IODINE: A Tool to Automatically Infer Dynamic Invariants for Hardware Designs

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Motivation for Dynamic Analysis

We simulate designs extensively.
Simulation runs contain lots of information.
How can this information be used?

1) Understanding behavior of the design
2) Automatically extracting design properties
3) Understanding impact of design differences
   ...

Property Checking Challenges

- Potential payoff of formal property checking is huge
  ... but in practice:
  - hard to write design properties
  - hard to write input constraints
  - Expert knowledge is scarce
  - Design documentation is missing (or wrong!)
  - How do you know when all properties are written?
  - Only proof that code works is that it passes a test suite

- Formally verifying protocols in the abstract is insufficient
  - Formal verification is applied to what % of million-line Verilog programs?
Dynamic Invariants

- Proposed by Michael Ernst for software programs
  - Worked well for small programs

- Basic Idea:
  - Hypothesize a space of invariants
  - Analyze invariants on test inputs (assumed to pass)
  - Rule out invariants which do not hold

- Invariants detected may be unsound!
  - That's ok – incorrect invariants indicate a coverage hole
  - For hardware designs, testsuites are expected to be nearly complete; exposing missing coverage is also valuable
A Hardware Invariant Detector

- IODINE: dynamic analysis for common hardware invariants
  - trade-off: complexity & cost v/s exhaustiveness & noise
- Invariants are *pervasive* and *complete*
  - reduced search depth (useful for bounded model checking)
- Easier for designers to certify rather than write invariants
- Invariants on block's inputs can become constraints
- Analyzers extract different kinds of information
- Analyzers can query other analyzers
IODINE Features

- Invariants can be ranked on the basis of confidence
- Extensible set of analyzers
- Invariants involving up to 4 variables considered
  - User can specify own expressions of interest
- Smart multi-pass analysis algorithms to speed analysis
  - Analysis time is $O(\text{few hours})$, i.e. $O(\text{simulation time})$
## IODINE Analyzer Library

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<td>Onehists, Onecolds, # Bits on/off</td>
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<td>ReqAck</td>
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</table>

Examples from Dual-core UltraSPARC™ microprocessor follow
Req-Ack Analyzer

- Exhaustively extracts Req-Ack pairs
  - \( R \rightarrow A \)
  - \( R \rightarrow (A1 \mid A2) \)

Examples from Dual-core UltraSPARC™ microprocessor
Memory Controller Write Protocol

Labels indicate [min...max] delay between assertion of source and destination

Early version of request

Discovered Automatically!

Performance Counters

Real request

Real Ack

Delayed Ack

Example from Dual-core UltraSPARC™ microprocessor
FIFO Analyzer: Example

Following invariant exposes functional coverage hole:

```
fifo -depth 8 -req mrq_war_chk_a2 -deq dispatch_write1_st
    -enq_data latest_pa   -deq_data mwq_pa_out
```

Example from Dual-core UltraSPARC™ microprocessor

Diagram:
- `latest_pa`: Incoming physaddr
- `mrq_war_chk_a2`: Enter Q for WAR check
- `9 entry FIFO`: (only 8 entries inferred)
- `dispatch_write1_st`: WAR hazard clear
- `mwq_pa_out`: Outgoing physaddr
Summary

- IODINE extracts dynamic invariants automatically
  - Useful for formal property checking
  - Automatic functional coverage information
  - Aid for design understanding, evolution
- Invariants are pervasive and complete
  - Reduces search depth for FV tools
- See paper for details on analyzers and invariants
Related Work & Thanks

- [Nimmer, Ernst] Software work for Daikon and ESC-Java
- [Yang, Evans] Temporal properties (2 vars) using QREs

Thanks to:
Monica Lam, Stanford University
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Ajit Pasi, IIT Delhi

For more information:
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Backup Slides
Req-Ack Analyzer

- Exhaustively extracts Req-Ack pairs
  - $R \rightarrow A$
  - $R \rightarrow (A1 \mid A2)$
Fifo Analyzer

Extracts Fifo's and Outstanding-id's

0in fifo -depth 8 -req mrq_war_chk_a2
-req dispatch_write1_st
-enq_data latest_pa
-deq_data mwq_pa_out