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# Software Engineering 2

## Static analysis in practice

## Symbolic Execution

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# Verification & Validation

Static analysis in practice

# Static analysis tools

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- Various tools available
- The analyses are language-specific but many tools support multiple programming languages
- The first static analysis tool was a Unix utility, Lint, developed in 1978 for C programs. From this, simple static analysis is also called linting
- Lists of currently available tools are available from various sources:
  - https://en.wikipedia.org/wiki/List_of_tools_for_static_code_analysis
  - https://github.com/analysis-tools-dev/static-analysis

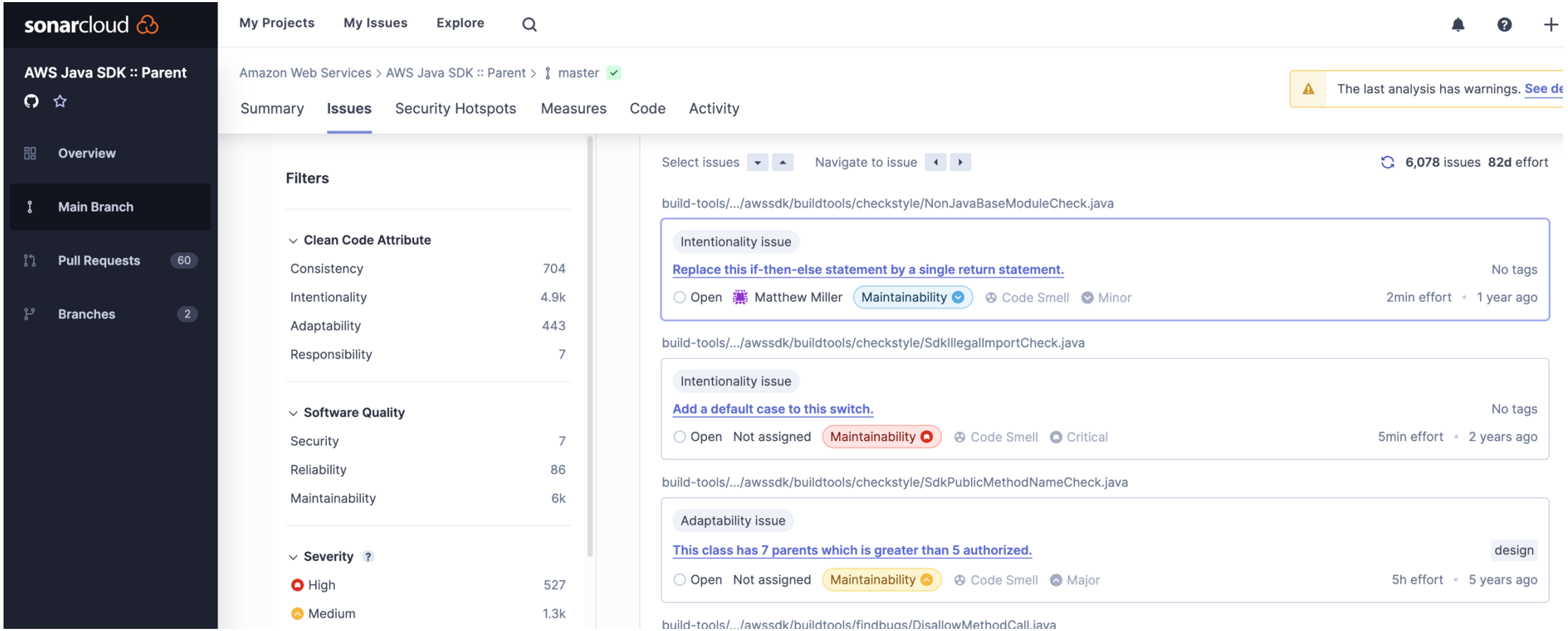
# Comparing some static analysis tools

https://www.comparitech.com/net-admin/best-static-code-analysis-tools/

| Tool/Features | SonarQube | Checkmarx | Synopsys Coverity | Micro Focus Fortify SCA | Veracode Static Analysis | Snyk Code |
|---|---|---|---|---|---|---|
| **Language Support** | Multiple | Multiple | Multiple | Multiple | Multiple | Multiple |
| **Integrations** | Various IDEs, CI/CD | Various IDEs, CI/CD | Various IDEs, CI/CD | Various IDEs, CI/CD | Various IDEs, CI/CD | Various IDEs, CI/CD |
| **Free Trial** | Yes | Yes | No | Yes | Yes | Yes |
| **On-Premises/Cloud** | Both | Both | Both | Both | Both | Cloud |
| **Automated Scans** | Yes | Yes | Yes | Yes | Yes | Yes |
| **Compliance Reporting** | Yes | Yes | Yes | Yes | Yes | Yes |
| **Vulnerability Database** | Yes | Yes | Yes | Yes | Yes | Yes |
| **Real-Time Feedback** | Yes | Yes | No | No | No | Yes |

# Example of issues report from SonarCloud/SonarQube

https://sonarcloud.io/project/issues?resolved=false&id=aws_aws-sdk-java-v2



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# Verification & Validation

## Symbolic Execution

# Static vs dynamic, again

- Static analysis
  - without executing the software
  - on generic/abstract inputs (symbolic constraints)
  - based on over-approximation
- Dynamic analysis
  - while executing the software
  - on specific/concrete inputs
  - based on concrete sequences of states

Symbolic Execution

Symbolic execution executes programs on symbolic values, so that the output is expressed as a function of symbolic input

# Static vs dynamic, again

- Static analysis
  - without executing the software
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  - based on over-approximation
- Dynamic analysis
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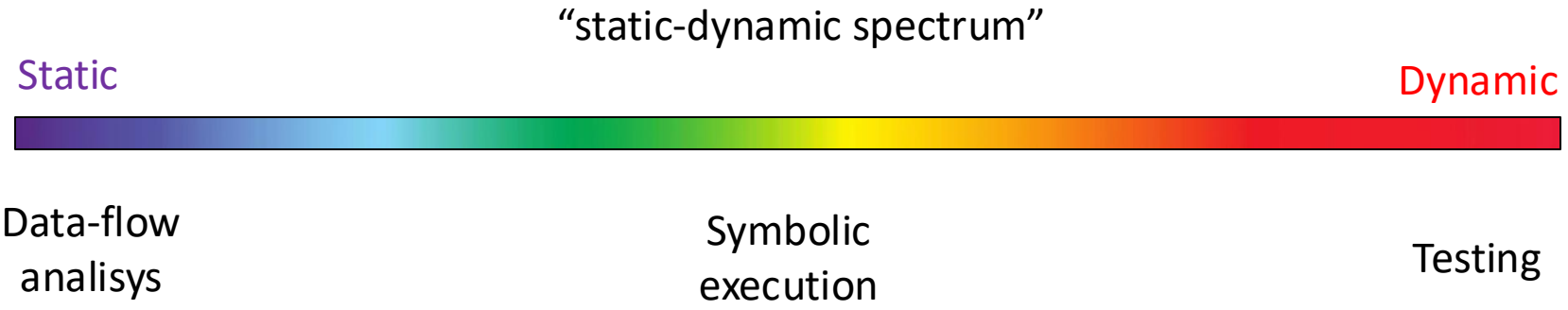
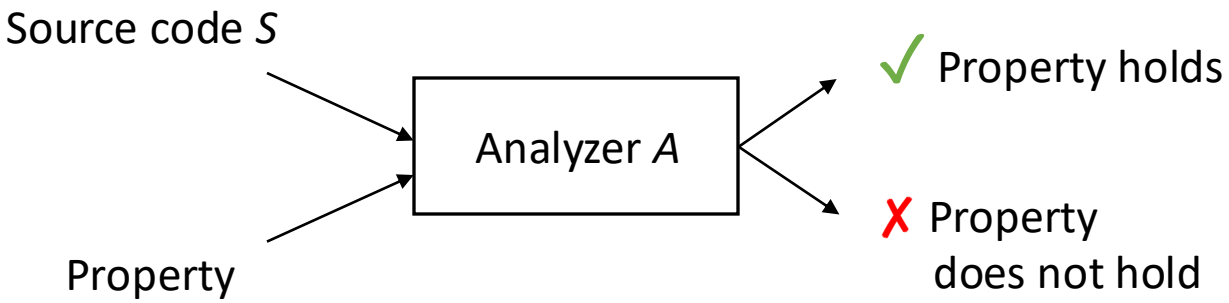


# Symbolic execution

- The very idea
  - Analyzes **real** source code
  - Analyzes **reachability** and **path feasibility** properties
  - Can be used to **generate test cases**
  - Is **automatic**
  - **May fail** to analyze all possible paths



# Types of checked properties

- Reachability: does some execution of the program reach the location **`l`** in *S*?
  - Symbolic exec tries to **verify that `l` cannot be reached**, or alternatively **spots the condition under which `l` can be reached**

```
…
k:    try {
k+1:    …
l-1:  } catch (e) {
l:      /* error */
…     }
```

```
…
l-1:  if (x < 0) {
l:      /* safe */
```

- Path feasibility: Is the given path *p* feasible?
  - Symbolic exec tries to **verify that *p* cannot be executed**, or alternatively **spots the condition under which *p* can be executed**

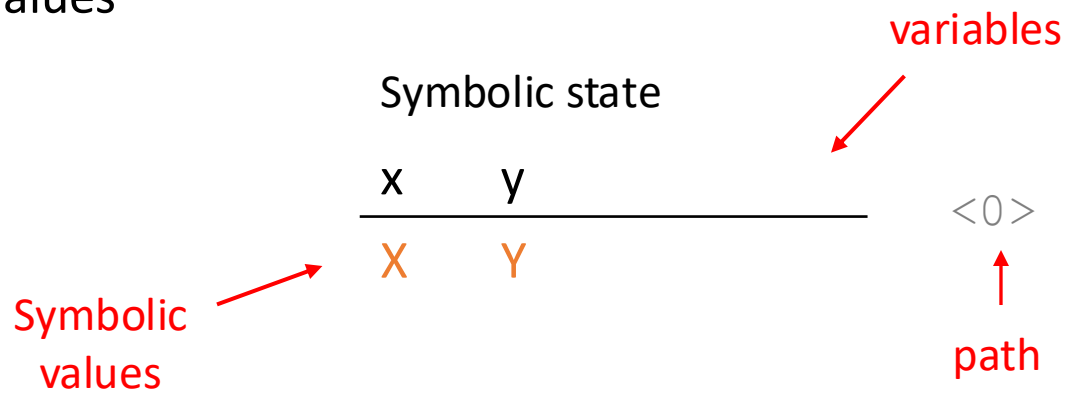
$p = \langle 0, 1, \ldots, k, \ldots, n \rangle$

# Symbolic state and path condition

- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

Inputs are initialized with symbolic (generic) values

```
0: void foo(int x, int y) {
1:   …
```



# Symbolic state and path condition

- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

Executing a statement updates the symbolic state

```
0: void foo(int x, int y) {
1:   int z := x
```

Symbolic state

| x | y | z | |
|---|---|---|---|
| X | Y | X | <0,1> |

# Symbolic state and path condition

- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

Executing a branch splits the symbolic state
A path condition π represents the constraint of a path

```
0: void foo(int x, int y) {
1:   int z := x
2:   if (z < y)
```

Symbolic state

| | x | y | z | π | |
|---|---|---|---|---|---|
| Condition at point 2 true: | X | Y | X | X<Y | <0,1,2> |
| Condition at point 2 false: | X | Y | X | X≥Y | <0,1,2> |

# Symbolic state and path condition

- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

The execution continues along feasible paths (path condition π is satisfiable)

```
0: void foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
```

Symbolic state

| x | y | z | π | |
|---|---|---|---|---|
| X | Y | 2X | X<Y | <0,1,2,3> |

# Symbolic state and path condition

- Symbolic execution executes programs on symbolic values
  - Symbolic states keep track of the (symbolic) value of variables

The execution continues along feasible paths (path condition π is satisfiable)

```
0: void foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
4:   if (x < y && z >= y)
```

Symbolic state

Condition at point 4 true:

| x | y | z | π | |
|---|---|---|---|---|
| X | Y | 2X | X<Y<br>X<Y ∧ 2X≥Y | <0,1,2,3,4> |

Condition at point 4 false:

| x | y | z | π | |
|---|---|---|---|---|
| X | Y | 2X | X<Y<br>X≥Y ∨ 2X<Y | <0,1,2,3,4> |

# Final states

- Possible outcomes of symbolic execution:
  - SAT exit (π is satisfiable): any satisfying assignment to variables in π is an **input** that satisfies the given property in a **concrete execution**
  - UNSAT exit (π is not satisfiable): the given property cannot be satisfied by **any concrete execution**
- **Example**: is location 5 reachable?

```
0: int foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
4:   if (x < y && z >= y)
5:     print(z) //location
6: }
```

| x | y | z | π |
|---|---|---|---|
| X | Y | 2X | X<Y |
| | | | X<Y ∧ 2X≥Y |

<0,1,2,3,4,5>

SAT exit

Example of satisfying assignment: X = 2, Y = 3

# Final states

- Possible outcomes of symbolic execution:
  - SAT exit (π is satisfiable): any satisfying assignment to variables in π is an **input** that satisfies the given property in a **concrete execution**
  - UNSAT exit (π is not satisfiable): the given property cannot be satisfied by **any concrete execution**
- **Example**: is path <0,1,2,4,5> feasible?

```
0: int foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
4:   if (x < y && z >= y)
5:     print(z) //location
6: }
```

Condition at point 4 true:

| x | y | z | π |
|---|---|---|---|
| X | Y | X | X≥Y |
| | | | X<Y ∧ X≥Y |

<0,1,2,4>

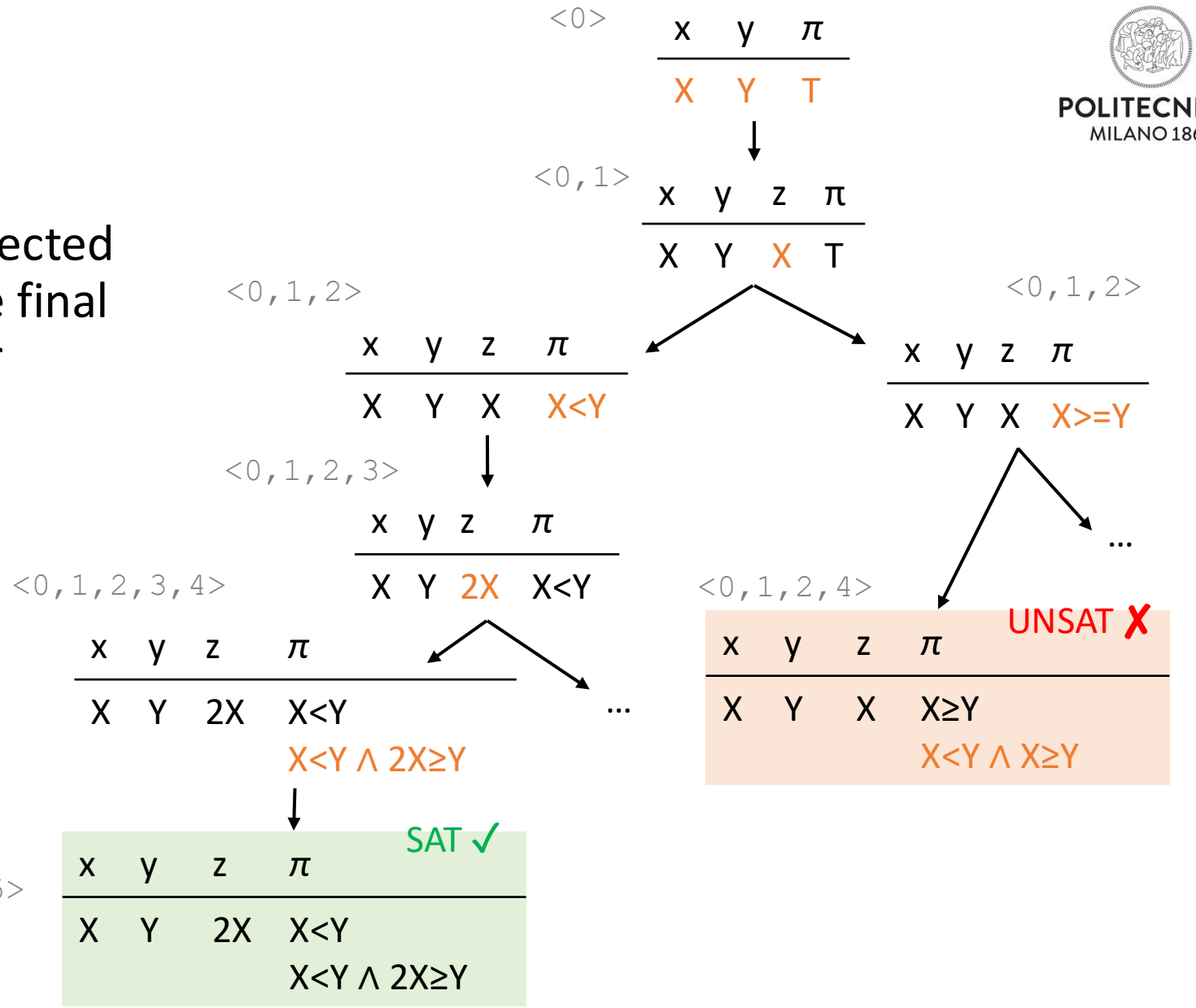
UNSAT exit

There is no satisfying assignment

# Execution tree

- Execution paths can be collected in an execution tree, where final states are marked as SAT or UNSAT

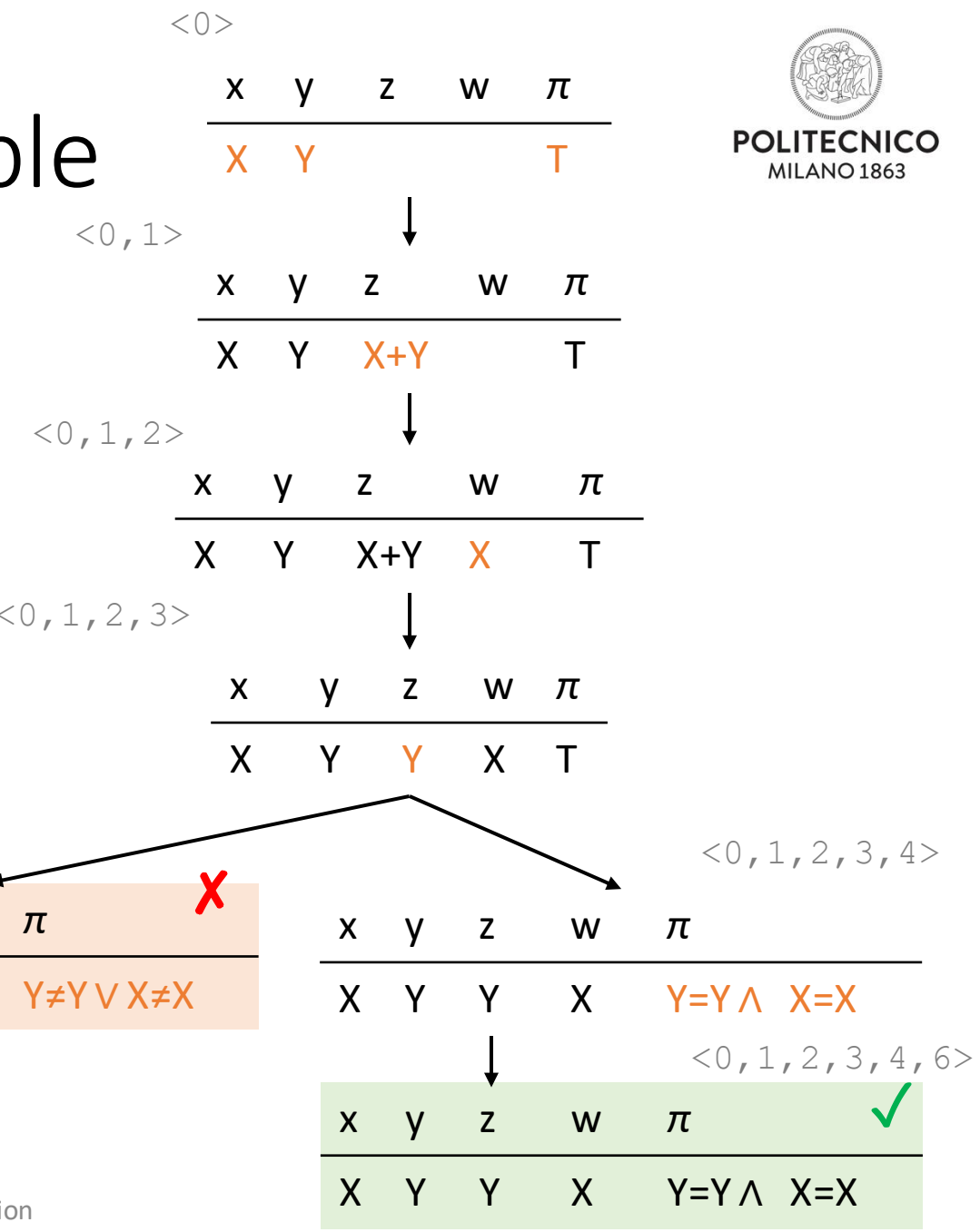
```
0: int foo(int x, int y) {
1:   int z := x
2:   if (z < y)
3:     z := z*2
4:   if (x < y && z >= y)
5:     print(z) //location
6: }
```



# Symbolic execution: example

- What are the feasible paths of the program `swap`?

```
0: void swap(int x, int y) {
1:   int z := x + y
2:   int w := z - y
3:   z := z - w
4:   if (z != y || w != x)
5:     print("error")
6: }
```




- Result
  - Path <0,1,2,3,4,5,6> unfeasible
  - Path <0,1,2,3,4,6> feasible

# Symbolic execution: exercise

- Consider the following program `bar`. Is the path `<0 1 2 3 4 5 8 2 3 4 7 8 2 10 11>` feasible?

```
0:   int bar( ) {
1:     int y, x := input()
2:     while (x > 0) {
3:       y := 2*x
4:       if (x > 10)
5:         y := x - 1
6:       else
7:         x := x + 2
8:       x := x - 1
9:     }
10:    x := x - 1
11:    return x
12: }
```

<0>

| x | y | π |
|---|---|---|
| | | T |

<0,1>

| x | y | π |
|---|---|---|
| X | | T |

<0,1,2>

| x | y | π |
|---|---|---|
| X | | X>0 |

<0,1,2,3>

| x | y | π |
|---|---|---|
| X | 2X | X>0 |

<0,1,2,3,4>

| x | y | π |
|---|---|---|
| X | 2X | X>0 |
| | | X>10 |

<0,1,2,3,4,5>

| x | y | π |
|---|---|---|
| X | X-1 | X>10 |

<0,1,2,3,4,5,8>

| x | y | π |
|---|---|---|
| X-1 | X-1 | X>10 |

<0,1,2,3,4,5,8,2>

| x | y | π |
|---|---|---|
| X-1 | X-1 | X>10 |
| | | X-1>0 |

<0,1,2,3,4,5,8,2,3>

| x | y | π |
|---|---|---|
| X-1 | 2(X-1) | X>10 |

<0,1,2,3,4,5,8,2,3,4>

| x | y | π |
|---|---|---|
| X-1 | 2(X-1) | X>10 |
| | | X-1≤10 |

# Symbolic execution: exercise (continue)

- Consider the following program `bar`. Is the path `<0 1 2 3 4 5 8 2 3 4 7 8 2 10 11>` feasible?

```
0:   int bar( ) {
1:     int y, x := input()
2:     while (x > 0) {
3:       y := 2*x
4:       if (x > 10)
5:         y := x - 1
6:       else
7:         x := x + 2
8:       x := x - 1
9:     }
10:    x := x - 1
11:    return x
11: }
```

<0,1,2,3,4,5,8,2,3,4>

| x | y | π |
|---|---|---|
| X-1 | 2(X-1) | X>10 |
| | | X≤11 |

<0,1,2,3,4,5,8,2,3,4,7>

| x | y | π |
|---|---|---|
| X+1 | 2(X-1) | X>10 |
| | | X≤11 |

<0,1,2,3,4,5,8,2,3,4,7,8>

| x | y | π |
|---|---|---|
| X | 2(X-1) | X>10 |
| | | X≤11 |

<0,1,2,3,4,5,8,2,3,4,7,8,2>

| x | y | π |
|---|---|---|
| X | 2(X-1) | X>10 |
| | | X≤11 |
| | | X≤0 |

✗

- Conclusion: path `<0 1 2 3 4 5 8 2 3 4 7 8 2 10 11>` is unfeasible

# Symbolic execution: weaknesses

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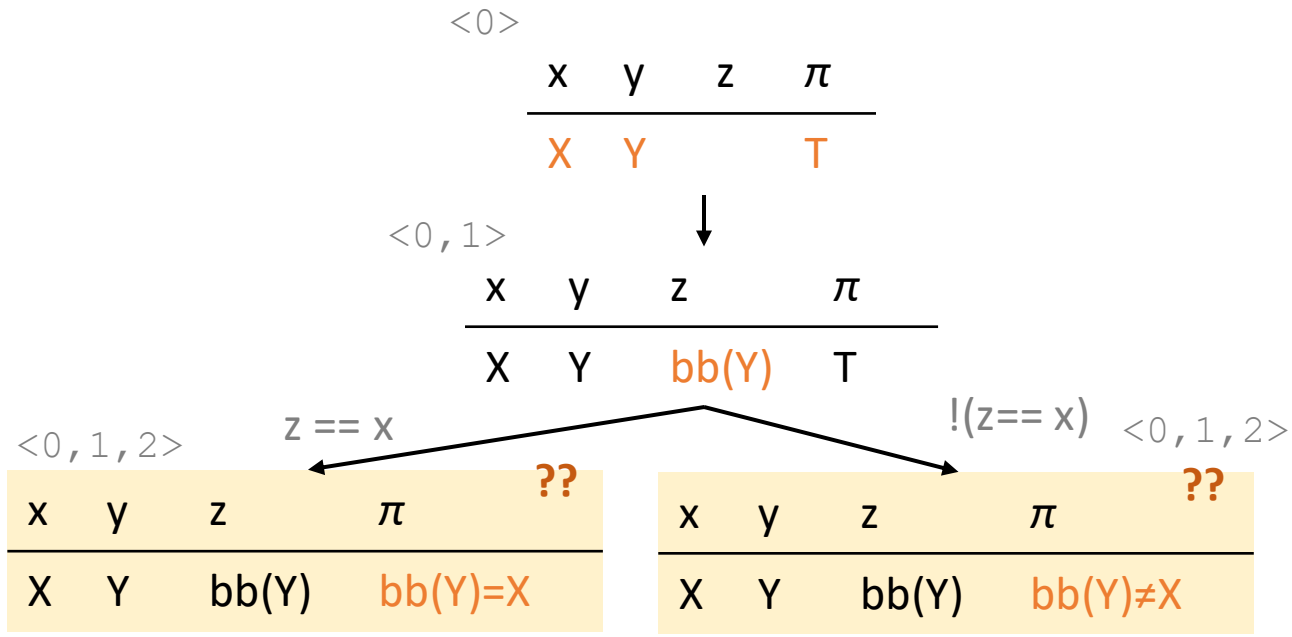
- It seems symbolic execution can be used to verify the correctness of any program, however…
- Limitations
  - Path conditions may be too complex for constraint solvers
    - Solvers are very good at checking linear constraints
    - It is harder for them to reason on non-linear arithmetic, bit-wise operations, string manipulation
  - Impossible/hard to use when number of paths to be explored is infinite/huge
    - unbounded loops give rise to infinite sets of paths
    - Even if set of paths is finite, checking all loops is expensive/unfeasible in practice
      - rule of thumb: approximate the analysis by considering 0, 1, and 2 iterations
  - There may be external code
    - Sources not available (e.g., pre-compiled library) → unknown behavior for the solver

# Limitations: example

```
0: void bar(int x, int y) {
1:   int z := bb(y) //black-box function
2:   if (z == x) {
3:     z := y + 10
4:     if (x <= z)
5:       print("error")
6:   }
7:   print("end") //location
8: }
```

Solver cannot find satisfying assignments (*bb* behavior is unknown) =>
Paths remain unexplored



# Symbolic execution: evolution

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- Symbolic execution was first introduced in 1976
  - James C. King. (IBM Thomas J. Watson Research Center) 1976. Symbolic execution and program testing. Commun. ACM 19, 7 (July 1976), 385–394. https://doi.org/10.1145/360248.360252
- Became practical about 30 years later
  - Progress in constraint solving (SMT solvers)
  - Concolic techniques (presented as part of testing):
    - Combination of concrete (or dynamic) and symbolic execution
    - Can alleviate several weaknesses of classical symbolic execution
    - Can be used to generate test cases covering alternative execution paths

# References


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