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 <u>lots</u> 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 ?

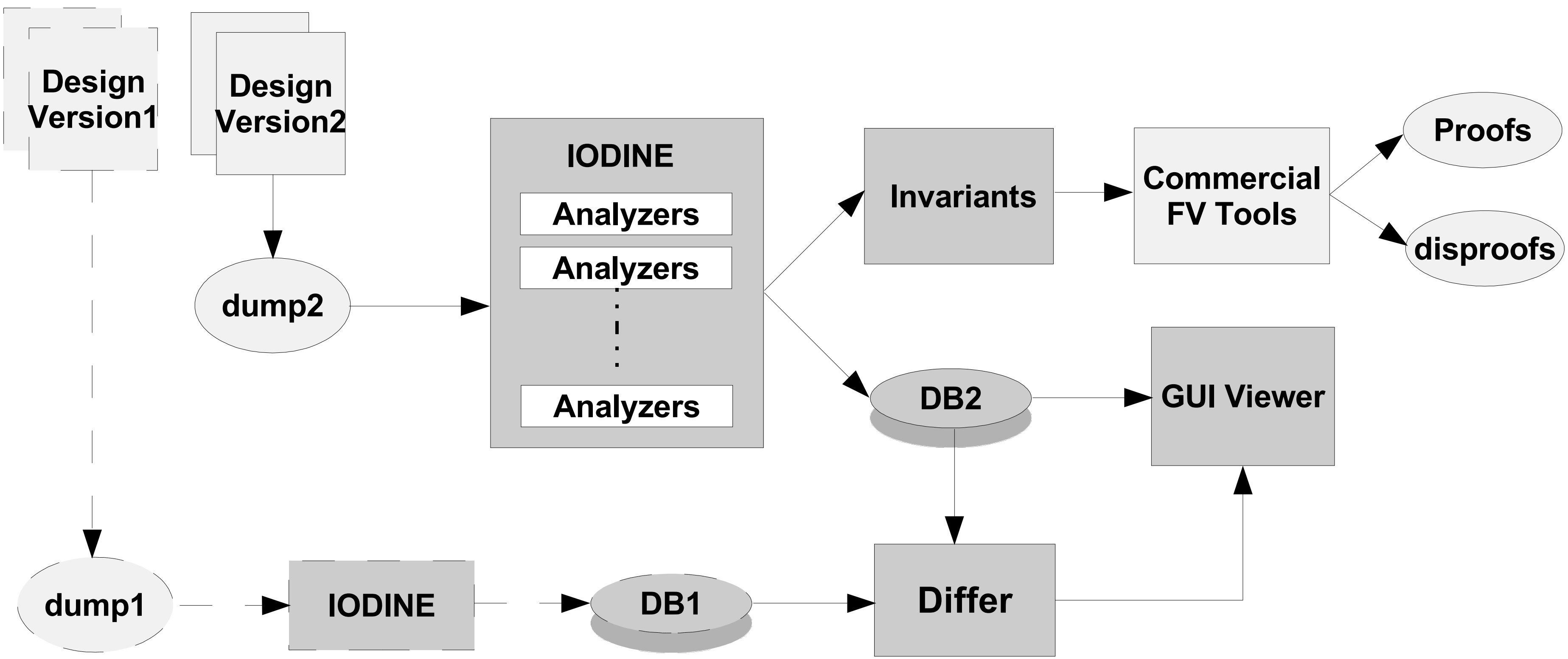
Dynamic Invariants

- 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

Framework



- 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(few hours), i.e. O(simulation time)

IODINE Analyzer Library

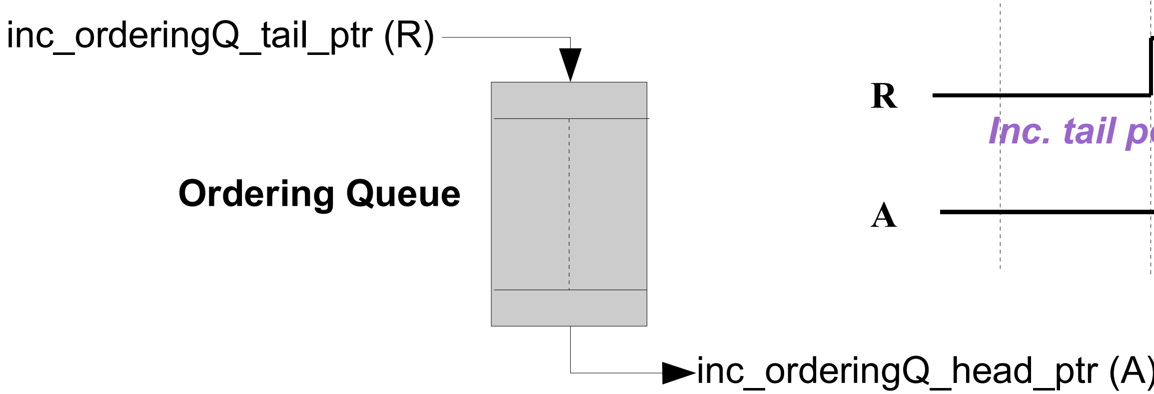
Analyzers	Invariants
Onehot	Onehots, Onecolds, # Bits on/off
ReqAck	Req-Ack pairs or triples,Multi-reqs/Multi-acks, Event Protocols, Fixed Delay pairs
Fifo	Fifo's, Out of order scoreboards, Pipeline data flow
State	FSM transitions, Up/Down Counters
CrossProduct	Mutual exclusion conditions
Equals	Dynamic Aliases
Constants	Constant Signals
Freq	Support Analyzer
Vector	Support Analyzer

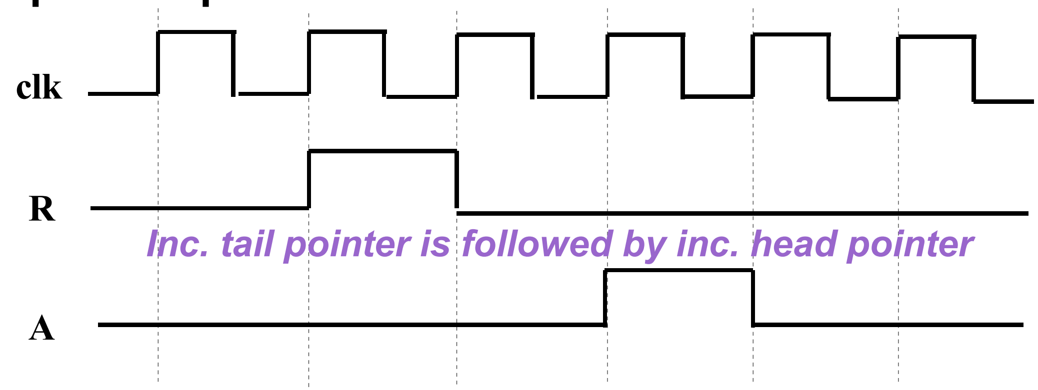
Examples from Dual-core UltraSPARC™ microprocessor follow

Req-Ack Analyzer

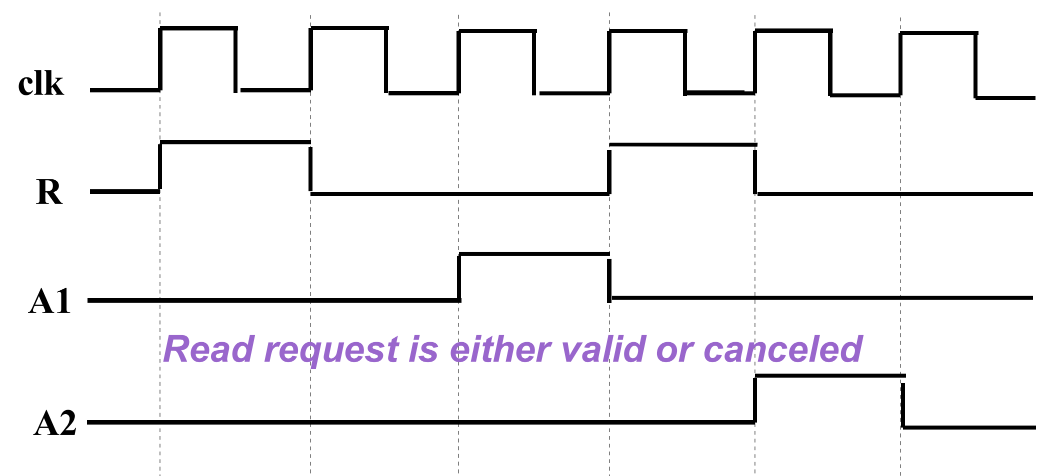
- Exhaustively extracts Req-Ack pairs

$- R \rightarrow A$



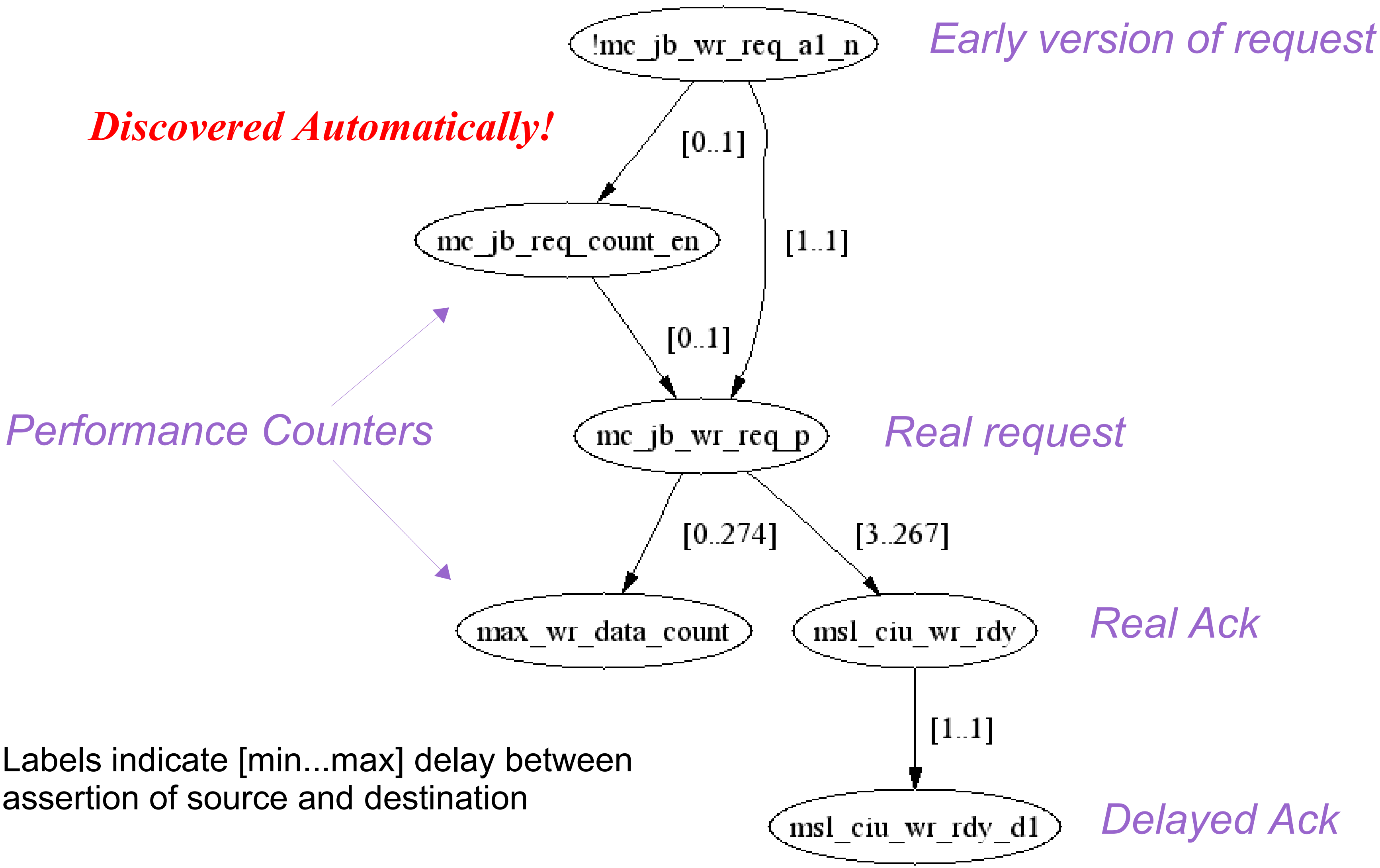


$- R \rightarrow (A1 \mid A2)$



Examples from Dual-core UltraSPARC™ microprocessor

Memory Controller Write Protocol



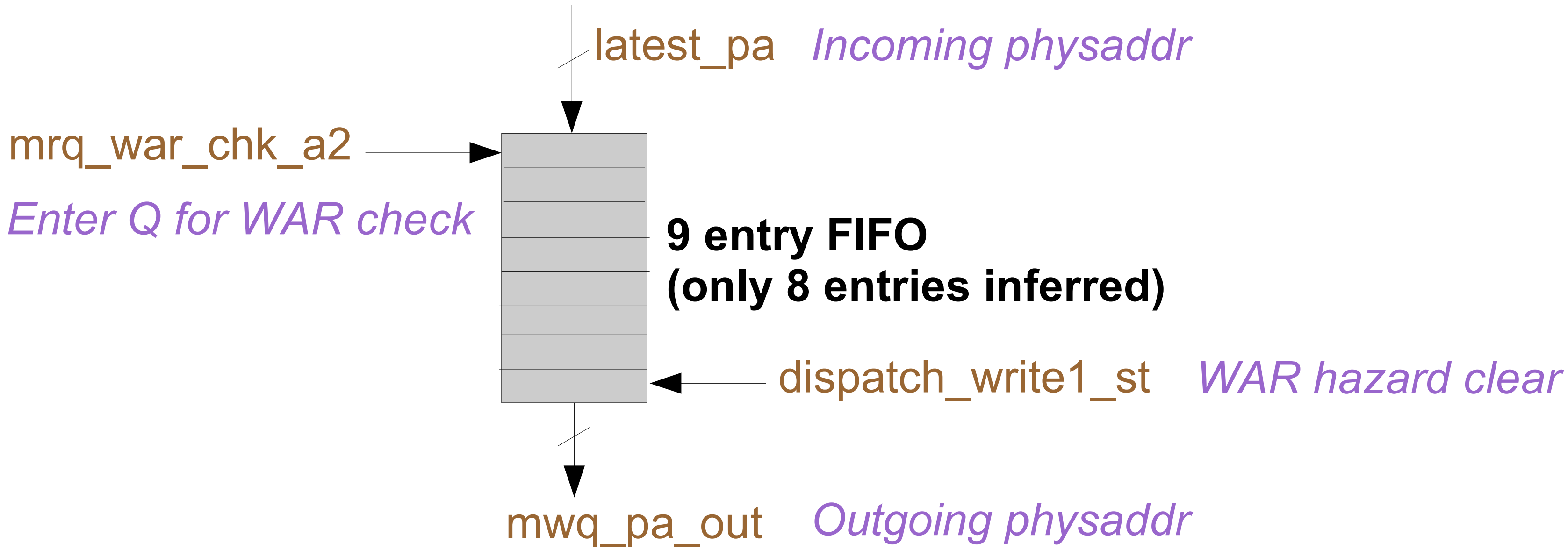
Labels indicate [min...max] delay between assertion of source and destination

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

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

Michael Ernst, MIT

Ajit Pasi, IIT Delhi

For more information:

http://xenon.stanford.edu/~hangal/iodine.html

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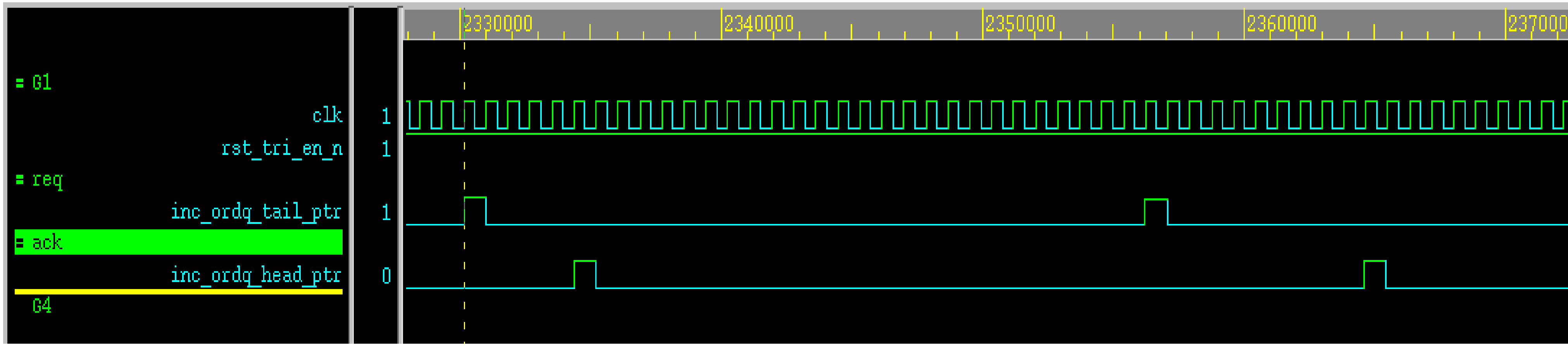
Backup Slides

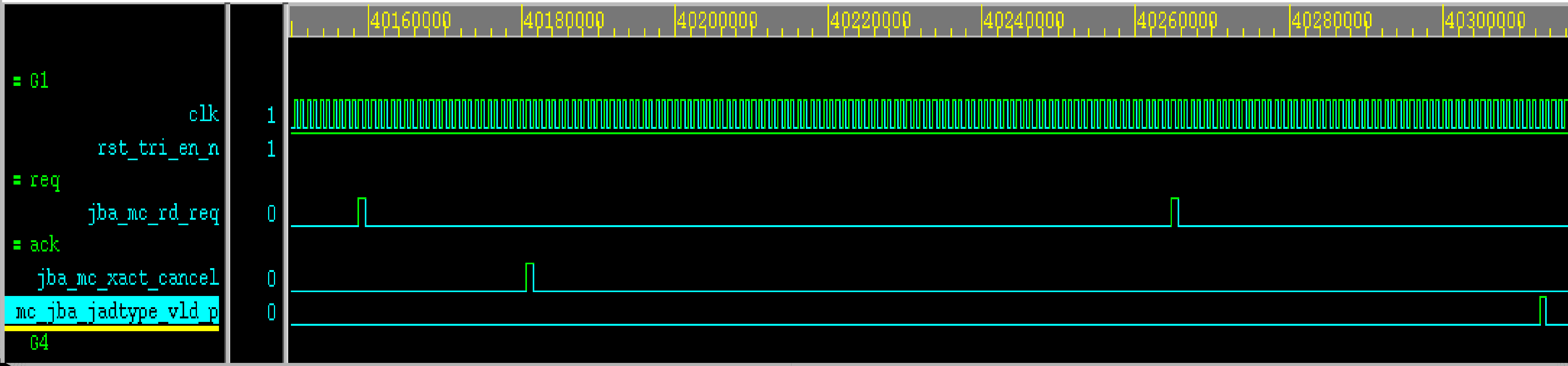
Req-Ack Analyzer

- Exhaustively extracts Req-Ack pairs

  - R → A



  - R → (A1 | A2)



Fifo Analyzer

Extracts Fifo's and Outstanding-id's

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