Program Synthesis with **Jennisys**

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Concolic Synthesis

with **Jennisys**

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Program Extrapolation

with **Jennisys**

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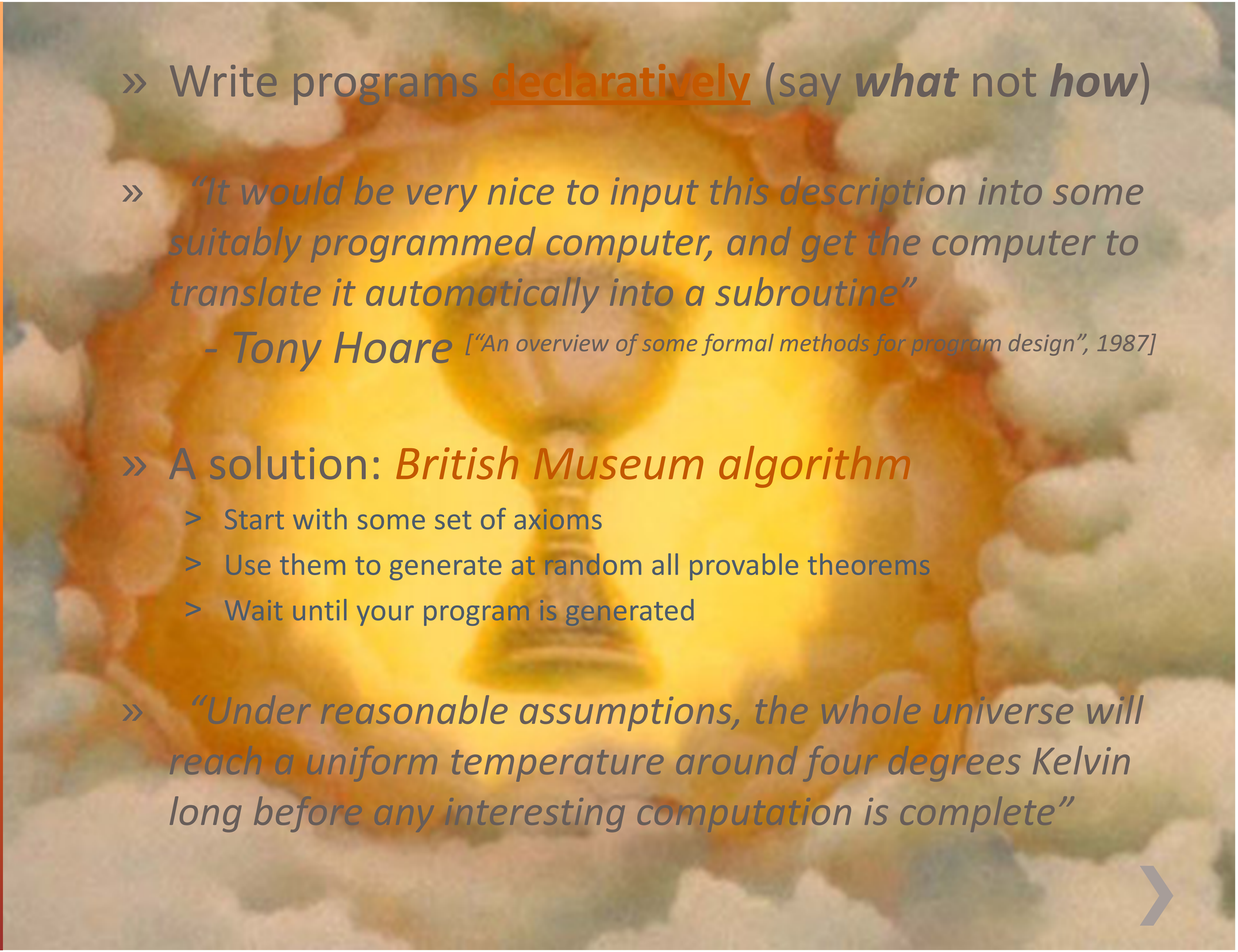
On Specifications ›

- Specifications are good
  - Formally give meaning to your programs
- Typically used to check a *separate* program
  - Program verification
  - Proving the absence of safety/security violations
  - Test case generation
- Also convenient
  - Elegantly and succinctly express complex properties/invariants
- We would like to use specs even **for writing programs**



- Write programs declaratively (say ***what*** not ***how***)

- *"It would be very nice to input this description into some suitably programmed computer, and get the computer to translate it automatically into a subroutine"*
  - *Tony Hoare* *["An overview of some formal methods for program design", 1987]*

- A solution: *British Museum algorithm*
  - Start with some set of axioms
  - Use them to generate at random all provable theorems
  - Wait until your program is generated

- *"Under reasonable assumptions, the whole universe will reach a uniform temperature around four degrees Kelvin long before any interesting computation is complete"*

Approaches

» Executable specifications

- Specification are executed directly at runtime
- Typically a constraint solver is used to search for a model
- The solution is valid for the current program state only
- Preferably integrated within an existing programming language

» Program synthesis

- Statically generate imperative code equivalent to given declarative spec
- Covers all cases at once

	Executable Specifications	Program Synthesis
running time	✓ Big	✗ Huge
frequency	✗ At every invocation	✓ once, statically
power	✓ NP-hard specs	✗ (mostly) linear algorithms

	Executable Specifications	Program Synthesis
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frequency	✗ At every invocation	✓ once, statically
power	✓ NP-hard specs	✗ (mostly) linear algorithms

» Combine the green checkmarks of both?

> Synthesis and executable specs are still quite orthogonal

» **Instead**: find a sweet spot of synthesis

> Identify a category of programs that can be easily synthesized

> The synthesis should be fully automatic

> It shouldn’t be super slow: order of seconds, not hours

> The only input from the user is the spec (declarative, first-order)

> **Implementation**:

→ execute specifications and **generalize** from concrete instances

Goal ›

Public interface

```
interface Set {
  var elems: set[int]

  constructor Empty()
    ensures elems = {}

  constructor Singleton(t: int)
    ensures elems = {t}

  constructor Double(p: int, q: int)
    requires p != q
    ensures elems = {p q}

  method Contains(p: int) returns (ret: bool)
     ensures ret = p in elems
}
```

Data-model

```
datamodel Set {
  var root: SetNode

  invariant
    root = null ==> elems = {}
    root != null ==> elems = root.elems
}
```

- » Public interface: high-level interface in terms of abstract fields
- » Data-model: data description, concrete fields, additional invariants
- » Code: implementation code for methods that could not be synthesized

Jennisys›

```
interface SetNode {
  var elems: set[int]

  constructor Init(x: int)
    ensures elems = {x}

  constructor Double(a: int, b: int)
    ensures elems = {a b}

   method Contains(p: int) returns (ret: bool)
     ensures ret = (p in elems)
}
```

```
datamodel SetNode {
  var data: int
  var left: SetNode
  var right: SetNode

  invariant
    elems = {data} + (left != null ? left.elems : {}) + (right != null ? right.elems : {})
    left != null  ==> forall e :: e in left.elems ==> e < data
    right != null ==> forall e :: e in right.elems ==> e > data
}
```

Outline

- **Techniques**
  - Solving for concrete instances that meet the spec
  - Generalizing from concrete heap instances
  - Inferring branching (flow) structure
  - Delegating to method calls
- **Application**
  - Synthesizing Constructors
  - Synthesizing Recursive Functional-Style Methods

» Synthesizing Constructors – Initial Idea

- Constructors only initialize the object fields
  □ enough to find assignments to all object fields
- Execute the constructor specification to find a concrete instance
  (a model that satisfies all constraints of the spec)
- Print out straight-line code that assigns values to
  fields according to the model
- Use **Dafny** program verifier to execute specifications

Executing Specs ›

» Example (Executing Specification)

Jennisys

```
interface SetNode {
  invariant
    …
}
```

```
interface Set {
  constructor SingletonZero()
     ensures elems = {0}
}
```

Dafny

```
class SetNode {
  ghost var elems: set<int>;
  var data: int;
  var left: SetNode;
  var right: SetNode;

  function Valid(): bool
  {
     user-defined invariant &&
     left != null ==> left.Valid() &&
     right != null ==> right.Valid()
  }
}
```

```
class Set {
  ghost var elems: set<int>;
  var root: SetNode;

  function Valid():  bool { … }

  method SingletonZero()
    modifies this;
  {
    // assume invariant and postcondition
    assume Valid();
    assume elems == {0};
    // assert false
    assert false;
  }
}
```

Counterexample encodes an instance for which all constraints hold

Executing Specs ›

» Example (Synthesized Code)

Jennisys

```
interface SetNode {
  invariant
    …
}
```

```
interface Set {
  constructor SingletonZero()
     ensures elems = {0}
}
```

Dafny

```
class SetNode {
  ghost var elems: set<int>;
  var data: int;
  var left: SetNode;
  var right: SetNode;

  function Valid(): bool { ... }
}

class Set {
  ghost var elems: set<int>;
  var root: SetNode;

  function Valid():  bool { ... }
```

```
  method SingletonZero()
    modifies this;
    ensures Valid && elems == {0};
  {
    var gensym74 := new SetNode;
    this.elems := {0};
    this.root := gensym74;
    gensym74.data := 0;
    gensym74.elems := {0};
    gensym74.left := null;
    gensym74.right := null;
  }
}
```

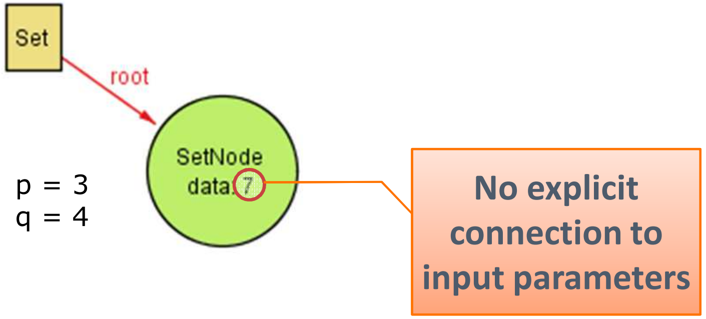
No-arg Constructors ›

» Constructors with Parameters

- > Assigning concrete values obtained from the solver is no longer enough

```
interface Set {
 constructor SingletonSum(p: int, q:
int)
    ensures elems = {p + q}
}
```

Spec



No explicit connection to input parameters

Concrete Instance

- > Simply matching up values of unmodifiable fields (e.g. method input args) with values assigned to fields is not enough

➔ **Custom spec evaluation**:
evaluate parts of the spec wrt the current instance

Generalizing ›

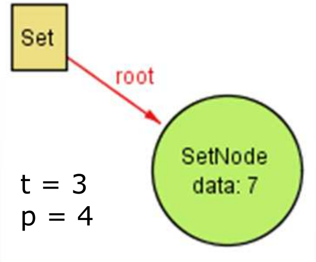
» Custom Spec Evaluation

```
datamodel Set {
  invariant
    root = null ==> elems = {}
    root != null ==> elems = root.elems

  constructor SingletonSum(p: int, q: int)
     ensures elems = {p + q}
}
```

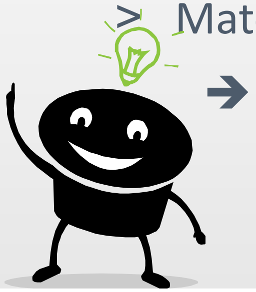
```
datamodel SetNode {
  invariant
    elems = {data} + (left != null ? left.elems : {})
                        + (right != null ? right.elems : {})
    left != null  ==> forall e :: e in left.elems ==> e < data
    right != null ==> forall e :: e in right.elems ==> e > data
}
```

{7} □ {p + q}
7 □ p + q



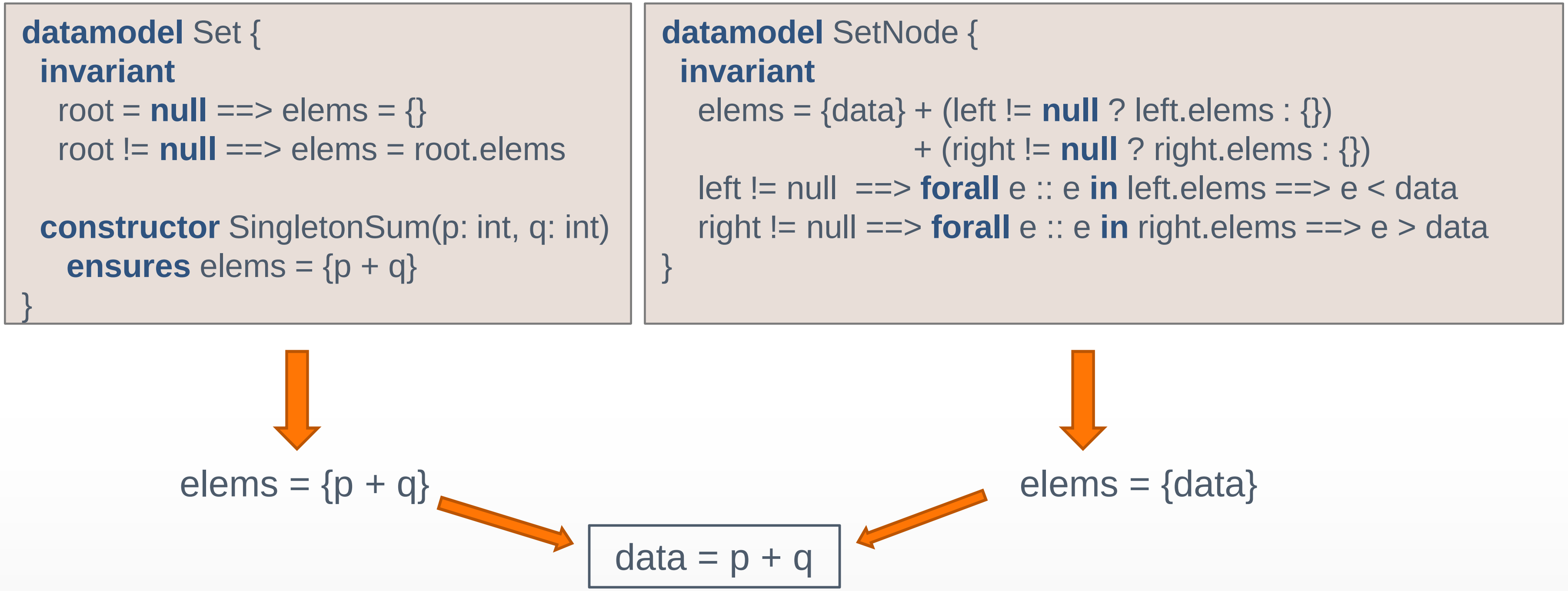
true

- Evaluate the spec without resolving unmodifiable fields
- Then do the match-up
- Matching up can still be ambiguous



➔ better approach: use **concolic spec evaluation** and **unification**

» Concolic Spec Evaluation



```
datamodel Set {
  invariant
    root = null ==> elems = {}
    root != null ==> elems = root.elems

  constructor SingletonSum(p: int, q: int)
     ensures elems = {p + q}
}
```

```
datamodel SetNode {
  invariant
    elems = {data} + (left != null ? left.elems : {})
                        + (right != null ? right.elems : {})
    left != null  ==> forall e :: e in left.elems ==> e < data
    right != null ==> forall e :: e in right.elems ==> e > data
}
```

elems = {p + q}

elems = {data}

data = p + q

- Evaluate the spec against the instance without resolving anything
  - This gets us a simpler spec for the current instance
- Use unification to obtain symbolic values for fields

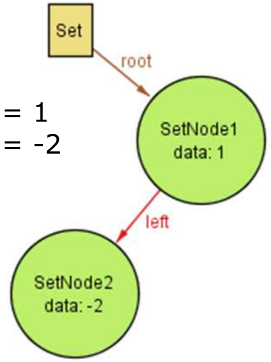
» Inferring Branching (Flow) Structure

- Straight-line code is no longer enough

```
interface Set {
  constructor Double(p: int, q: int)
    requires p != q
    ensures elems = {p q}
}
```

Spec

p = 1
q = -2



Concrete Instance

- A correct solution has to consider two cases
  (1) p > q, and **(2)** p < q
- **Approach**:
  - → Find a concrete instance
  - → Generalize and try to verify
  - → If it doesn't verify
    - → **Infer** the needed **guard** using custom spec evaluation

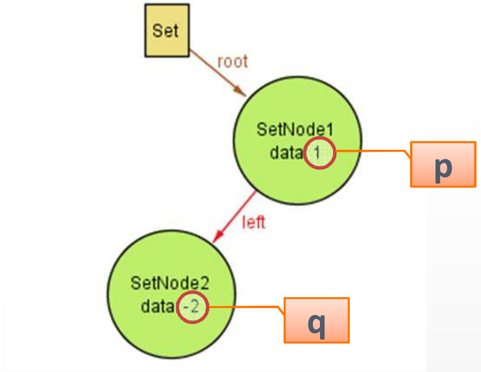
» Inferring Guards

```
datamodel Set {
  invariant
    root = null ==> elems = {}
    root != null ==> elems = root.elems

  constructor Double(p: int, q: int)
     ensures elems = {p q}
}
```

```
datamodel SetNode {
  invariant
    elems = {data} + (left != null ? left.elems : {})
                        + (right != null ? right.elems : {})
    left != null  ==> forall e :: e in left.elems ==> e < data
    right != null ==> forall e :: e in right.elems ==> e > data
}
```

{p q} = {p q}
true



q < p

- > Evaluate the spec without resolving unmodifiable fields
- > Find all true clauses and try to use them as **if** guards
  - → *Concolic evaluation discovers clauses hidden behind the declarativness*
- > If it verifies, negation the inferred guard and go all over again.

» **Delegating** to existing methods

- So far, all objects are initialized in the constructor for the root object
  - → Breaks encapsulation
- Instead, each object should be initialized in its own constructor
- **Approach**:
  - → Find a solution as before
  - → For each child object infer a spec needed for its initialization
  - → Find an existing constructor that meets this spec, or create a new one

» Spec Inference for Child Objects

- Simply use the obtained assignments to all of its public fields

» Finding existing methods that meet a given spec

- Use syntactic unification with a few semantics rules
- Limitation: in some cases valid candidate methods can be missed

Delegating ›

» Delegation Example

```
class Set {
  method Double(p: int, q: int)
    more_spec
    ensures elems == {p q}
  {
    var sym80 := new SetNode;
    sym80.Double(p, q);
    this.elems := {q, p};
    this.root := sym80;
  }
}
```

```
class SetNode {
  method Double(p: int, q: int)
    more_spec
    ensures elems == {p q}
  {
    if (b > a) {
      this.DoubleBase(b, a);
    } else {
      this.DoubleBase(a, b);
    }
  }
    ...
```

```
  method DoubleBase(x: int, y: int)
     more_spec
     requires x < y;
     ensures elems == {x, y};
   {
     var sym88 := new SetNode;
     sym88.Init(x);
     this.data := y;
     this.elems := {y, x};
     this.left := null;
     this.right := sym88;
   }
 }
```

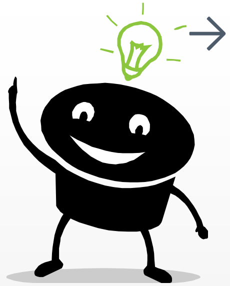
» Finding existing methods that meet a given spec

- Use syntactic unification with a few semantics rules
- Limitation: in some cases valid candidate methods can be missed

Delegating›

» Synthesizing **Recursive Methods**

- Goal: synthesize simple functional-style methods:
  - → assignments to fields are in the form of function compositions (as opposed to arbitrary statement sequences with mutable variables)
- Idea:
  - → Again, generalize from concrete instances
  - → Again, obtain a set of true clauses using concolic evaluation
  - → (**new**) use an inference engine to derive additional logical conclusion
  - → (**new**) use unification to match up clauses from the knowledge base with specs of the existing methods



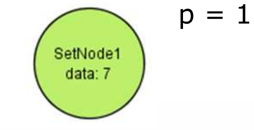
Recursive Methods ›

» Example (SetNode.Contains)

```
interface SetNode {
  constructor Contains (p: int) returns (ret: bool)
    ensures ret = p in elems
}
```

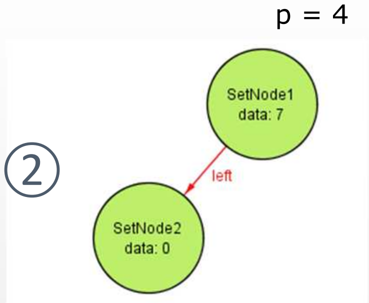
```
datamodel SetNode {
  invariant
    elems = {data} + (left != null ? left.elems : {})
                   + (right != null ? right.elems : {})
    left != null  ==> forall e :: e in left.elems ==> e < data
    right != null ==> forall e :: e in right.elems ==> e > data
}
```

①



guard: left == null && right == null
assignments: ret = (p == data)

②



KB:
elems = {data} + left.elems
left.elems = {left.data}
left.data < data
ret = p in elems

---

ret = p in ({data} + left.elems)

---

false
ret = p in {data} || p in left.elems
ret = p in left.elems

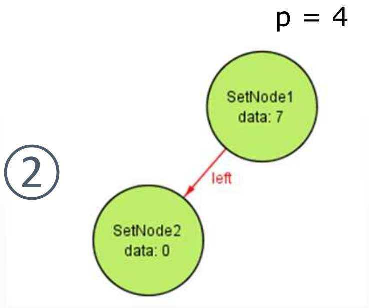
transitivity

domain specific rules

» Example (SetNode.Contains)

```
interface SetNode {
  constructor Contains (p: int) returns (ret: bool)
    ensures ret = p in elems
}
```

```
datamodel SetNode {
  invariant
    elems = {data} + (left != null ? left.elems : {})
                   + (right != null ? right.elems : {})
    left != null  ==> forall e :: e in left.elems ==> e < data
    right != null ==> forall e :: e in right.elems ==> e > data
}
```



```
KB:   elems      = {data} + left.elems
      left.elems = {left.data}
      left.data  < data
      ret        = p in elems
      ret        = p in ({data} + left.elems)
      ret        = p in left.elems
      ---------------------------------------------
      $ret       = $p in $this.elems   (Contains($p))
      ---------------------------------------------
      ret        = left.Contains(p)
```

Unification

Add method specs

```
method Contains(n: int) returns (ret: bool)
  requires Valid();
  ensures Valid();
  ensures ret == (n in elems);
{
  if (left != null && right != null) {
    ret := n == data || left. Contains(n) || right. Contains(n);
  } else {
    if (left != null && right == null) {
      ret := n == data || left. Contains(n);
    } else {
      if (right != null && left == null) {
        ret := n == data || right. Contains(n);
      } else {
        ret := n == data;
      }
    }
  }
}
```

SetNode.Contains

» Domain Specific Rules

$$\text{e in } (\text{set}_1 + \text{set}_2) \quad \Leftrightarrow \quad (\text{e in set}_1) \mathbin{||} (\text{e in set}_2)$$

$$|\text{seq}_1 + \text{seq}_2| \quad \Leftrightarrow \quad |\text{seq}_1| + |\text{seq}_2|$$

$$(\text{seq}_1 + \text{seq}_2)[\text{idx}] \Leftrightarrow \begin{cases} \text{seq}_1[\text{idx}], & \text{when idx} < |\text{seq}_1| \\ \text{seq}_2[\text{idx} - |\text{seq}_1|], & \text{when idx} \geq |\text{seq}_1| \end{cases}$$

$$\begin{aligned} &\text{forall e :: e in seq}_1 \Rightarrow \text{P(e)} \Leftrightarrow \\ &\quad |\text{seq}_1| > 0 \Rightarrow (\text{P}(\text{seq}_1[0]) \land (\text{foralle :: e in seq}_1[1..] \Rightarrow \text{P(e)})) \end{aligned}$$

Limitations

Expressiveness

- "Very declarative" specifications cannot be synthesized

```
constructor Sqrt(p: int) returns (ret: int)
   requires p > 0
   ensures ret * ret <= p && (ret+1)*(ret+1) > p
```

- Works mostly for specifications with assignments
- Takes advantage of recursively defined specifications

Synthesized Methods

- No loops (synthesizing loop invariants is a problem); recursion instead
- Not necessarily the most efficient implementation (e.g. like in Set.Contains()),
  - → but still faster than executing the same specification every time
- (currently) Simple read-only queries

Related Work›

- **Sketch** – Armando Solar Lezama [2008]
  - spec: a correct (but presumably inefficient) implementation
  - extras: a **sketch**: outlining the control structure of a desired solution
  - output: equivalent low-level procedure
- **Storyboard Programming** – Rishabh Singh [2011]
  - spec: **abstract** graphical **input/output examples**
  - extras: a similar **sketch** of the final solution
  - output: low-level procedure that works for the given examples
- **KIDS** (Kestrel Interactive Development System)
  – Douglas R. Smith [1990]
  - spec: high-level logical specification
  - extras: much more verbose than pre/post conditions, semi-automated
  - output: efficient implementation

- Finish up implementation for recursive methods
- Further explore the idea of concolic synthesis
- Try to generalize the idea of concolic synthesis to a broader range of (functional) programs
- Formalize the synthesis algorithm
- More examples
- Evaluation and comparison with other tools

Next Steps ›

- Finish up implementation for recursive methods
- Further explore the idea of concolic synthesis
- Try to generalize the idea of concolic synthesis to a broader range of (functional) programs
- Formalize the synthesis algorithm
- More examples
- Evaluation and comparison with other tools

THANK YOU!

›