Critical Variable Identifications using Register Vulnerability for Selective Protections

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Agenda

- Motivation
- Related works
- Problem definition
- Method Proposal
- Experiments
- Conclusions
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What is soft error?

- Soft Error?
  - A phenomenon that the bit of the transistor is temporarily reversed
    - Assume that this transistor contains bit value 0
    - This transistor is attacked by external radiation
    - The external radiation makes some charges
    - The extra charges make the bit value to 1
  - Soft error rate exponentially increase with technology scaling and near-threshold computing
Soft error is an increasing concern

- Soft error is a major threat to system reliability
- As computer systems are used more and more in industry and life, soft error is becoming important

If soft error occurs in auto-driving car [2017, Li]

- Only 1 bit of soft error can lead to misclassification of objects in DNN based vision technique
- Misclassification can result in the wrong action

![Diagram](image)
Soft error protection technique is required

- The progress of soft error protection
  - Detect soft error occurrence
  - Execute fault tolerance policy (correction, restart, rollback, etc..)
  - Make the system to operate normally

- Implement soft error protection

H/W based technique

S/W based technique
Hardware based technique

- **Hardware based protection technique**
  - Redundant H/W to detect or correct errors
    - Requires additional hardware costs
  - ECC (Error Correction Code) block on L1D (SEC-DED) [2006, chibani]
    - 215% increase runtime than unprotected one
    - 20% additional area occupancy and 300% more power consumption

- **ECC protection example**

  8 Data bits + 5 Parity bits

  ![Encoding / Decoding logic hardware]

<table>
<thead>
<tr>
<th>P0</th>
<th>P1</th>
<th>P2</th>
<th>D1</th>
<th>P4</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>P8</th>
<th>D5</th>
<th>D6</th>
<th>D7</th>
<th>D8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<td>1</td>
</tr>
</tbody>
</table>

  - 1 bit error correction = P0 will be **wrong**, P1,2,4,8 will be **index of error**
  - 2 bit error detection = P0 will be **correct**
Software based technique

- Software based protection technique
  - No additional hardware costs, flexible to apply and change
  - SWIFT: Insert error detection code on program by duplicating instructions [2005, reis]
    - 70% of errors detection coverage, 400% increase runtime

- SWIFT (Software Implemented Fault Tolerance) example
Full protections are highly expensive

- H/W and S/W full protection are highly expensive
  - Runtime overhead: at least 2 times slower
  - May not be suitable for modern computer systems (low-power, IoT)

- Selective protection
  - All variable protection is expensive
  - Only few variables are important, i.e., failure-critical

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<table>
<thead>
<tr>
<th>Original</th>
<th>SWIFT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variable A</strong></td>
<td><strong>Variable A</strong></td>
</tr>
<tr>
<td>Load R1, [Variable A]</td>
<td>Load R1', [Variable A']</td>
</tr>
<tr>
<td>R2 = R1 + 10</td>
<td>R2' = R1 + 10</td>
</tr>
<tr>
<td>Store R2, [Variable Result]</td>
<td>Store R2', [Variable Result']</td>
</tr>
</tbody>
</table>

**Variable A is used for Result (failure-critical)**

<table>
<thead>
<tr>
<th>Variable B</th>
<th>Variable B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load R2, [Variable B]</td>
<td>Load R2', [Variable B']</td>
</tr>
<tr>
<td>R3 = R2 + 10</td>
<td>R3' = R2' + 5</td>
</tr>
<tr>
<td>Store R3, [Variable C]</td>
<td>Store R3', [Variable B']</td>
</tr>
</tbody>
</table>

**Variable B is used for C (not critical)**

```
Load R2, [Variable B]
R3 = R2 + 10
Store R3, [Variable C]

Load R1, [Variable A]
R2 = R1 + 10
Store R2, [Variable Result]

Load R2, [Variable B]
R3 = R2 + 5
Store R3, [Variable C]

Cmp R1, R1'
br faultDetection
Cmp R3, R3'
br faultDetection
```
Selecting protection: a cost effective way

- H/W and S/W full protection are highly expensive
  - Runtime overhead: at least 2 times slower
  - May not be suitable for modern computer systems (low-power, IoT)

- Selective protection
  - All variable protection is expensive
  - Only few variables are important, i.e., failure-critical

**Original**

<table>
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</table>

<table>
<thead>
<tr>
<th>Variable B</th>
<th>Load R2, [Variable B]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R3 = R2 + 10</td>
</tr>
<tr>
<td></td>
<td>Store R3, [Variable C]</td>
</tr>
</tbody>
</table>

**SWIFT**

- **Selective protection**
  - Load R1, [Variable A]
  - \( R2' = R1 + 10 \)
  - Store \( R2' \), [Variable Result']
  - CMP R1, R1'
  - br fault Detection

- **Reduce cost**
  - Load R2, [Variable B]
  - \( R3 = R2 + 10 \)
  - Store R3, [Variable B]
Selective protection: a cost effective

- H/W and S/W technique are highly expensive
  - Runtime overhead: at least 2 times slower
  - May not be suitable for modern computer systems (low-power, IoT)

- Selective protection
  - All variable protection is expensive
  - Just some of them are important, i.e., failure-critical

Full protection

Identification of important variables

Selective protections on important variables can be cost effective
Selective protection: a cost effective

- Selective protection example
  - Mug cup with an invisible crack
  - The cup will be broken if knock the cracked part
  - Attaching the tapes to the only crack can prevent broken

Selective Protection (Effective and low cost)

We need to figure out where to be protected
Agenda

- Motivation
- Related works
  - Method for finding where to protect in H/W
  - Method for finding where to protect in S/W (Critical variables)
- Problem definition
- Method Proposal
- Experiments
- Conclusions
H/W Vulnerability Measurement

- AVF (Architectural Vulnerability Factor) [2003, Mukherjee]
  - Vulnerability: possibility that a fault in that particular structure will result in an error

- gemV toolset [2016, Tanikella]
  - Improve accuracy and scalability
  - Accuracy: CPU-cycle unit measurement (gem5 based)
  - Scalability: supports various hardware and components
  - Validation of vulnerability measurement by fault injection

Fault is overwritten, not vulnerable
- Before reading after writing (t2 ~ t7) is vulnerable
- Weakness: accuracy (instruction unit), scalability (limited H/W)
H/W Vulnerability Measurement

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Identification of Critical Variables using an FPGA-based Fault Injection Framework [Riefert, 2013]

- **The Critical variable**: a variable that significantly affect on program **execution and calculation results** (frequently used)
- In fault injection, critical variable will be highly injected
- Experiment: protecting 3 variables (Runtime 18% increase)

### S/W Vulnerability Measurement

<table>
<thead>
<tr>
<th></th>
<th>No Protection</th>
<th>3 Variables</th>
<th>Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of errors</strong></td>
<td>95</td>
<td>49</td>
<td>95</td>
</tr>
<tr>
<td><strong>Error</strong> decrease</td>
<td>51%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number of failures</strong></td>
<td>9</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td><strong>Failure</strong> decrease</td>
<td>88%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- However, Fault injection it takes large of time to run fault injection campaigns (at least 7,000 program run)
Agenda

- Motivation
- Related works
- Problem definition
  - Finding critical variable (fault injection) takes a lot of time
- Method Proposal
- Experiments
- Conclusions
Fault Injection for finding critical variables

- Fault injection is a good technique for finding critical variables
- A large number of faults will be injected into the critical variables
- Protecting critical variable, effective protection method at low cost
- But, fault injection takes a lot of time

Fault Injection takes a lot of time
Fault Injection takes a lot of time

- Fault Injection method for finding critical variables
  - Fault injection is a good technique for finding critical variables
  - A large number of faults will be injected into the critical variables
  - Protecting critical variable, effective protection method at low cost
  - But, fault injection takes a lot of time

N times fault injection

Count of faults = Variable A : 4 Variable B : 3 Variable C : 2
Agenda

- Motivation
- Related works
- Problem definition
- Method Proposal
  - Since fault injection takes lots of time, we develop an alternative way to find out the critical variable
  - The framework of variable vulnerability measurement with LLVM compiler and gem5 simulator
- Experiments
- Conclusions
Overview of our proposed technique

- Variable vulnerability method for finding critical variables

① Measures the vulnerability of variables that can cause an error
② LLVM maps variables and register
③ gem5 calculates actual CPU-cycle for vulnerability
Fault and Vulnerability

- Variable A (corrupted) can cause failure

Fault ①: Write to Variable A at time t1
Fault ②: Read from Variable A at time t4
Fault ③: Write to Variable A at time t7
① Variable Vulnerability Measurement

- Vulnerable Period

Variable A

Vulnerable
(faults in this period can cause failure)

Variable A' Vulnerability = t6 - t1 = 5 time units
① Variable Vulnerability Measurement

- Requirement for measurement

Variable A

Problem A
Need to know which variable is written to the register

Problem B
Need to know actual CPU-cycle

Variable A (corrupted)
can cause failure

Vulnerable in this period can cause failure

Variable A' Vulnerability = t6 - t1 = 5 time units
Mapping Register ↔ Variables

- **Modified LLVM Compiler**
  - Variables are assigned to registers during compile
  - Modify compiler to output variable ↔ register allocation information
  - Machine code with variable name

**Answer to problem A**
(Which variable is written to the register)

- **Source Code**
- **Compiler**
  - Virtual Register
- **Machine Code**
  - Register

```
load R0, [sp+10]
add R1, R2, R0
mov R0, #10
store R0, [sp+14]
```
③ Actual vulnerable period cpu-cycle

- **Answer to problem B** (need to know actual CPU-cycle)
  
- **gem5 calculate CPU-cycle**
  - Although the number of instructions is the same, the actual vulnerable time may be different

```
load R0, [sp+10]  add R1, R2, R0  mov R0, #10  store R0, [sp+14]
```

With our framework (vulnerability measurement with LLVM and gem5), Now we can calculate variable vulnerability clearly.
Agenda

- Motivation
- Related works
- Problem definition
- Method Proposal

- Experiments
  - Validate our vulnerability based framework with fault injection campaigns

- Conclusions
Experiments

- **Validation**
  - Are variables with high vulnerability be more fault injected?
  - Can assume variable with a high vulnerability is a critical variable?

- **Fault injection experiment setup**
  - Benchmark: 6 programs (MiBench version 1.0)
  - 4,000 times fault injection for each benchmark
  - gemV toolset is used for fault injection experiment
  - Trace faults and analysis result (normal, SDC, system HALT)
Result: Vulnerability method fit a fault occur

Stringsearch variables vulnerability, fault and failure rate

- 2 variables (1.5%) have 94% of the vulnerability
- The Vulnerability is a good fit for a fault occur
- 2 variables protection can remove 79% of failure

* Variables are sorted in descending order of vulnerability.
Result: Find critical variable with vulnerability

Top 5 high Vulnerability variables and failure rate

- Top 3 high vulnerability variables have 67% of the fault and 68% of failure
- Protecting 3 high variables can remove 68% of failure

* Variables are sorted in descending order of vulnerability.
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Conclusion

- Soft error is an important concern
- H/W and S/W full protection is expensive
- Need to identify the critical variables for selective protections
  - The higher the variable vulnerability, more faults are injected
- We propose a framework for critical variable identifications with vulnerability measurement
  - Modeling vulnerability of variable
  - Early estimation of critical variables (without fault injection)
- In the experiment, only protecting top 3 vulnerable variables, 68% failures can be removed (3 variable are critical variable)
- Provide protection priority for selective technique

Future work
- There is a difference between variable vulnerability and failure (Masking effect: not all faults cause failure)
- Research to minimize the difference caused by masking effect