CASM: Implementing an Abstract State Machine based programming language

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ATPS 2013

February 26, 2013

Coming up. . .

- CASM: programming language based on Abstract State Machines
- Interpreted/compiled (to C++), supports symbolic execution
- Our application: verified instruction set simulation

Definitions

Abstract State Machines

State: arbitrary data

Rules: specify data values in next state

Rules

- Pure
- Independent

→ Allow parallel execution

Example: Parallel Swap

```
function x : -> Int
function y : -> Int

rule swap = {
    x := y
    y := x
}
```

- Functions: state data
- Map locations (argument tuples) to values

Example: Parallel Swap

```
function x : -> Int
function y : -> Int

rule swap = {
    x := y
    y := x
}
```

- Rules: specify updates
- Independent evaluation of updates
- Update set captures all effects

Example: Parallel Swap

```
function x : -> Int
function y : -> Int

rule swap = {
    x := y
    y := x
}
```

- State transition: atomic application of all updates

Example: Parallel Swap

```
function x : -> Int
function y : -> Int

rule swap = {
    x := y
    y := x
}
```

Example

Initial state: $\{x = 3, y = 2\}$

Update set: $\{(x, 2), (y, 3)\}$

New state: $\{x = 2, y = 3\}$

Example: Naïve Fibonacci

```
function i : -> Int initially { 2 }
function fib : Int -> Int initially { 0 -> 0, 1 -> 1 }

rule nextfib = {
    i := i + 1
    fib(i) := fib(i-1) + fib(i-2)


}
```

Evaluations of `fib(...)`: lookups, not calls; Memoization built in!

Execution model: Repeat top-level rule until explicit termination.

Example: Naïve Fibonacci

```
function i : -> Int initially { 2 }
function fib : Int -> Int initially { 0 -> 0, 1 -> 1 }

rule nextfib = {
    i := i + 1
    fib(i) := fib(i-1) + fib(i-2)
    if i >= 100 then
        program(self) := undef   /* terminate */
}
```

`if` rule: empty update set if condition false

Sequential constructs

```
rule hundred_fibs =
    seqblock
        fib(0) := 0
        fib(1) := 1
        i := 2





    endseqblock
```

`seqblock`: Compute subrules sequentially.

Track intermediate update sets.

Sequential constructs

```
rule hundred_fibs =
    seqblock
        fib(0) := 0
        fib(1) := 1
        i := 2
        iterate
            if i < 100 then {
                i := i + 1
                fib(i) := fib(i-1) + fib(i-2)
            }
    endseqblock
```

`seqblock`: Compute subrules sequentially.
`iterate`: Repeat subrule until update set empty.
Track intermediate update sets.

Other language constructs

Parallel loop:

```
forall i in [0..3] do
    square(i) := i * i
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Derived expressions (“function definitions”):

```
derived d(a:Int, b:Boolean) = (a >= 3) and b
...
foo(y) := d(x, true)
```

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Parallel loop:

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forall i in [0..3] do
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Derived expressions ("function definitions"):

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```

Subrule invocation:

```
rule simulation = {
    call time_update()
    call system_update()
    call environment_update()
}
```

Type system

Static monomorphic type system with simple type inference.

Primitive types: `Int`, `Boolean`, ...

Type constructors: `List(...)`, `Tuple(..., ...)`

Symbols: `enum MyEnum = { one, two, three }`

No support (yet?) for algebraic datatypes.

Symbolic execution

```
function i : -> Int initially { 2 }
function fib : (symbolic) Int -> Int

rule nextfib = {
    i := i + 1
    fib(i) := fib(i-1) + fib(i-2)
}
```

Symbolic trace of successive states:

- $\{(i, 2)\}$

Symbolic execution

```
function i : -> Int initially { 2 }
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rule nextfib = {
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```

Symbolic trace of successive states:

- $\{(i, 2)\}$
- $\{(i, 3), (fib(0), s_0), (fib(1), s_1), (fib(2), s_0 + s_1)\}$

Symbolic execution

```
function i : -> Int initially { 2 }
function fib : (symbolic) Int -> Int

rule nextfib = {
    i := i + 1
    fib(i) := fib(i-1) + fib(i-2)
}
```

Symbolic trace of successive states:

- $\{(i, 2)\}$
- $\{(i, 3), (fib(0), s_0), (fib(1), s_1), (fib(2), s_0 + s_1)\}$
- $\{(i, 4), (fib(0), s_0), (fib(1), s_1), (fib(2), s_0 + s_1),$
  $(fib(3), (s_0 + s_1) + s_1)\}$
- ...

Application example: Instruction set simulation (1)

Implemented MIPS instruction set simulator in CASM.
Example instruction: and-immediate

```
rule andi(instr: Int) =
let rs = PARG(instr, FV_RS) in
let rt = PARG(instr, FV_RT) in
let imm = PARG(instr, FV_IMM) in
let imm_ex = BVZeroExtend(imm, 16, 32) in
    if rt != 0 then
        GPR(rt) := BVand(32, GPR(rs), imm_ex)
```

Instruction set specification: $\sim$ 600 lines

Application example: Instruction set simulation (2)

Execution model (simplified):

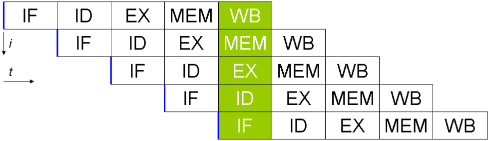
```
rule run_program =
    seqblock
        /* execute instruction at PC */
        call(PMEM(PC))(PC)
        /* update PC for next instruction */
        if BRANCH = undef then
            PC := PC + 4
        else {
            PC := BRANCH
            BRANCH := undef
        }
    endseqblock
```

Simple simulator model executes at ~ 1 MHz

Application example: Instruction set simulation (3)

Verified more complex simulator implementations:

- Specified pipelined execution models (1500 LOC instruction descriptions, 400 LOC execution models)



IF	ID	EX	MEM	WB				
	IF	ID	EX	MEM	WB			
		IF	ID	EX	MEM	WB		
			IF	ID	EX	MEM	WB	
				IF	ID	EX	MEM	WB

Image source: `http://en.wikipedia.org/wiki/File:Fivestagespipeline.png`

- Instructions in different pipeline stages execute independently
- Symbolic execution trace

→ Equivalence proof of simple and pipelined semantics

Summary

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- Pure (or: disciplined?), statically typed
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Thank you for your attention!

This work is supported by the Austrian Research Promotion Agency (FFG) under contract 827485, *Correct Compilers for Correct Application Specific Processors*, and Catena DSP GmbH.