Computer-Aided Reasoning for Software

CSE507

Symbolic Execution

courses.cs.washington.edu/courses/cse507/14au/

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Today

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Last lecture

- Bounded verification: forward VCG for finitized programs

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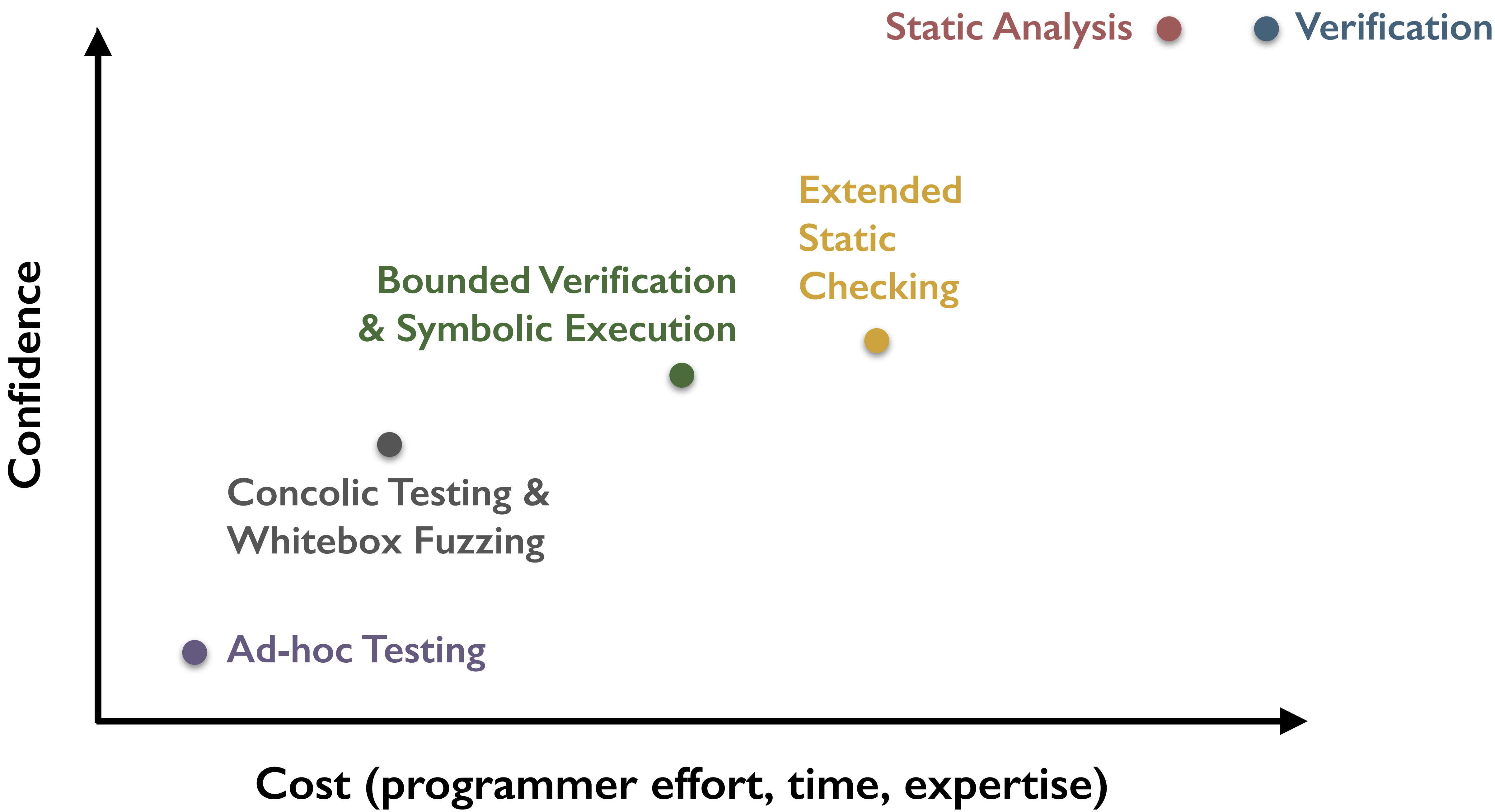
- Symbolic execution: a path-based translation
- Concolic testing

The spectrum of program validation tools



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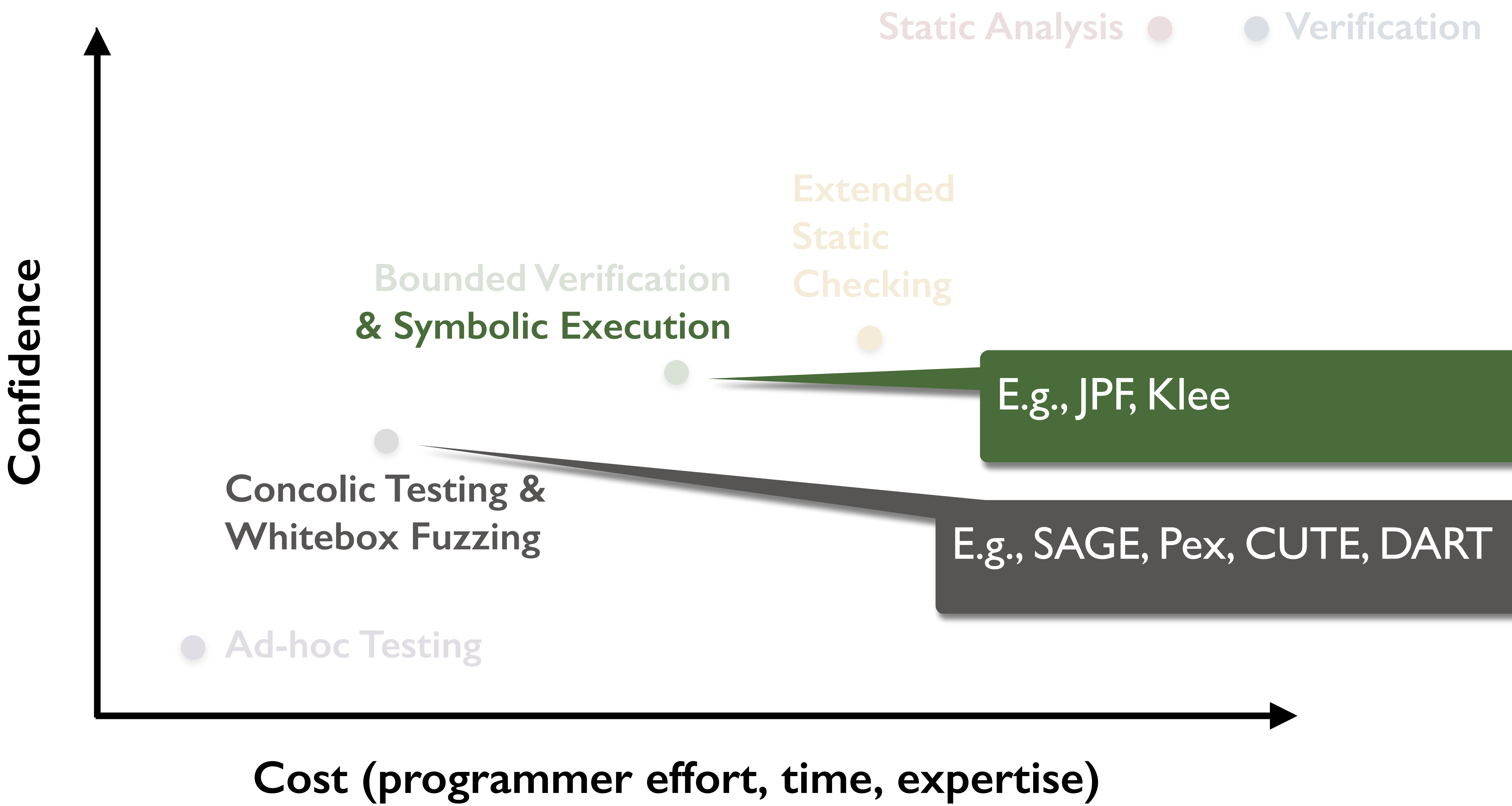

Symbolic execution

1976: *A system to generate test data and symbolically execute programs* (Lori Clarke)

1976: *Symbolic execution and program testing* (James King)

2005-present: practical symbolic execution

- Using SMT solvers
- Heuristics to control exponential explosion
- Heap modeling and reasoning about pointers
- Environment modeling
- Dealing with solver limitations

Classic symbolic execution

```
def f (x, y):
  if (x > y):
    x = x + y
    y = x − y
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    if (x − y > 0):
      assert false
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Execute the program on *symbolic values*.

Classic symbolic execution

x ↦ X
y ↦ Y

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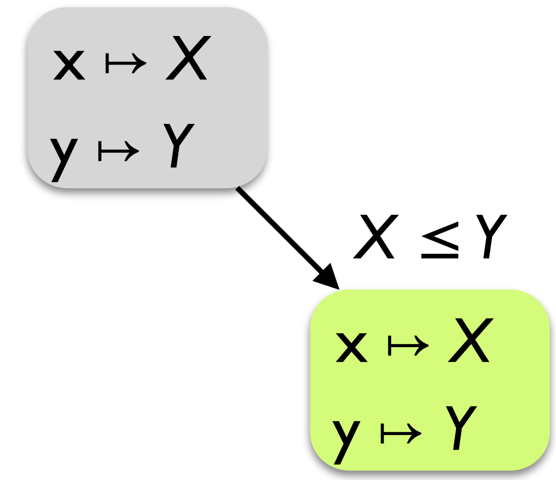

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Path condition is a quantifier-free formula over the symbolic inputs that encodes all branch decisions taken so far.

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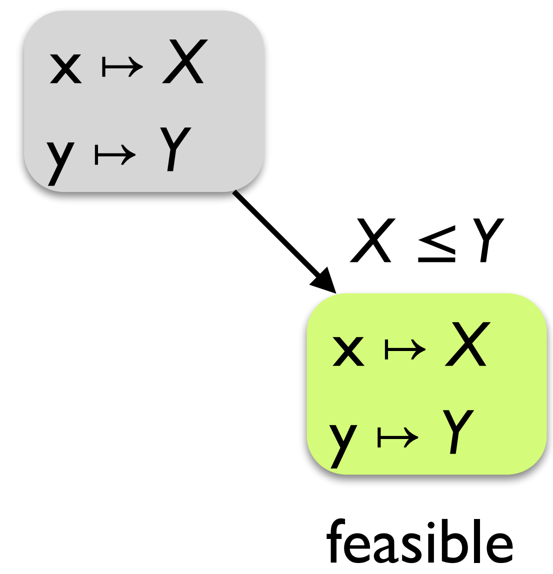

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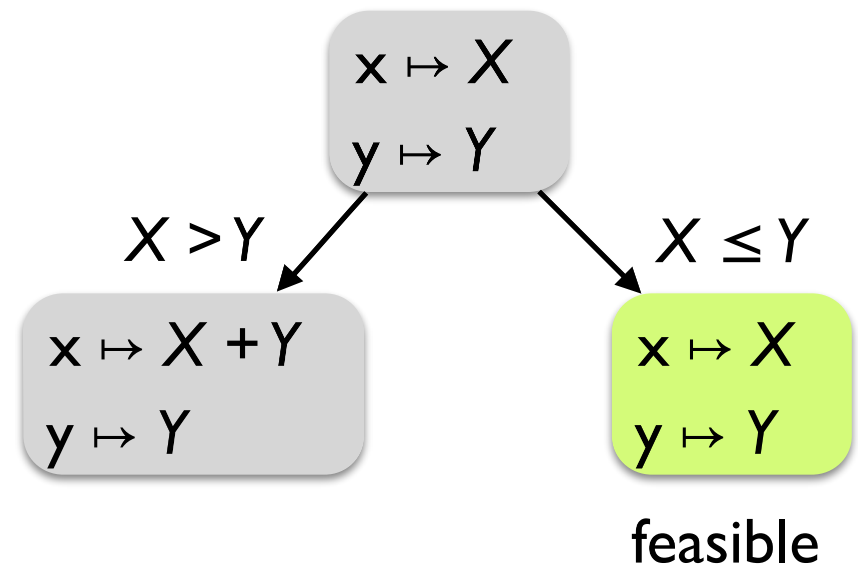

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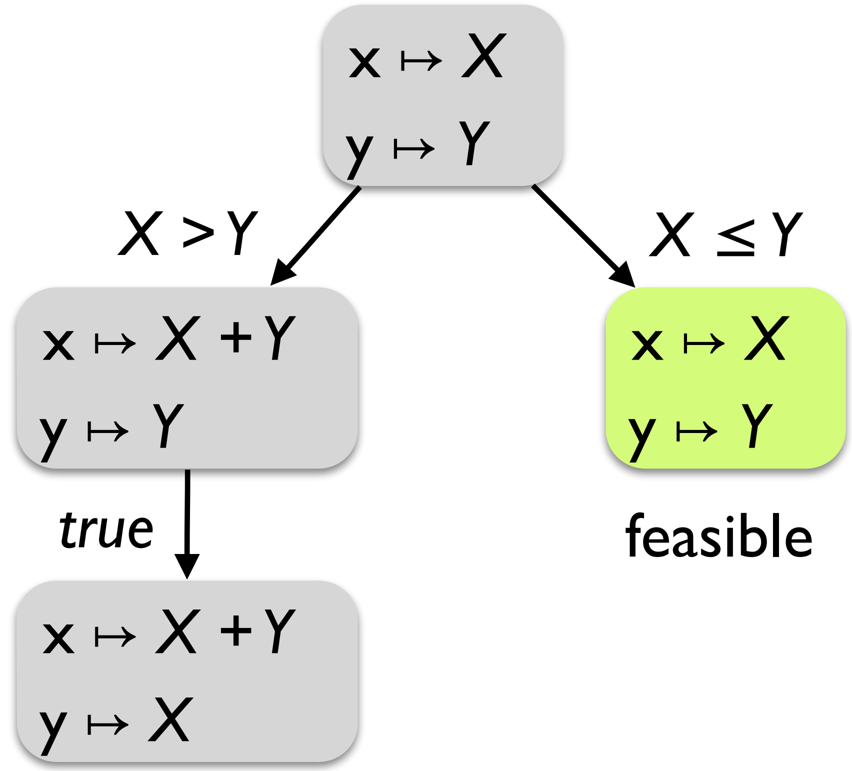

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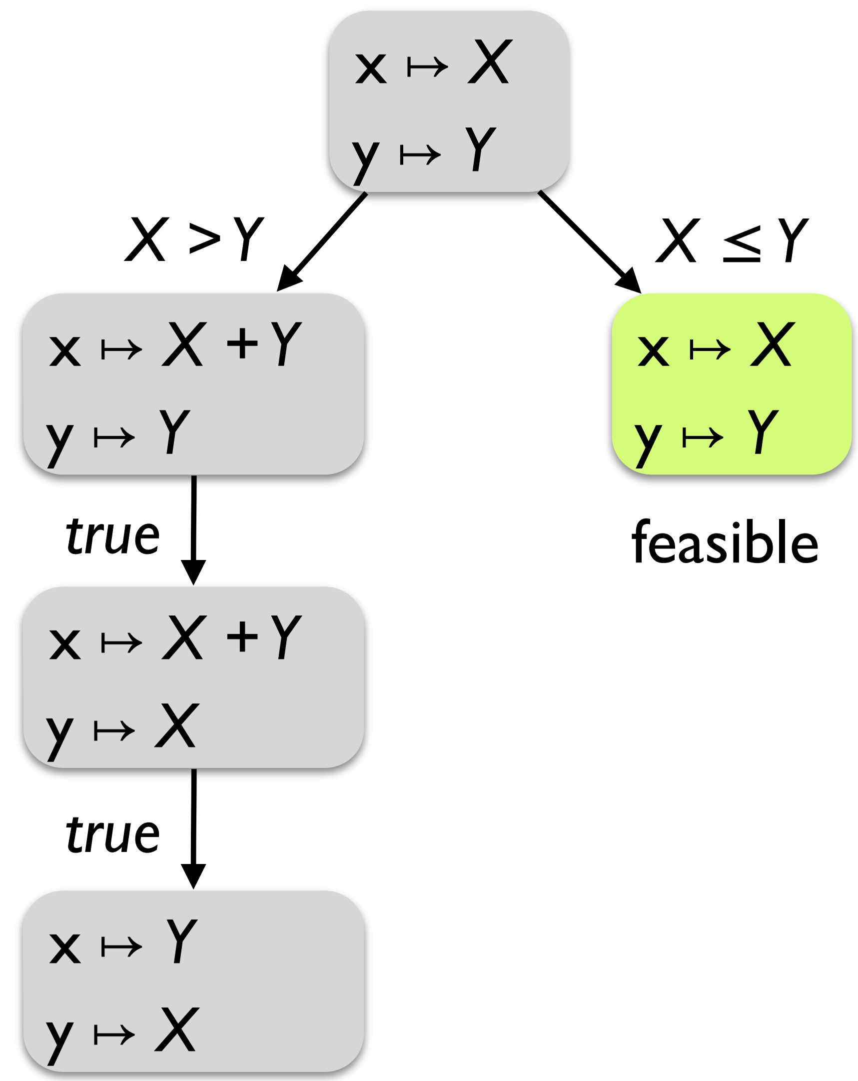

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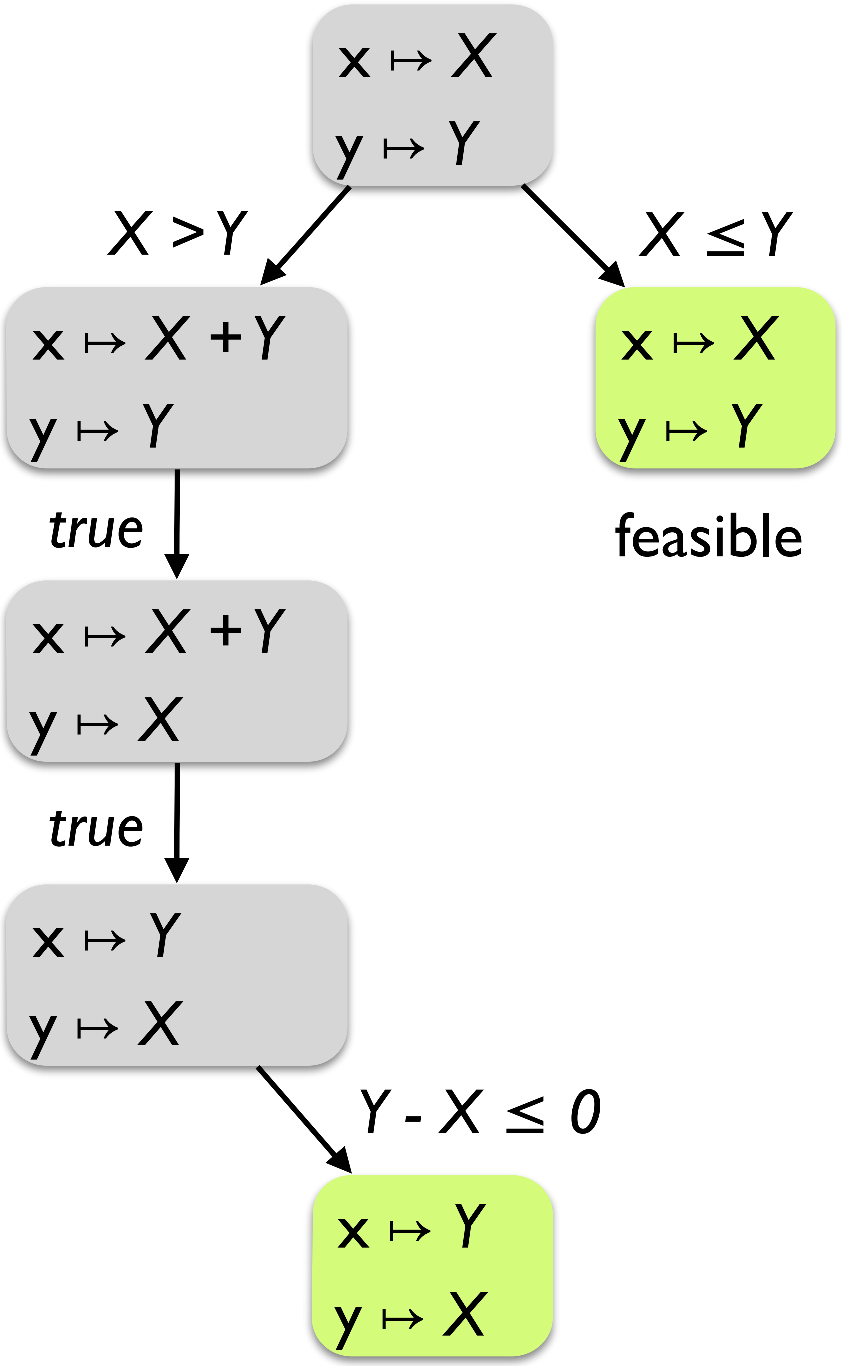

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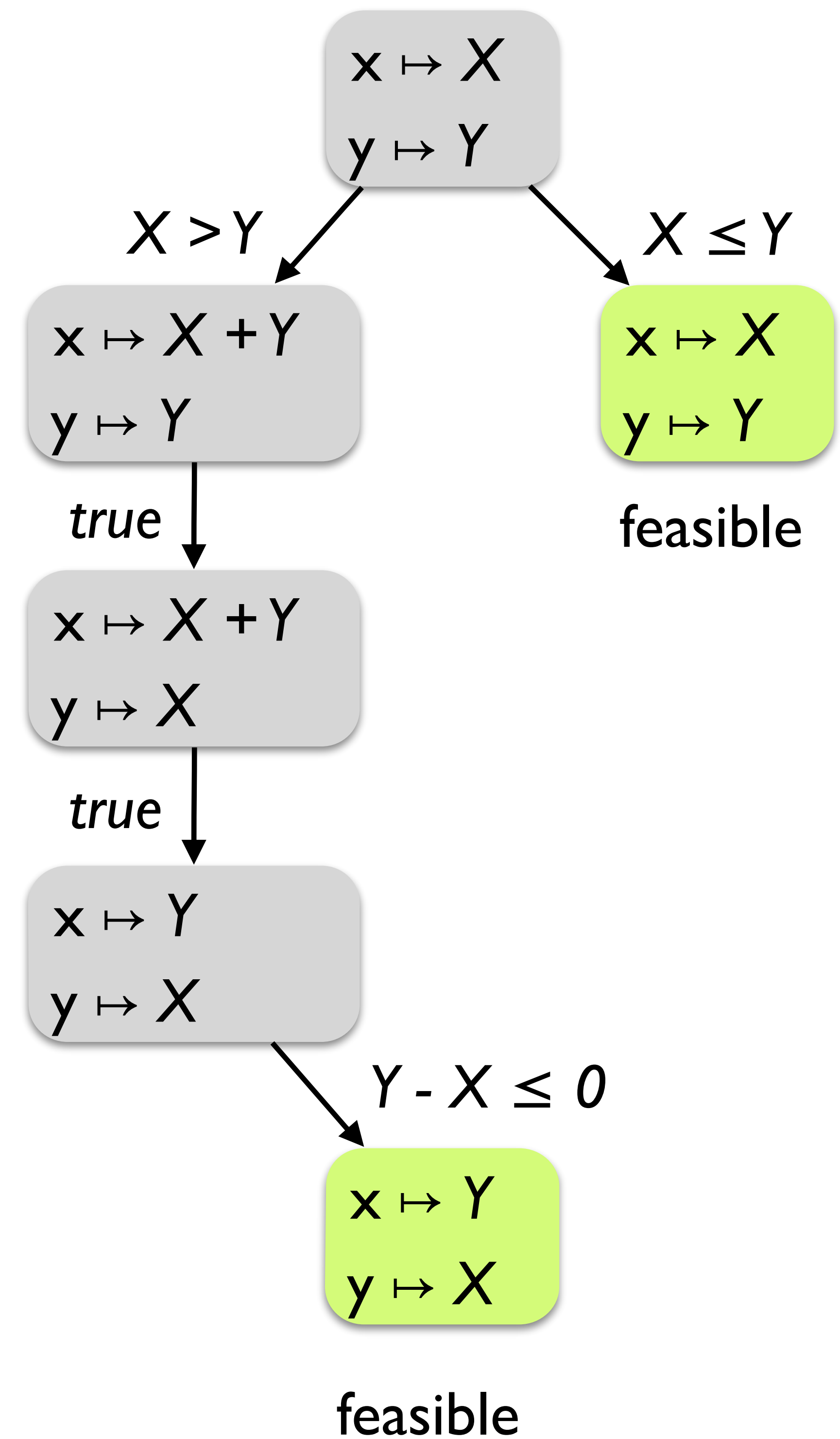

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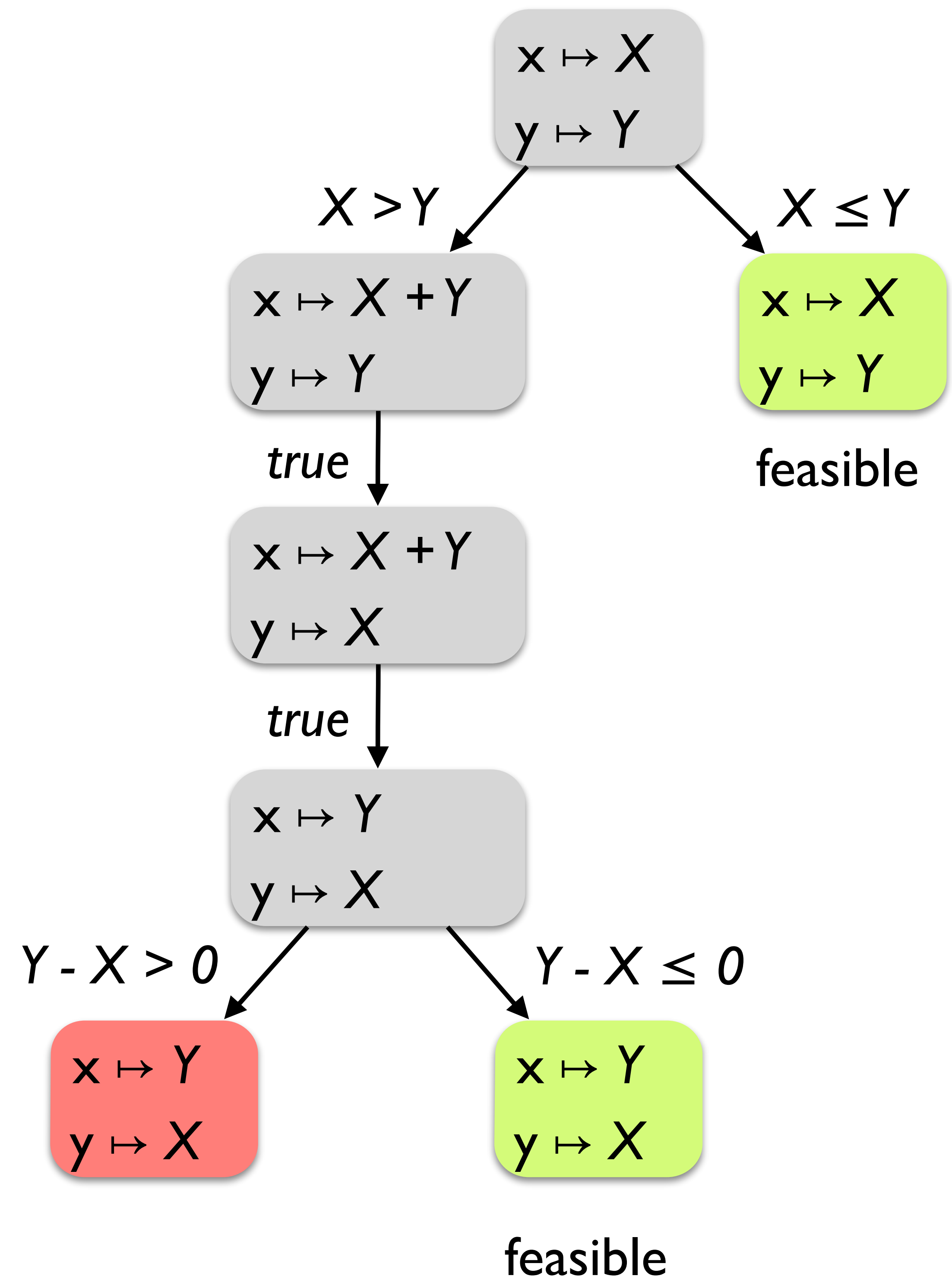

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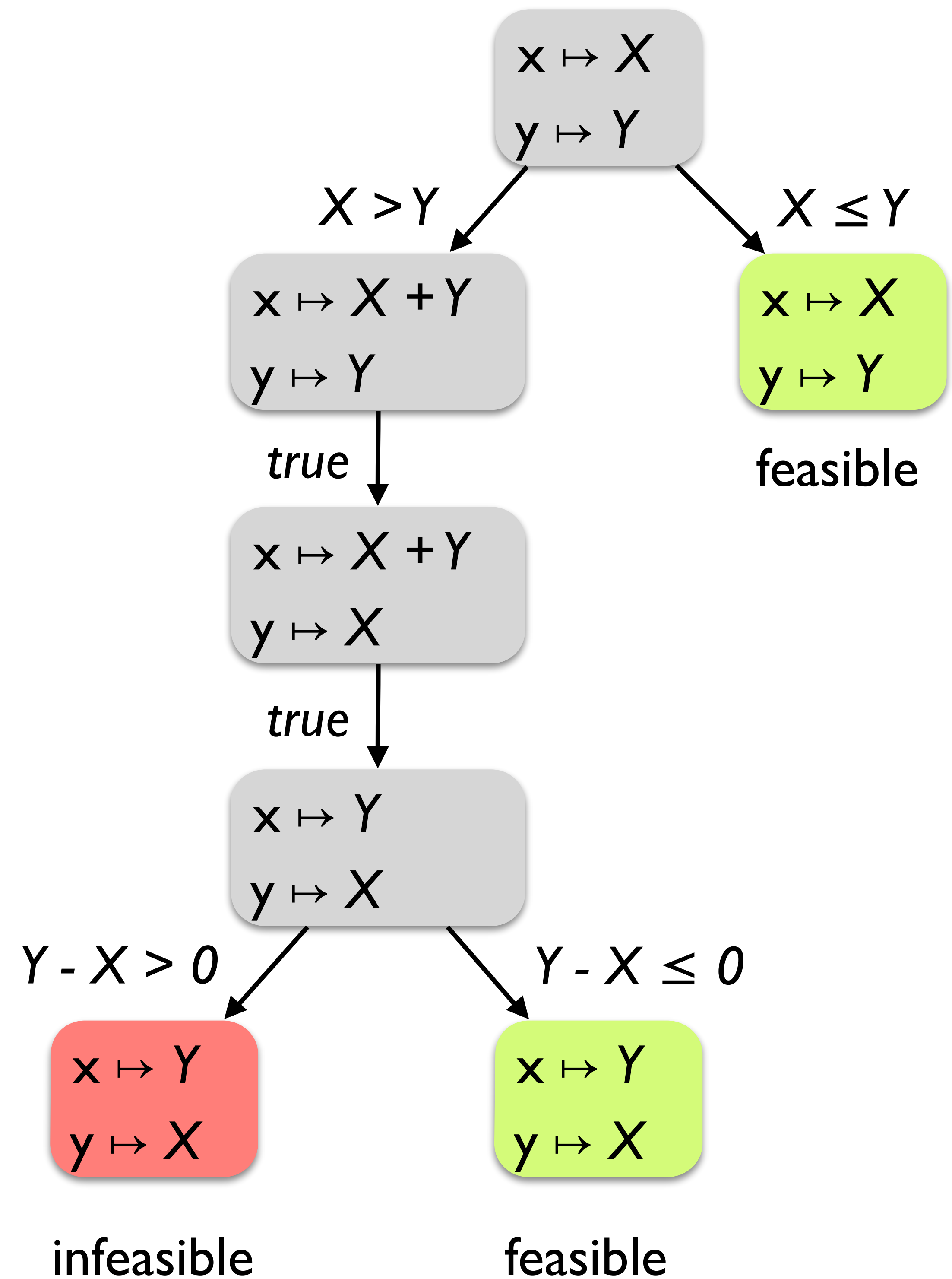

Classic symbolic execution: practical issues

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Loops and recursion: infinite execution trees

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Path explosion: exponentially many paths

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Heap modeling: symbolic data structures and pointers

Classic symbolic execution: practical issues

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Solver limitations: dealing with complex PCs

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Environment modeling: dealing with native / system / library calls

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Loops and recursion

Dealing with infinite execution trees:

- Finitize paths by limiting the size of PCs (bounded verification)
- Use loop invariants (verification)

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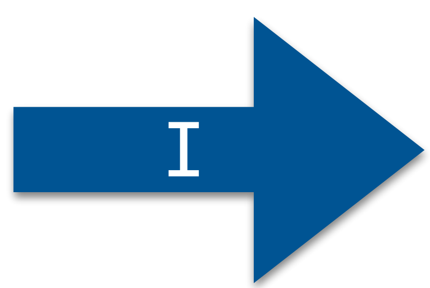
```
init;
while (C) {
  B;
}
assert P;
```



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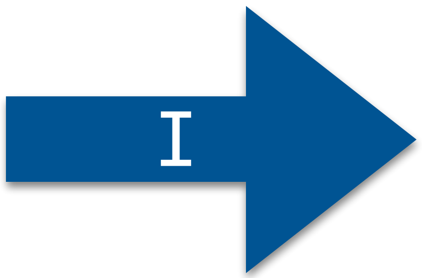


```
init;
assert I;
makeSymbolic(targets(B));
assume I;
if (C) {
  B;
  assert I;
} else
  assert P;
```

Path explosion

Achieving good coverage in the presence of exponentially many paths:

- Select next branch at random
- Select next branch based on coverage
- Interleave symbolic execution with random testing

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symbolic execution random testing interleaved execution

Heap modeling

Modeling symbolic heap values and pointers

- Segmented address space via the theory of arrays (Klee)
- Lazy concretization (JPF)
- Concolic lazy concretization (CUTE)

General lazy concretization

```
class Node {
  int elem;
  Node next;
}

n = symbolic(Node);
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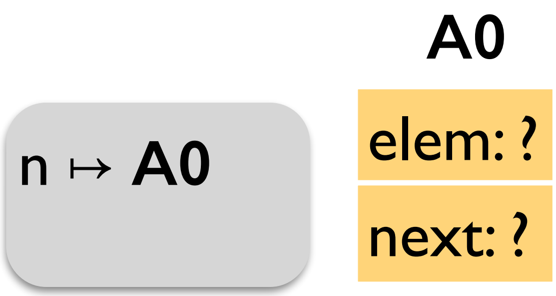

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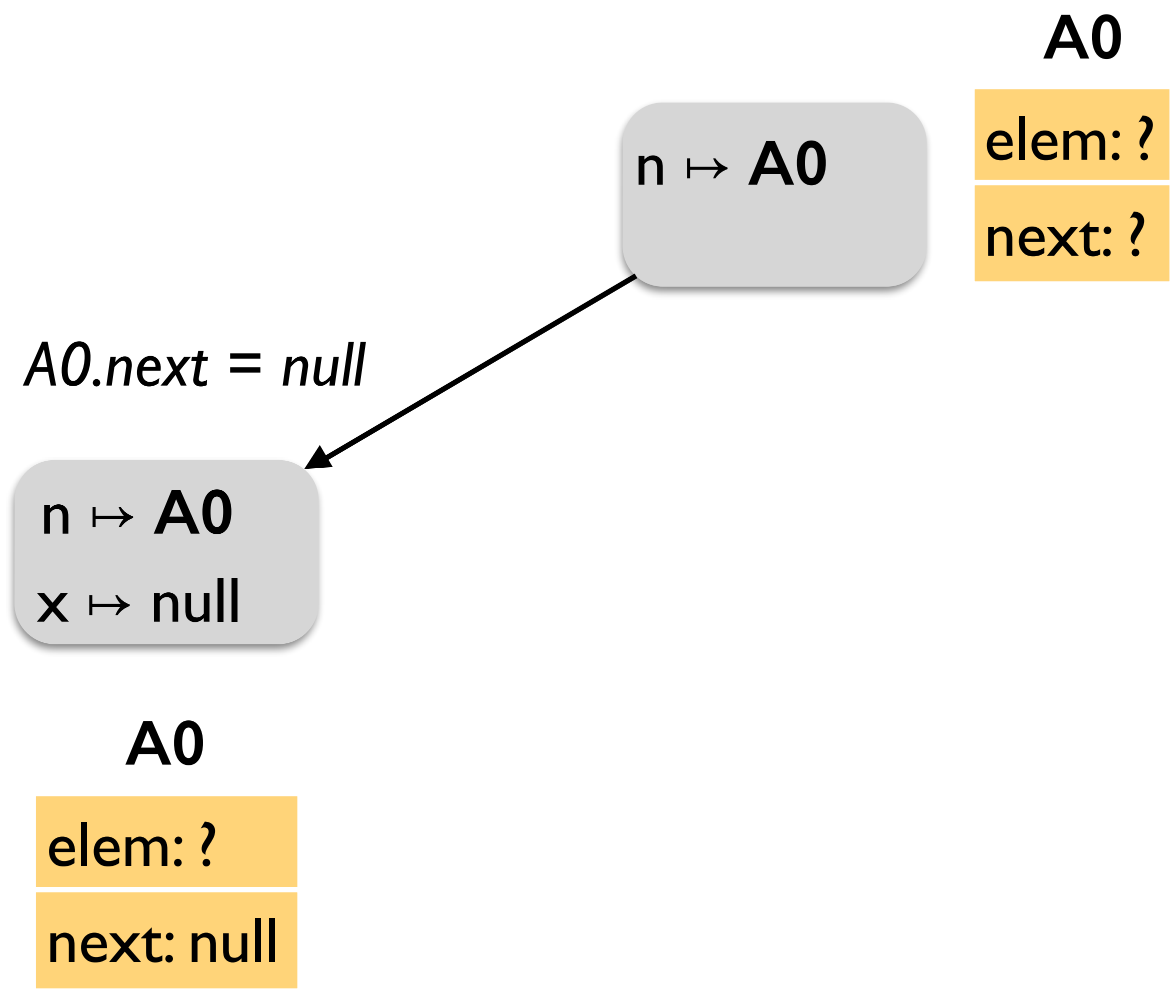

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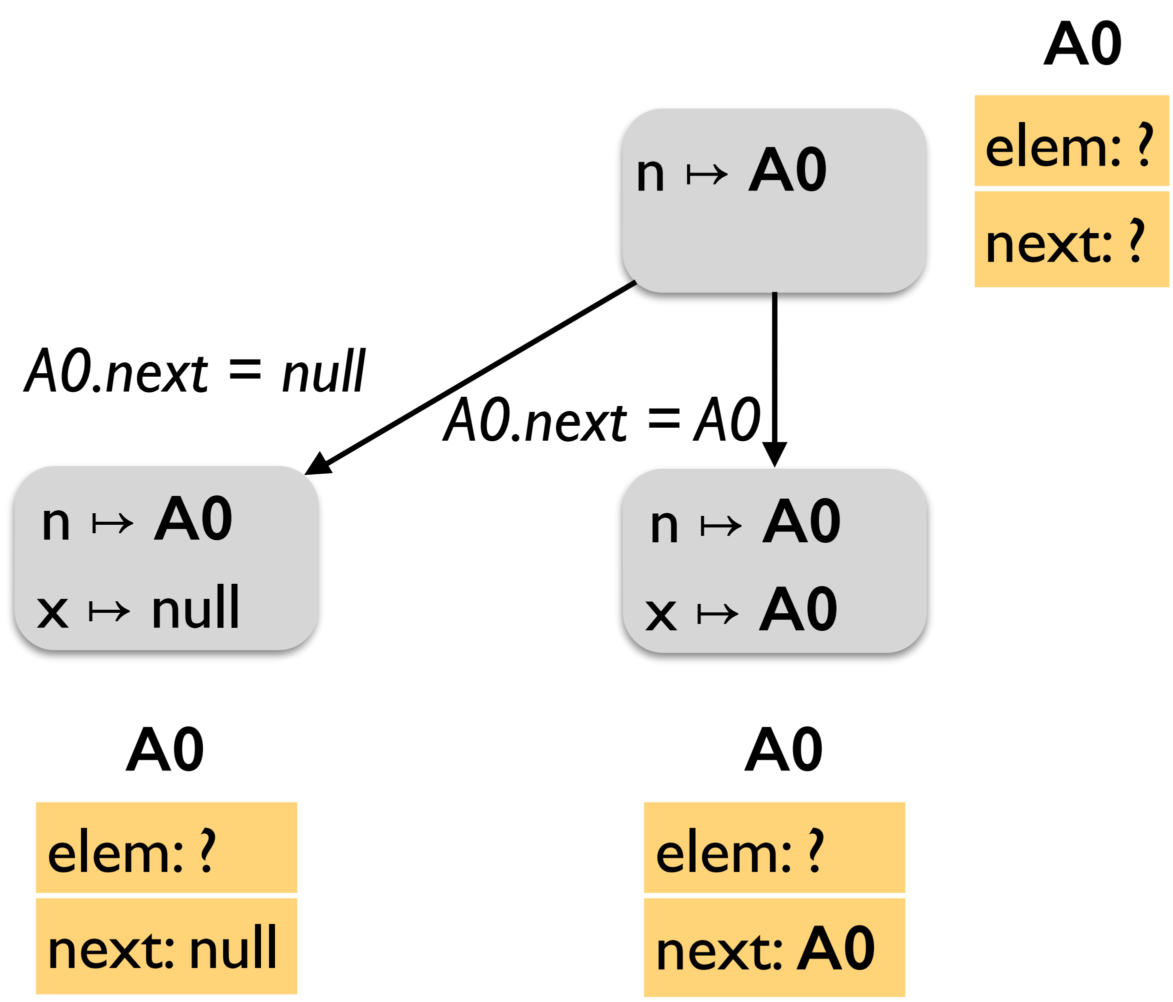

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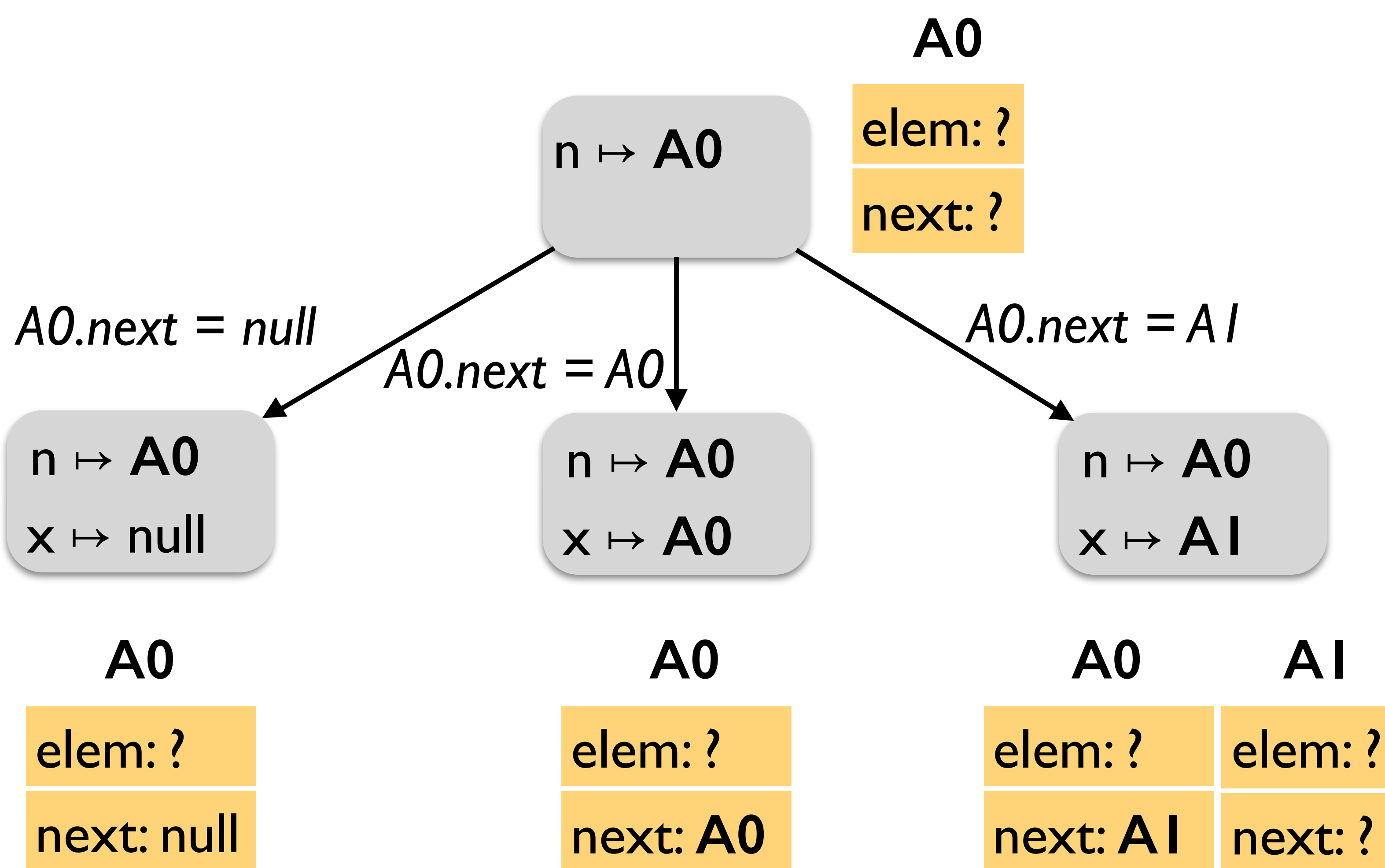

Concolic testing

```
typedef struct cell {
  int v;
  struct cell *next;
} cell;

int f(int v) {
  return 2*v + 1;
}

int testme(cell *p, int x) {
  if (x > 0)
    if (p != NULL)
      if (f(x) == p->v)
        if (p->next == p)
          abort();
  return 0;
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Concrete

$p \mapsto null$

$x \mapsto 236$

PC

$x > 0 \wedge \neg p{=}null$

Execute concretely and symbolically.

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	Concrete	PC
	$p \mapsto$ null $x \mapsto 236$	$x > 0 \wedge p = null$
A0 next: null v: 634	$p \mapsto$ **A0** $x \mapsto 236$	$x > 0 \wedge p \neq null \wedge p.v \neq 2x + 1$

Execute concretely and symbolically.

Negate last decision and solve for new inputs.

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A0 next: null v: 3	p ↦ **A0** x ↦ 1	$x > 0 \wedge p \neq null \wedge$ $p.v = 2x + 1 \wedge$ $p.next \neq p$

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A0 next: null v: 3	$p \mapsto$ **A0** $x \mapsto 1$	$x > 0 \wedge p \neq null \wedge$ $p.v = 2x + 1 \wedge$ $p.next \neq p$
A0 next: **A0** v: 3	$p \mapsto$ **A0** $x \mapsto 1$	$x > 0 \wedge p \neq null \wedge$ $p.v = 2x + 1 \wedge$ $p.next = p$

Execute concretely and symbolically.

Negate last decision and solve for new inputs.

Solver limitations

Reducing the demands on the solver:

- On-the-fly expression simplification
- Incremental solving
- Solution caching
- Substituting concrete values for symbolic in complex PCs (CUTE)

Environment modeling

Dealing with system / native / library calls:

- Partial state concretization
- Manual *models* of the environment (Klee)

Summary

Today

- Practical symbolic execution and concolic testing

Next lecture

- Basics of model checking