Unified Architectural Support for Soft-Error Protection or Software Bug Detection

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Motivation

- It is a great challenge to build reliable computer systems with buggy software and unreliable hardware
  - Software bugs account for **40%** of system failures
  - With technology scaling, transient faults are predicted to grow **at least in proportion** to the number of devices

Proposed Approach

- **Observation**:
  - Soft-errors and software bugs manifest in similar ways.
  - program localities can be used to detect abnormal behavior (soft-errors or bugs) during program execution.

- **Unified Architectural Support**:
  - Utilize a type of value locality – Limited Variance in Data Values (LVDV) to detect abnormal behavior
  - A cache-like structure tracks LVDV locality and detects violations

Presentation Outline

- Using localities to detect abnormal behavior
- Limited variance in data values (LDVD) locality
- Proposed architectural design
- Locality based soft-error protection
- Locality based software-bug detection
- Summary

Using Locality to Detect Abnormal Behavior

- Execution results of instruction A:

  20, 20, 20, 20, ... , 33554452

- Execution results of instruction B:

  1, 2, 3 1, 2, 3 ... 1, 2, 3, 4

- Violation of the constant or stride locality hints the possibility of an error, or a software bug.

Limited Variance in Data Values (LVDV)

- Variance between two values is defined as a simple XOR
- The variance specifies the **fraction of bits which vary** between the two values – the rest of the bits do not change and can be protected

An Example of LVDV Locality

- Execution results of instruction A:

1, 60

00000000000000000000000000	111101

- The result of **1 XOR 60**

An Example of LVDV Locality

- Execution results of instruction A:

1, 60, 12

00000000000000000000000000	110000

- The result of **60 XOR 12**

An Example of LVDV Locality

- Execution results of instruction A:

1, 60, 12, 40

00000000000000000000000000	100100

- The result of **12 XOR 40**

An Example of LVDV Locality

- Execution results of instruction A:

1, 60, 12, 40, 2

00000000000000000000000000	101010

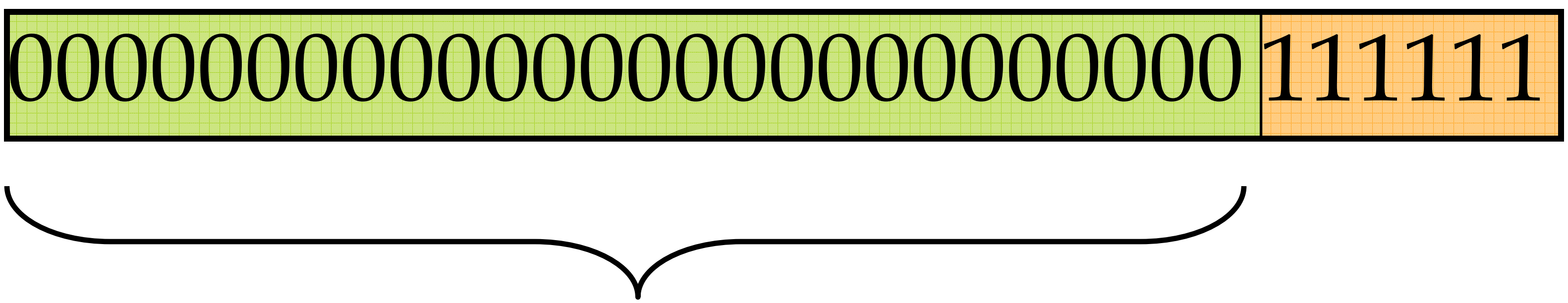
- The result of **40 XOR 2**

An Example of LVDV Locality

- Execution results of instruction A:

  1, 60, 12, 40, 2, ...

- No apparent pattern! However, the values are usually within a certain small range.



portion of result bits protected by LVDV

An Example of LVDV Locality

- Execution results of instruction A:

1, 60, 12, 40, 2, ... , 33554452

00000010000000000000000000	010110

- The result of **2 XOR 33554452**

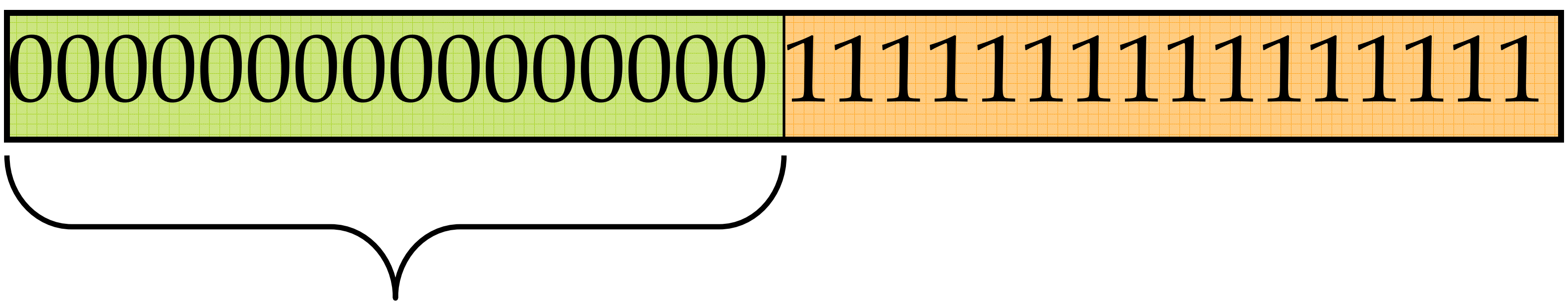
LVDV Captures Region Locality

- Memory addresses produced by instruction A:

0x11112654, 0x11117838 ...

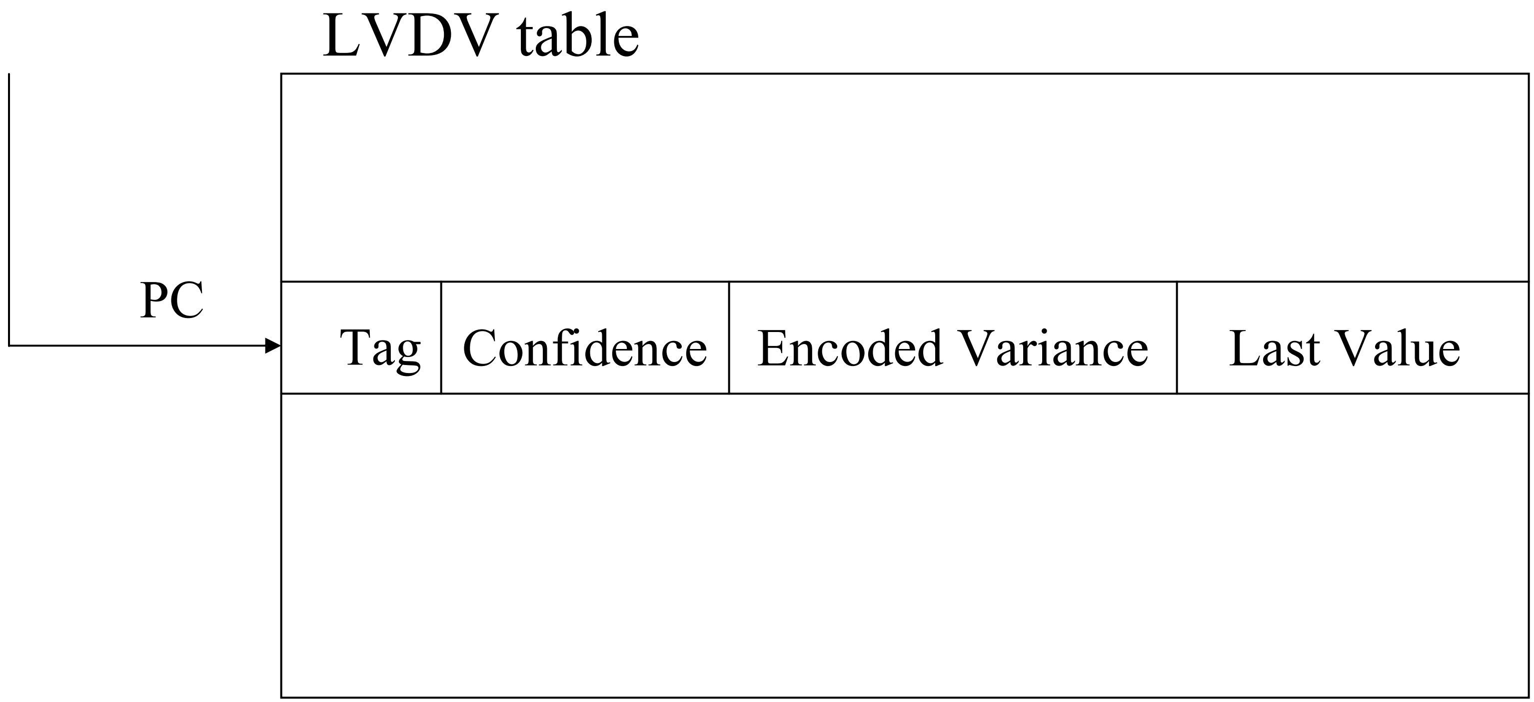
0x11111200, 0x11119088, 0x**0**1119088

- Heap memory addresses produced by instruction A exhibit no stride locality.



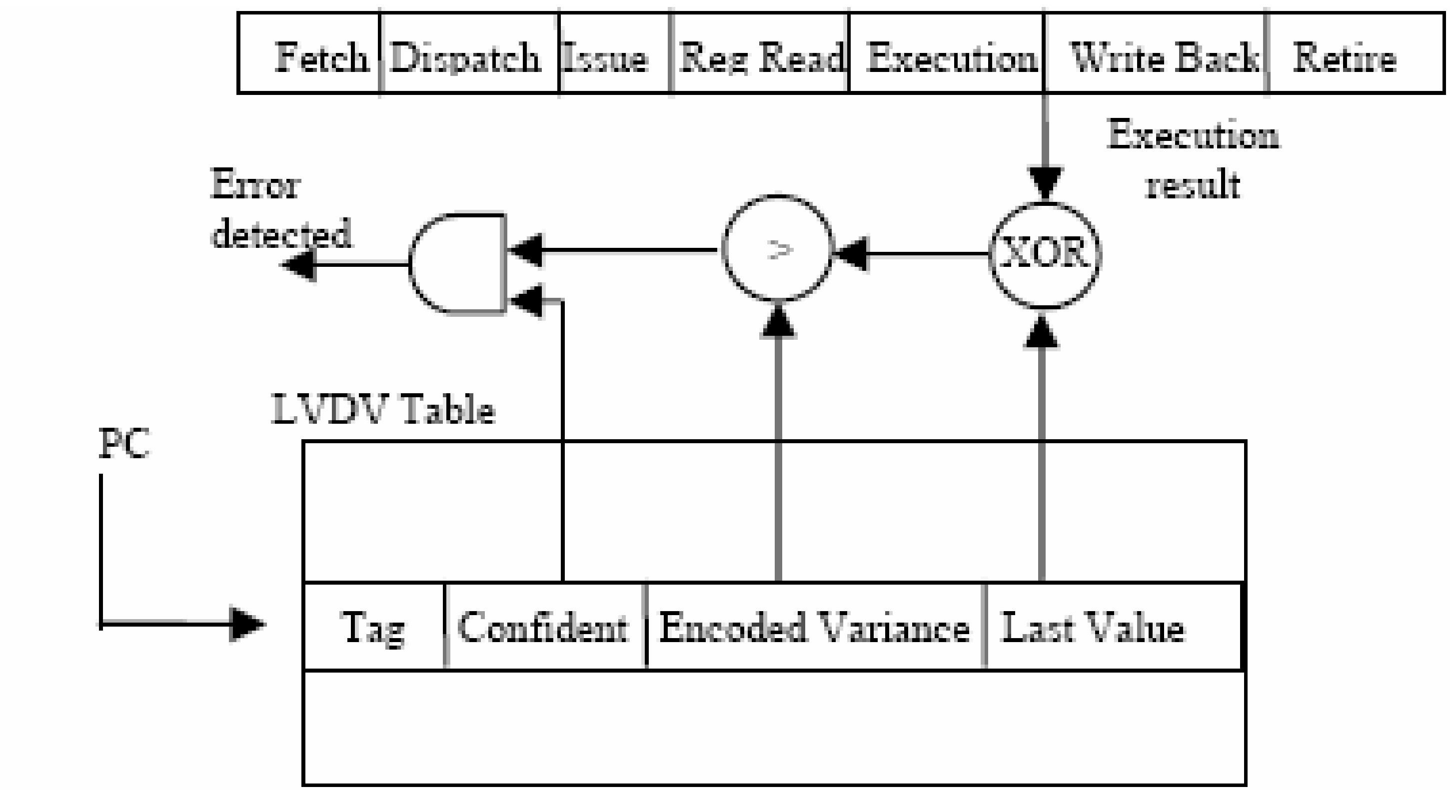
portion of result bits protected by LVDV

Proposed Architectural Support



- The main structure in our architecture is an LVDV table.

Interaction of the LVDV table with the processor pipeline



Locality-Based Soft-Error Detection

- When an anomaly is detected, squash the pipeline as in a branch misprediction
- The anomaly is detected **promptly** and re-execution fixes the soft-error
- A single LVDV table can catch soft-errors in the computational logic, control logic – such as decoder, renaming table, issue queue and operand selection logic

Benefits of Locality-Based Soft-Error Detection

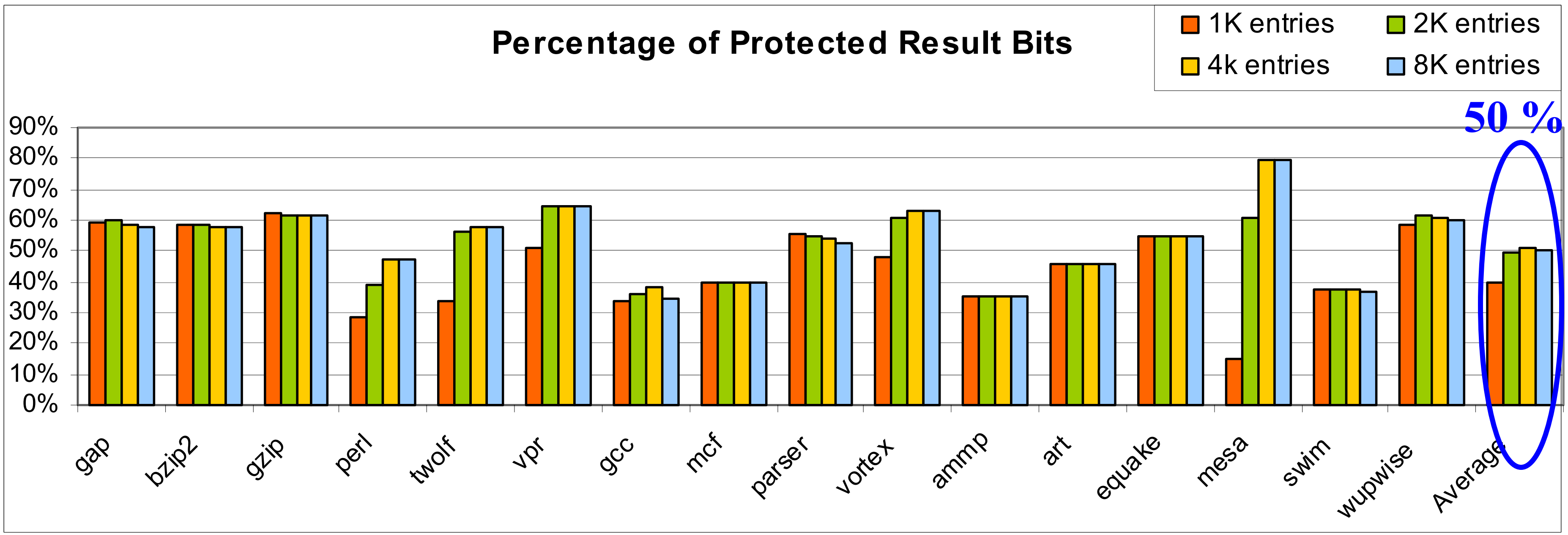
- Provides information redundancy (no redundant execution required)

- Provides efficient, opportunistic protection of multiple hardware structures

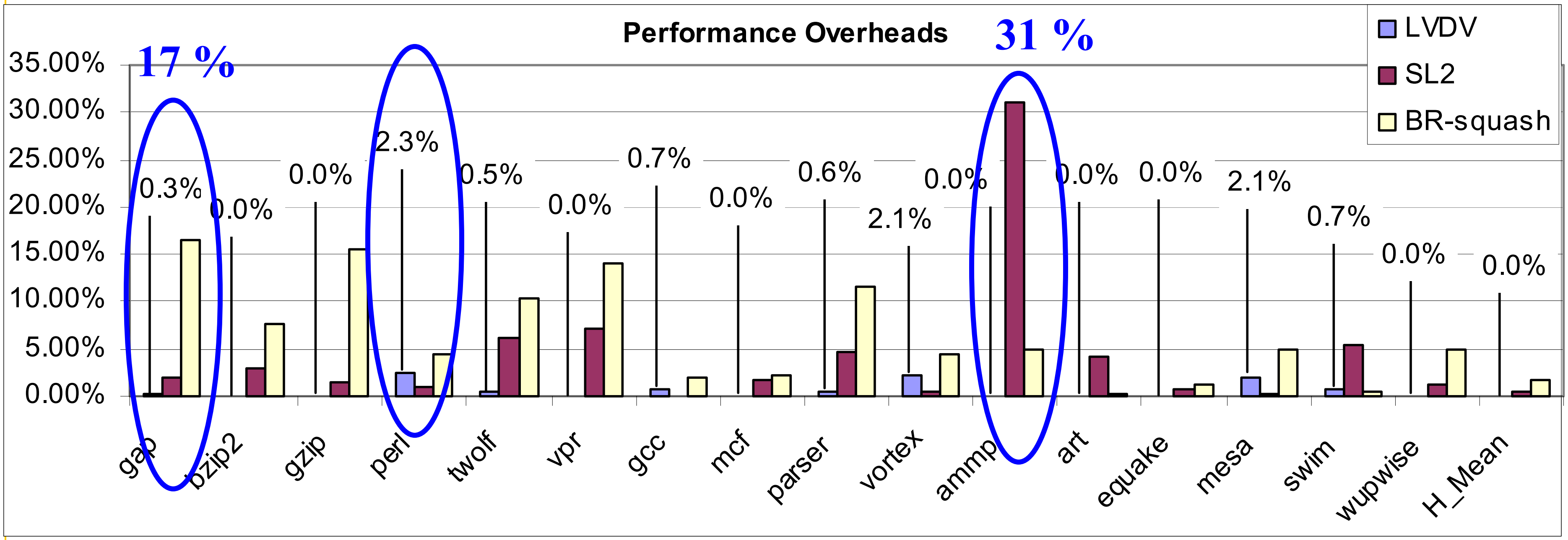
Experimental Methodology

- Error injection into the Issue Queue and Functional Units
- Compare our approach to:
  - Implicit Redundancy Through Reuse (IRTR) [Gomaa et al., ISCA 2005]
  - Squash on L2-cache miss (SL2) [Weaver et al., ISCA 2004]
  - Squash on Branch misprediction (BR-squash) [Wang et al., DSN 2005]

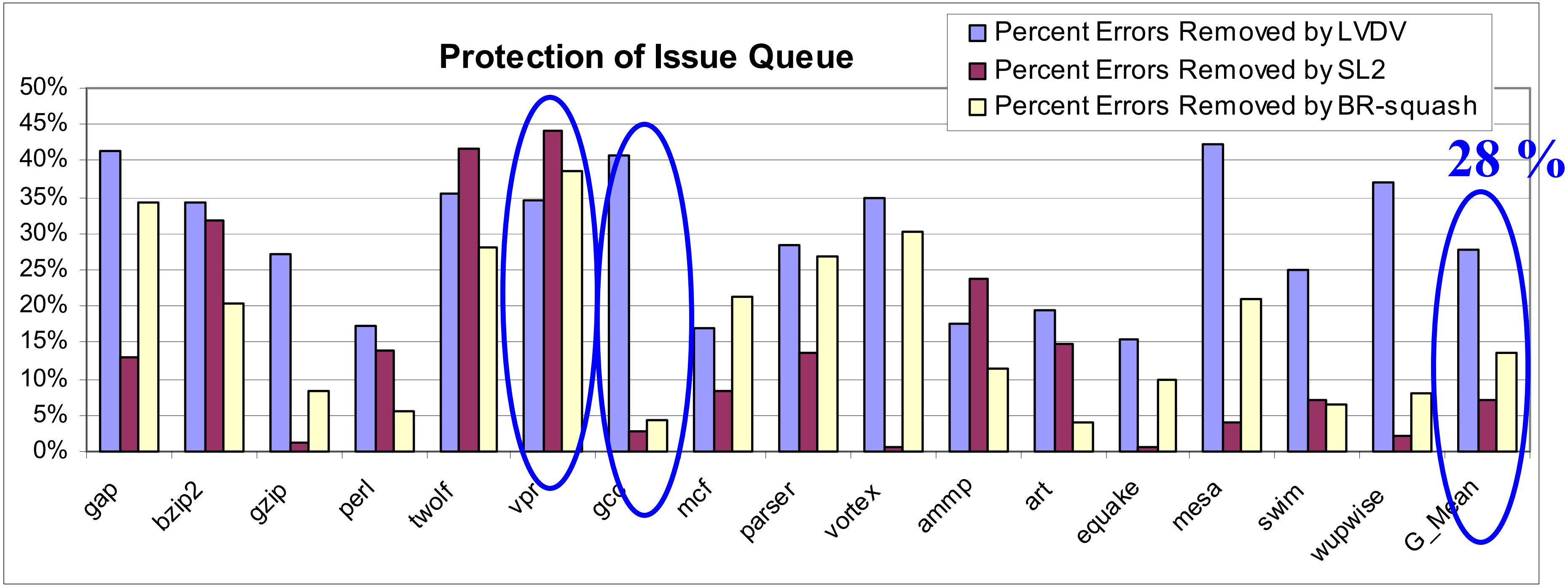
Strength of the LVDV Locality



Performance Overhead

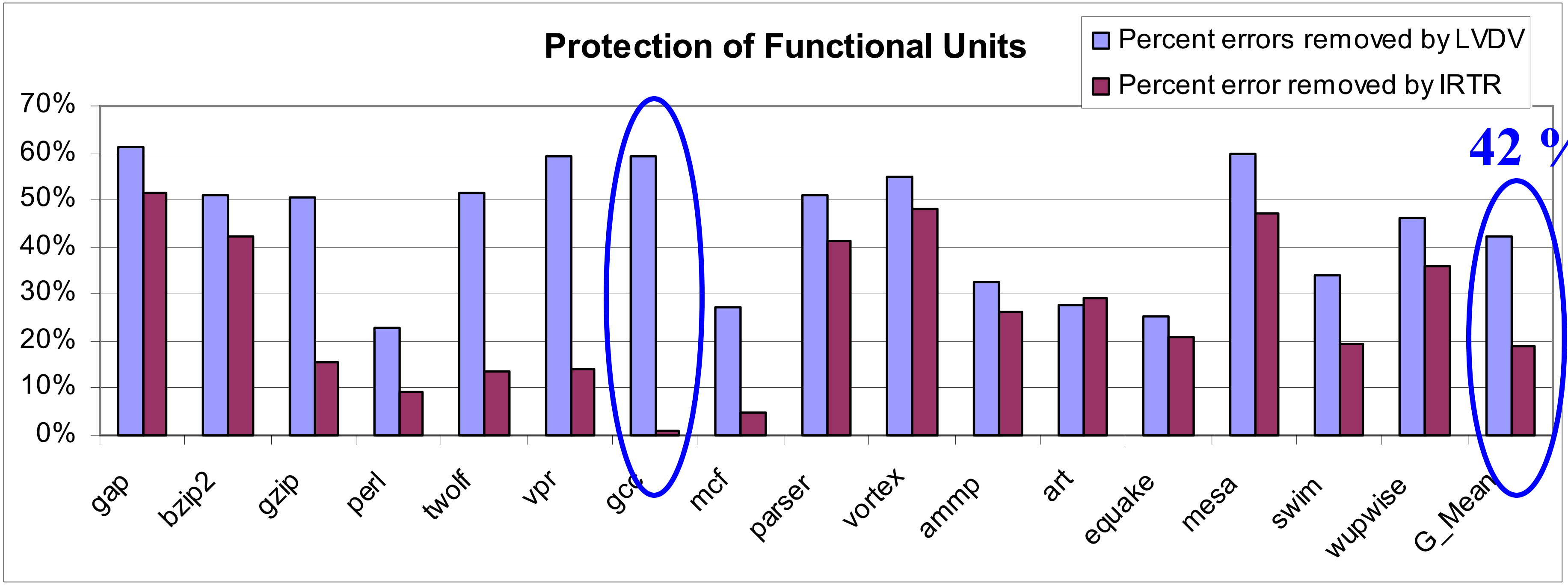


Soft-Error Protection of Issue Queues



- LVDV removes 28% of critical errors
- MTTF improvement of 39%

Soft-Error Protection of Functional Units



- LVDV removes up to 61% of critical errors and 42% on average
- MTTF improvement of up to 156% and 72% on average

Locality-Based Software Bug Detection

- Training phase
  - LVDV table learns invariance information from multiple successful program runs OR from a single long run.
- Bug detection phase
  - LVDV table detects anomalies during the failing run
  - Anomalies are reported as possible root-causes of a software bug
  - Misses in the LVDV table are also signaled as "new-code" anomalies
- We used a 4K entries table and tracked the variance in every store instruction

Locality-Based Software Bug Detection

- Shown to pinpoint latent program bugs
- Can detect bugs, which do not violate any programming rules
- Our approach can be viewed as a hardware implementation of DIDUCE [Hangal et al, ICSE 2002]
- Hardware offers the following advantages:
  - Performance efficiency
  - Binary compatibility
  - Runtime monitoring

Case Study
Incorrect Bounds Checking

```
char newname[MAX];

/* convert the filename */
for(i=0;i<strlen(original);i++){ /*bug*/
 if( isupper( original[i] ) ){
  newname[i]= tolower(original[i]);
  continue;
 }
 newname[i] = original[i]; /*detection*/
}
newname[i] = '\0'; /*detection*/
```

A buffer overflow in polymorph-0.4.0

Case Study
Warm-up Phase

```
char newname[MAX];

/* convert the filename */
for(i=0;i<strlen(original);i++){ /*bug*/
  if( isupper( original[i] ) ){
    newname[i]= tolower(original[i]);
    continue;
  }
  newname[i] = original[i]; /*detection*/
}
newname[i] = '\0';     /*detection*/
```

&newname[3]:	7fffaf33
&newname[6]:	7fffaf36
&newname[11]:	7fffaf3b
&newname[2]:	7fffaf32
&newname[17]:	7fffaf41
&newname[9]:	7fffaf39
&newname[5]:	7fffaf35
…	…
&newname[16]:	7fffaf40

conf: 15   *prev_result*: 7fffaf40   *encoded variance*: 7

Case Study
Detection Phase

```
char newname[MAX];

/* convert the filename */
for(i=0;i<strlen(original);i++){ /*bug*/
  if( isupper( original[i] ) ){
    newname[i]= tolower(original[i]);
    continue;
  }
  newname[i] = original[i]; /*detection*/
}
newname[i] = '\0';     /*detection*/
```

&newname[85]: 7fffaf85

conf: 15 *encoded variance*: 7 *variance*: **8**

Summary of Results

- 4K LVDV provides similar bug detection capabilities as software approach DIDUCE
- Also similar number of false-positives as DIDUCE

	Polymorph	bc	Ncompress (input 1)	ncompress (input 2)	gzip
DIDUCE	2	45	1	0	6
4K LVDV	2	54	1	0	6

Summary

- Soft-errors and software bugs manifest in similar ways during execution
- We can use localities to detect both
- Proposed mechanism protects multiple structures from soft-errors (39% and 72% MTTF of IQ and FU)
- Similar bug detection capabilities to DIDUCE (a software based bug detection scheme)