Computer-Aided Reasoning for Software

CSE507

Symbolic Execution

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Today

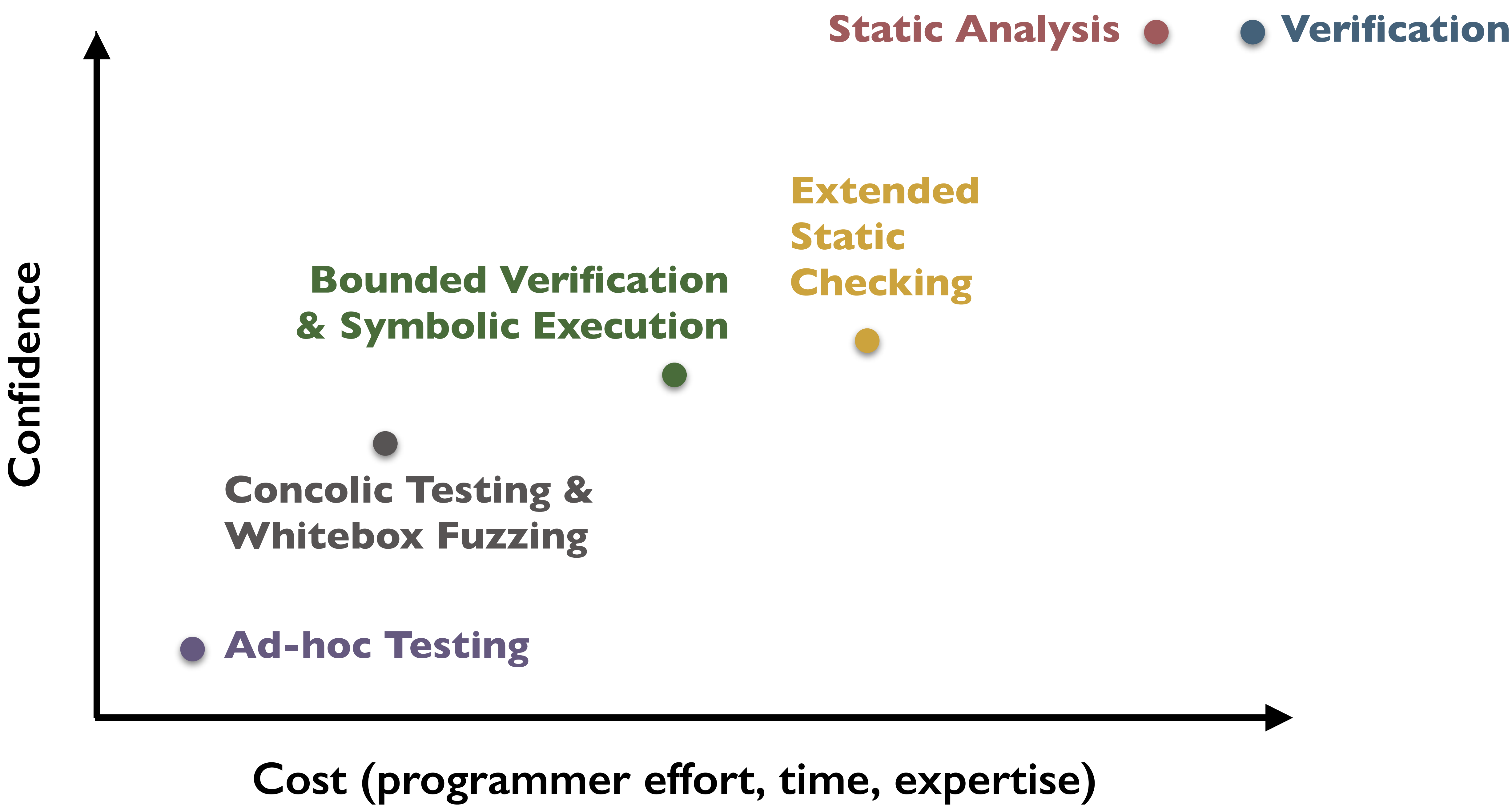
Last lecture

- Verification with Dafny

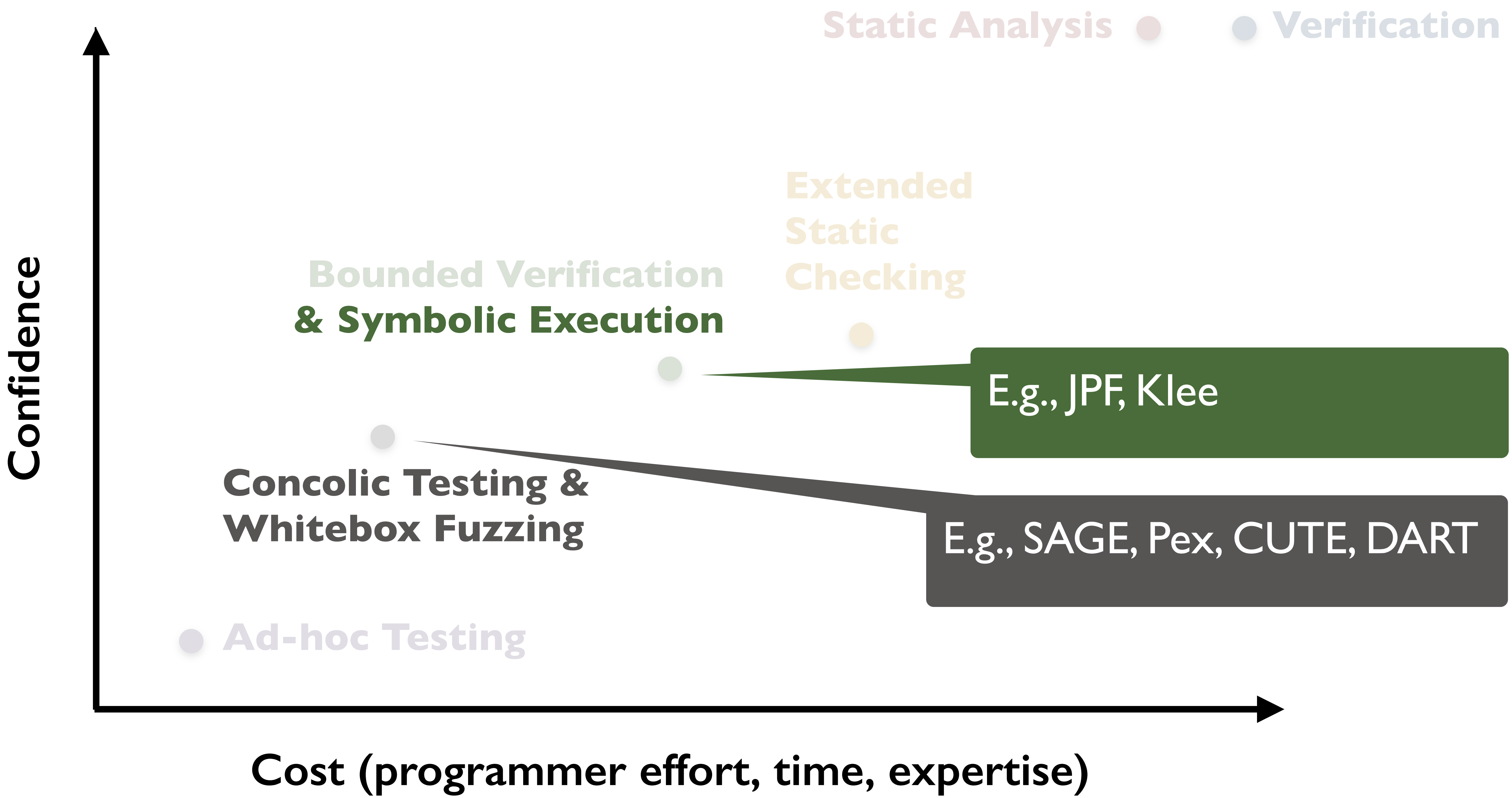
Today

- Symbolic execution: strongest postconditions for finite programs
- Concolic testing

The spectrum of program validation tools



The spectrum of program validation tools



A brief history of 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

Symbolic execution: basic idea

```
def f (x, y):
  if (x > y):
    x = x + y
    y = x − y
    x = x − y
    if (x − y > 0):
      assert false
  return (x, y)
```

Symbolic execution: basic idea

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def f (x, y):
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Execute the program on *symbolic values*.

Symbolic execution: basic idea

$x \mapsto A$
$y \mapsto B$

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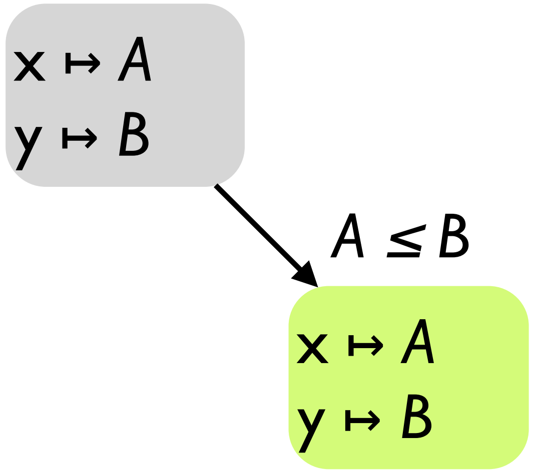
Path condition is a quantifier-free formula over the symbolic inputs that encodes all branch decisions taken so far.



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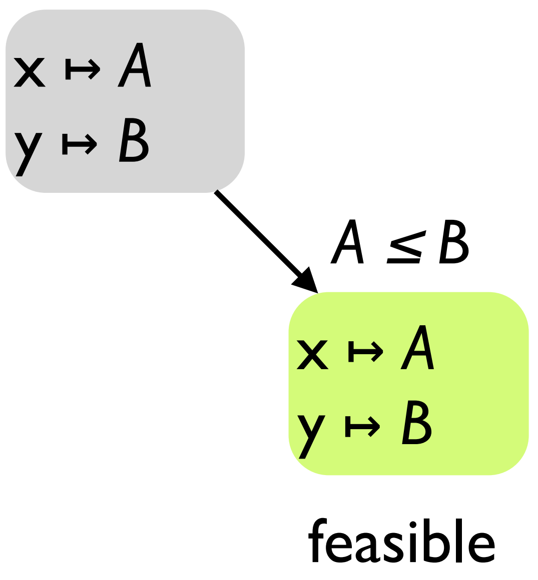

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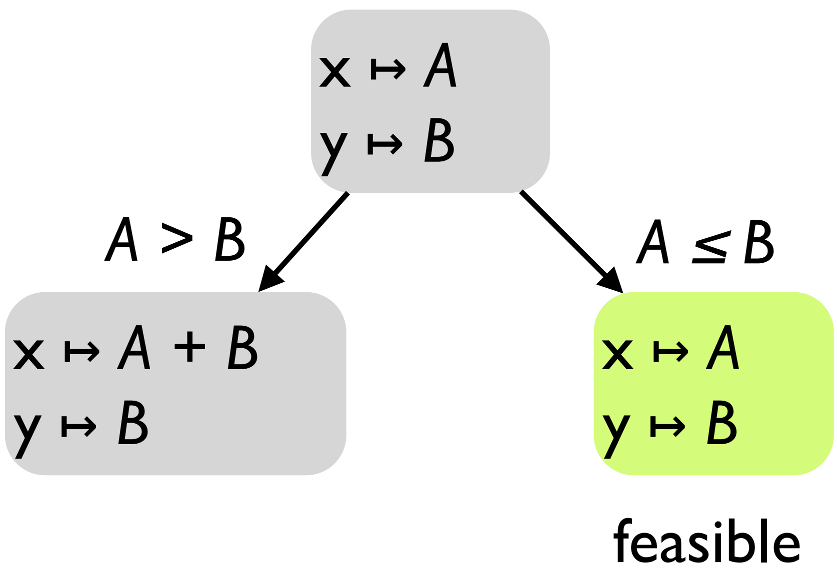

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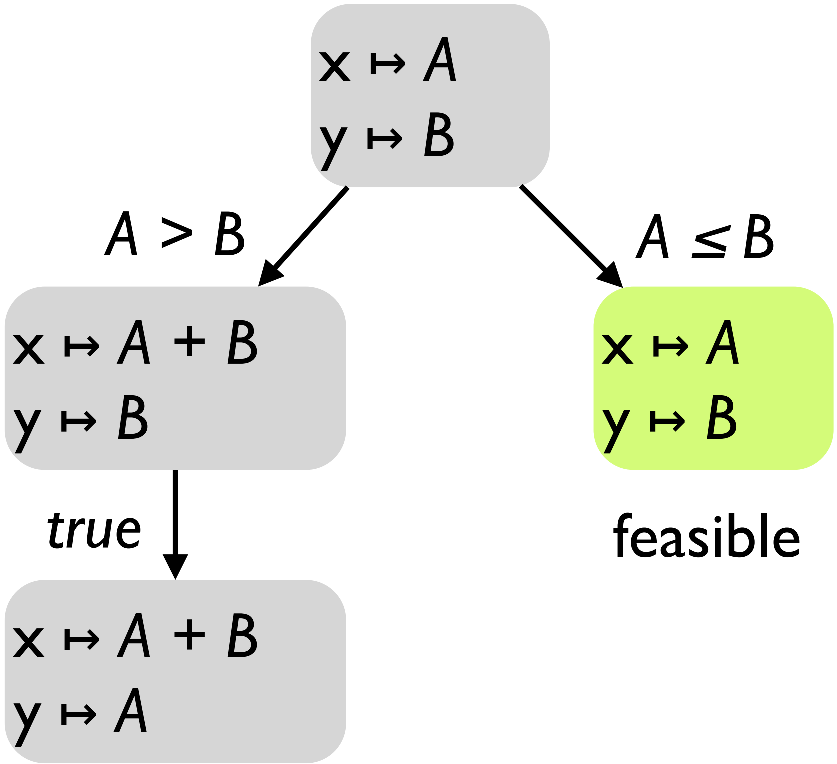

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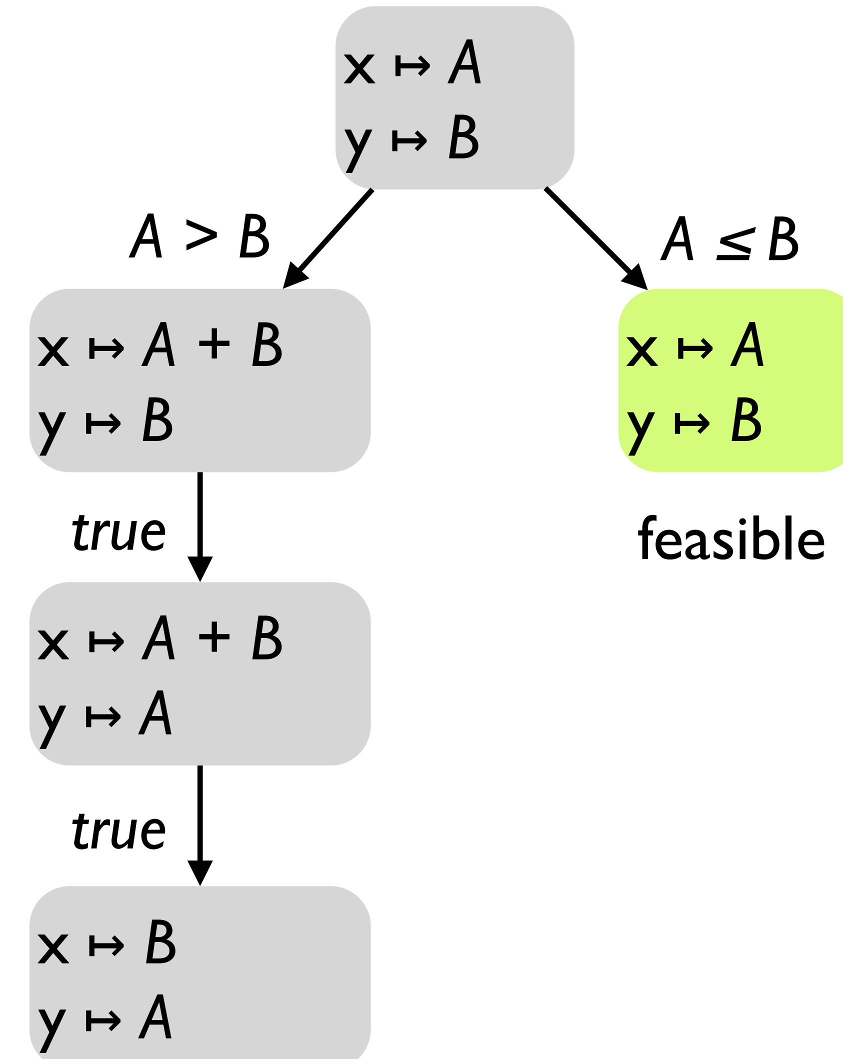

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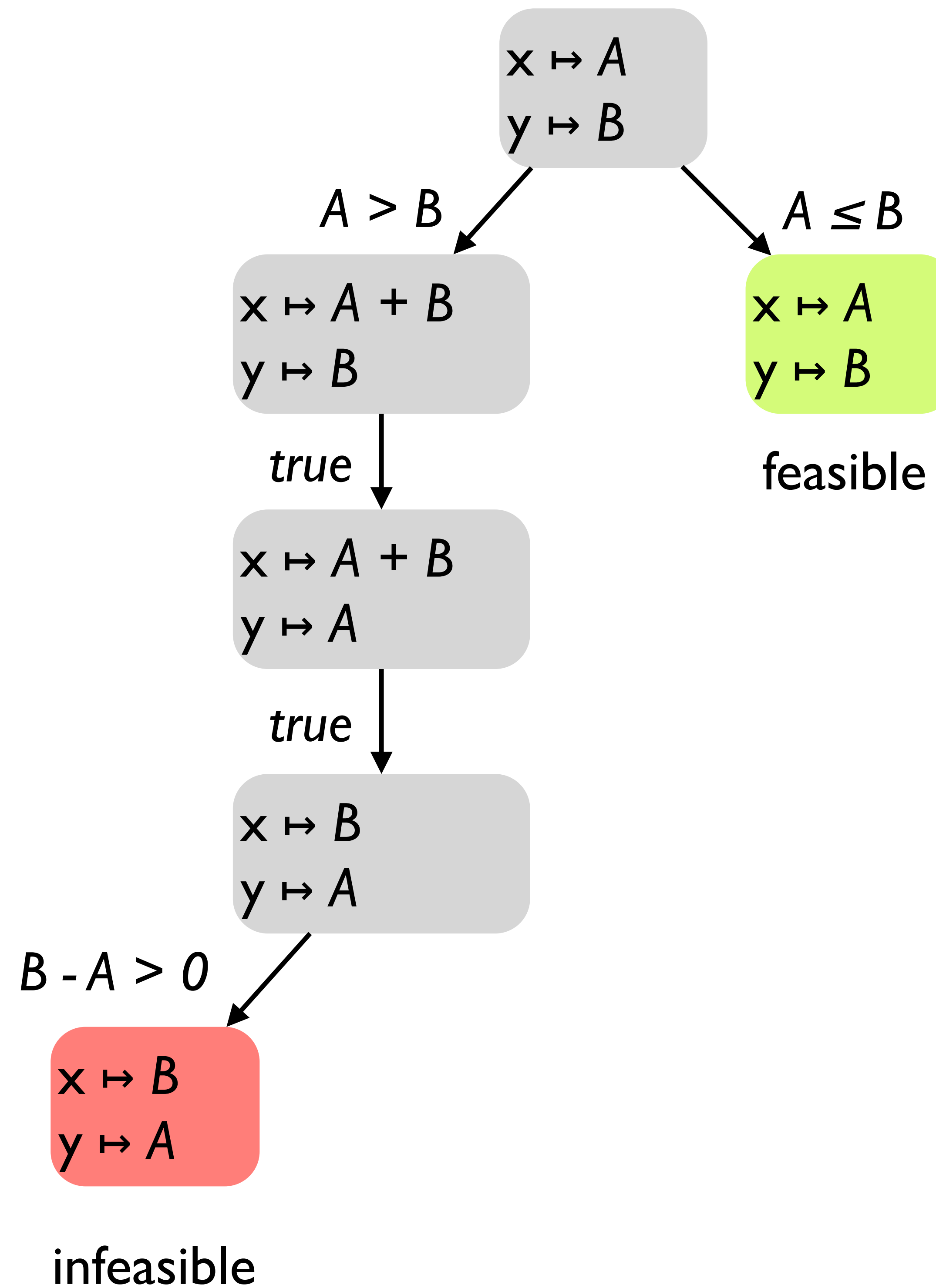

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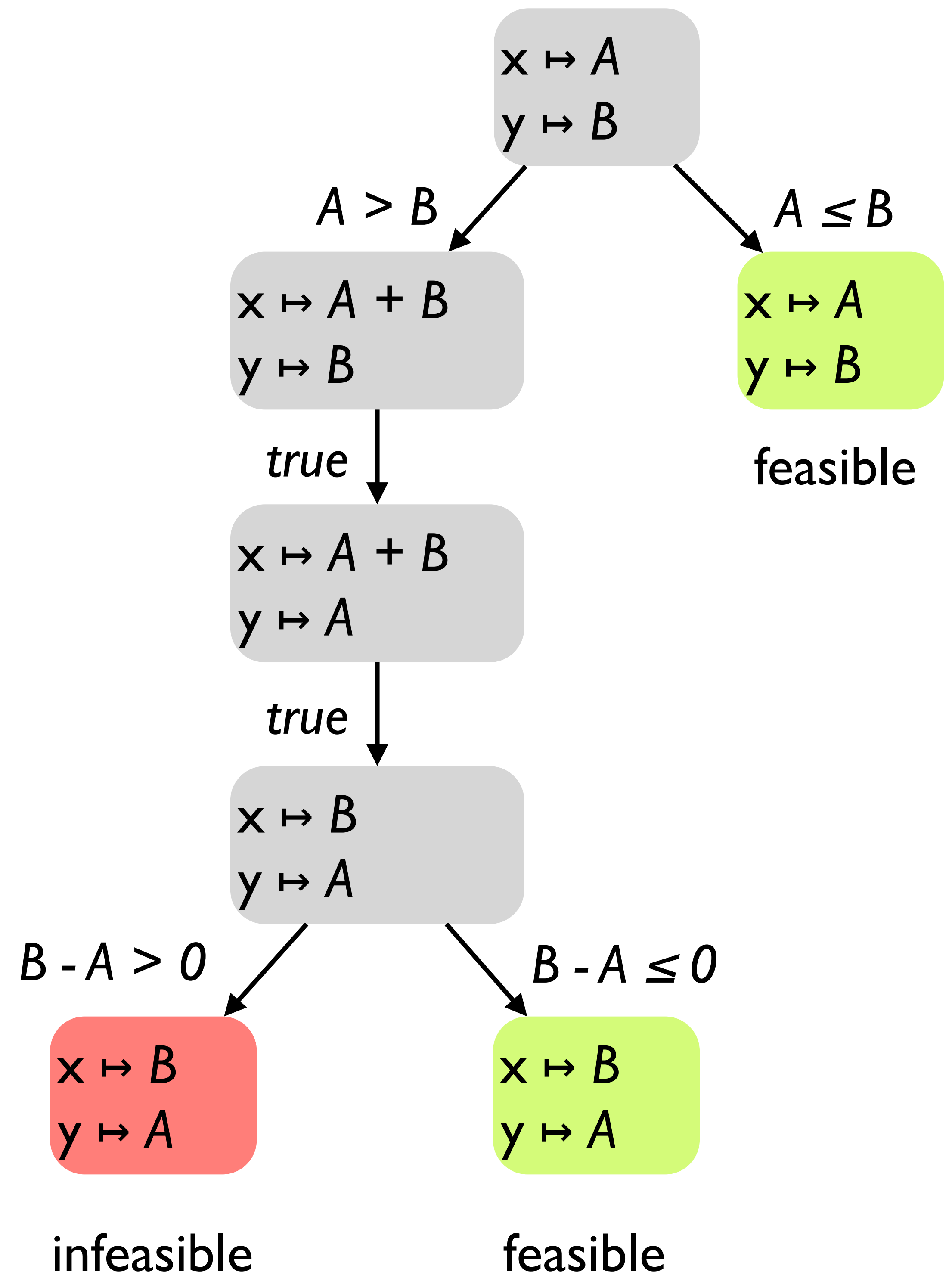

Symbolic execution: practical issues

Loops and recursion: infinite execution trees

Path explosion: exponentially many paths

Heap modeling: symbolic data structures and pointers

Solver limitations: dealing with complex PCs

Environment modeling: dealing with native / system / library calls

Loops and recursion

Dealing with infinite execution trees:

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

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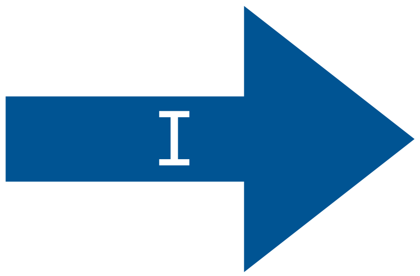
init;
while (C) {
  B;
}
assert P;
```



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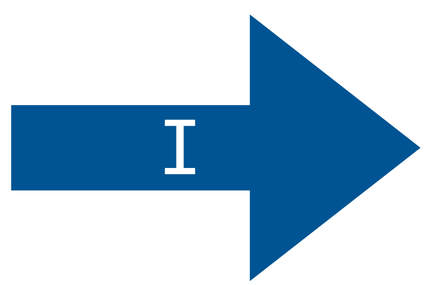


```
init;
assert I;
havoc targets(B);
assume I;
if (C) {
  B;
  assert I;
  assume false;
}
assert P;
```

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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Heap modeling

Modeling symbolic heap values and pointers

- Bit-precise memory modeling with the theory of arrays (EXE, Klee, SAGE)
- Lazy concretization (JPF)
- Concolic lazy concretization (CUTE)

Heap modeling: lazy concretization

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

n = symbolic(Node);
x = n.next;
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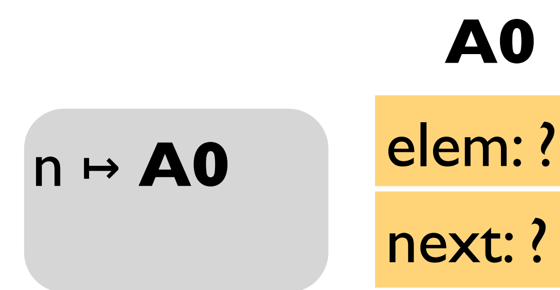

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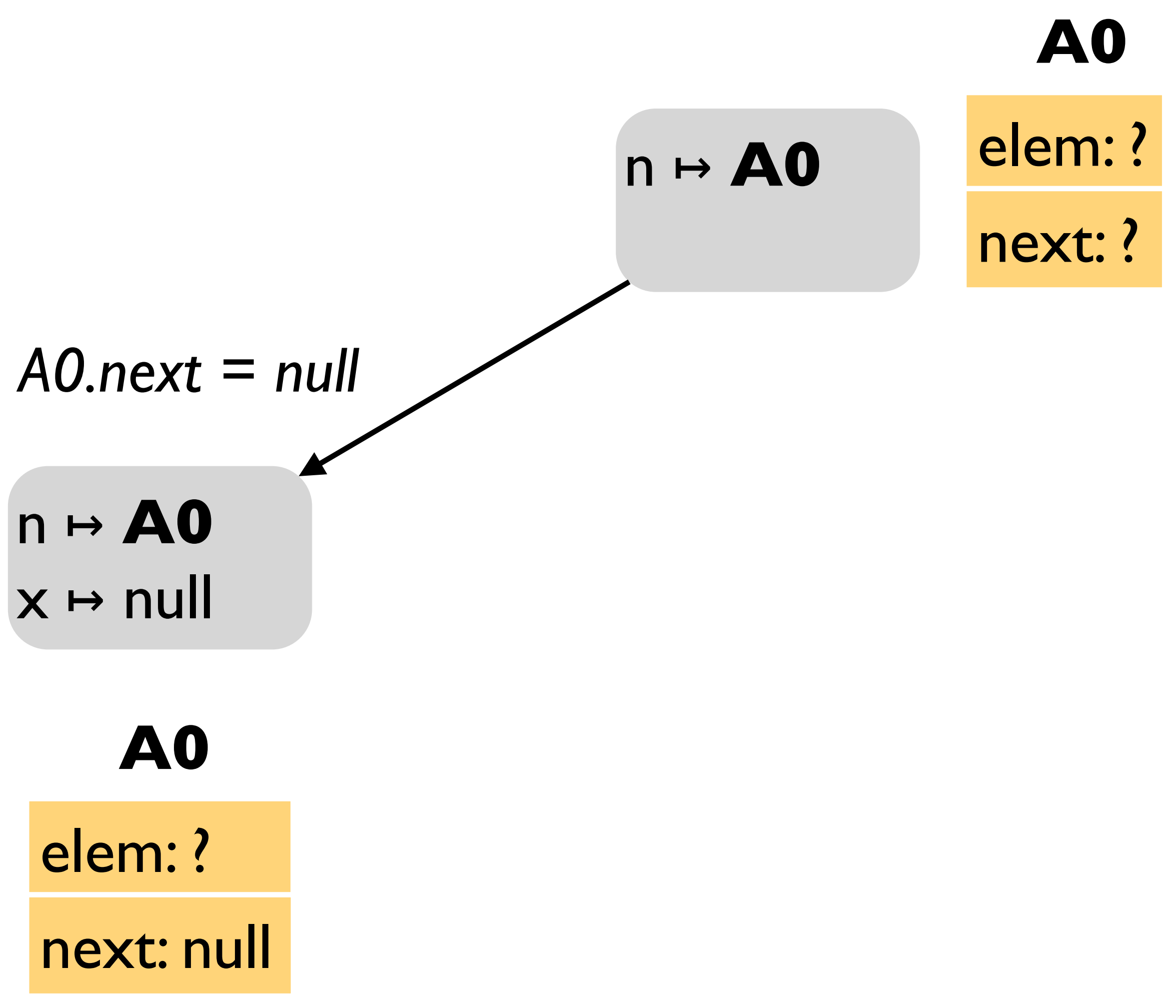

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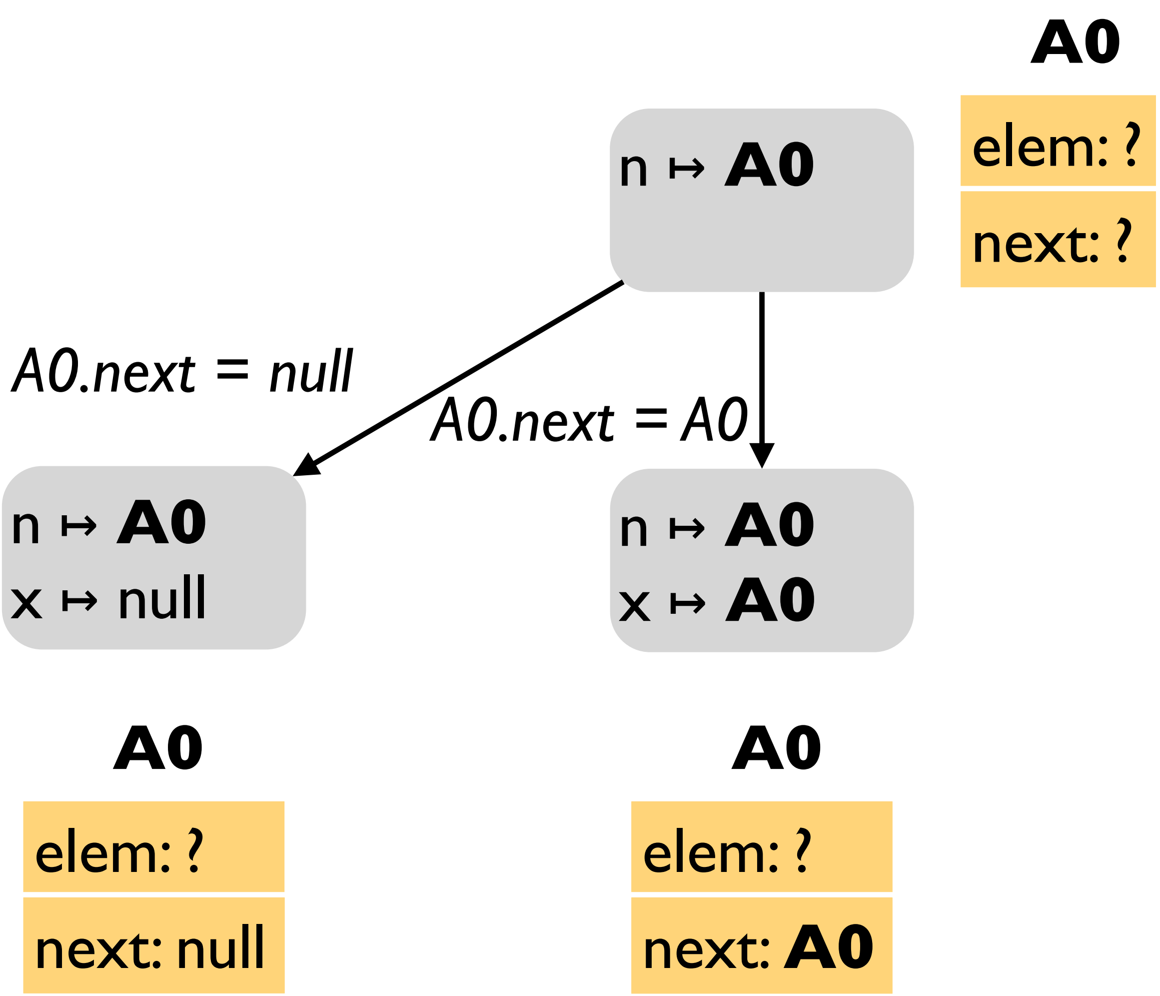

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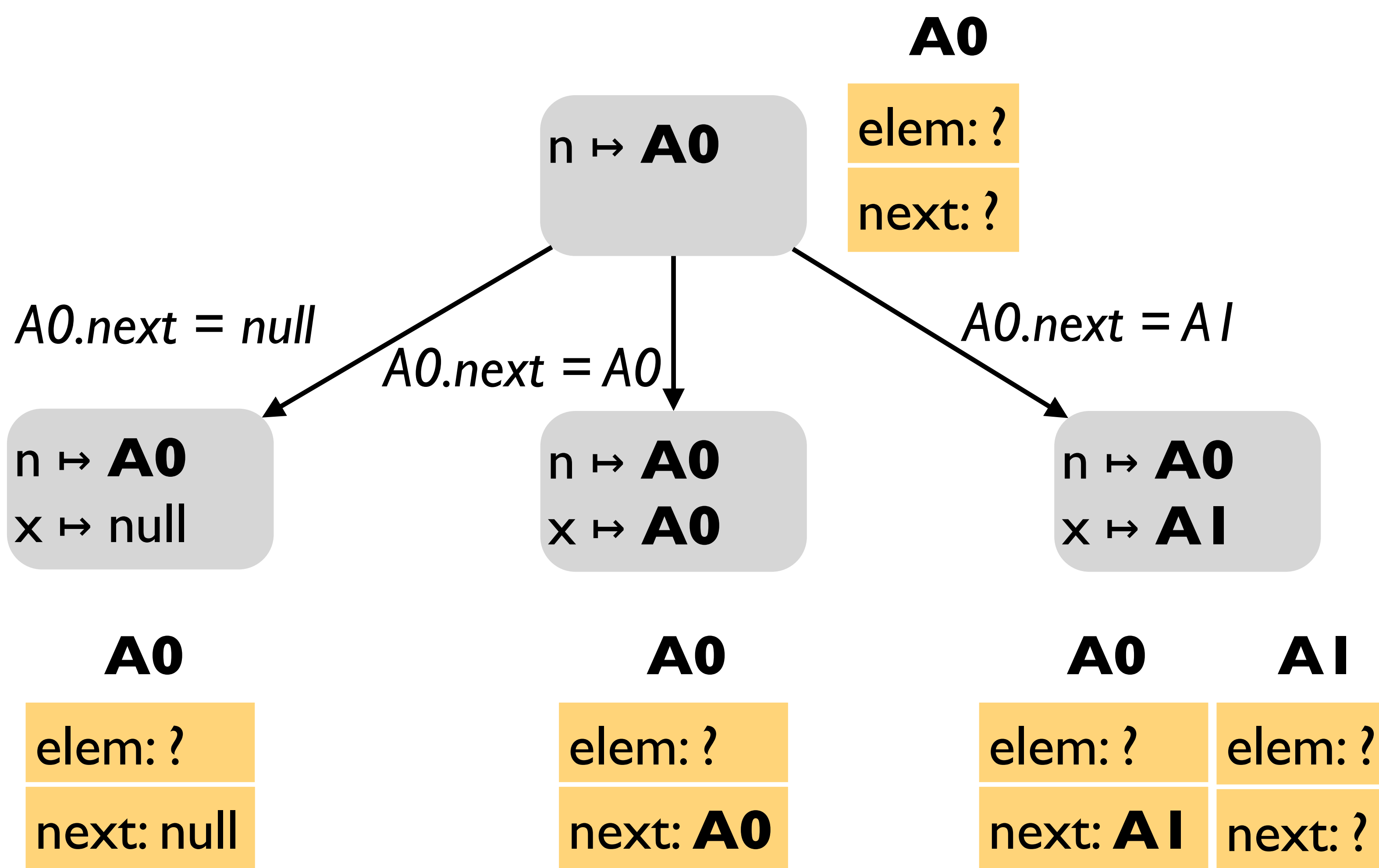

Heap modeling: concolic testing

```
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)
          assert false;
  return 0;
}
```

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Concrete	PC
p ↦ null x ↦ 236	$x > 0 \land p = null$

Execute concretely and symbolically. Negate last decision and solve for new inputs.

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

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Heap	Concrete	PC
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A0 next: null v: 634	p ↦ **A0** x ↦ 236	$x > 0 \wedge p \neq null \wedge p.v \neq 2x + 1$
A0 next: null v: 3	p ↦ **A0** x ↦ 1	$x > 0 \wedge p \neq null \wedge p.v = 2x + 1 \wedge p.next \neq p$

Execute concretely and symbolically. Negate last decision and solve for new inputs.

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Heap	Concrete	PC
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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

- Angelic execution