A Prototype Embedding of Bluespec SystemVerilog in the SAL Model Checker

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Introduction

- Bluespec SystemVerilog (BSV) is a language for high level hardware design
- Developed from Term Rewriting Systems (TRS)
  - A language for designing and formally verifying hardware
- Elegant semantics => well suited for formal verification
- To date, a number of BSV designs have been verified with hand proof, but little work conducted on the application of automated reasoning.
- We have investigated automated reasoning for BSV, in the SAL model checker, and also the PVS theorem prover

Why Use Automated Reasoning?

- Hand proofs are convenient, but:
  - Can contain errors (analogy - doing arithmetic by hand v.s. on a calculator)
  - Proofs for large systems can be time consuming and tedious
- Automated reasoning has the potential to provide rigorous and efficient verification for some classes of systems...
  - … and these classes are ever expanding

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Automated Reasoning for BSV

- Two approaches:
  - Verifying BSV designs with a model checker:
    - Presented today
  - Verifying BSV designs with a theorem prover:
    - ***A Prototype Embedding of Bluespec SystemVerilog in the PVS Theorem Prover***, Second NASA Formal Methods Symposium, Washington D.C. April 13 – 15, 2010
- Currently compile by hand

In This Presentation...

- Introduce BSV
- Introduce the SAL language
- Outline key challenges of embedding BSV in SAL
- Outline of our approach
- Experimental results: verifying a BSV implementation of Peterson's Protocol

Take Home Information

- Basic understanding of BSV SAL languages
- How to embed BSV in SAL
  - Surprisingly simple
- Understanding of advantages of verifying the embedding
  - Makes proof more rigorous
- Motivation to look at the paper for a strategy for verifying the translation

Bluespec SystemVerilog

- A Hardware Description Language based on the guarded action model of concurrency
- Hardware specified with modules, which associate elements of state with:
  - **Rules:** guarded actions that spontaneously change the state
  - **Methods:** functions that return values from the state and/or transform it
    - Methods from one module can be used to compose the rules and methods of other modules

Rules in BSV

```
rule my_rule (rl_guard);
  statement_1;
  statement_2;
  ...
endrule
```

The Semantics of a BSV Module

- Behaviour of a module can be understood with a simple semantics called Term Rewriting System (TRS) semantics
  - Also called one-rule-at-a-time semantics
- In a given state, a module chooses *one* rule for which the guard evaluates to `true' and applies the associated action
- If more than one guard is true, a non-deterministic choice is made

Bluespec SystemVerilog

- Reg module:
  - A register with 1 element of state and 2 methods: _read and _write
- Other modules can create instances of Reg, and use _read and _write in their rules and methods. Eg:

```
rule request_rl (!request._read && !acknowledge._read));
  request._write(True);
endrule
```

The SAL Language

- Also a guarded action language, but simpler
- Guarded action systems defined in contexts that define:
  - Type of state
  - An initial state
  - A transition relation

The SAL Language

```
TRANSITION
[
    guarded_action_1 : guard_1 --> action_1
[]
    guarded_action_2 : guard_2 --> action_2
[]
    ...
]
```

The Challenges of Embedding BSV in the SAL Language

- BSV is a guarded action language
- Similar to specification languages of several proof tools:
  - Model checkers: SAL, SPIN etc.
  - Model checkable subset of the PVS theorem prover
- However, BSV is a more complex language in some respects...

The Challenges of Embedding BSV in a Automated Proof Tools

- Complex language constructs:
  – Modules and methods
- Widespread presence of data paths:
  – Can't always directly apply model checking to designs with data paths due to state space explosion
  – In SAL etc., we can build a specification that excludes data paths...
  – … but with BSV, the design *is* the specification

The Challenges of Embedding BSV in a Guarded Action Language

- Bridge the semantic gap
  - Express the constructs of BSV with the more limited constructs of the target language
- Bridge the abstraction gap
  - Abstract away from data path complexity to give abstract specifications that can be efficiently verified
- Our work concentrates on bridging the semantic gap

Bridging the Semantic Gap

- Translate BSV to SAL specifications that can be efficiently model checked, but bear little resemblance to the original BSV
  - Problematic, because difficult to rule out false positives and false negatives
- Verify the BSV-to-SAL translation with deductive proof
  - Currently performed in the PVS theorem prover
  - Simple proof, could possibly be done with an SMT solver

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An Example Rule

```
rule p_critical (pcp._read == Critical && fifo.notFull);
  fifo.enq (True);
  pcp._write (Sleeping);
  turn._write (False);
endrule
```

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A Primitive Embedding in SAL

```
Reg {T : type} : CONTEXT = BEGIN
    State : type = [# data : T #];
END

FIFOF1 {T : type} : CONTEXT = BEGIN
    State : type = [# notFull : bool, notEmpty : bool, data : T #];
END
```

A Primitive Embedding in SAL

```
PC: TYPE = {Sleeping, Trying, Critical};
...
pcp : Reg{PC}!State,

pcq : Reg{PC}!State,

turn : Reg{bool}!State,

fifo : FIFOF1{bool}!State
```

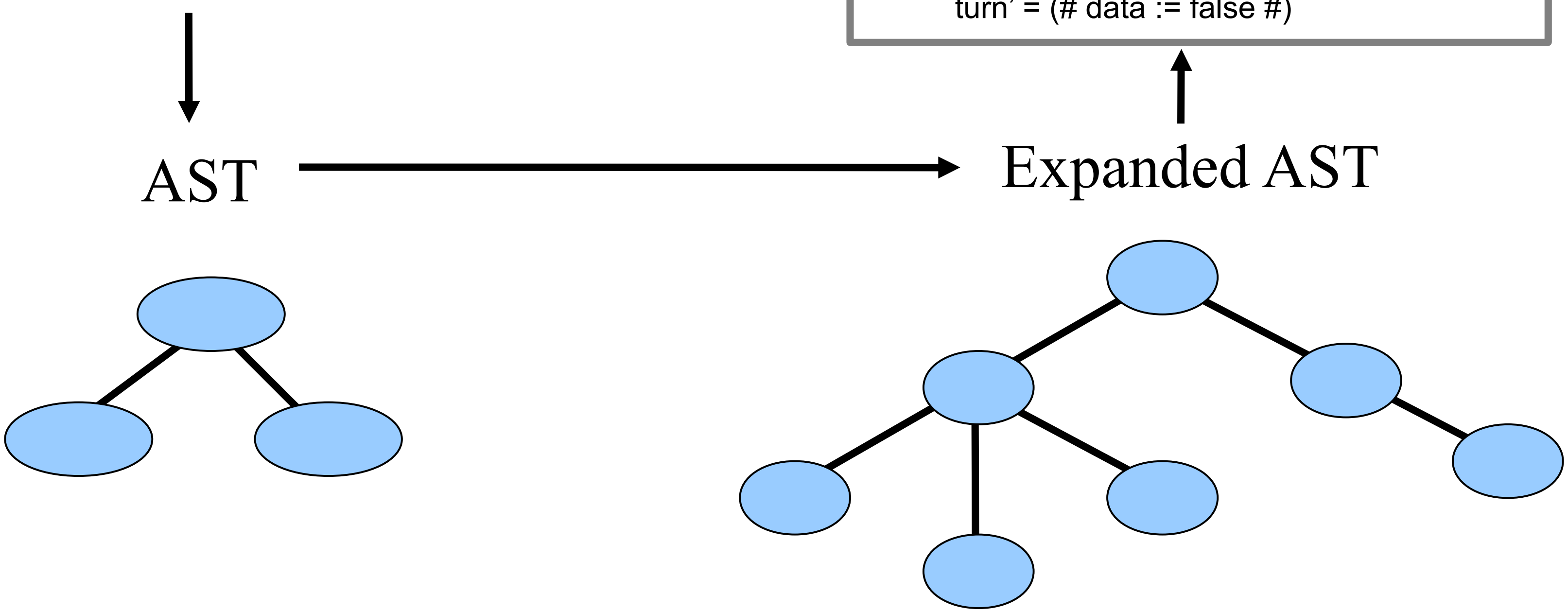
Rules in BSV

```
p_critical : pcp.data = Critical and fifo.notFull
  --> fifo' = (# data := true,
                 notFull := false,
                 notEmpty := true #);
      pcp' = (# data := Sleeping #);
      turn' = (# data := false #)
```

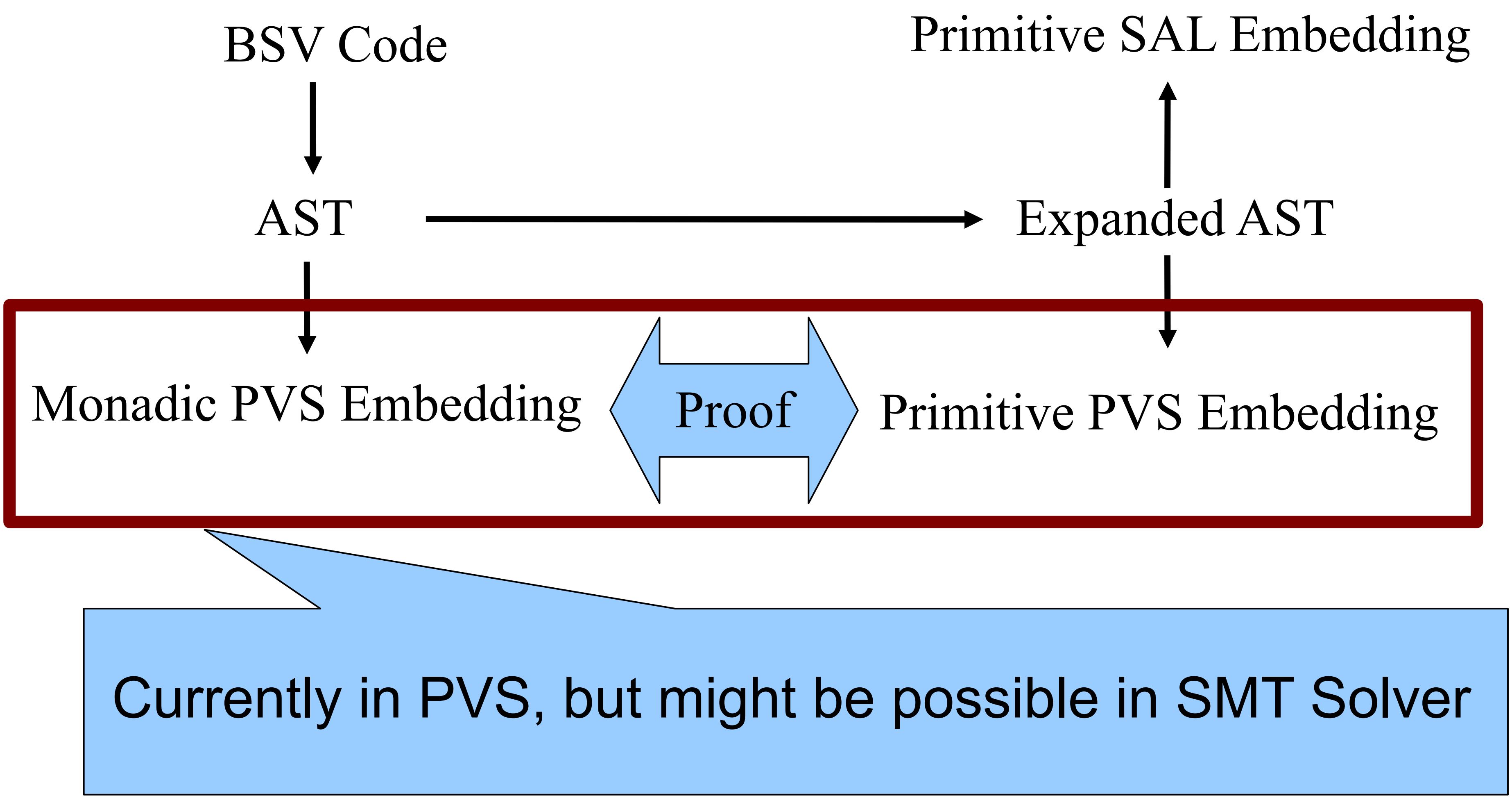
BSV-to-SAL Translation

```
rule p_critical (pcp._read == Critical && fifo.notFull);
  fifo.enq (True);
  pcp._write (Sleeping);
  turn._write (False);
endrule
```

```
p_critical : pcp.data = Critical and fifo.notFull
  --> fifo’ = (# data := true,
                 notFull := false,
                 notEmpty := true #);
      pcp’ = (# data := Sleeping #);
      turn’ = (# data := false #)
```



BSV-to-SAL Translation



A Module's State in PVS

```
Peterson : type = [# pcp : Reg [PC],
                     pcq : Reg [PC],
                     turn : Reg [bool],
                     fifo : FIFOF1 [bool]
                  #]
```

Primitive Embedding in PVS

```
p_critical_primitive (pre, post : Peterson) : bool
   = pre‘pcp‘data = Critical ∧ pre‘fifo‘notFull
     ∧ post = pre with [(fifo)  := (# data          := true,
                                      notFull       := false,
                                      notEmpty := true #),
                         (pcp) := (# data          := Sleeping #),
                         (turn) := (# data          := false #)]
```

A Monadic Embedding in PVS

```
p_critical = rule (pcp‘read = Critical ∧ fifo‘notFull)
                  (fifo‘enq (true) ≫
                   pcp‘write (Sleeping) ≫
                   turn‘write (false))
```

Rules in BSV

```
rule p_critical (pcp._read == Critical && fifo.notFull);
    fifo.enq (True);
    pcp._write (Sleeping);
    turn._write (False); endrule
```

```
p_critical = rule (pcp‘read = Critical ∧ fifo‘notFull)
                  (fifo‘enq (true) ≫
                  pcp‘write (Sleeping) ≫
                  turn‘write (false))
```

Experimental Results: Peterson's Protocol

- Verified a BSV implementation of 2 process Peterson's Protocol
- 50 lines of BSV code (extracts provided in paper)
- Hand embedded BSV code in SAL
- Verified the BSV translation in PVS
- All code will shortly be on sourceforge
  - Search on sourceforge for “Bluespec”

Example: Peterson's Protocol

mutex: THEOREM

System |- G(NOT(pcp.data = Critical AND pcq.data = Critical))

“The two processes will never be in critical mode at the same time”

liveness: THEOREM

System |- (G(F(pcp.data = Trying)) => G(F(pcp.data = Critical)))
and (G(F(pcq.data = Trying)) => G(F(pcq.data = Critical)))

“A Trying process will always (eventually) gain access to the Critical mode”

Conclusion

- BSV is a semantically elegant HDL
  - Well suited for formal reasoning
  - But little work carried out on application of automated reasoning
- We have carried out investigations into the application of model checking and theorem proving for verifying BSV designs
- Today, I presented a strategy for embedding a subset of BSV in SAL model checker, where BSV-to-SAL translation is verified in PVS