Verifying Data Structure Correctness in the Hob and Jahob Systems

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Data Structure Correctness

- Internal correctness (single data structure)
  - Internal representation consistent
  - Procedure specifications sound (precondition implies postcondition)
- Client correctness (clients use data structures correctly)
- External correctness (multiple data structures)
  - Inclusion constraints
  - Disjointness constraints
  - Equality constraints

Our Goal

- Verify data structure correctness
  - Internal properties
  - Usage properties
  - External properties
- Before program executes
- For all possible program executions
- Two systems
  - Hob (abstract sets of objects)
  - Jahob (abstract sets and relations)

Queue Specification in Hob System

```
spec module Queue {
  format Entry;
  sets Content : Entry;
  proc add(e : Entry)
    requires not (e in Content)
    modifies Content
    ensures Content' = Content + e;
  proc removeFirst() returns e : Entry
    requires card(Content)>=1
    modifies Content
    ensures (Content' = Content - e) & (e in Content);
  proc isEmpty() returns b : bool
    ensures b <=> (card(Content)=0);
}
```

Queue Specification in Hob System

Program is set of modules

Each module has specification

```
spec module Queue {
  format Entry;
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```

- Modules have abstract sets of objects
- Sets typically model data structure contents

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}
```

Modules have procedures

Procedures have
- preconditions
- postconditions
- modifies clauses

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Can't call removeFirst unless there is something in the queue

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```

Can’t call removeFirst unless there is something in the queue

What Are We Missing (so far)?

- Implementation
- Verification
  - Connection (implementation and specification)
  - Verification algorithm

Implementation in Hob

```
impl module Queue {
  format Entry { next : Entry; }
  reference root, tail : Entry;
  proc add(e : Entry) {
    e.next = null;
    if (tail != null) tail.next = e;
     else root = e;
    tail = e;
  }
  proc removeFirst() returns e : Entry {
    Entry res = root;
    if (tail == root) tail = null;
    root = root.next;
    return res;
  }
  proc isEmpty() returns b : bool { return root == null; }
}
```

Standard imperative language

- objects with fields
- global variables
- procedures
  - compute values
  - update fields, variables

Abstraction Modules in Hob

```
abst module Queue {
    use plugin "PALE";
    Content = {x : Entry | "root<next*>x"};

    invariant
        "type Entry = {
                data next : Entry;
         }";
    invariant "data root:Entry;";
}
```

Definition of abstract set Content

Abstraction Modules in Hob

```
abst module Queue {
  use plugin "PALE";
  Content = {x : Entry | "root<next*>x"};

  invariant
    "type Entry = {
         data next : Entry;
     }";
  invariant "data root:Entry;";
}
```

Identification of verification algorithm (multiple plugins)

Eliminating Errors in Queue Clients

```
e1 = new Entry();
Queue.add(e1);
Queue.add(e1);
```

```
e1 = new Entry();
e2 = Queue.removeFirst();
e3 = Queue.removeFirst();
```

Eliminating Errors in Queue Clients

```
e1 = new Entry();
Queue.add(e1);
Queue.add(e1);
```

Error (double add)

```
e1 = new Entry();
e2 = Queue.removeFirst();
e3 = Queue.removeFirst();
```

Errors in Queue Clients

```
e1 = new Entry();
Queue.add(e1);
Queue.add(e1);
```

Error (double add)

```
e1 = new Entry();
e2 = Queue.removeFirst();
e3 = Queue.removeFirst();
```

Error (empty remove)

Hob Minesweeper Experience

- Abstract Sets of Objects
  - Exposed cells
  - Unexposed cells
  - Mined cells
- State
  - Game Over

Hob Minesweeper Experience

Enforced Constraints

- Individual data structures
  - Correct implementations
  - Used correctly
- Multiple data structures
  - Sets of exposed and unexposed cells are disjoint
  - No mined cells are exposed unless game is over
  - When game is over, all cells are exposed

Hob Minesweeper Experience

Enforced Constraints

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Rules of Game!

Key Hob Point

Can prove properties that relate directly to concepts that users understand

No Relations in Hob

- Hash table

  Hash.insert(k1,v1);

  Hash.insert(k2,v2);

  v = Hash.lookup(k);
- What Hob can specify

  If k $\in$ {k1, k2} then v $\in$ {v1, v2}

  Otherwise v = null
- What Hob can't specify

  If k = k1 then v = v1

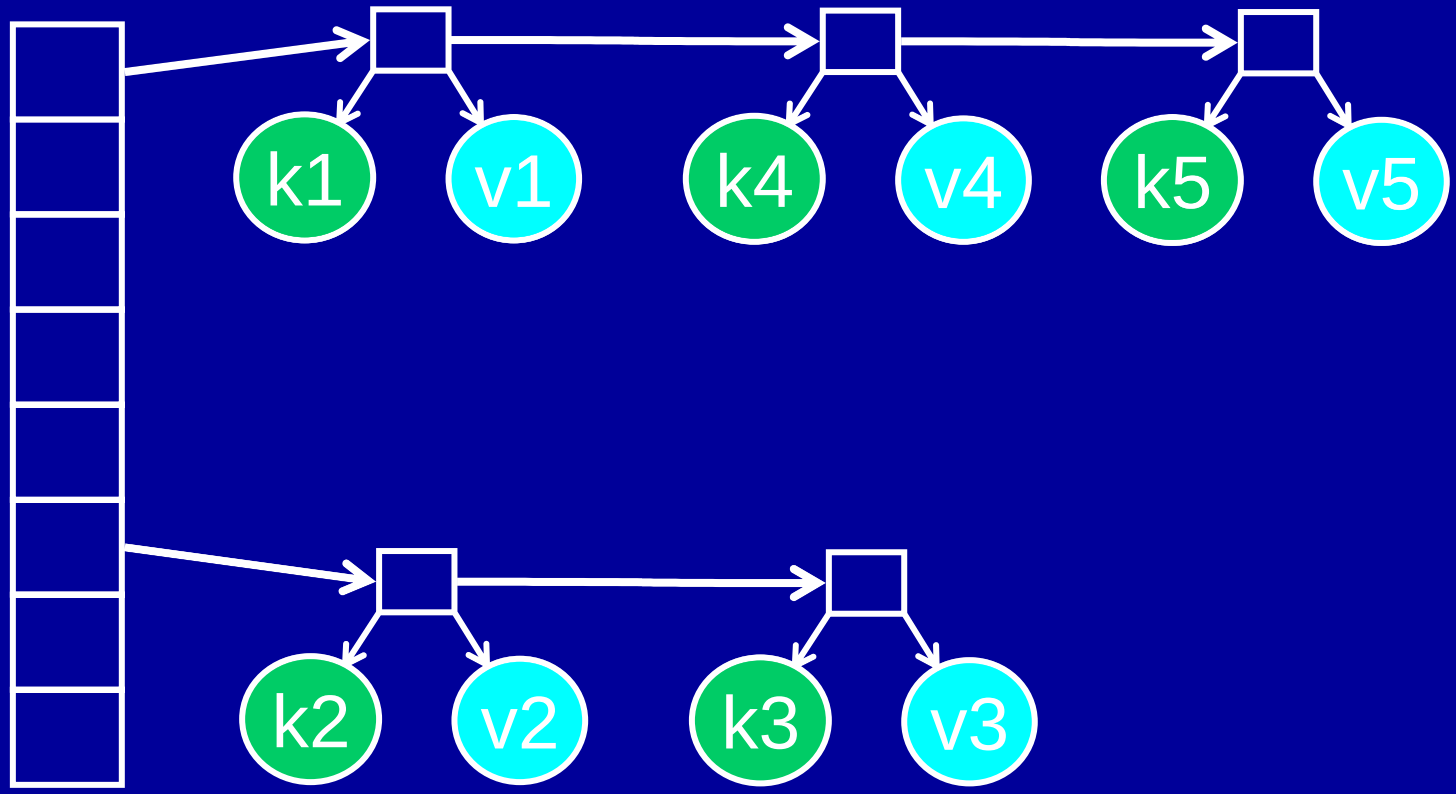
  If k = k2 then v = v2

  Otherwise v = null

Jahob

- Annotation and verification system for Java
- Data structure consistency properties
- Includes relations

Jahob Hash Table Implementation



Layered implementation: Hash Table uses Association List

Jahob Hash Table Specification

- Hash table =
  { <k1,v1>, <k2, v2>, <k3, v3>, <k4, v4>, <k5, v5> }
- insert(k,v) adds <k,v> to Hash table
- lookup(k) returns v such that either
  - <k,v> in Hash table
  - v is null and no <k,x> in Hash table
- Complete functional correctness
  (modulo non-termination) of data structure

Verifying Properties

- Complex properties
  - Full boolean algebra
  - Lots of quantifiers over sets of objects
- Basic idea
  - Derive verification conditions
  - Discharge conditions in Isabelle using
    - Proof assistants
    - Clever decision procedures
    - Manual theorem proving
      (graduate students)

Results

- Hob specification and verification system
- Systems implemented in Hob
  - Data structures (lists, trees, arrays)
  - Minesweeper
  - Hob web server
  - Water (scientific computation)
- Jahob specification and verification system
- Data structures implemented in Jahob
  - Doubly-linked list, array list, association list
  - Hash table, binary search tree
  - Priority queue (balanced tree stored in array)

Future

- Library of verified data structures
- Loop invariant inference
- Program analysis for simplifying data structure verification

Discussion Point

- We can prove/verify very sophisticated properties about lots of data structures
- What properties are useful for people here?