# Symbolic Execution

Testing, Quality Assurance, and Maintenance
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based on slides by Prof. Johannes Kinder and others

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# Symbolic Execution

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

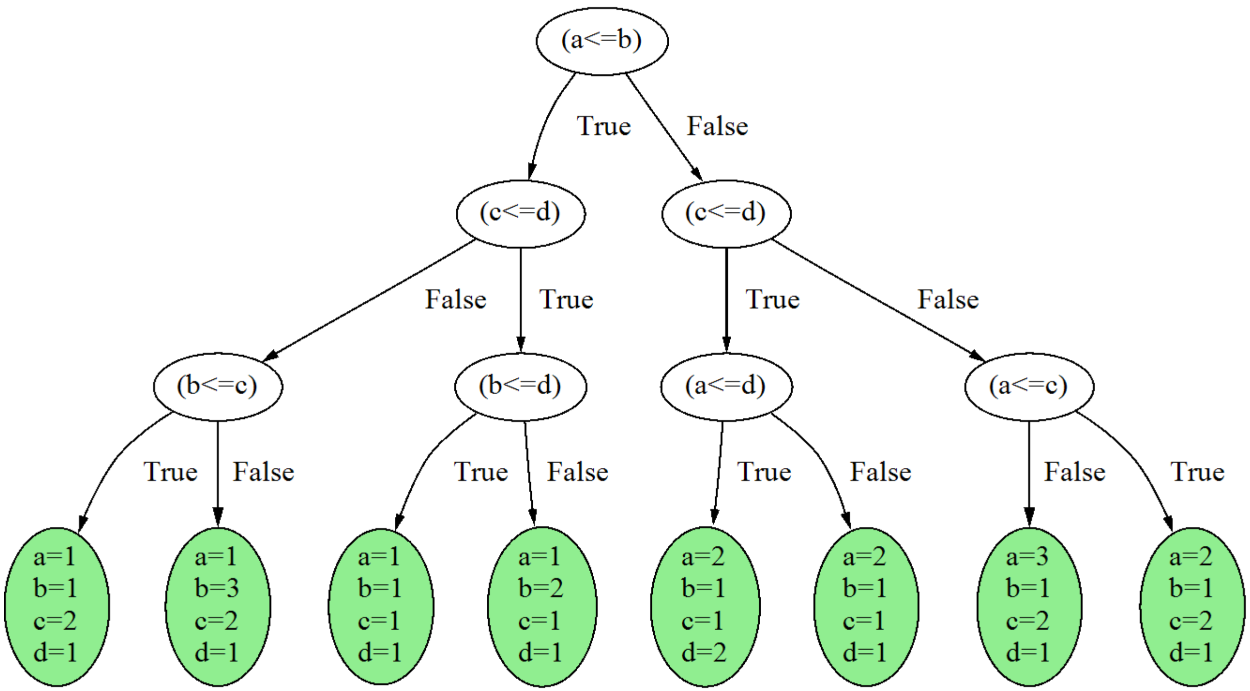
Conceptual breakthroughs (Dynamic Symbolic Execution)

- 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;
}
```



# Checking Path Feasibility

```
(declare-fun a () Int)
(declare-fun b () Int)
(declare-fun c () Int)
(declare-fun d () Int)
(assert (< 0 a))
(assert (< 0 b))
(assert (< 0 c))
(assert (< 0 d))
(assert (<= a b))
(assert (> b c))
(assert (> c d))
(check-sat)
(get-model)
```

▶ tutorial home

'▶' sh

```
at
model
 (define-fun b () Int
   3)
 (define-fun a () Int
   1)
 (define-fun c () Int
   2)
 (define-fun d () Int
   1)
```

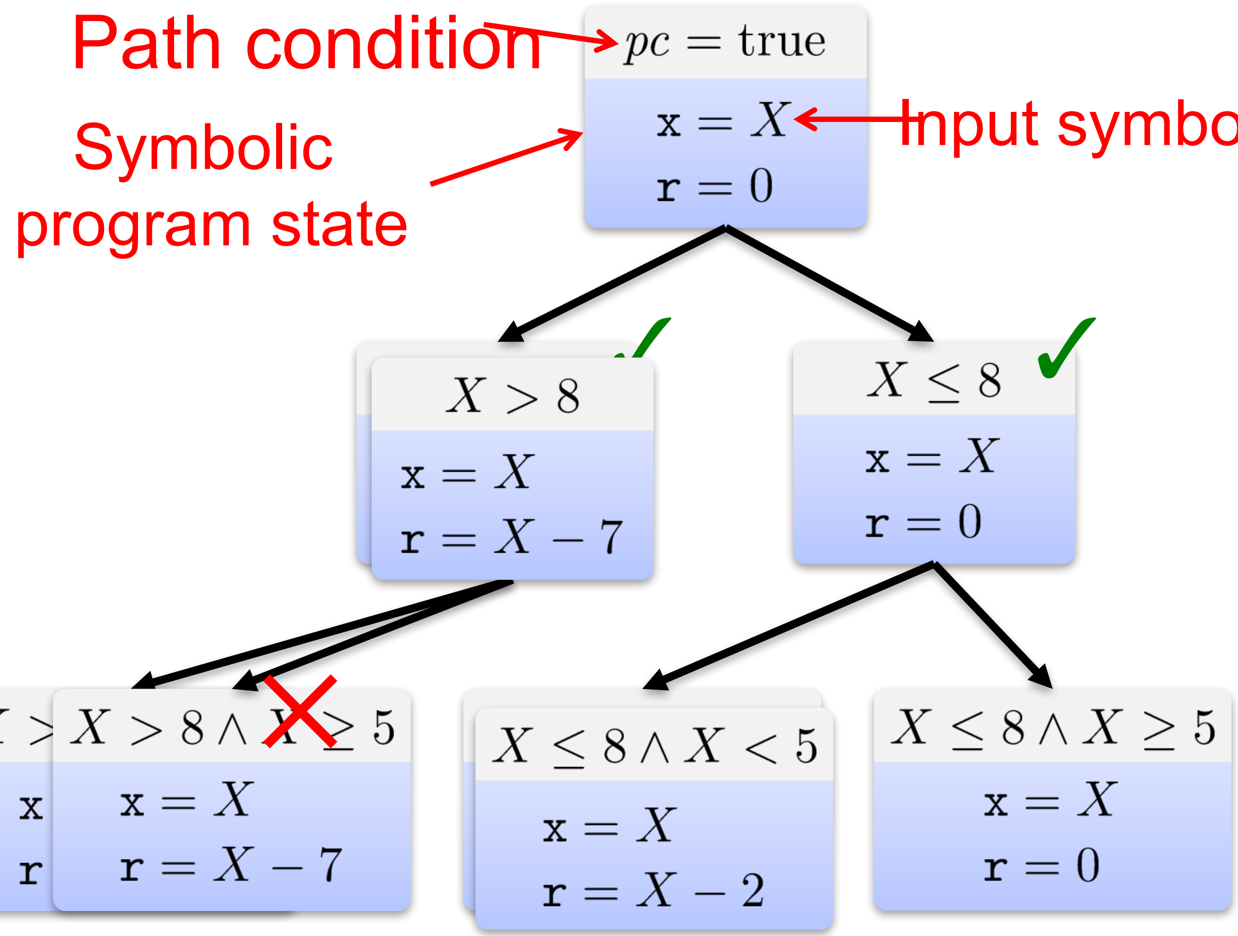
```
int proc(int x) {

 int r = 0

 if (x > 8) {
   r = x - 7
 }

 if (x < 5) {
   r = x - 2
 }

 return r
}
```




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 State

A ***symbolic state*** is a pair S = (Env, PC), where

- Env : L -> E is a mapping, called an ***environment***, from program variables to symbolic expressions (i.e., FOL terms)
- PC is a FOL formula called a ***path condition***

A concrete state M : L -> Z satisfies a symbolic state S = (Env, PC) iff

$$M \models (Env, PC) \text{ iff } \left( \left( \bigwedge_{v \in L} M(v) = Env(v) \right) \wedge PC \text{ is SAT} \right)$$

Program semantics are extended to symbolic states

- each program statement updates symbolic variables and
- extends the path condition to reflect its operational semantics

# Example: Symbolic State Satisfiability

$$Env = \begin{cases} x \mapsto X \\ y \mapsto Y \end{cases} \qquad PC = X > 5 \land Y < 3$$

$$[x \mapsto 10, y \mapsto 1] \models ?S \qquad [x \mapsto 1, y \mapsto 10] \models ?S$$

$$Env = \begin{cases} x \mapsto X + Y \\ y \mapsto Y - X \end{cases} \qquad PC = 2 * X - Y > 0$$

$$[x \mapsto 10, y \mapsto 1] \models ?S \qquad [x \mapsto 1, y \mapsto 10] \models ?S$$

# Symbolic Evaluation/Execution

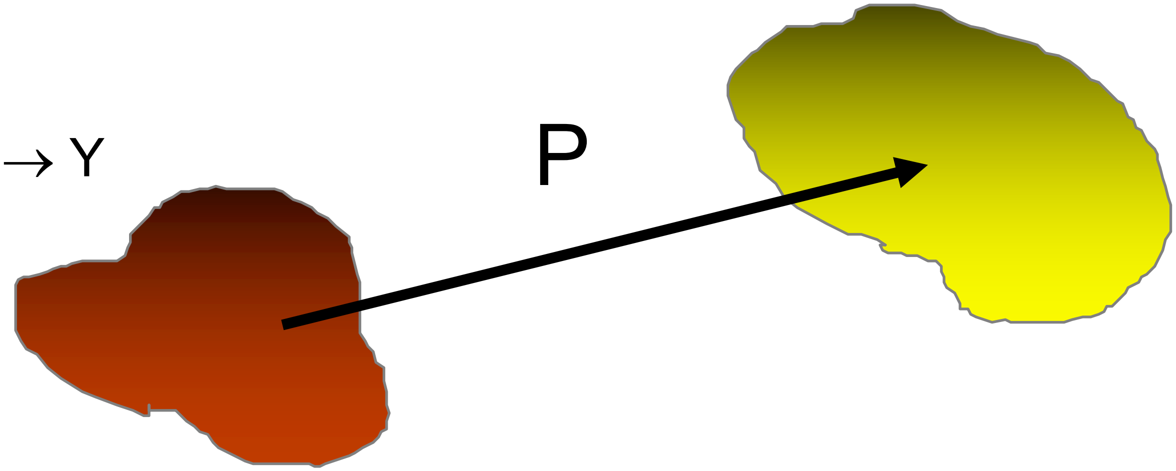
Symbolic execution creates a functional representation of a path in a Control Flow Graph of a program

For a path $P_i$

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

# Functional Representation of an Executable Component

$P : X \rightarrow Y$




P is composed of partial functions corresponding to the executable paths

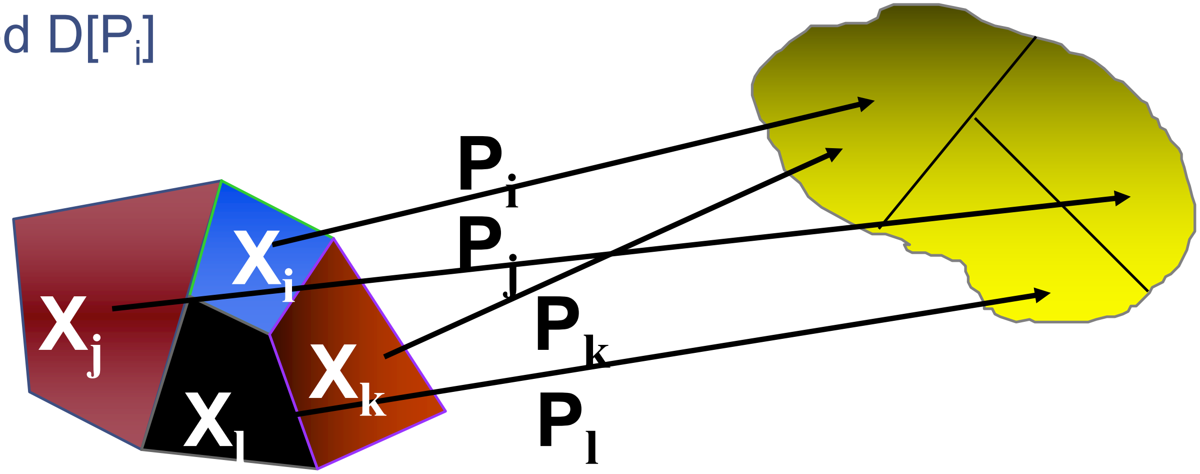
$P = \{P_1, \ldots, P_r\}$

$P_i : X_i \rightarrow Y$

# Functional Representation of an Executable Component

$X_i$ 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);
```

**a = α, b = β, c = γ**

x=0, y=0, z=0

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int x=0, y=0, z=0;
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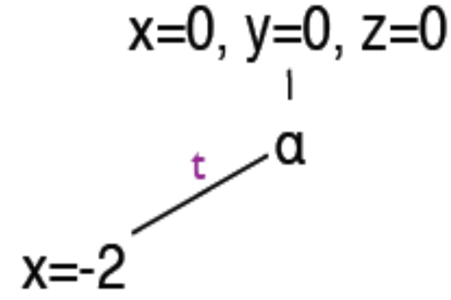

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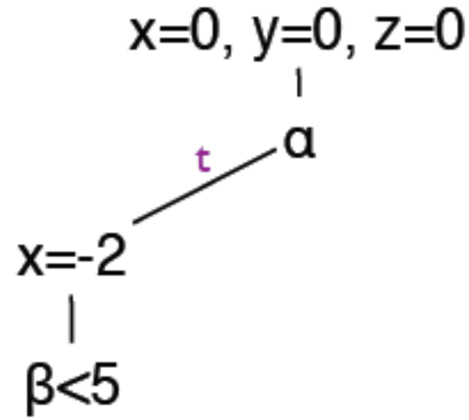

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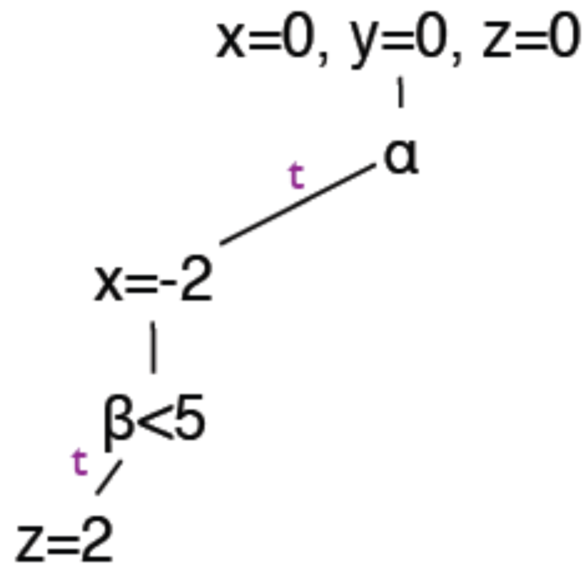

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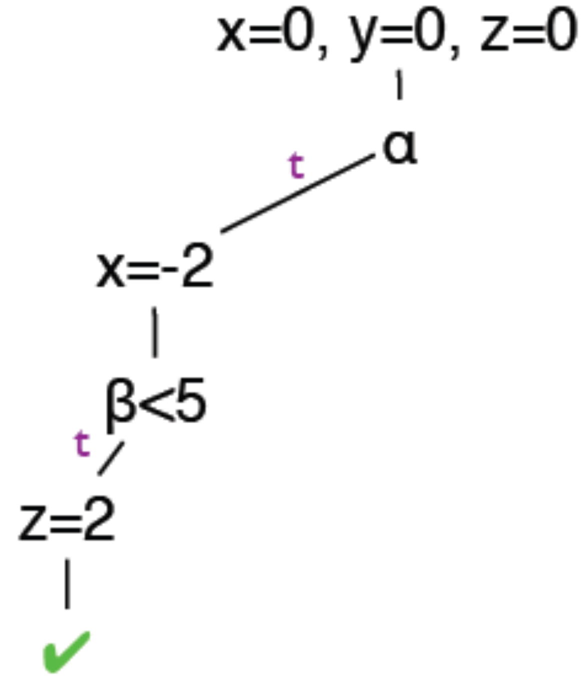

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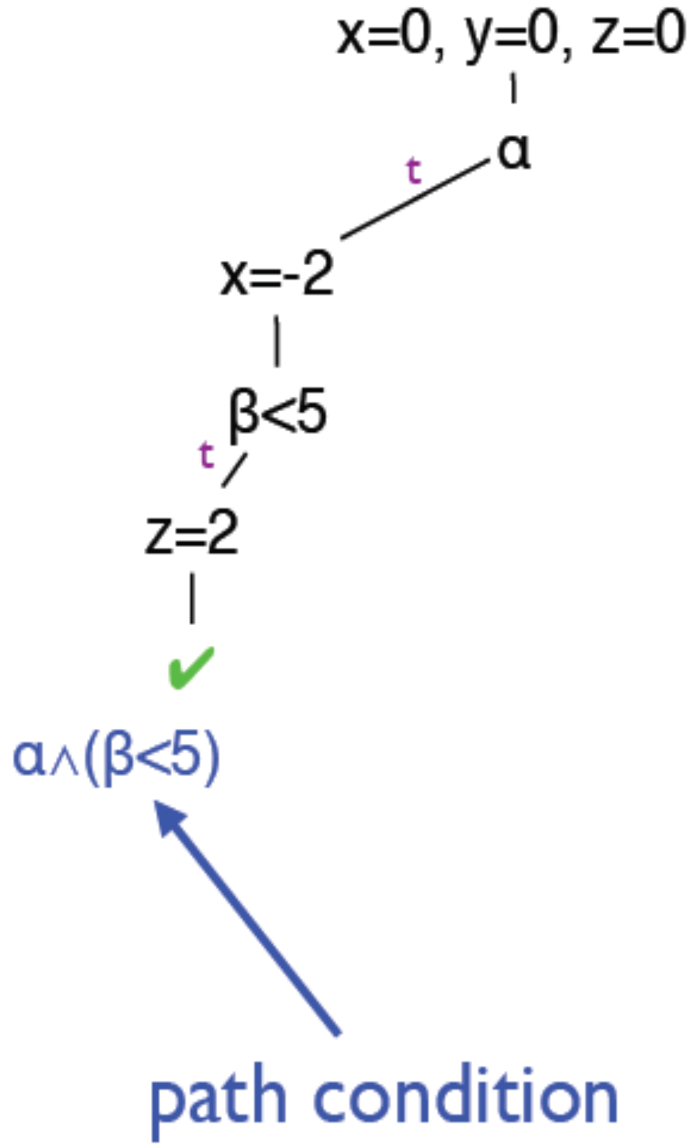

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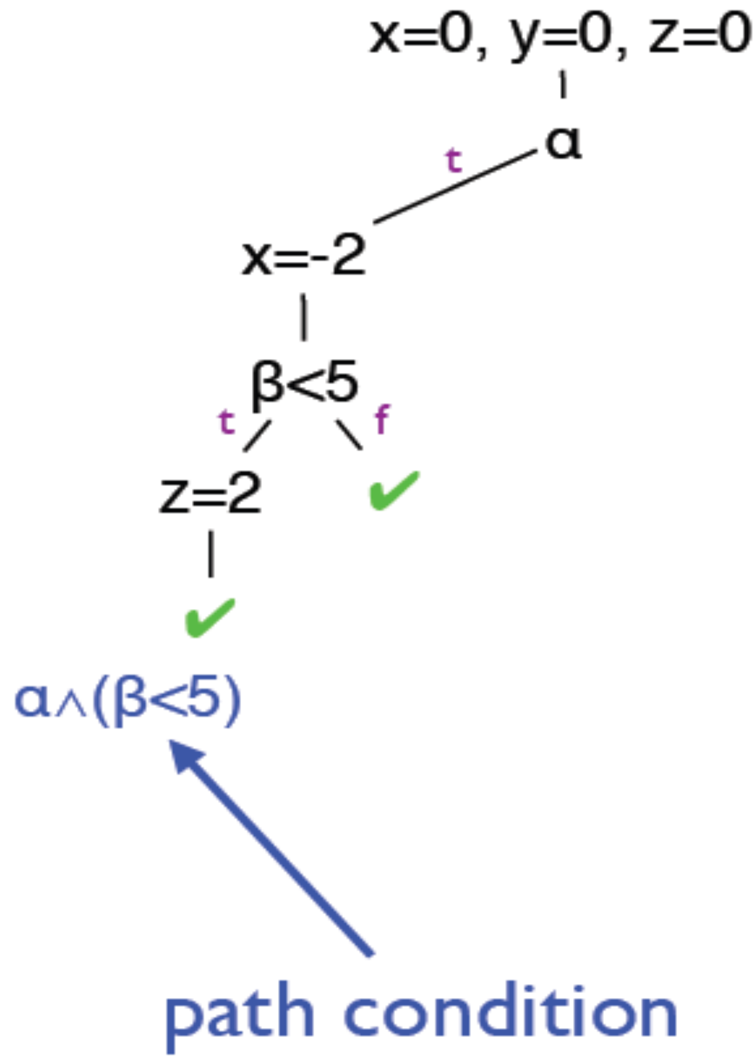

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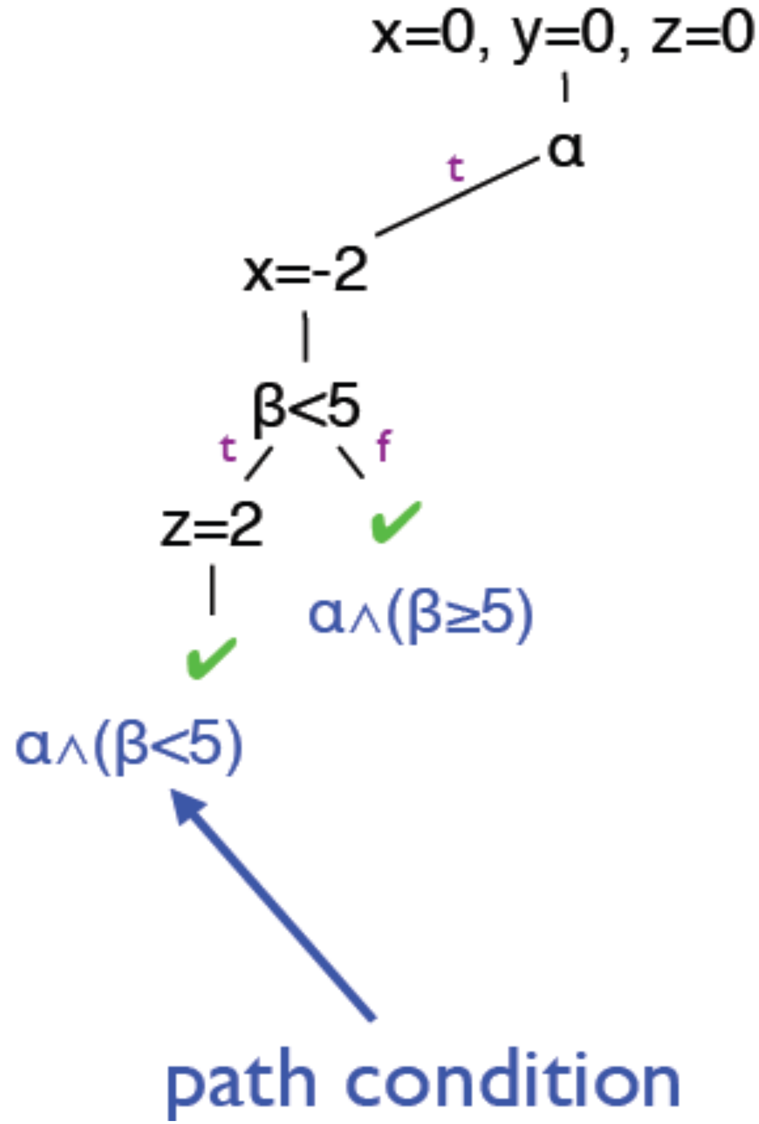

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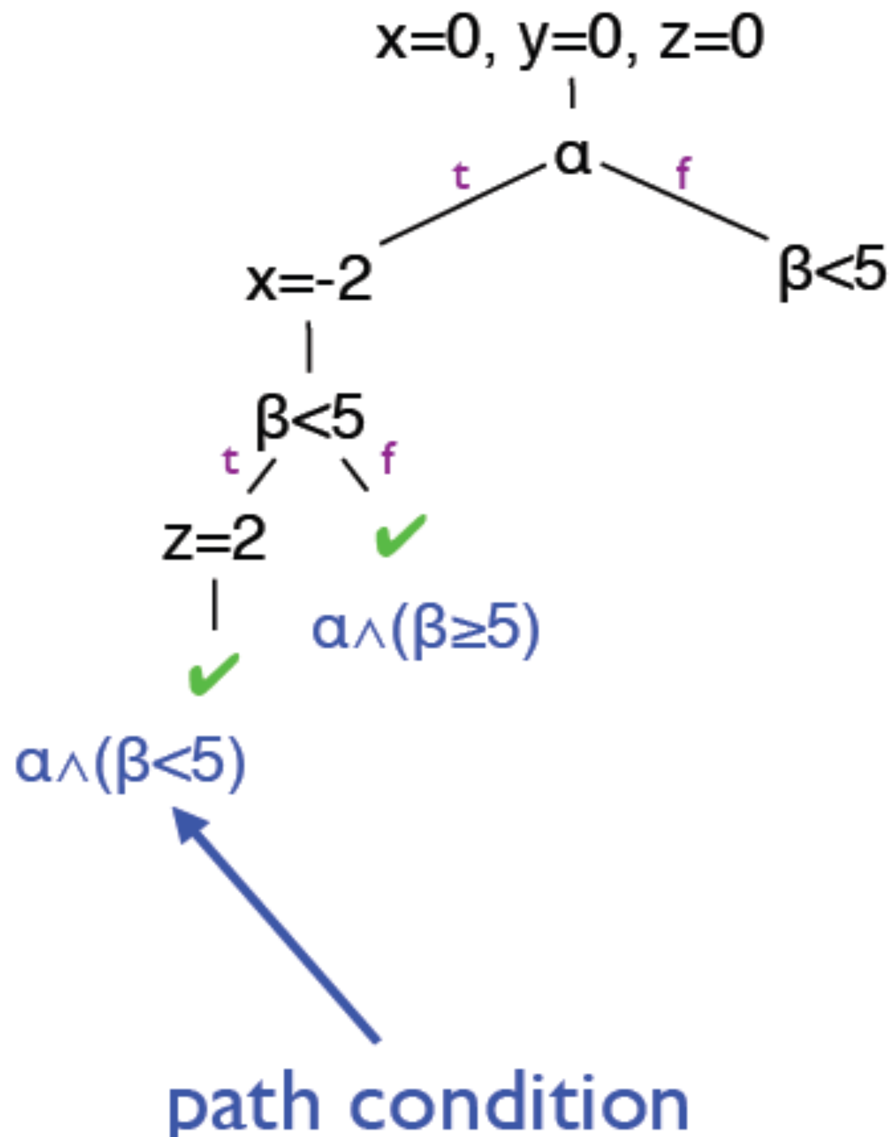

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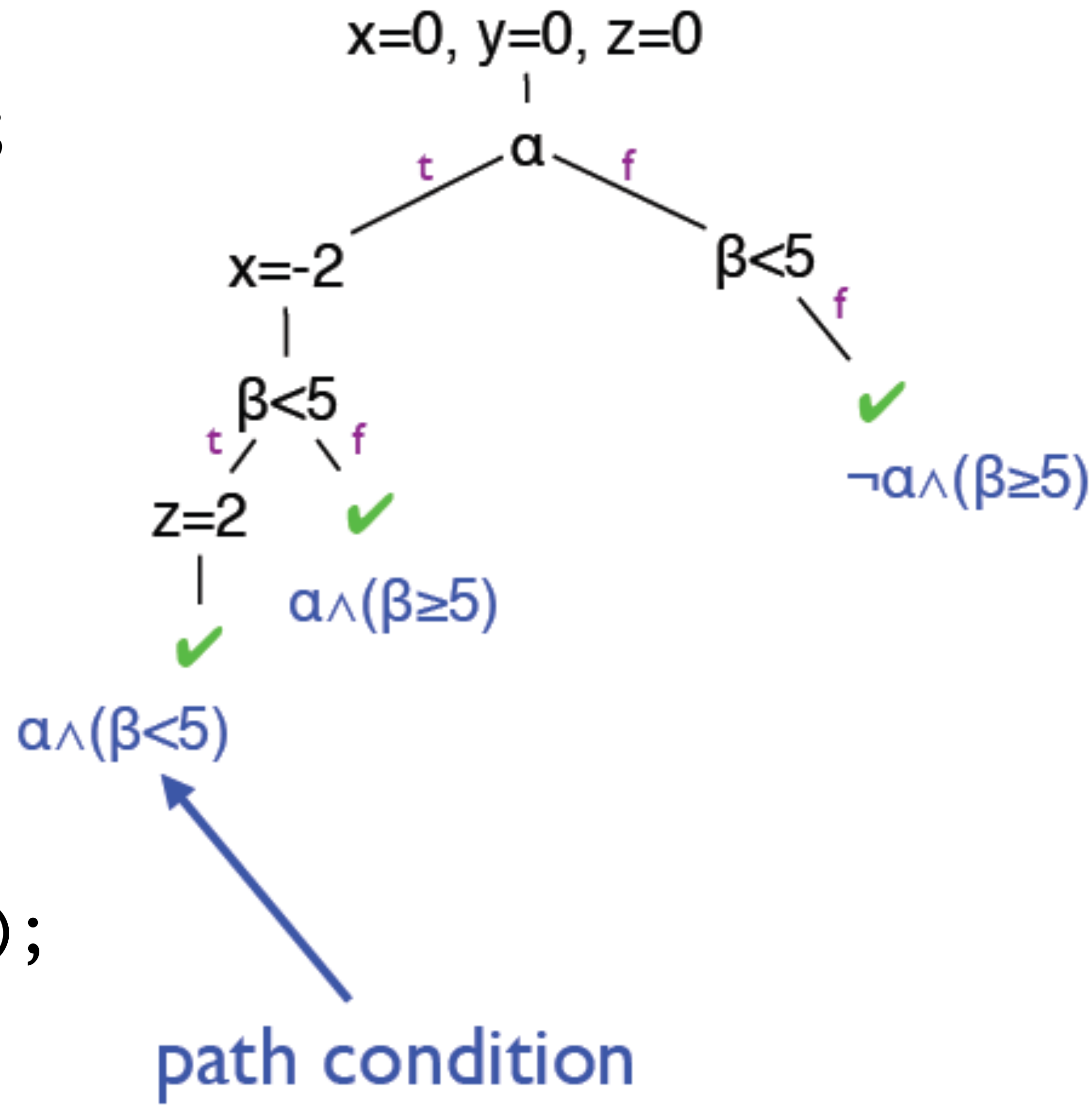

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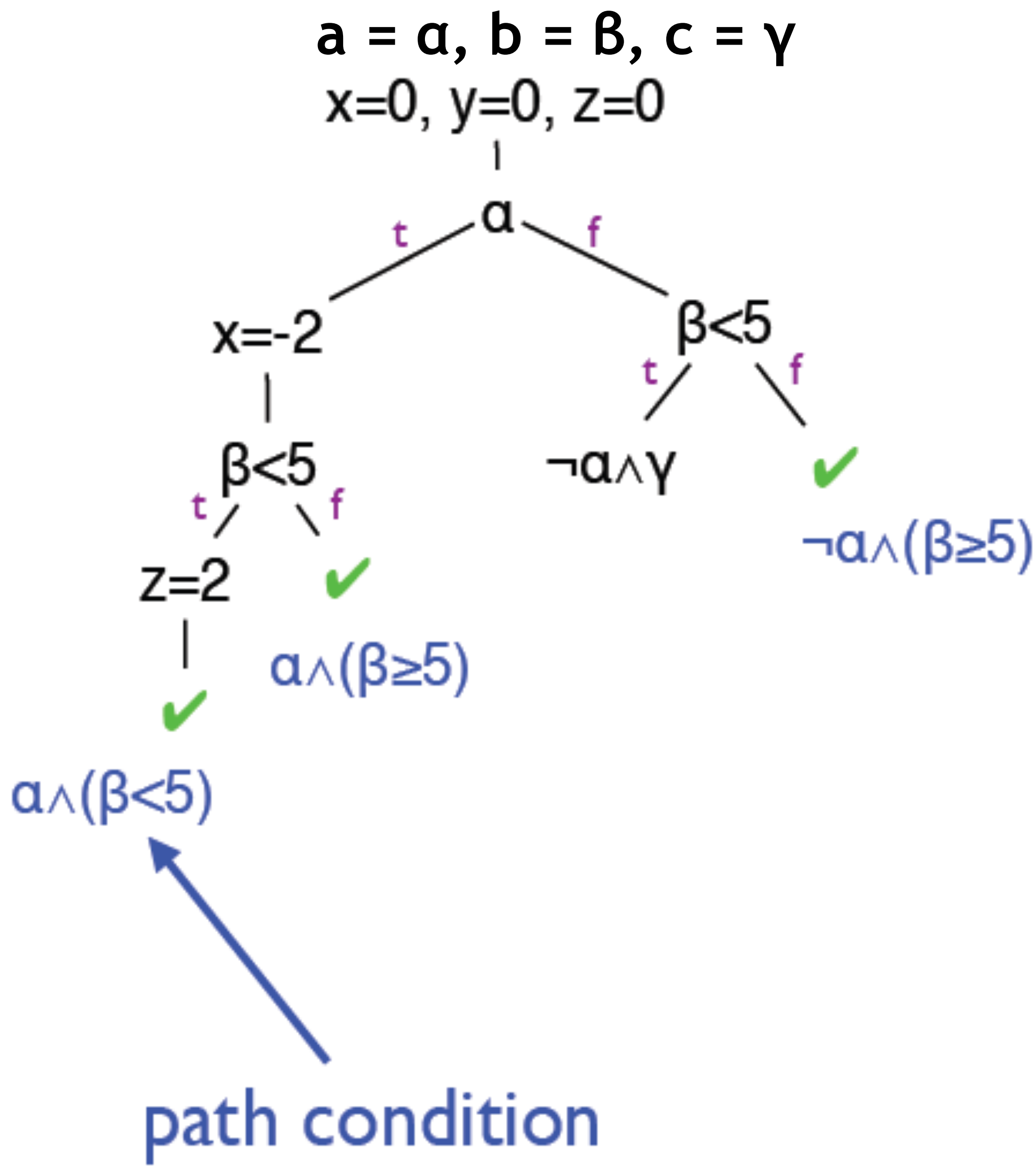

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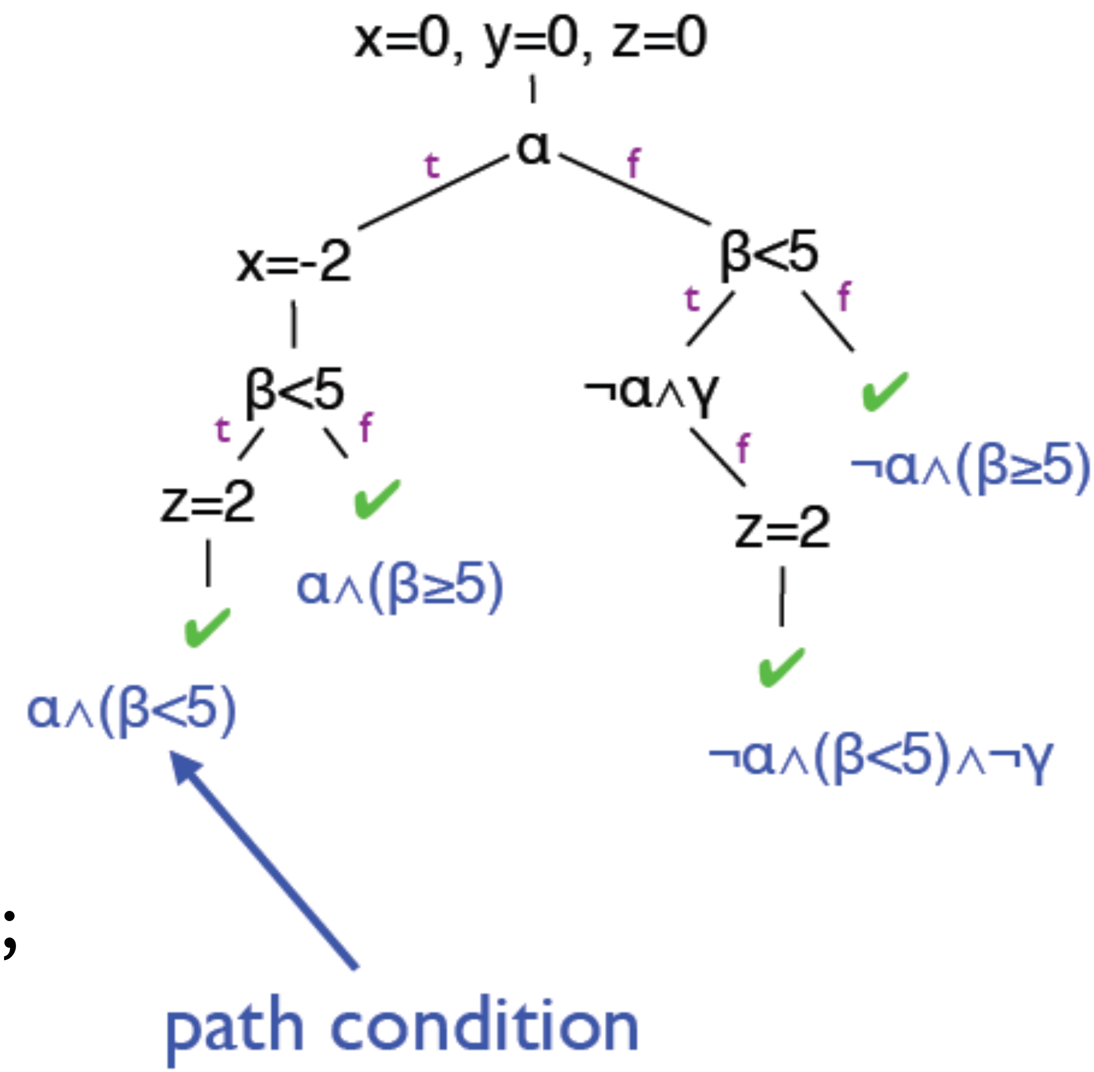

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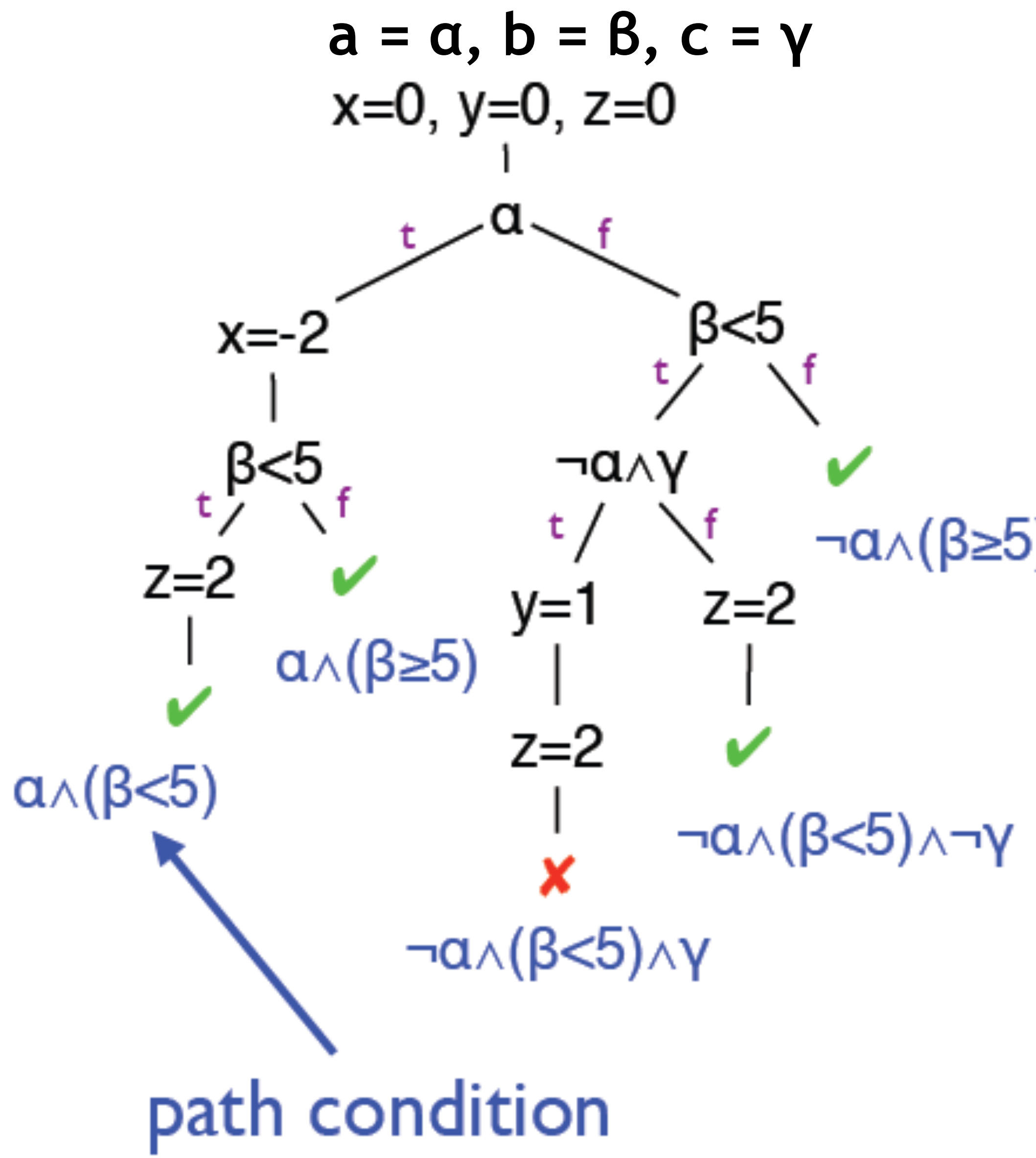

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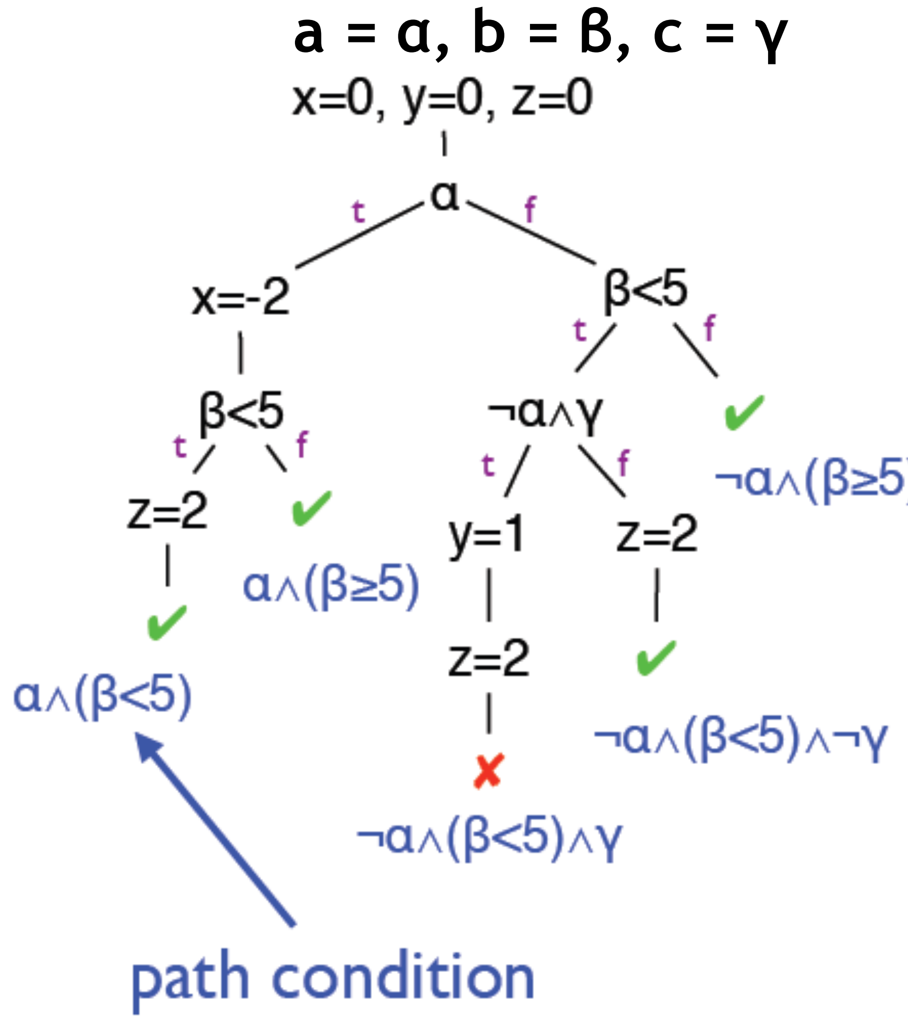


**a = false, b = 2, c = true -> x = 0, y = 1, z = 2 : Assert(0+1+2 != 3)**

# Finding Bugs

Symbolic execution enumerates paths

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

Error conditions

- Treat assertions as conditions
- Creates explicit error paths

```
assert x != NULL
```

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

# Finding Bugs

Instrument program with properties

- Translate any safety property to reachability

Division by zero

```
y = 100 / x
```

→

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

Buffer overflows

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

→

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

Implementation is usually implicit

# Many problems remain

Code that is hard to analyze

Path explosion

- Complex control flow
- Loops
- Procedures

Environment (what are the inputs to the program under test?)

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