Extending a Compiler Backend for Complete Memory Error Detection

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Outline

1. Motivation
2. Error detection, AN encoding
3. The extended compiler backend
4. Evaluation
5. Summary
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Motivation

- Frequency of transient HW faults (aka. soft errors) is increasing.
  - Traditional cause of faults: cosmic rays.
  - Vulnerability is increasing due to smaller feature sizes and lower operating voltages.
  - Dark/dim silicon in memory modules:
    - Extended refresh cycles for DRAM.
    - Lower supply voltage for SRAM.

- Memory errors: ECC memory modules have their limitations.
  - Typically SEC-DED codes (single error correction, double error detection).
  - Large fractions of memory errors cannot be handled by SEC-DED codes (Hwang et al., ASPLOS 2012).
  - ECC not necessarily extended to the entire memory hierarchy. (Load-store queues?)

Software-implemented error detection has the flexibility to detect also complex error patterns.
Software-implemented error detection

- Manual incorporation of integrity checks.
  - Laborious and cumbersome.
  - Mixes functional and non-functional requirements.
  - Requires expert knowledge.
  - Error detection limited to anticipated errors.

- Automated, disciplined approaches.
  - Enable comprehensive error detection.
  - Source-to-source transformation.
  - Aspects.
  - Compiler-based approaches:
    - Transformation of machine code.
    - Transformation of intermediate representation (IR).

-越来越流行的自编码错误检测
- 自动化和纪律化的方法。
  - 增强全面的错误检测。
  - 源到源的转换。
  - 方面。
  - 编译器基础的方法：
    - 机器代码的转换。
    - 中间表示的（IR）转换。

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Limitations of software-implemented error detection

- To detect errors in memory ...
  - Which variables are kept in memory?
  - When are variables kept in memory?
  - Are there any hidden variables that are put into memory?

Ultimately, the compiler knows all this … … but only very late!

Percentage of dynamic memory accesses (loads) that are present in the program IR or inserted by the compiler backend:

(Twelve test programs, labeled A-L)

In some cases (H, L) virtually all loads are inserted by the compiler backend!
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Memory error detection by DMR

- DMR (dual modular redundancy).
  - In the context of software-implemented error detection: duplication of data.

```
store i64 %0, i64* %p
...
%1 = load i64* %p
```

- DMR may introduce race conditions in multi-threaded applications.
  - State-of-the-art work usually assumes memory is protected by ECC (in hardware).
AN encoding

- **AN encoding:**
  - Fix an integer constant $A$.
  - Encode integer values by multiplying by $A$: $n_{enc} = n \times A$
  - Decode by dividing by $A$: $n = n_{enc} / A$
  - Check for errors: $n_{enc} \mod A = 0$

- Error-detecting capability varies with the constant $A$.
  - Generally, multi-bit errors can be detected by suitable $A$.
  - $A = 58659$ is known to have good properties; can detect up to 5 bit flips, Hoffmann et al., 2015.

- AN encoding introduces large overheads if used to protect operations: several $10^x$-$100^x$.  

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Memory error detection by AN encoding (1)

- Detection of multi-bit errors in memory, including caches, load-store queues.
- Apply AN encoding only to values stored to memory → low overhead due to AN encoding.
- AN encoding is applied at the LLVM IR level.
  - Common approach in software-implemented fault tolerance schemes.

Error detection at the IR level misses memory accesses that are inserted by the compiler backend.

```
 ENTITLE

encode before storing:
%01 = mul i64 %00, A
store i64 %01, i64* %p

check and decode after loading:
%1 = load i64* %p
%2 = srem i64 %1, A
%f0 = icmp eq i64 %2, 0
br i1 %f0, label continue, label recover
%3 = sdiv i64 %2, A
...
```
Memory error detection by AN encoding (2)

- Remember this plot:

![Graph showing memory access percentages across different test cases]

- Backend for the C programming language inserts memory accesses for:
  - Register spills (spill).
  - Callee-saved registers (csr).
  - Frame pointer (fptr).
  - Return address (return).
  - Function arguments (arg).
  - Jump tables (jt).

```
# Implement function calls
```

```
foo.c -> Clang frontend -> program IR -> AN encoder -> IR with AN encoding -> extended backend -> binary with AN encoding and DMR -> foo.exe
```

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The extended compiler backend

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  - Return address (return).
  - Function arguments (arg).
  - Jump tables (jt).

- Implement error detection in the compiler backend by DMR:
  - Faster than AN encoding.
  - Keeps function calls efficient.
  - Adds (almost) no register pressure.

- Duplicated store/load:
  - Additional memory accesses are "cheap".
  - Memory locations already in the cache.
  - (All) memory accesses are thread-local.
DMR for register spills

- Comparison memory/register is specific to x86 – more generally, CISC machines.
- RISC machines? $\rightarrow$ cmp mem/reg might be sensible ISA extension.

```
mov eax, -0x30(ebp)
...
mov -0x30(ebp), eax
add eax, (esi)
```

```
mov eax, -0x34(ebp)
mov eax, -0x30(ebp)
...
mov -0x30(ebp), eax
cmp -0x34(ebp), eax
jne <error_handler>
add eax, (esi)
```
DMR for function arguments

- Requires co-operation between caller and callee (modified calling convention).
- Library calls still work. (Caller can ignore duplicated arguments).
- The number of arguments passed on the stack may be low (depending on the architecture).
DMR for the return address

- Modified calling convention: pass return address in register ebx.
- No modification required on, e.g., ARM or MIPS.
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Fault injection

- Assumptions:
  - Only a single fault affect program execution.
  - Only single bit flips occurs.

Commonly justified by the rarity of faults.
(SEU – single event upset)

- Simulate symptoms of faults by ...
  - ... flipping a bit in a memory location that is loaded from.

- Perform exhaustive fault injections:
  - Flip a bit in all possible locations in all loads from memory

<table>
<thead>
<tr>
<th>letter</th>
<th>test case</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>array reduction</td>
</tr>
<tr>
<td>B</td>
<td>bubblesort</td>
</tr>
<tr>
<td>C</td>
<td>CRC-32</td>
</tr>
<tr>
<td>D</td>
<td>DES encryption</td>
</tr>
<tr>
<td>E</td>
<td>Dijkstra (shortest path)</td>
</tr>
<tr>
<td>F</td>
<td>expression evaluation</td>
</tr>
<tr>
<td>G</td>
<td>token lexer</td>
</tr>
<tr>
<td>H</td>
<td>expression parser</td>
</tr>
<tr>
<td>I</td>
<td>matrix multiplication</td>
</tr>
<tr>
<td>J</td>
<td>array copy</td>
</tr>
<tr>
<td>K</td>
<td>quicksort</td>
</tr>
<tr>
<td>L</td>
<td>switch</td>
</tr>
</tbody>
</table>
Full memory error detection

no error detection:

AN encoding and DMR in the backend:
AN encoding dominates the slow down.

Test programs:

- i386 (32bit)
- x86_64 (64bit)

Subset of SPEC CINT2006:

- i386 (32bit)
- x86_64 (64bit)

Slow down dominated by register spills.
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Automatic code transformation that introduced memory error detection not comprehensive when applied above the level of machine code.

- Transformations at the level of source code or IR desirable for productivity.

Supporting memory error detection with DMR introduced by the compiler backend ...

- ... leads to full memory error detection,
- ... incurs a runtime overhead of
  - 1.50 on i386 (SPEC CINT2006),
  - 1.13 on x86_64 (SPEC CINT 2006).

Absence of vulnerabilities introduced by the compiler backend required for ...

- ... (reliable analysis/evaluation of) relaxed fault tolerance schemes.
- ... applications with strict safety and reliability requirements.

The stack has been found a major weakness.
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Thank you.