Computer-Aided Reasoning for Software

CSE507

# Angelic Execution

# Today

## Last lecture

- Symbolic execution

## Today

- Solvers as angelic oracles

# So far, we have used solvers as demonic oracles

Program P

Spec S

Verifier

$P \wedge \neg S$

Solver

An input i on which P violates S

# But solvers can also act as angelic oracles

```
P() {
 y = choose();
 …
 assert S;
}
```

Angelic Interpreter

$P \wedge S$

Solver

A trace of P that satisfies S

1. Definitions
2. Implementations
3. Applications

# Angelic non-determinism, two ways

**Angelic choice:**

`choose(T)`

Non-deterministically chooses a value of (finite) type T so that the program terminates successfully.

Designed to abstract away the details of backtracking search.

Robert Floyd, 1967

A programming abstraction

**Specification statement:**

`x₁, …, xₙ ← [pre, post]`

Carroll Morgan, 1988

# Angelic non-determinism, two ways

**Angelic choice:**
`choose(T)`

Robert Floyd, 1967

A programming abstraction

**Specification statement:**
`x1, …, xn ← [pre, post]`

Non-deterministically modifies the values of frame variables $x_1, \ldots, x_n$ so that *post* holds in the next state if *pre* holds in the current state.

Designed to enable derivation of programs from specifications via step-wise refinement.

Carroll Morgan, 1988

A refinement abstraction

# Angelic non-determinism, two ways: an example

**Angelic choice:**

`choose(T)`

**Specification statement:**

$x_1, \ldots, x_n \leftarrow$ [pre, post]

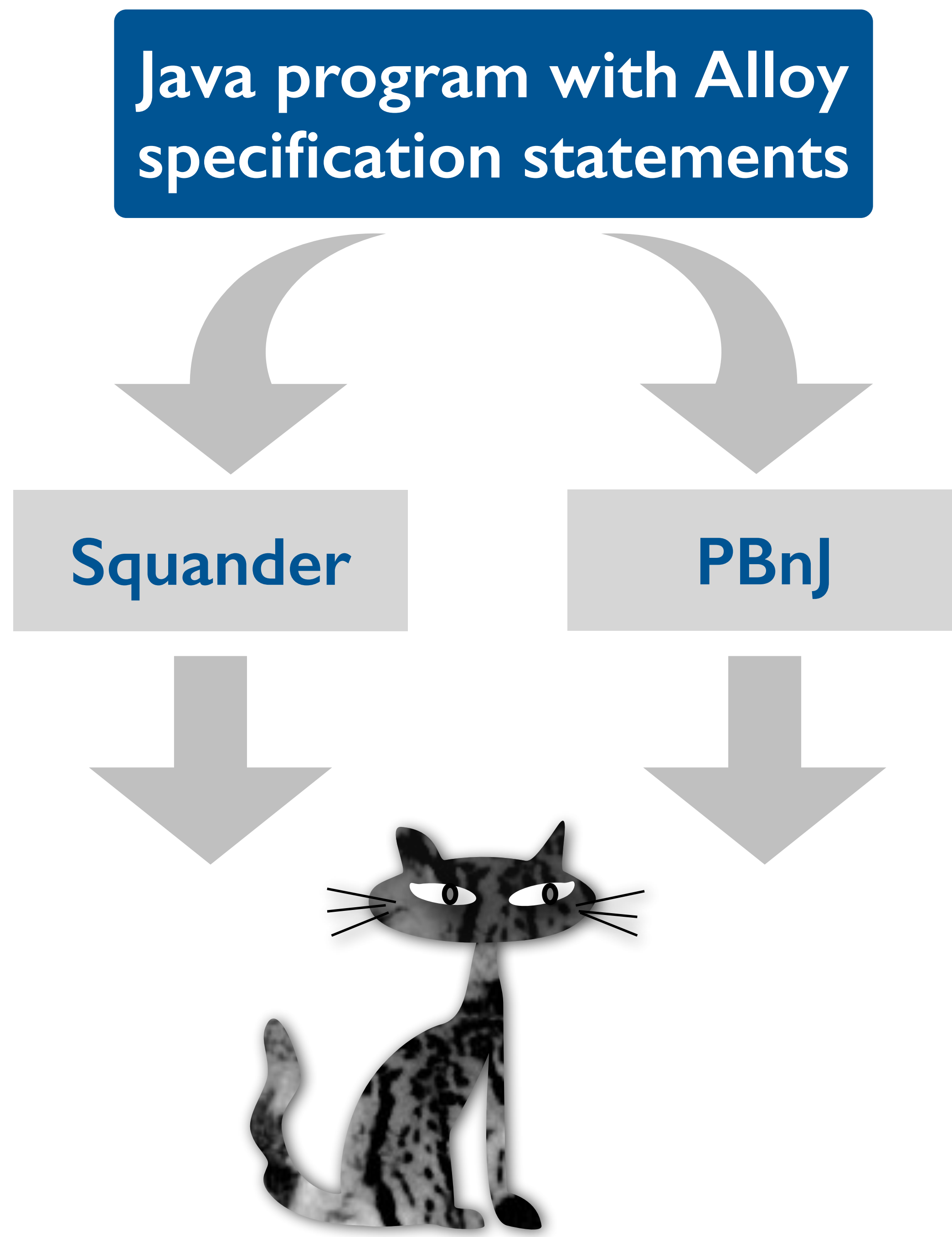
```
s = 16
r = choose(int)
if (r ≥ 0)
  assert r*r ≤ s < (r+1)*(r+1)
else
  assert r*r ≤ s < (r-1)*(r-1)
```

"Angelic Interpretation"

```
s = 16
r ← [true,
     (r ≥ 0 ∧
      r*r ≤ s < (r+1)*(r+1)) ∨
     (r < 0 ∧
      r*r ≤ s < (r-1)*(r-1))]
```

"Mixed Interpretation"

# Mixed interpretation with a model finder (1/4)



# Mixed interpretation with a model finder (2/4)

```
@Requires("z.key !in this.nodes.key")
@Ensures("this.nodes = @old(this.nodes) + z")
@Modifies("this.root,
           this.nodes.left | _<1> = null,
           this.nodes.right | _<1> = null")

public void insert(Node z) {
  Squander.exe(this, z); }
```

Specification statements describing insertion of a new node z into a binary search tree.

**Execution steps:**

- Serialize the relevant part of the heap to a universe and bounds
- Use Kodkod to solve the specs against the resulting universe / bounds
- Deserialize the solution (if any) and update the heap accordingly

# Mixed interpretation with a model finder (3/4)

```
@Requires("z.key !in this.nodes.key")
@Ensures("this.nodes = @old(this.nodes) + z")
@Modifies("this.root,
           this.nodes.left | _<1> = null,
           this.nodes.right | _<1> = null")

public void insert(Node z) {
  Squander.exe(this, z); }
```

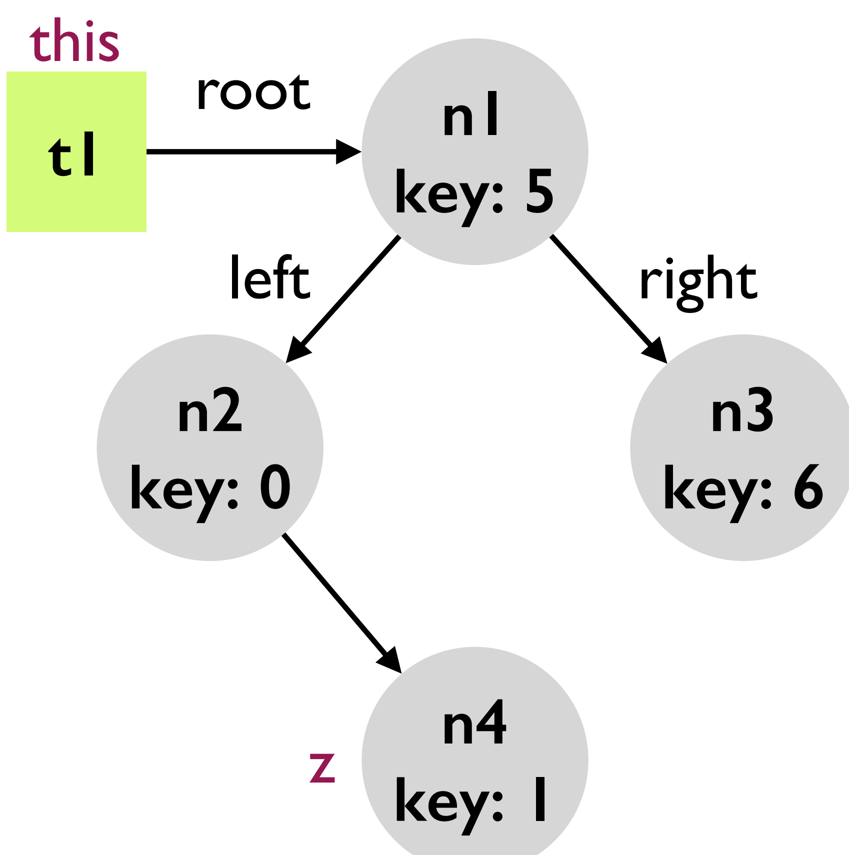
**pre-state**

$\textbf{key}_{old} = \{\langle n_1, 5\rangle, \ldots, \langle n_4, 1\rangle\}$

$\textbf{root}_{old} = \{\langle t_1, n_1\rangle\}$

$\textbf{left}_{old} = \{\langle n_1, n_2\rangle, \ldots, \langle n_4, null\rangle\}$

$\textbf{right}_{old} = \{\langle n_1, n_3\rangle, \ldots, \langle n_4, null\rangle\}$




**reachable objects**

$\mathbf{T} = \{\langle t_1\rangle\}$

$\mathbf{N} = \{\langle n_1\rangle, \ldots, \langle n_4\rangle\}$

$\textbf{null} = \{\langle null\rangle\}$

$\textbf{this} = \{\langle t_1\rangle\}$

$\mathbf{z} = \{\langle n_4\rangle\}$

$\textbf{ints} = \{\langle 0\rangle, \langle 1\rangle, \langle 5\rangle, \langle 6\rangle\}$

**post-state**

$\{\} \subseteq \textbf{root} \subseteq \{t_1\} \times \{n_1, \ldots, n_4, null\}$

$\{\langle n_1, n_2\rangle\} \subseteq \textbf{left} \subseteq \{n_2, n_3, n_4\} \times \{n_1, \ldots, n_4, null\}$

$\{\langle n_1, n_3\rangle\} \subseteq \textbf{right} \subseteq \{n_2, n_3, n_4\} \times \{n_1, \ldots, n_4, null\}$

# Mixed interpretation with a model finder (4/4)

```
@Requires("z.key !in this.nodes.key")
@Ensures("this.nodes = @old(this.nodes) + z")
@Modifies("this.root,
           this.nodes.left | _<1> = null,
           this.nodes.right | _<1> = null")

public void insert(Node z) {
  Squander.exe(this, z); }
```

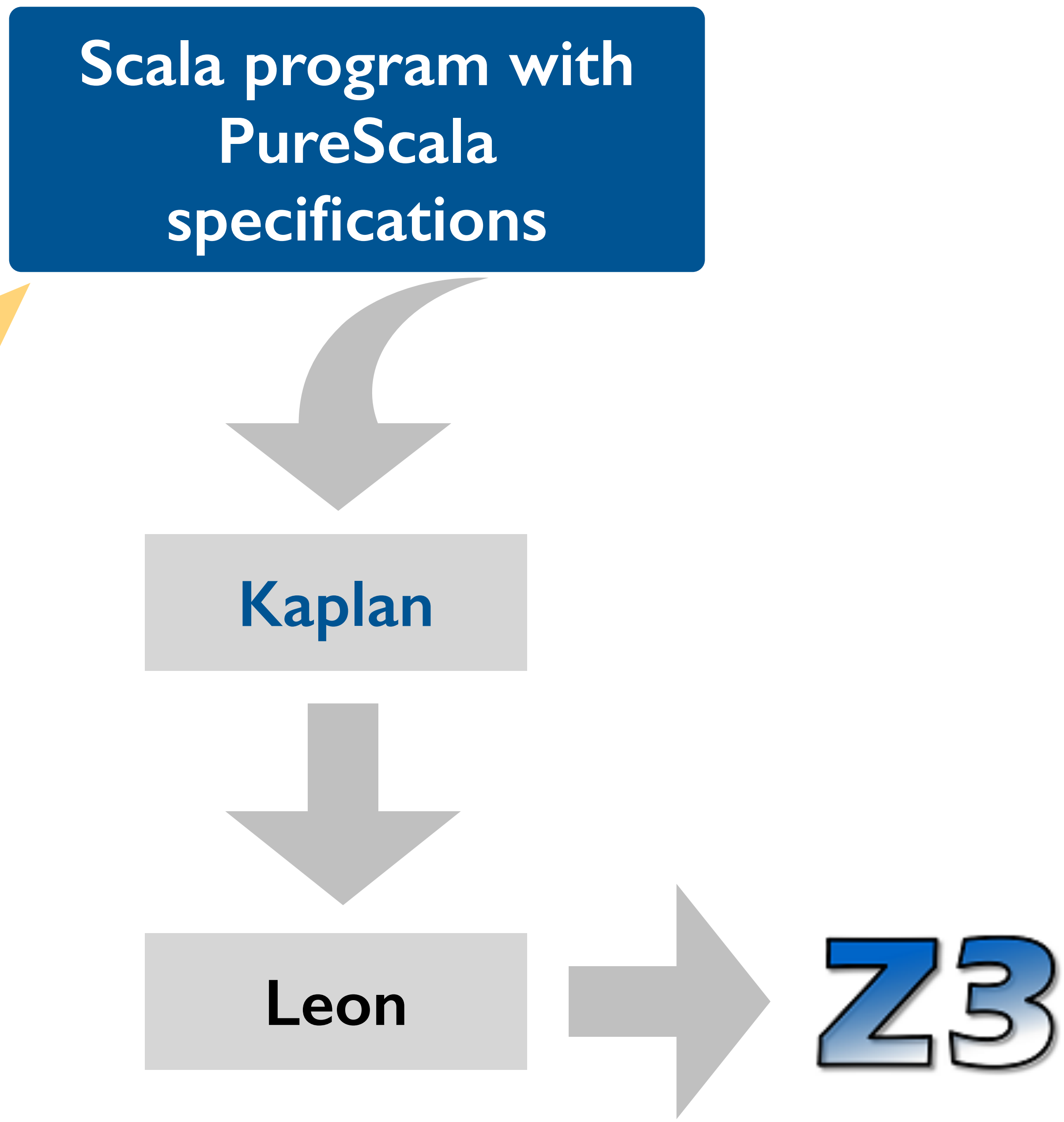
Incompleteness due to finitization: Squander bounds the number of new instances of a given type that Kodkod can create to satisfy the specification.

Many more features (e.g., support for obtaining all solutions, support for data abstraction, etc.).

See Unifying Execution of Declarative and Imperative Code for details.

# Mixed interpretation with an SMT solver (1/3)

PureScala is a pure, Turing complete subset of Scala that supports unbounded datatypes and arbitrary recursive functions.



# Mixed interpretation with an SMT solver (2/3)

```
@spec def noneDivides(from: Int, j: Int) : Boolean {
  from == j ||
  (j % from != 0 && noneDivides(from+1, j))
}

@spec def isPrime(i: Int) : Boolean {
  i >= 2 && noneDivides(2, i)
}

val primes =
((isPrime(_Int)) minimizing
 ((x:Int) => x)).findAll

> primes.take(10).toList
List(2, 3, 5, 7, 11, 13, 17, 19, 23, 29)
```

Recursive specification functions. Mutual recursion also allowed.

**Two execution modes:**

- Eager: uses Leon to find a satisfying assignment for a given specification.
- Lazy: accumulates specifications, checking their feasibility, until the programmer asks for the *value* of a logical variable. The variable is then frozen (permanently bound) to the returned value.

Call the Kaplan mixed interpreter to obtain the first 10 primes.

# Mixed interpretation with an SMT solver (3/3)

```
@spec def noneDivides(from: Int, j: Int) : Boolean {
  from == j ||
  (j % from != 0 && noneDivides(from+1, j))
}

@spec def isPrime(i: Int) : Boolean {
  i >= 2 && noneDivides(2, i)
}

val primes =
((isPrime(_Int)) minimizing
 ((x:Int) => x)).findAll

> primes.take(10).toList
List(2, 3, 5, 7, 11, 13, 17, 19, 23, 29)
```

Incompleteness due to undecidability of PureScala.

Many more features (e.g., support for optimization).

See Constraints as Control for details.

# Angelic interpretation with a solver

```
s = 16
r = choose(int)
if (r ≥ 0)
  assert r*r ≤ s < (r+1)*(r+1)
else
  assert r*r ≤ s < (r−1)*(r−1)
```

**Execution steps:**

- Translate to the entire program to constraints using either BMC or SE.
- Query the solver for one or all solutions that satisfy the constraints.
- Convert each solution to a valid program trace (represented, e.g., as a sequence of choices made by the oracle in a given execution).

# Applications of angelic execution

**Declarative mocking** [Samimi et al., ISSTA'13]

**Angelic debugging** [Chandra et al., ICSE'11]

**Imperative/declarative programming** [Milicevic et al., ICSE'11]

**Algorithm development** [Bodik et al., POPL'10]

**Dynamic program repair** [Samimi et al., ECOOP'10]

**Test case generation** [Khurshid et al., ASE'01]

**...**

# Summary

## Today

- Angelic nondeterminism with specifications statements and angelic choice
- Angelic execution with model finders and SMT solvers
- Applications of angelic execution

## Next lecture

- Program synthesis