Runtime Checking for Program Verification Systems

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Workshop on Runtime Verification
Background

- **Jahob program verification system**
  - Statically show program corresponds to specification
  - Specification
    - Higher-order logic (HOL) using Isabelle syntax
  - Implementation
    - Sequential, memory-safe subset of Java
    - Compile (run) under standard Java compilers (runtimes)
    - Not full Java (currently not supported: exceptions, inheritance, concurrency, Java 1.5 features)
    - Supports dynamic allocation and arrays
    - Sufficient to express data structures and client programs
Data Structures Verified using Jahob

- Data Structures
  - Singly- and doubly-linked lists
  - Array list
  - Association list
  - Binary heap
  - Binary search tree
  - Hash table
- Functional and imperative implementations
- Various interfaces
  - set, relation, list, map, priority queue

- “Using First-Order Theorem Provers in the Jahob Verification System” [VMCAI07]
Motivation

- Verifying programs is difficult
- What does it mean when the prover fails?
  - Lemma is too difficult for prover
  - Error in specification and/or implementation
- Runtime checking helps find problems due to incompleteness of theorem provers
- How to check logic formulas?
- Similar to executing declarative program
Quantifiers and Sets

- Universal quantification: \( \forall (x : \text{int}). x > 0 \Rightarrow P(x) \)
- Existential quantification: \( \exists (x : \text{int}). x > 0 \Rightarrow P(x) \)
- Set comprehension: \( \{ x. x > 0 \& P(x) \} \)
- FO quantification over bounded domain
  - Not: \( \forall (j : \text{int}). x[j] : \text{content} \)
  - \( \forall (j : \text{int}). 0 \leq j \& j < x.\text{length} \Rightarrow x[j] : \text{content} \)
  - Not: \( \forall (x : \text{obj}). x.\text{next} \neq \text{head} \)
  - \( \forall (x : \text{obj}). x : \text{allocatedObjects} \& x : \text{Node} \Rightarrow x.\text{next} \neq \text{head} \)
However...

ALL (x : obj).
  x : allocatedObjects & x : Node → x.next ≠ head

- Do we really want to look at every Node object in the heap?
- What if we had (doubly-linked list):
  ALL (x : obj) (y : obj).
    x : allocatedObjects & x : Node &
    y : allocatedObjects & y : Node & x.next = y →
    y.prev = x
Optimizations

ALL (x : obj) (y : obj).
\[ x : \text{allocatedObjects} \& x : \text{Node} \&
\[ y : \text{allocatedObjects} \& y : \text{Node} \& x.\text{next} = y \Rightarrow y.\text{prev} = x \]

- Notice:
  - If we know x, we know y.
  - Quantification over y is for the purposes of naming

- Conclusion:
  If we have an equality defining the quantified variable, we can avoid enumerating over the domain

- Other opportunities:
  ALL (x : obj).
\[ x : \text{allocatedObjects} \& x : \text{content} \Rightarrow P(x) \]
Outline

- Background
- Quantifiers and Set Comprehensions
- Specification Variables (Model Fields)
- Old Expressions
- Related Work
- Conclusion
Specification variables

- Specification variables and ghost variables
- JML terminology: model fields and ghost fields
- Specification variables
  - Defined by an HOL formula
- Ghost variables
  - Updated by the programmer
  - Can have types other than standard Java types
    - Sets, tuples, sets of tuples, etc.
  - Support for infinite sets
Deferred Evaluation Example

```java
//: private ghost specvar InfSet :: int set = {};
int x = 0;
//: InfSet := { y . y > 0 };
//: assert "x ~: InfSet";
x = x + 1;
//: assert "x : InfSet";
```

- Use deferred evaluation + formula simplification
- \( x : \{ y . P(y) \} \) rewritten into \( P(x) \)
- Formula simplification can also evaluate \( x : \{ y . y > 0 \} \)
Old Expressions

- Used in postconditions and assertions
- Refer to the value of expression in pre-state
- In JML, fully evaluated in pre-state
  - Restricted syntactically
  - Illegal: $(\forall \text{int } i; 0 \leq i \&\& i < 7; \text{\old}(i < y))$
- Unrestricted in Jahob
  - All $(x : \text{obj}). P(x) \Rightarrow x.f = (\text{old } x.f)$
- More flexible, but need to track pre-state
- Recovery (recursive) cache
Recovery Cache

- Horning et al. [1974] (fault-tolerant computing)
- Stack of frames: push on entry
- On first write: record location of write + original value
- On subsequent writes: no update to cache needed
- To access pre-state:
  - Look up original value in cache, if any
  - If not in cache, then heap holds current value
- On procedure exit, merge frames
- Implications
  - No overhead on reads except of old values
  - Greatest overhead on initial write
  - Smaller overhead on subsequent writes
Extension for Labels

- JML: `\old(expr, label)`
- Syntactic restriction to evaluate `expr` at `label`
- Extend recovery cache mechanism for labels
  - Use global clock (counter)
  - Increment time at each label
  - Cache entries contain time of write
  - Add new entry if value in cache is older
  - To read value, find entry with same or later time
  - Merge frames by taking earliest entry in top frame
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Related Work

- **High-level**
  - Specifications similar to implementations
  - Specifications in logic
    - More difficult to execute
    - Easier to understand semantics, proofs
    - More expressive

- **JML (tool-dependent)**
  - Quantifiers: domain restricted using range predicate
  - Set comprehension: function of an existing set
  - Old expressions: evaluated in pre-state

- **Spec#**
  - Quantifiers and comprehension: restricted syntactically
  - Old expressions: evaluated in pre-state
Conclusion

- Runtime checker for logic formulas
  - Debugging programs and specifications
  - Loop invariant inference
- Quantifiers and set comprehensions
  - Optimizations to avoid enumeration
- Specification variables
  - Deferred evaluation of some formulas
  - Can talk about infinite sets
- Old expressions
  - Supported using recovery (recursive) cache
  - Extension to support labels
- Prototype implementation
  - Interpreter
Future Work

- Compile checks
- Modular checking using constraint solving
- Higher-order quantification
The End
HO Quantification

- Currently not supported, but...
- 120 classes with quantification, none HO
- When might someone use HO quantification?
  - Isomorphism: EX (f : obj → obj). f x = y
  - Shortest path:
    ALL (r : obj → obj). path(r) → dist(sp) ≤ dist(r)
- Why don’t we see it?
  - Different types of programs
More Jahob Background

- **Expected usage scenario**
  - Verify, using shape analysis and theorem proving, that an implementation conforms to its specification in HOL.

- **Specifications**
  - Specification variables (model fields)
    - HOL formula definitions
    - Ghost variables (ghost fields) updated by programmer
      ```
      //: gv := \{x . g(x)\}
      ```
  - Class invariants
  - Requires clause (precondition)
  - Ensures clause (postcondition)
  - Modifies clause (frame condition)
  - Assertions