An Efficient Runtime Validation Framework based on the Theory of Refinement

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Property-based Testing Methodology

Given an implementation

1. Define a set of properties
2. Design a test suite and define oracles
3. Execute tests and check for property violations
4. Analyze the violations and fix
   - Implementation
   - Properties

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Changes in specification

Property-based Testing Methodology

Implementation

IF	ID	RF	EX	WB		
IF	ID	RF	EX	WB		
	IF	ID	RF	EX	WB	
	IF	ID	RF	EX	WB	
		IF	ID	RF	EX	WB
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Set of Properties

1. Correct arithmetic operations
2. Detecting and stalling the pipeline on data hazards
3. Branch/Jump instructions
4. ...

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Trends in Functional Verification: A 2014 Industry Study[1]

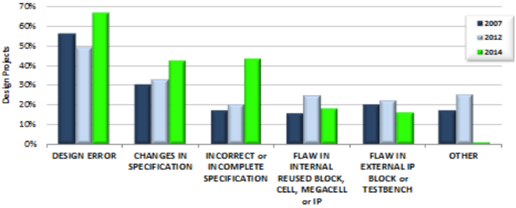

Figure 17. Root Cause of Functional Flaws

[1] Harry Foster, DAC 2015 (reproduced)

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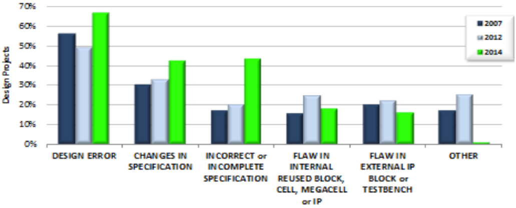

Figure 17. Root Cause of Functional Flaws

Refinement-based testing methodology

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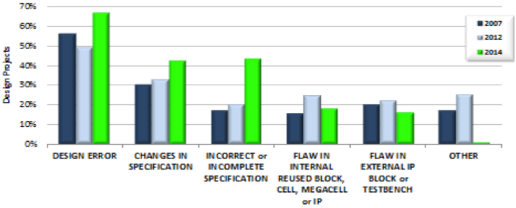

Figure 17. Root Cause of Functional Flaws

Refinement-based testing methodology

Compile the refinement conjecture to a runtime check

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Refinement-based Testing Methodology

Implementation $\lesssim_r$ **Specification**

IF	ID	RF	EX	WB		
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	IF	ID	RF	EX	WB	
	IF	ID	RF	EX	WB	
		IF	ID	RF	EX	WB
		IF	ID	RF	EX	WB

Instruction Set Architecture

- *add rd, ra, rb*
- *sub rd, ra, rb*
- *jnz imm*
- . . .

Concrete System **Abstract System**

Refinement-based Testing Methodology

Implementation $\lesssim_r$ **Specification**

IF	ID	RF	EX	WB		
IF	ID	RF	EX	WB		
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Instruction Set Architecture

- *add rd, ra, rb*
- *sub rd, ra, rb*
- *jnz imm*
- ...

Concrete System

Abstract System

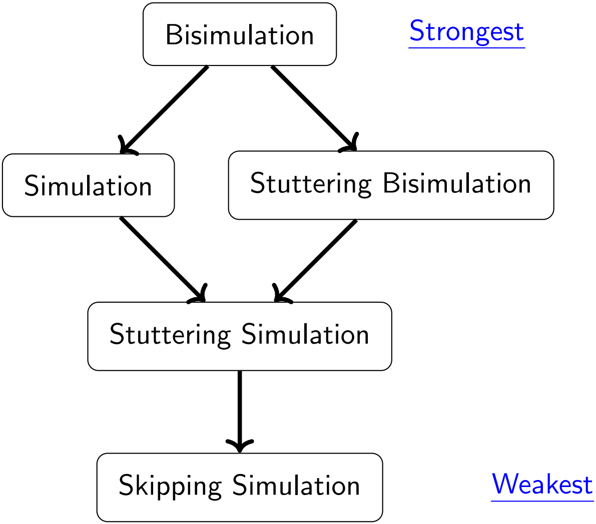
One Property

Challenges

- $\mathcal{A}$ and $\mathcal{C}$ may differ
  - Data representation
  - Number of state components
  - Atomicity of a computation step
  - ...

Relate behaviors of systems expressed at different levels of abstraction

Notions Of Refinement



Applications

- Microprocessor verification
- Compiler verification
- Distributed/Concurrent systems
- Microkernels
- ...

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Local characterizations for effective reasoning

Refinement Conjecture

A local characterization of Skipping Simulation

$$\begin{tikzcd} s \arrow[r, dash] \arrow[d] & w \arrow[d] \\ u \arrow[r, dash] & v \end{tikzcd}$$

one step

$\langle \exists v : w \rightarrow v : uBv \rangle$

$$\begin{tikzcd} s \arrow[r, dash] \arrow[d] & w \arrow[d, "\geq 2"] \\ u \arrow[r, dash] & v \end{tikzcd}$$

skipping on the right

$\langle \exists v : w \rightarrow^{\geq 2} v : uBv \rangle \rangle$

$$\begin{tikzcd} s \arrow[r, dash] \arrow[d] & w \arrow[dl, dash] \\ u & \end{tikzcd}$$

stuttering on left

$(uBw \wedge rankT(u, w) \prec rankT(s, w))$

$$\begin{tikzcd} s \arrow[r, dash] \arrow[d] \arrow[dr, dash] & w \arrow[d] \\ u & v \end{tikzcd}$$

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$\langle \exists v : w \rightarrow v : sBv \wedge$

$rankL(v, s, u) < rankL(w, s, u) \rangle$

Refinement Conjecture

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Concrete system does not skip

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Refinement Conjecture

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stuttering on left

$(uBw \wedge rankT(u, w) \prec rankT(s, w))$

Abstract system does not stutter

Refinement Conjecture

Runtime Checker

$$\begin{tikzcd} s \arrow[r, dash] \arrow[d] & w \arrow[d] \\ u \arrow[r, dash] & v \end{tikzcd}$$

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$$\xrightarrow{\textit{Compile}}$$

Algorithm 1: Refinement Check

Input : s: concrete system state
n: number of steps to run
r: refinement map
$rankT$: rank of concrete state

Output: Partition, Error Status

$w \leftarrow r(s)$; $error \leftarrow false$; $partition \leftarrow \langle\rangle$; $i \leftarrow 0$; $j \leftarrow 0$;

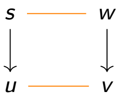
do
- $u \leftarrow Select\text{-}concrete\text{-}next\text{-}state(s)$;
- $\boxed{\langle match, v\rangle \leftarrow Match\text{-}abstract\text{-}next\text{-}state(w, u)}$;
- **if** $match$
  - $partition \leftarrow partition :: \langle i, j\rangle$;
  - $i \leftarrow i + 1$; $j \leftarrow j + 1$;
  - $s \leftarrow u$; $w \leftarrow v$;
- **else if** $\boxed{r(u) = w \ \wedge \ rankT(u, w) \prec rankT(s, w)}$
  - $i \leftarrow i + 1$;
  - $s \leftarrow u$;
- **else** $error \leftarrow true$;
- $n \leftarrow n - 1$;

while $n > 0 \wedge \neg error$;

return $\langle partition, error\rangle$;

Refinement Conjecture

Runtime Checker



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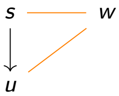
Compile $\longrightarrow$



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Local proof method $\rightsquigarrow$ efficient runtime refinement checker

Evaluation: RISC-V Sodor

- 5-stage pipeline Sodor Processor
  - Single issue in-order pipeline processor
  - Supports full bypassing between functions units
- Spike, executable RISC-V ISA simulator
  - High-level specification
  - Serves as the oracle

Evaluation

- Effectiveness in detecting bugs
- Overhead cost of the refinement checker

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- Effectiveness in detecting bugs

Errors Injected	Detect
Instruction classification	✓
Control: Stall Mechanism	✓
Control: Pipeline hazard detection	✓
Arithmetic-logic unit	✓
Load store unit	✓

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Evaluation

- Effectiveness in detecting bugs
- Overhead cost of the refinement checker

  1. Match concrete and abstract states
  2. Computing the refinement map
  3. Computing the rank of a concrete state

Algorithm 1: Refinement Check

...
do
  $u \leftarrow \textit{Select-concrete-next-state}(s)$;
  $\boxed{\langle \textit{match}, v\rangle \leftarrow \textit{Match-abstract-next-state}(w, u)}$;

  if *match* **then**
    $\textit{partition} \leftarrow \textit{partition} :: \langle i, j\rangle$;
    $i \leftarrow i + 1$; $j \leftarrow j + 1$;
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  end
  else if $\boxed{r(u) = w \ \wedge \ \textit{rankT}(u) < \textit{rankT}(s)}$
   then
    $i \leftarrow i + 1$;
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Conclusion

An alternate testing methodology based on the theory of refinement.

Refinement implies functional correctness

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Robust to changes in the implementation

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Thank You

References

- An efficient refinement-based testing methodology

Skipping refinement
Mitesh Jain and Pete Manolios
CAV, 2015, 2017

Proving skipping refinement using ACL2s
Mitesh Jain and Pete Manolios
ACL2, 2015