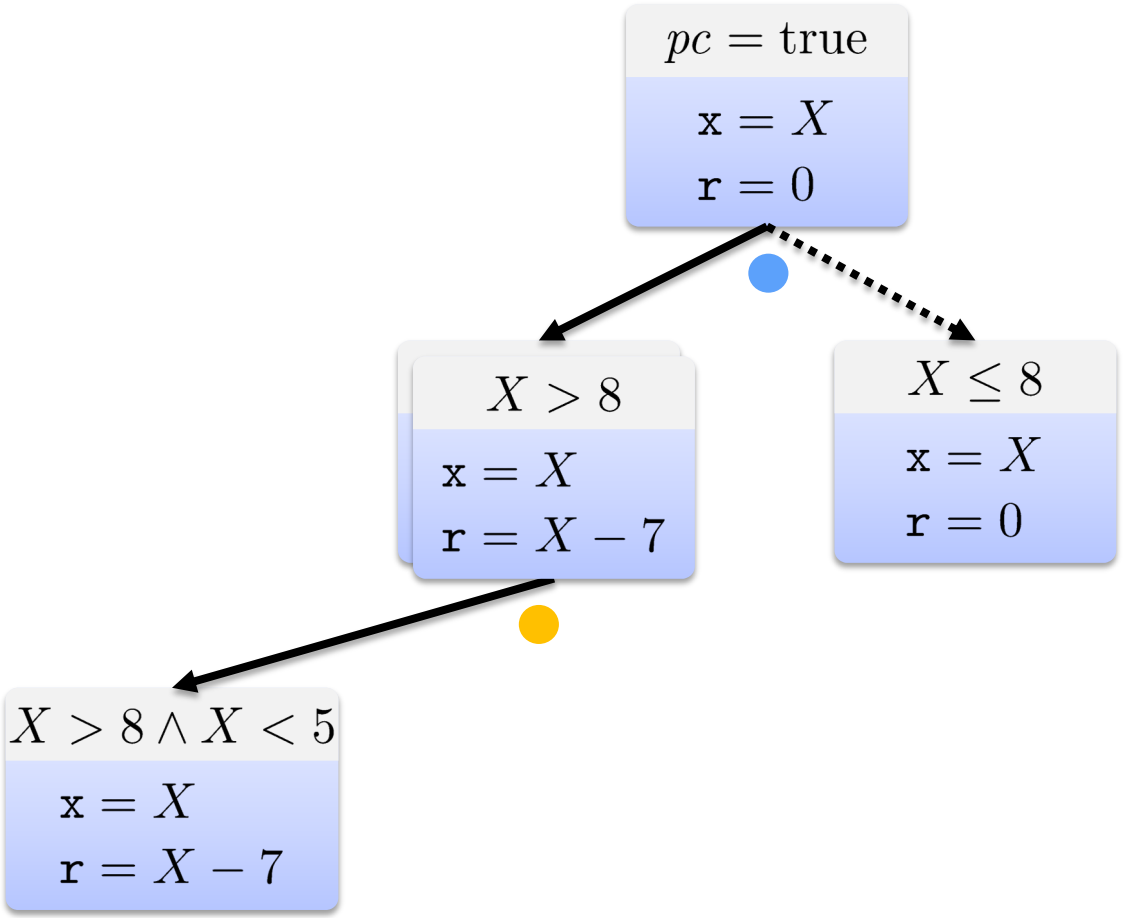

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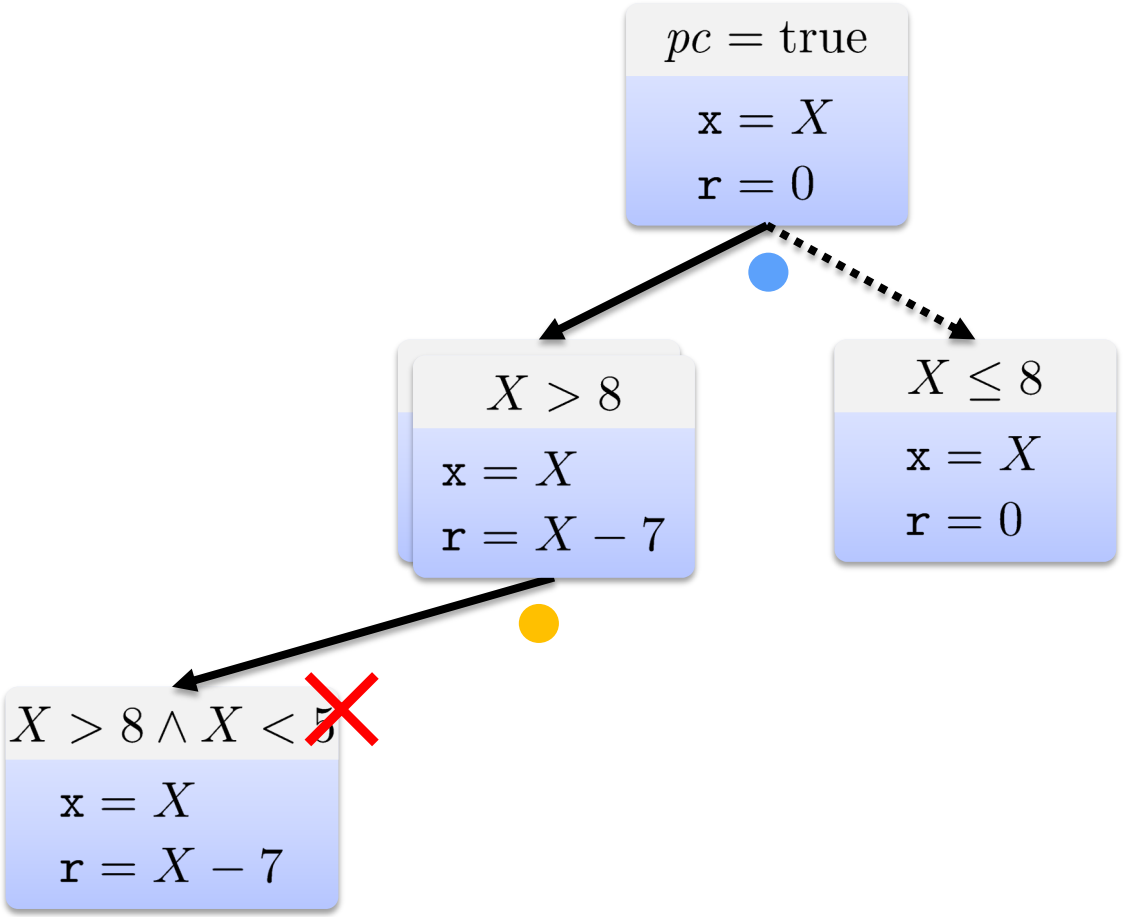

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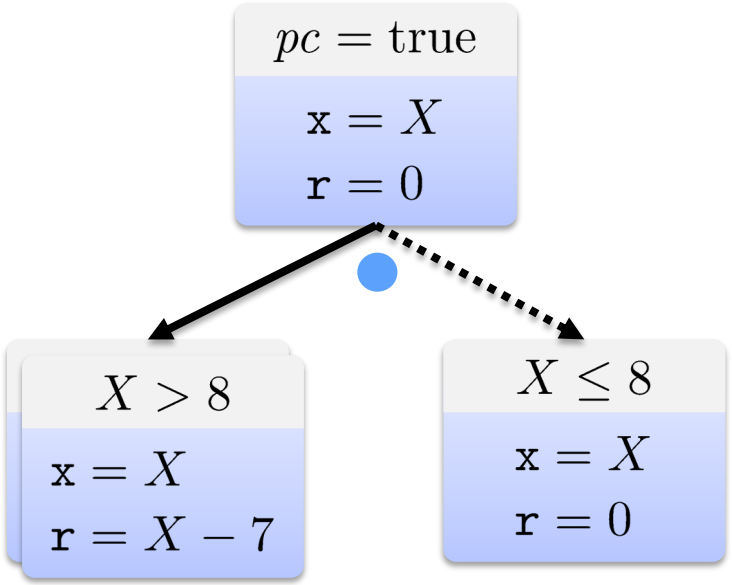

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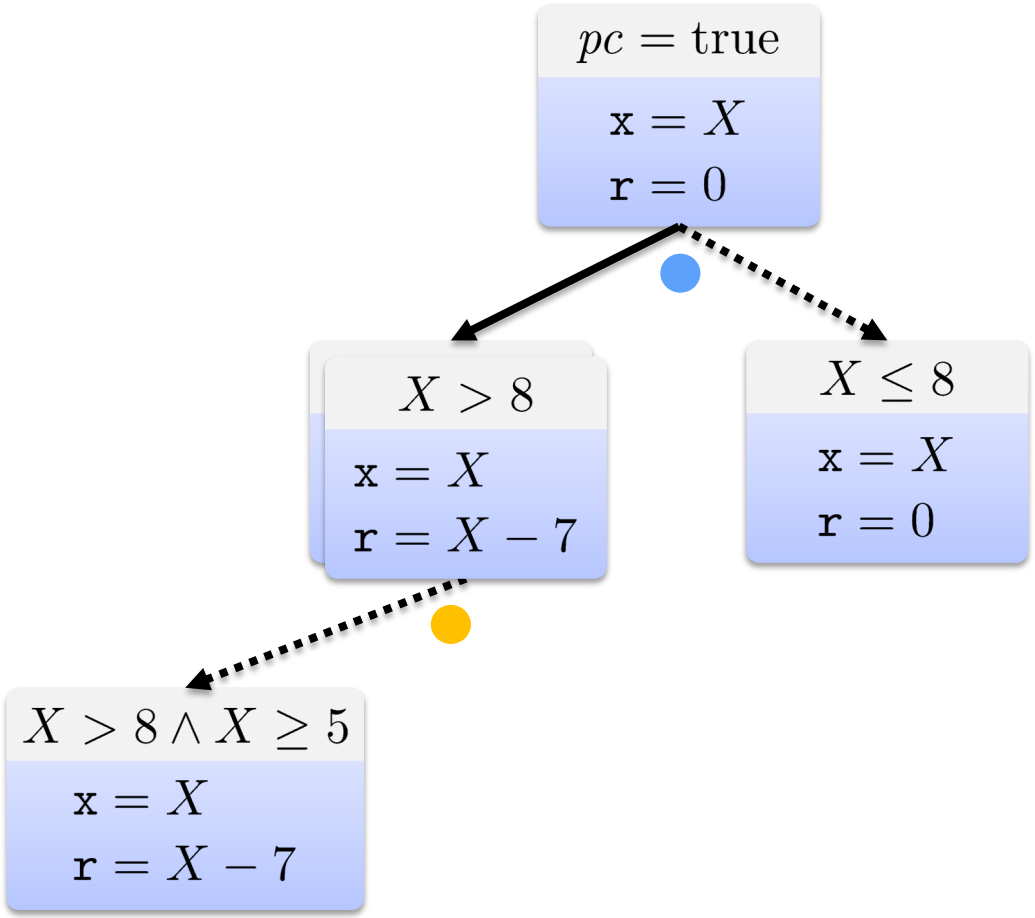

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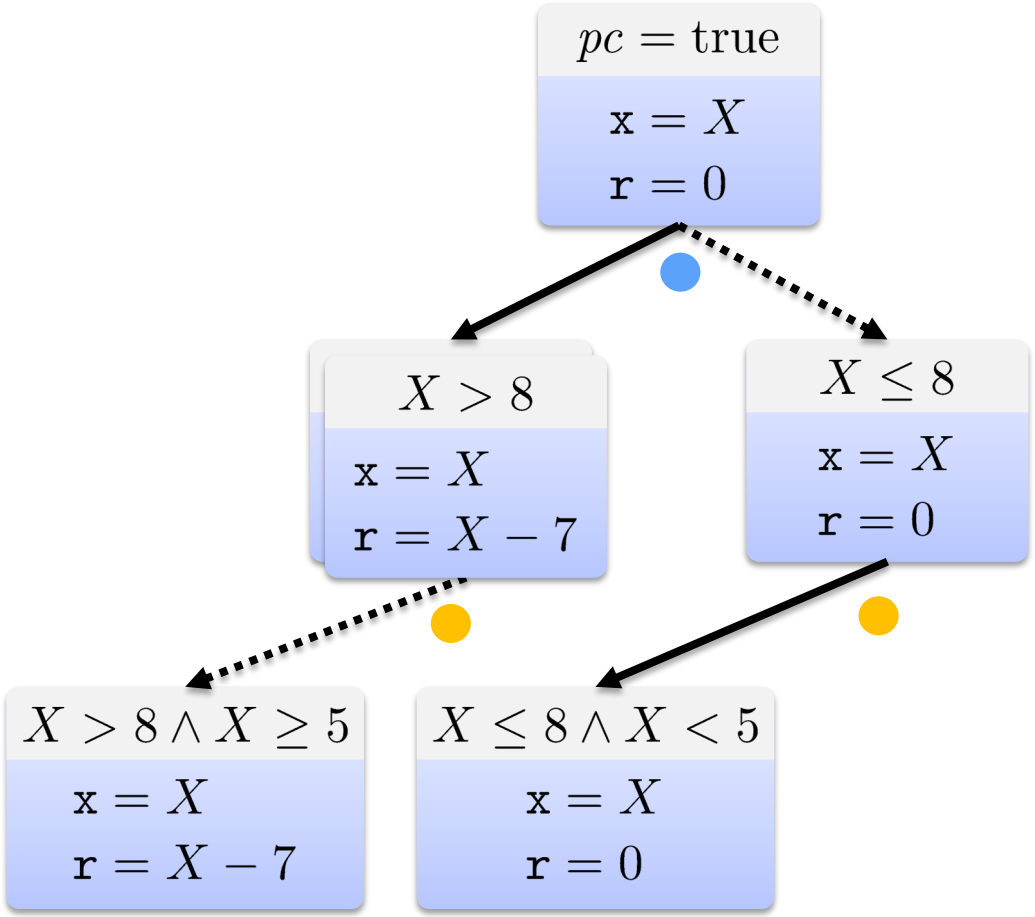

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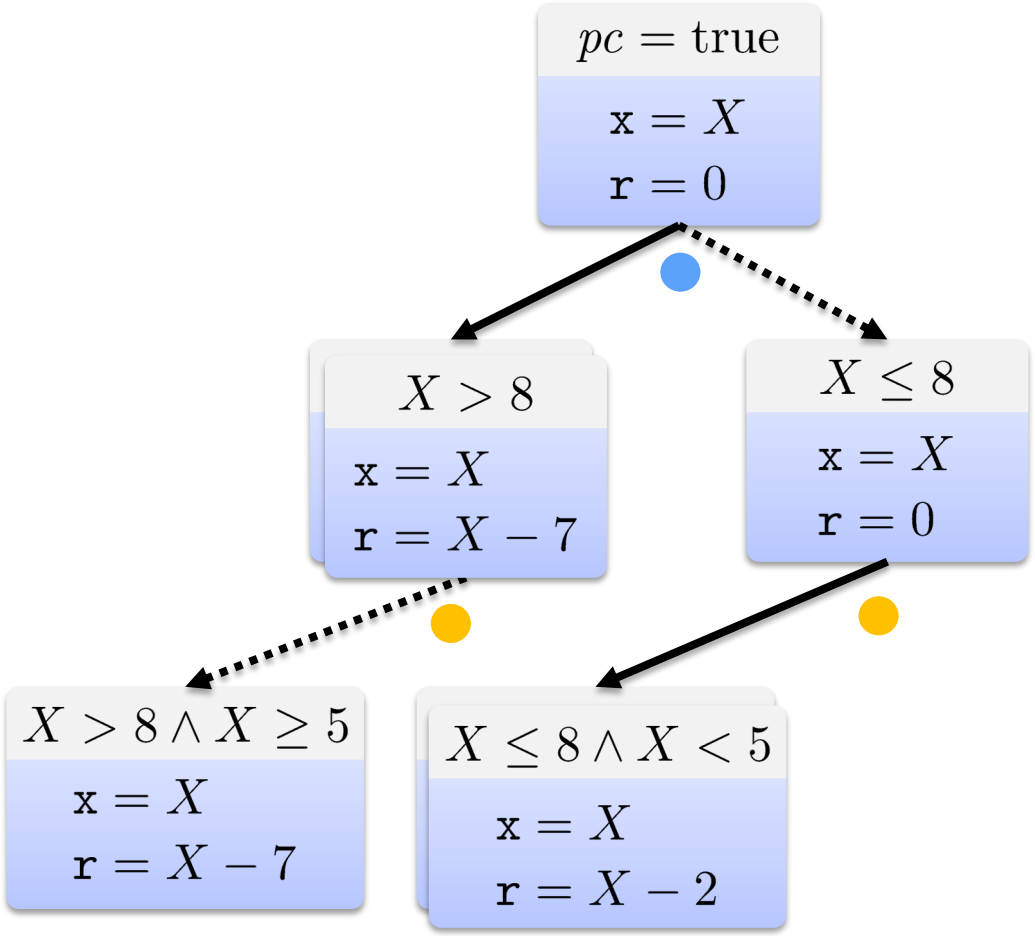

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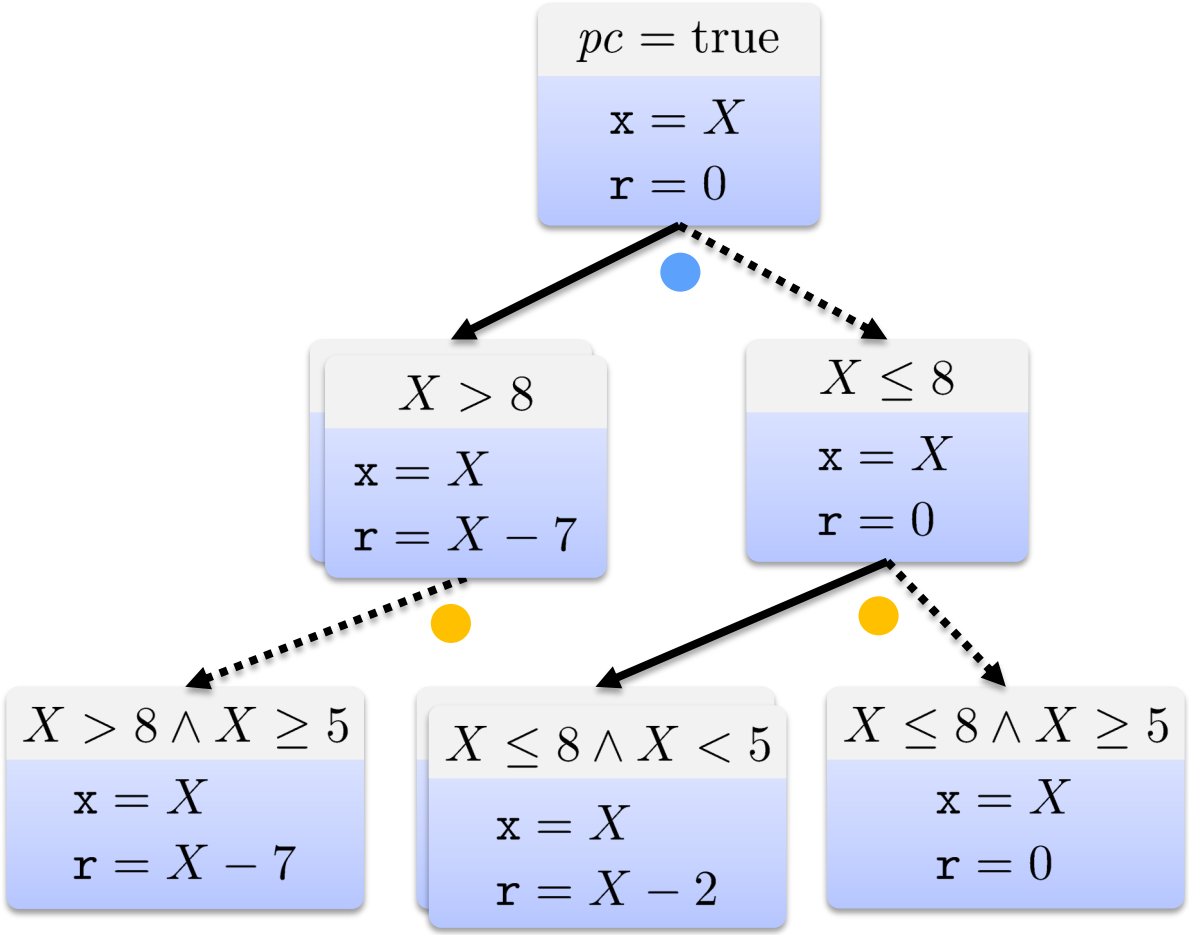

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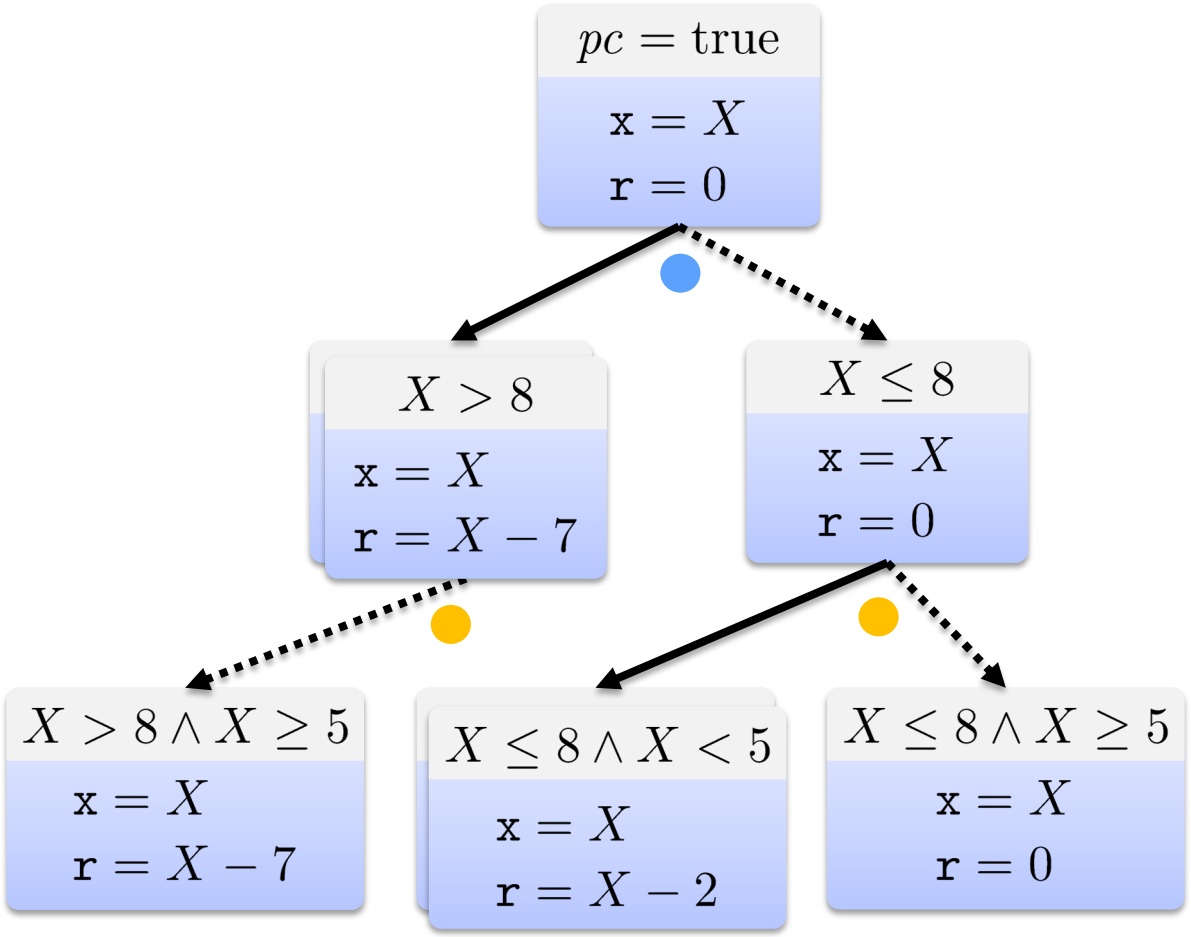


Satisfying assignments:

X = 9 X = 4 X = 7

Test cases:

proc(9) proc(4) proc(7)

Symbolic Execution

Analysis of programs by tracking symbolic rather than actual values

- a form of Static Analysis

Symbolic reasoning is used to reason about *all* the inputs that take the same path through a program

Builds constraints that characterize

- conditions for executing paths
- effects of the execution on program state

Symbolic Execution

Uses symbolic values for input variables.

Builds constraints that characterize the conditions under which execution paths can be taken.

Collects **symbolic path conditions**

- a path condition for a path P is a formula PC such that PC is satisfiable if and only if P is executable

Uses theorem prover (**constraint solver**) to check if a path condition is satisfiable and the path can be taken.

Symbolic Execution: Alternative Explanation

Symbolic execution creates a functional representation of each path in a Control Flow Graph of a program

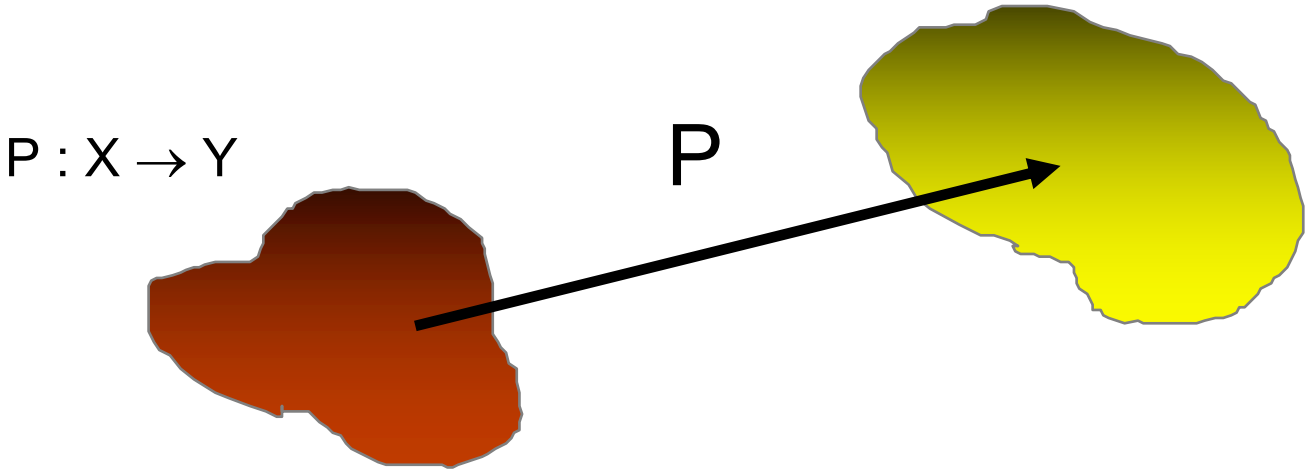
- i.e., each program path becomes a function from inputs to outputs

Notation:

For a program path P (i.e, a sequence of instructions)

- D[P] is the domain for path P
  - the inputs that force the program to take path P_i
- C[P] is the computation for path P
  - the result of executing the path

Program as a Function



Program P is composed of partial functions corresponding to the executable paths

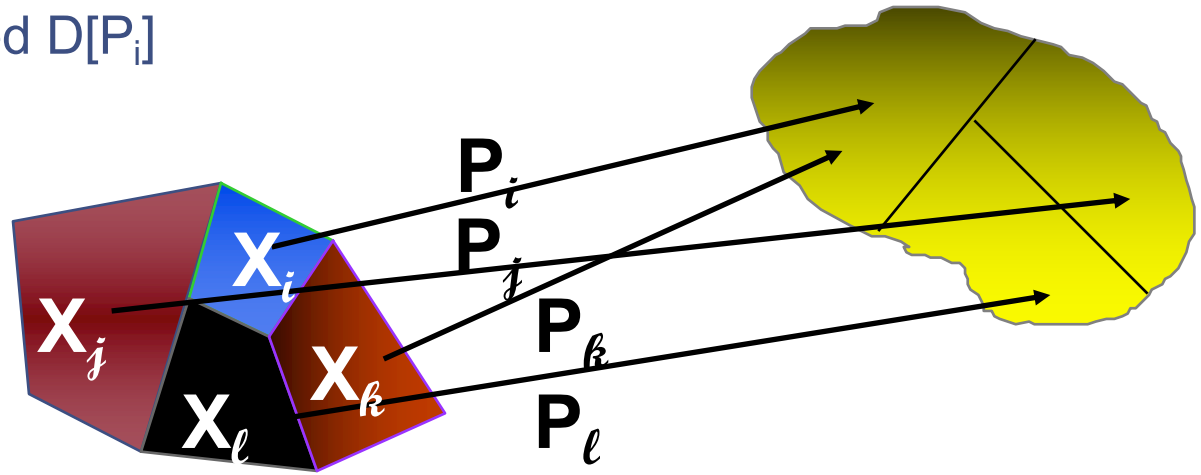
$P = \{P_1,...,P_r\}$

Each partial function $P_i : X_i \rightarrow Y$ maps some part of the input of the program to the output

Effect of Symbolic Execution

X_i is the domain of path P_i

Denoted $D[P_i]$



$X = D[P_1] \cup ... \cup D[P_r] = D[P]$

$D[P_i] \cap D[P_j] = \emptyset,\ i \neq j$

Exercise: Find a Violation

```
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);
```

$$true$$
$$x = 0, y = 0, z = 0$$

Common to all states:

$$a = A, b = B, c = C$$

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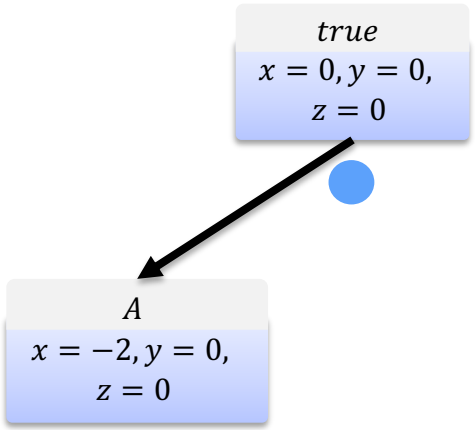

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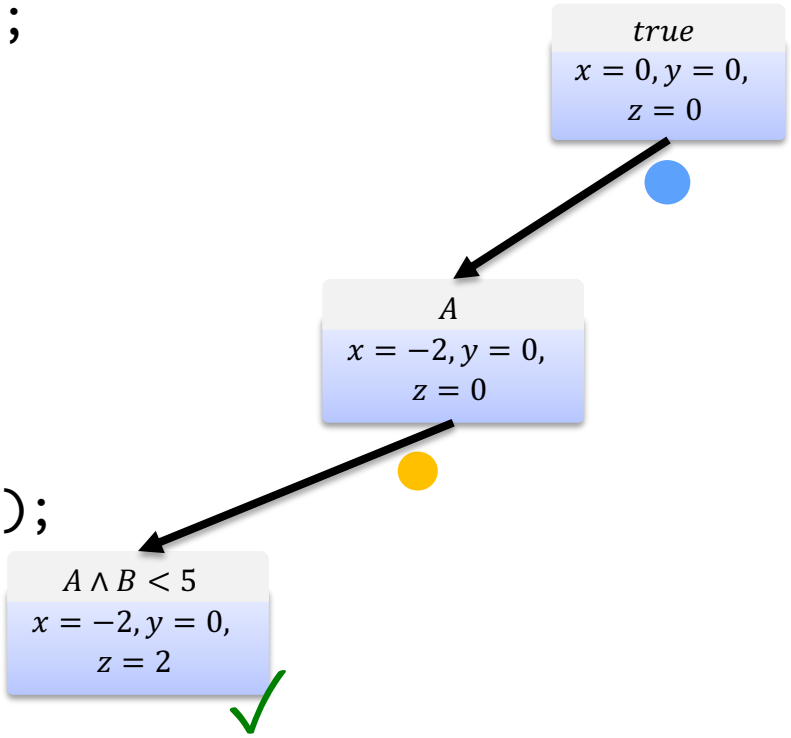

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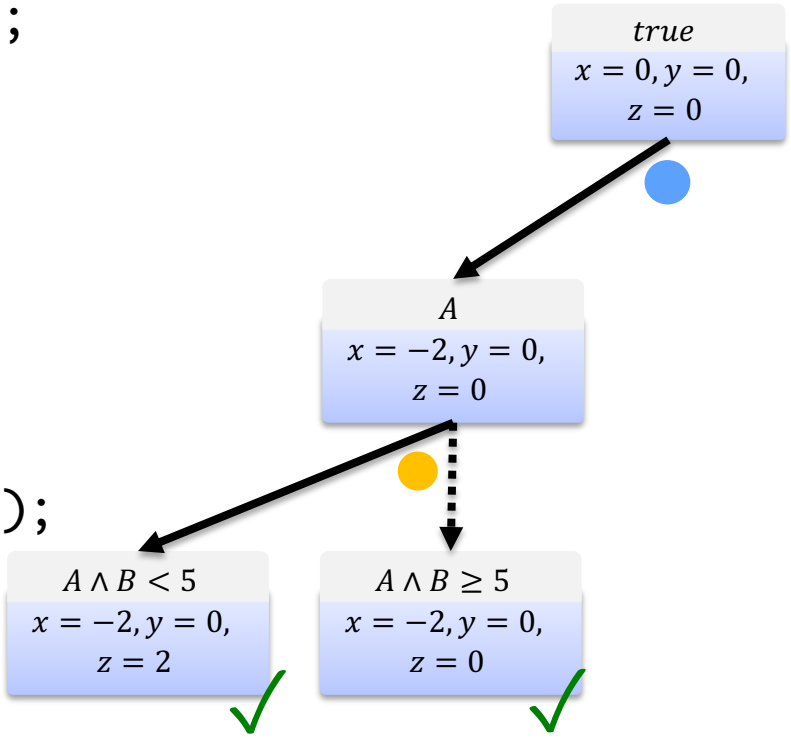

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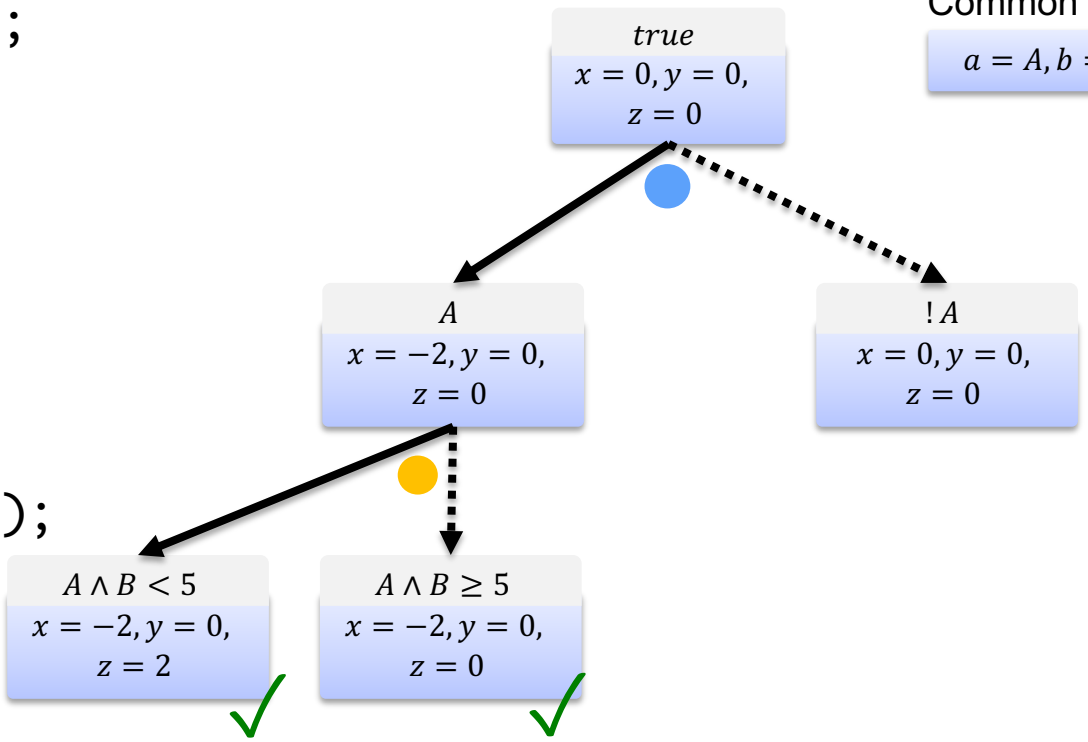

Exercise: Use SymExec to Find a Violation

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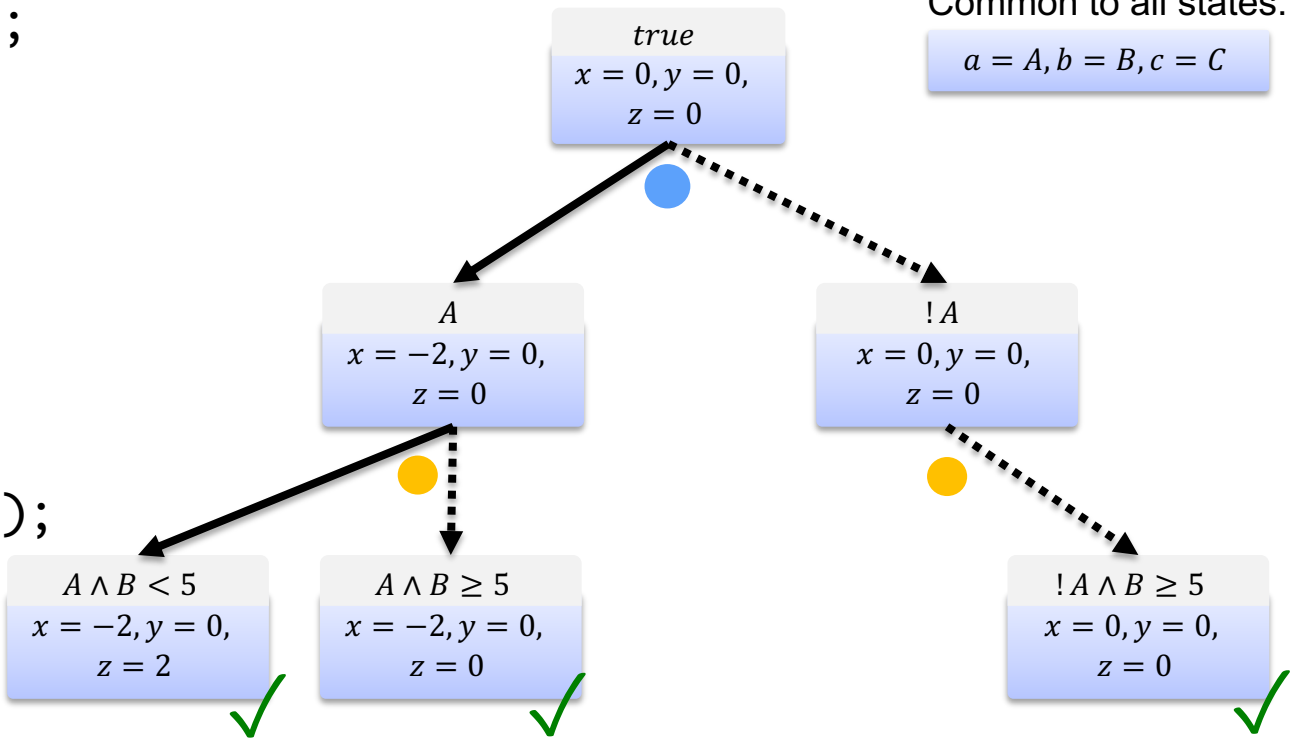

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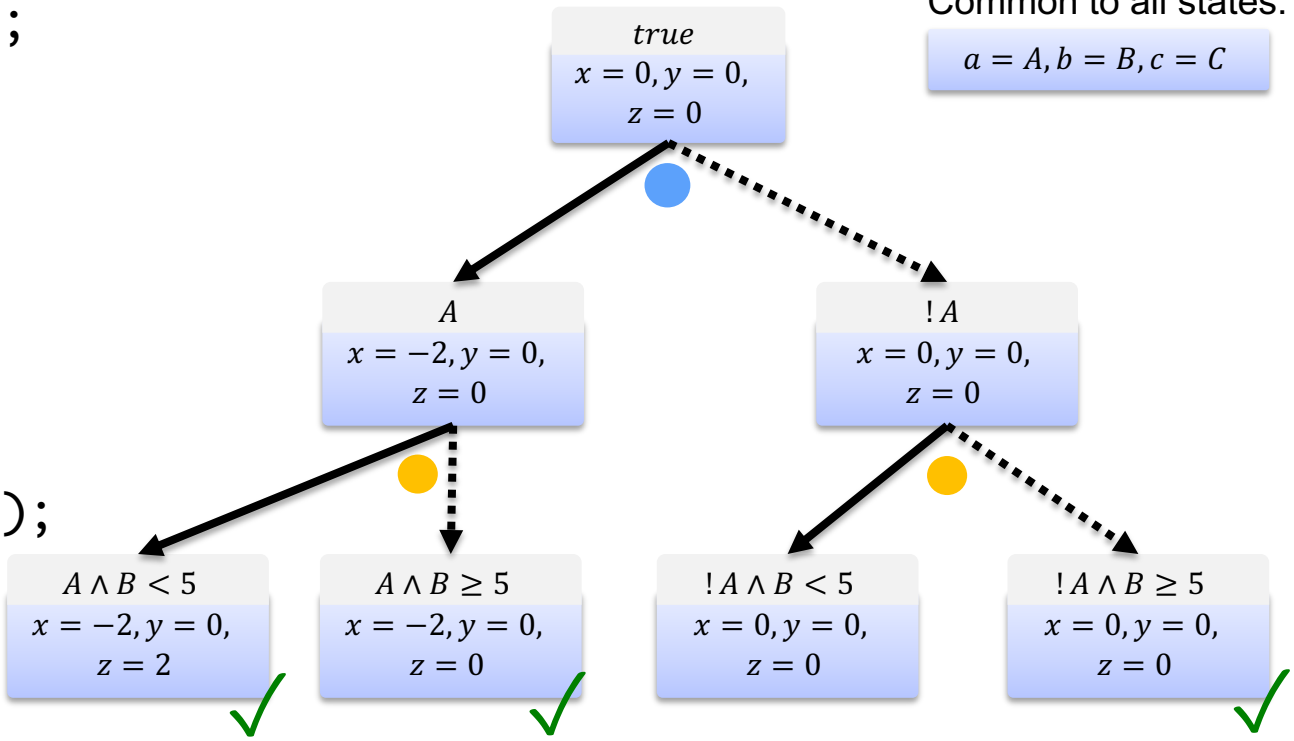

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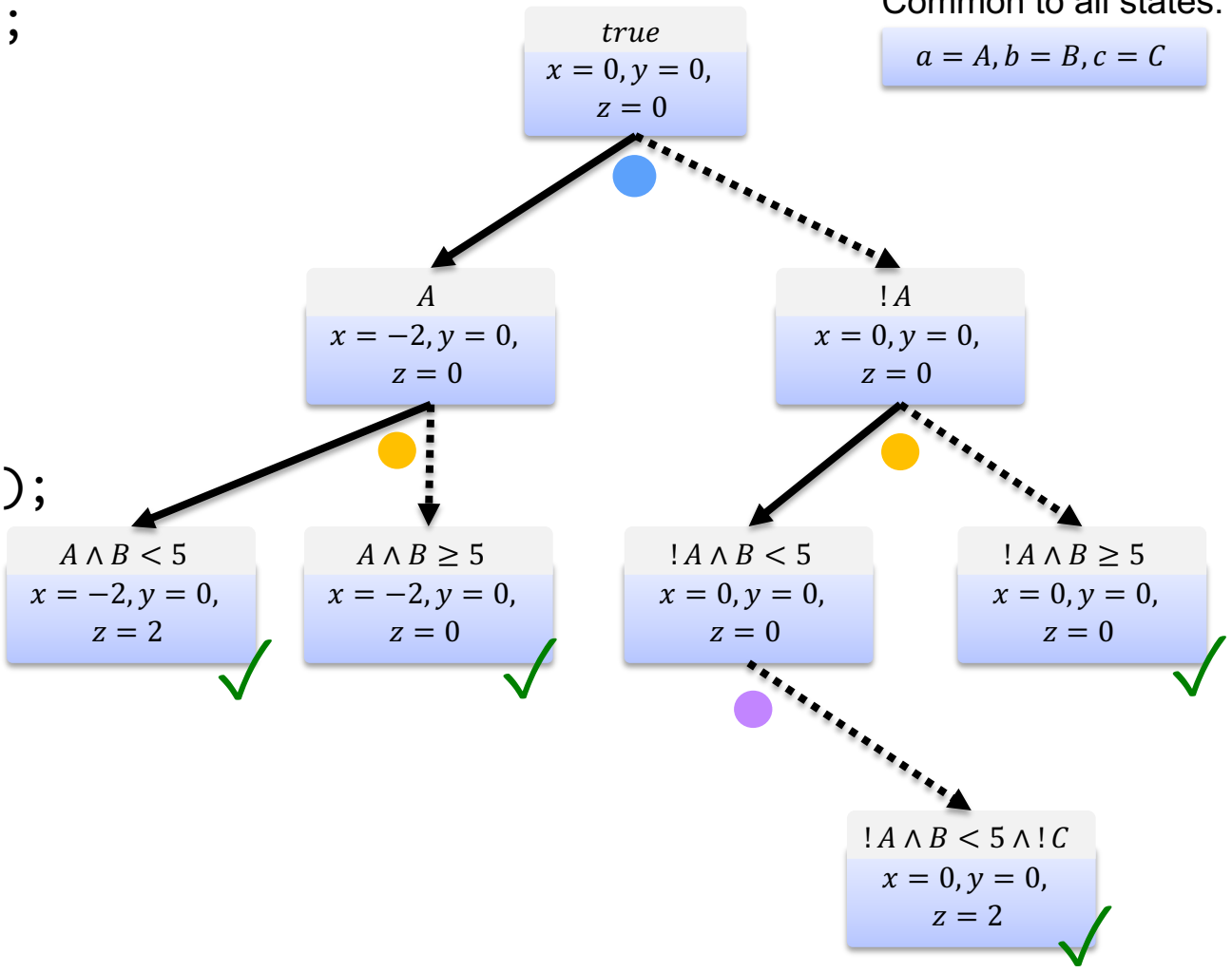

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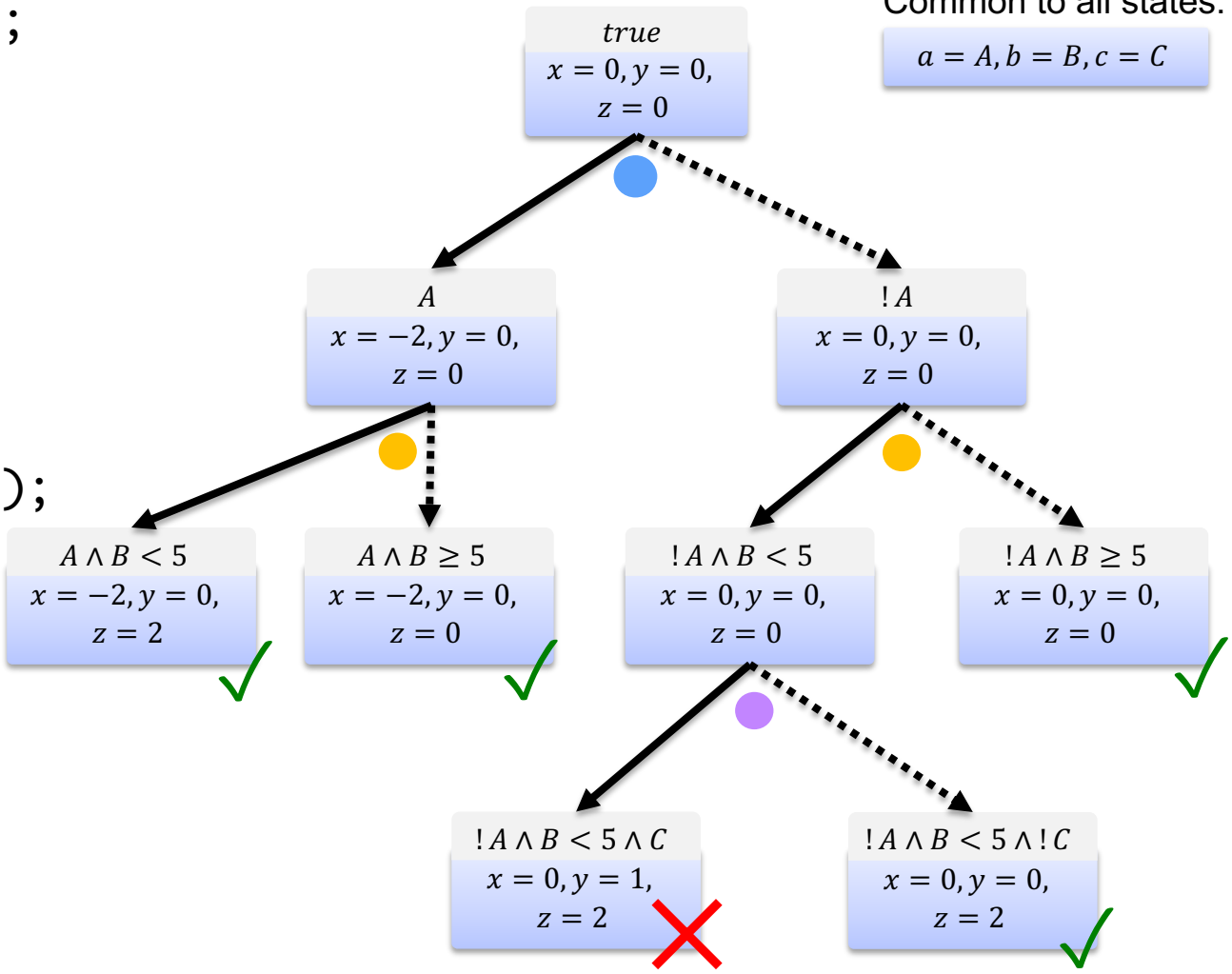

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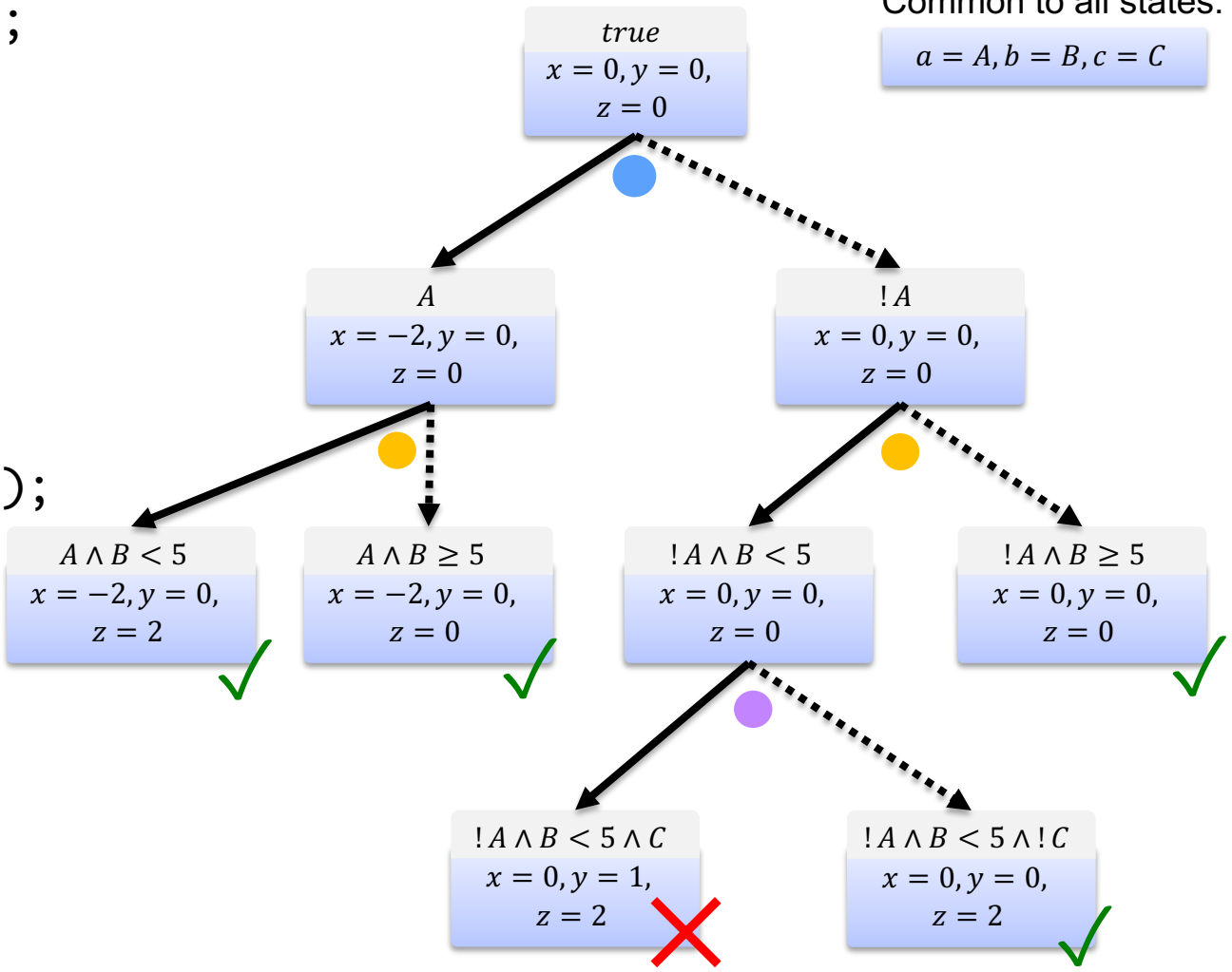

a = false, b = 2, c = true -> x = 0, y = 1, z = 2 : assert(0+1+2 != 3)

Finding Bugs using Symbolic Execution

Symbolic execution enumerates paths

- Runs into bugs that trigger whenever path executes
- Assertions, buffer overflows, division by zero, etc., require specific conditions

Assertions (and other oracles) are compiled into conditionals

- Treat assertions as conditions
- Creates explicit error paths
- Bug exists if error() call is reachable

```
assert x != NULL
```

```
if (x == NULL)
    error();
```

Finding Bugs with Symbolic Execution

Instrument program with properties

- Translate any safety property to reachability
- Same as fuzzing

Division by zero

```
y = 100 / x
```

```
assert x != 0
y = 100 / x
```

Buffer overflows

```
a[x] = 10
```

```
assert x >= 0 && x < len(a)
```

Implementation can be explicit or implicit

- explicit: like sanitizers, instrument the code with checks
- Implicit: symbolic execution engine injects extra checks at runtime

Problems of (Classical) Symbolic Execution

Some code is hard to analyze

- it is surprising how hard it can be to solve even very simple-looking constraints
- some code (e.g., crypto hash) is provably hard to invert

Path explosion

- Number of paths is exponential in the size of the program
- control flow, loops, procedures, concurrency, …

Inputs: real code has more than just integers!

- pointers, data structures, …
- files, databases, …
- threads, thread schedules, …
- sockets, …