flexMEDiC: flexible Memory Error Detection by Combined data encoding and duplication

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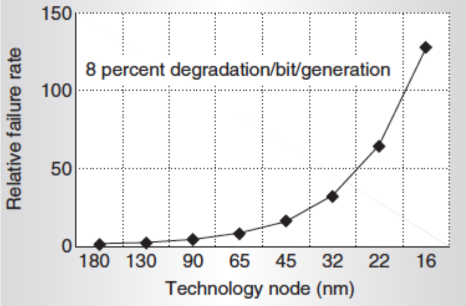
Motivation

- 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.



S. Borkar, "Designing reliable systems from unreliable components: …," IEEE Micro, vol. 25, no. 6, 2005.

- Limitations of ECC memory modules.
  - 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).

→ Software-implemented error detection can be flexibly adjusted to detect complex (multi-bit) error patterns as well.

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Motivation – cont'd

- The simple **AN encoding** scheme is capable of detecting multi-bit errors:
  - Fix an integer constant A.
  - Encode integer values by multiplying by A: $n_{enc} = n * A$
  - Decode by dividing by A: $n = n_{enc} / A$
  - Check for errors: $n_{enc} \mathit{mod} A = 0$
- Error-detecting capability varies with the constant A.
  - Powers of 2 are ill-suited to error detection.
  - 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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flexMEDiC

- Detection of multiple bit errors in memory, including caches, load-store queues.
- Apply AN encoding only to values stored to memory → low overhead due to AN encoding.

encode before storing:

```
%0 = mul i64 %0,  A
store i64 %0, i64* %p
```

check and decode after loading:

```
%1 = load i64* %p
%2 = srem i64 %1, A
...
%3 = sdiv i64 %2, A
```

- 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.

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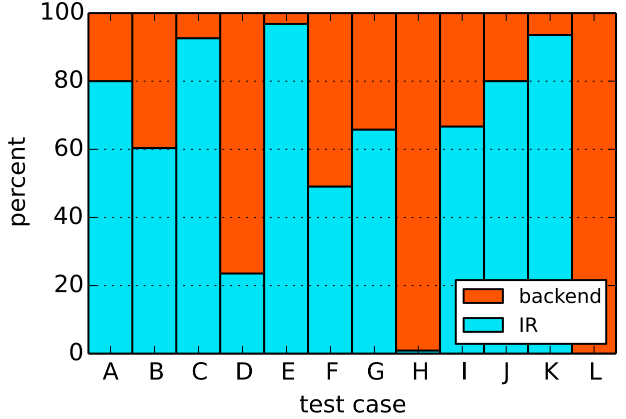
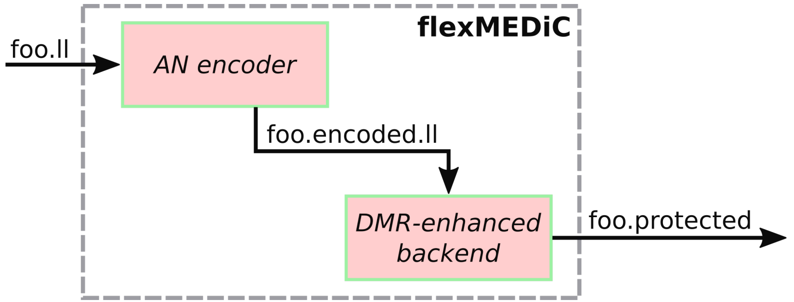
flexMEDiC – cont'd

- Frequency of unprotected memory accesses (at the level of LLVM IR):



Apply DMR to backend-inserted memory accesses:



- Two major sources of backend-inserted memory accesses: **register spills, function calls.**
- Using DMR keeps function calls efficient.
- DMR can detect **arbitrarily many bit flips** within the same data word.

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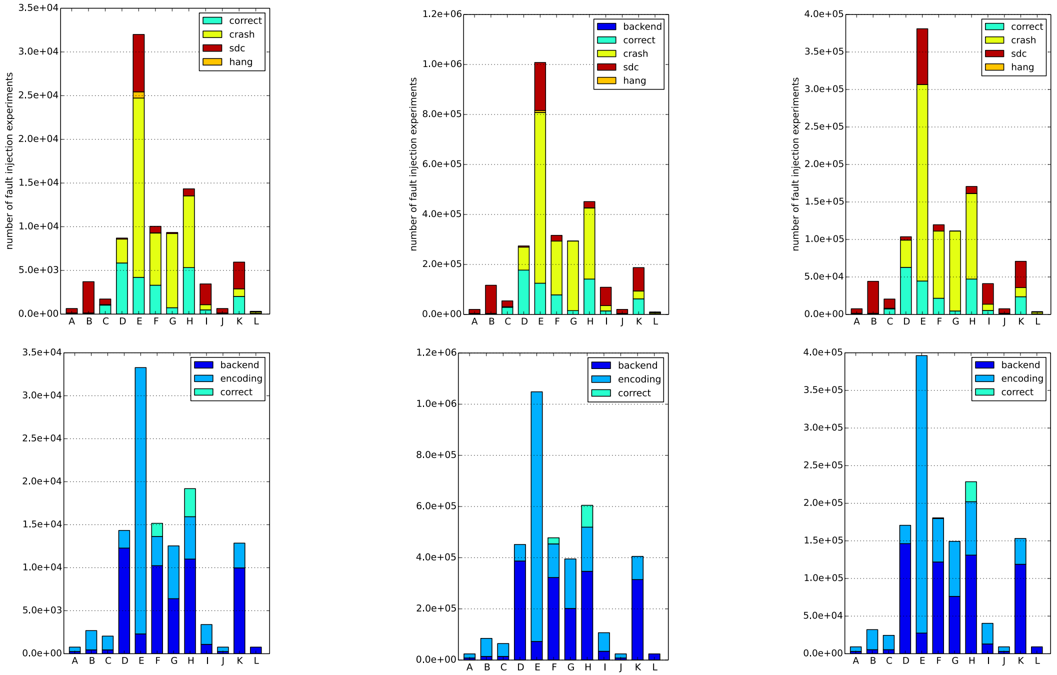
Full memory error detection

letter	test case
A	array reduction
B	bubblesort
C	CRC-32
D	DES encryption
E	Dijkstra (shortest path)
F	expression evaluation
G	token lexer
H	expression parser
I	matrix multiplication
J	array copy
K	quicksort
L	switch

single bit flip **double bit flip** **5-bit flip***



*) sampled 0.01% of all possible error patterns within a single data word.

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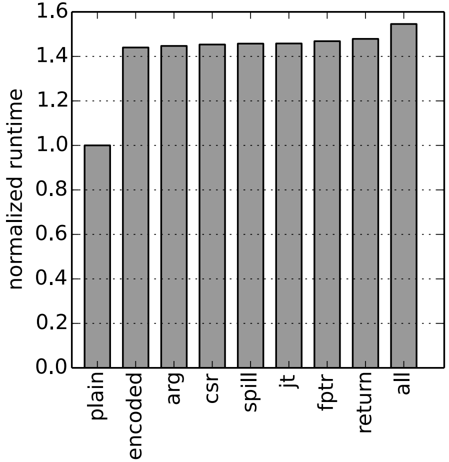
Runtime overhead

Geometric means across test programs*:



Overhead due to DMR only*:

DMR	overhead
frame pointer	1.020
callee-saved register	1.009
jump tables	1.013
return address	1.027
function arguments	1.005
register spills	1.012
all	1.073

*) runtime measurements performed on 64-bit Intel Core i7, at 3.6GHz

- Total runtime overhead due to **flexMEDiC** is **1.55x.**
- **AN encoding** introduces an overhead of only about **1.4**x.
- **DMR measures** inserted by the **compiler backend** introduce an overhead of only **1.07**x.
- Memory overhead of AN encoding is **log(A)** bits per data word.
- Memory overhead of DMR is 100%, but used sparingly.

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Summary and outlook

- flexMEDiC can successfully **detect multi-bit errors** in memory.
- The number of detectable bits can be adjusted flexibly by varying the encoding constant A.
  - Finding appropriate A is a fundamental problem in AN encoding.
- flexMEDiC relies on DMR only for local memory accesses → applicable to multi-threaded applications with shared memory.
- What hardware support can one think of to efficiently support the memory overhead of AN encoding of log(A)?
- Have observed similar distributions of program responses to varying numbers of bit flips.
  - Is there a fundamental reason for this (e.g. due to the nature of certain programs)?
  - How can one capitalize on this for the purpose of software-implemented fault tolerance?

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Thank you.