On Formal Analysis of OO Languages using Rewriting Logic: Designing for Performance

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Outline

1. Rewriting Logic Semantics and KOOL
2. Analysis in KOOL with Rewriting Logic
3. Improving Performance
4. Conclusion

The KOOL Language

KOOL is

- *object-oriented*: classes, methods, dynamic dispatch, exceptions; all values objects
- *dynamic*: dynamically typed, adding extensions for modifying code at runtime
- *concurrent*: multiple threads of execution, shared memory, locks acquired on objects
- *extensible*, with various features “plugged in”: synchronized methods, semaphores, reflective capabilities

Design Motivations for KOOL

- Experiment with *optional* and *pluggable* type systems
- Investigate interaction of language features with verification and analysis
- Create a language suitable for languages courses, without some “confusing” features from other languages

A Sample KOOL Program

```
class Factorial is
  method Fact(n) is
    if n = 0 then
      return 1;
    else
      return n * self.Fact(n-1);
    fi
  end
end

console << (new Factorial).Fact(200)
```

Rewriting Logic Semantics of Programming Languages

- Rewriting logic is an extension of equational logic with support for concurrency
- Language semantics provides formal definitions of language features
- Rewriting logic semantics: formal language definitions using rewriting logic
- Definitions are executable with rewriting logic engines, like Maude

The Rewriting Logic Semantics Project

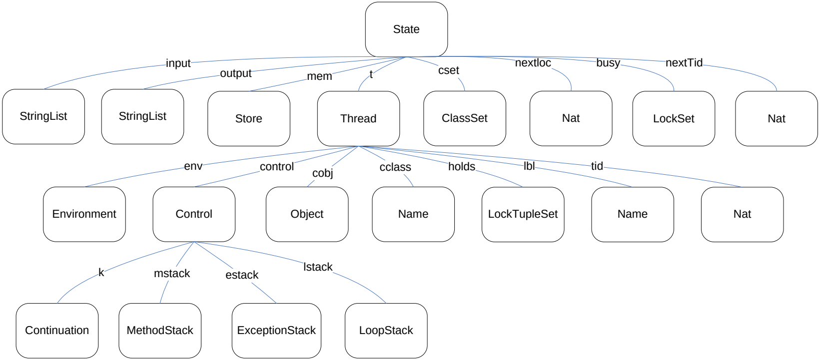
- KOOL is part of ongoing work on rewriting logic semantics
- Other work includes many languages and supporting tools, researchers at multiple universities
- Java, Beta, Scheme, Prolog, Haskell, PLAN, BC, CCS, MSR, ABEL, SILF, FUN, π-calculus, variants of λ-calculus, others

KOOL Program States

- States in KOOL represented as multisets of state components
- Multisets formed by putting components next to one another

```
op _ _ :  KState KState -> KState [assoc comm id:  empty]
```

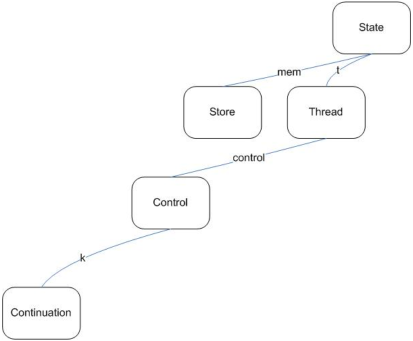
KOOL Program States



KOOL Program States: A Simple Term

```
stmt(if E then S else S' fi)
```

KOOL Program States: A More Complex Term



```
t(control(k(llookup(L) -> K) CS) TS) mem(Mem)
```

Sample KOOL Semantics

Equations represent non-competing transitions, and have the general form $eq\ l = r$ (unconditional) or $ceq\ l = r\ if\ c$ (conditional):

```
 eq stmt(if E then S else S' fi) = exp(E) -> if(S,S') .
 eq val(primBool(true)) -> if(S,S') = stmt(S) .
 eq val(primBool(false)) -> if(S,S') = stmt(S') .
```

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```

Rules represent transitions which may compete, and have the general form $rl\ l => r$ (unconditional) or $crl\ l => r\ if\ c$ (conditional):

```
crl t(control(k(llookup(L) -> K) CS) TS) mem(Mem) =>
    t(control(k(val(V) -> K) CS) TS) mem(Mem)
 if V := Mem[L] /\ V =/= undefined .
```

Running KOOL Programs

- Programs parsed, converted to Maude, and executed, with results displayed to user
- KOOL programs execute directly in the language semantics, defined using rewriting logic
- Stats: 335 equations in semantics, 15 rules, 1406 lines
- No type checker; violations (message not understood, wrong number of arguments, etc) handled at runtime with exceptions

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Analysis Overview

KOOL uses analysis capabilities of Maude to provide program analysis:

- **Search** allows a breadth-first search over the program state space
- **Model Checking** allows verification of finite-state systems using LTL formulae
- Rewriting logic *rules* determine size of state space/transitions between states

Breadth-First Search

- KOOL provides breadth-first search over output values "out-of-the-box"
- Can either find all output values or search for a specific value

Search Example: Output Interleavings

```
class Main is
  var p1, p2;

  method Test(id) is
    console << "ID is " << id;
  end

  method Run is
    spawn(self.Test(1));
    spawn(self.Test(2));
    console << "Done";
  end
end

(new Main).Run
```

Output Interleavings Results

```
> runkool -s Spawn5.kool

Solution 1 (state 16)
states: 38  rewrites: 8325 in 464ms cpu (471ms real) (17940
    rewrites/second)
SL:[StringList] --> "Done"

...

Solution 13 (state 455)
states: 456  rewrites: 70193 in 4944ms cpu (4994ms real) (14196
    rewrites/second)
SL:[StringList] --> "ID is ","2","ID is ","1","Done"

No more solutions.
```

Search Example: The Thread Game

KOOL version of a problem formulated by J. Moore

```
class ThreadGame is
  var x;

  method ThreadGame is
    x <- 1;
  end

  method Add is
    while true do x <- x + x; od
  end

  method Run is
    spawn(self.Add); spawn(self.Add);
    console << x;
  end
end
(new ThreadGame).Run
```

Thread Game Results

```
> runkool -t 5 ThreadGame.kool

Solution 1 (state 769)
SL:[StringList] --> "5"
```

Model Checking

- KOOL uses Maude to provide basic model checking capabilities
- Extended with labeled statements; labels can be used in LTL formulae
- Runtime allows custom Maude modules with new LTL properties to be loaded and used during verification

Dining Philosophers

```
class Philosopher is
  method Run(id,left,right) is
    while true do
      // thinking here...
      hungry:
        acquire left;
        acquire right;
      eating:
        release left;
        release right;
    od
  end
end
```

Model Checking the Dining Philosophers

```
> runkool DP.kool -m ... model checking arguments ...
```

- Model checking arguments generally include formula to check
- When formula doesn't hold, a counterexample is generated
- When formula holds, `true` is returned

A Problem Arises

Analysis is slow, we quickly hit maximum problem size.

Ph's	No Optimizations	
	Counterex	DeadFree
2	0.830	1.530
3	0.912	34.924
4	1.466	1226.323
5	6.465	NA
6	66.683	NA
7	805.278	NA
8	NA	NA

Figure: Dining Philosophers Model Checking Performance

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- All operations will require memory lookups, since even numbers are objects
- All memory lookups are rules
- Rules increase the size of the state space
- In addition, heap constantly changes, making many more programs infinite state (impossible to model check)
- Shows that a reasonable definition for *execution* may not work well for analysis

Our Goal

Reduce the number of rule applications by changing the semantics of KOOL while still maintaining observable program behavior

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Optimizing KOOL

Two approaches to optimizing KOOL programs for analysis:

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- Change semantics to reduce usage of rules, focusing on changes that also speed up normal execution (e.g. reduce number of message sends)
- Change semantics to reduce usage of rules, even at the expense of slower program execution

Auto-Boxing in KOOL

```
(1 + 2) * 3 // desugars as (1.+(2)).*(3)
```

- In KOOL, this involves creation of 5 objects, 2 method calls, multiple primitive manipulation operations
- Heavy use of memory causes execution and analysis performance problems
- Familiar problem in OO languages (Smalltalk and SELF, for instance)
- Goal: use scalar values instead, automatically converting to objects (auto-boxing, as in C#) when needed
- With auto-boxing, 2 operations, neither requiring memory lookup

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- Step 3: Return scalars from some operations that currently return objects (e.g. primitive integer addition) (50 equations)
- Step 4: Box scalars when needed (4 equations)
- 8 more additional changes – most changes for auto-boxing mechanical

Auto-Boxing Results

Ph's	No Optimizations		Auto-boxing	
	Counterex	DeadFree	Counterex	DeadFree
2	0.830	1.530	0.799	0.878
3	0.912	34.924	0.899	2.901
4	1.466	1226.323	1.346	23.451
5	6.465	NA	5.226	237.714
6	66.683	NA	45.747	2501.498
7	805.278	NA	476.916	NA
8	NA	NA	NA	NA

Figure: Dining Philosophers Model Checking Performance

The KOOL Memory Model

- KOOL memory represented as finite map, $Location \rightarrow Value$
- Object references are *Location*s, objects are *Value*s
- Memory at toplevel, since all threads share same memory space
- Memory accesses use rules, since accesses in different threads can compete

Memory Pools

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- **Answer:** Yes, if we're careful...
  - Local variable accesses should never compete
  - Object-level variable accesses *may* compete
  - If a variable may be shared, anything reachable through it may be shared as well
  - Conservative assumption: if it can be shared, make it shared, else leave it unshared; once shared, never goes back (simple rule, room for improvement)

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- On spawn of arbitrary expression, contents of current environment (all names in scope) shared (1 rule)
- On assignment to shared location, share new reachable locations (included in above)
- Overall, fewer changes compared to auto-boxing, but more complex

Shared Memory and Auto-Boxing Combined

Ph's	No Optimizations		Auto-boxing + Memory Pools	
	Counterex	DeadFree	Counterex	DeadFree
2	0.830	1.530	0.758	0.782
3	0.912	34.924	0.812	1.270
4	1.466	1226.323	1.070	4.192
5	6.465	NA	2.264	22.467
6	66.683	NA	9.236	124.818
7	805.278	NA	50.527	797.308
8	NA	NA	299.630	4744.427

Figure: Dining Philosophers Model Checking Performance

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6	45.747	2501.498	9.236	124.818
7	476.916	NA	50.527	797.308
8	NA	NA	299.630	4744.427

Figure: Dining Philosophers Model Checking Performance

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Conclusions

- Methods to define languages using rewriting logic semantics fairly well understood
- Good definitions for *execution* can have poor analysis performance
- Optimizations from analysis and programming languages can be applied to improve analysis performance
- Two straight-forward implementations of optimizations shown here; both improve performance dramatically

Future Work

- Provide GC for KOOL, which should help improve memory performance
- Investigate ways to optimize definitions automatically, and/or prove changes preserve behavior
- Look for other optimizations that could further improve performance
- Investigate modularity of optimizations – can optimized memory model be applied to memory model for other languages, for instance?

Related Work

- Rewriting Logic Semantics: *The Rewriting Logic Semantics Project*, José Meseguer and Grigore Roşu, TCS, Volume 373(3), pp 217–237, 2007.
- Rewriting Logic Definition Performance: *On Modelling Sensor Networks in Maude*, Dilia E. Rodríguez, WRLA'06.
- Analysis Performance in Maude: *State Space Reduction of Rewrite Theories Using Invisible Transitions*, Azadeh Farzan and José Meseguer, AMAST 2006; *Partial Order Reduction for Rewriting Semantics of Programming Languages*, Azadeh Farzan and José Meseguer, WRLA 2006.