

Karlsruhe Institute of Technology

Reliable Computing I

Lecture 9: Concurrent Error Detection

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Today's Lecture



- Concurrent error detection
- Watchdog timers
- Watchdog processor
- Heartbeats
- Consistency and capability checking
- Data audits
- Runtime generated assertions

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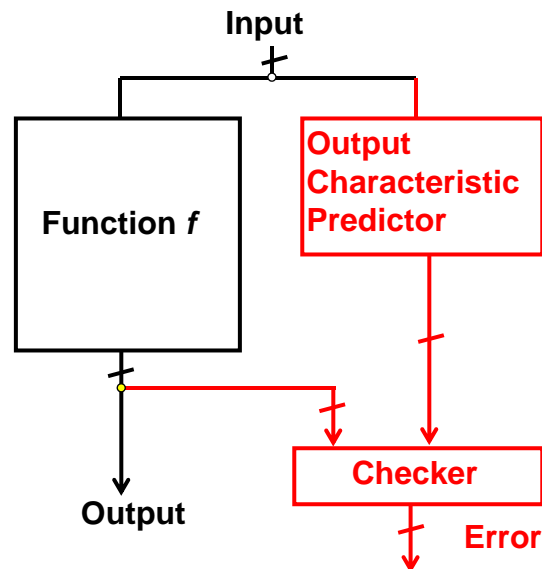
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Concurrent Error Detection (CED)



- Employed during normal operation
- Detect errors as they occur
 - Data integrity ensured
 - Correct outputs or
 - Error indicated for incorrect outputs
 - **Fault-secure property**

General CED Structure



Output “Characteristics”



- Output itself
 - Duplication
- Output parity
 - Parity prediction
- Residue
 - Residue codes
- 1s or 0s count in output word
- Many others


All output characteristics are not equally effective

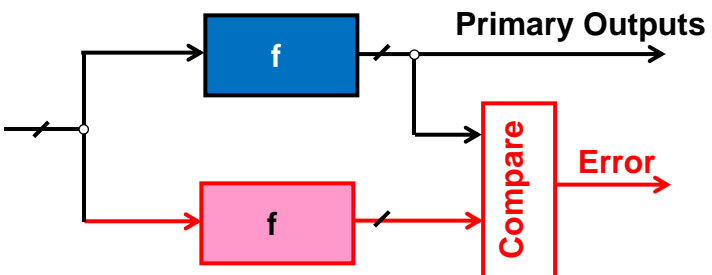
CED Classification & Examples



	Hardware	Software
Application independent	Identical Duplication Diverse Duplication Parity Prediction Residue codes Multi-threading Watchdog processor	Duplicated instruction Identical or Diverse Data Control-flow checking N-version programs
Application specific	Compression, Encryption, Signal processing, RESO, ...	Assertion checks Algorithm-based fault-tolerance

Duplication for CED






- Two implementations: Identical or diverse
- Widely used (aka duplex system)
 - e.g., IBM G5, G6 processors, shuttle
- Issues
 - Common-mode failures, synchronization

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Fault Effects in Duplex Systems



- Single module failure
 - Guaranteed data integrity
- Multiple independent failures
 - Data integrity not guaranteed
 - Both modules generating identical errors
 - Very low probability
- Common-mode failures
 - Data integrity not guaranteed
 - More frequent

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Common-Mode Failures (CMFs)



- Multiple faults
 - Single cause
 - More probable than multiple independent failures
- Examples
 - Power-supply dip,
 - Single source radiation causing multiple upsets,
 - Design faults
- Antidote for CMF
 - Design Diversity
 - Diverse implementations
 - Error effects caused by CMFs are different

Watchdog Timer



- An inexpensive method of error detection
- Process being watched must reset the timer before the timer expires,
 - otherwise the watched process is assumed as faulty
- Watchdog timers only detect errors which manifest themselves as a control-flow error such that the system does not continue to reset the timer
- Only processes with relatively deterministic runtimes can be checked, since the error detection is based entirely on the time between timer resets

Watchdog Timer



- A watchdog timer provides only an indication of possible process failure
 - a partially failed process may still be able to reset the timer
- Coverage is limited, as neither the data nor the results are checked
- When used to reset the system, a watchdog timer can improve availability (the mean time to recovery is shortened) but not reliability (failures are just as likely to occur)
 - when the availability of a system is more important than the loss of data, the use of a watchdog timer to reset the system on the detection of an error is an appropriate choice.

Example Applications of Watchdog Timers



- NASA's Mars Pathfinder mission
 - mars rover uses a real-time preemptive multithreaded operating system
 - tasks scheduled based on priorities that reflect their relative urgency
- **Major failure event:** priority inversion between tasks with different priorities
 - system deadlock
- Watchdog timer used to detect such scenario and restart the system
 - full restart causes loss of data
 - repetitive resets seriously limit the correct work of the system
 - the problem eventually diagnosed as a software bug
 - software patch reestablishes proper behavior
- **A traditional system reset is a drastic but robust measure used in engineering practice**
 - **availability of the system is more important than the lost data due to the system reset**

Example Applications of Watchdog Timers



■ Telephone Switch System

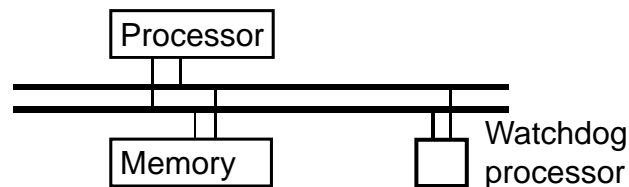
- External watchdog timers monitor correct program operation by triggering recovery when timers are not periodically reset
- Allows an early (before the error propagates) detection of problems caused by software errors and consequently easier recovery

Watchdog Processor & Control Flow Checking




■ Watchdog processor: “Simple” processor

- Generalized version of watchdog timer
- Program control flow checked
- Assertion checks for computation errors
- Can be integrated into the processor itself



Structural Integrity Checking (SIC)




- Program broken into basic blocks
 - Branch-free sequence of instructions
- Unique signature for each basic block
- Signatures explicitly transferred to watchdog
- Signature sequence checked by watchdog
- Automated at compiler level
 - Assignment of signatures
 - Instructions to send signatures to the watchdog.
 - Watchdog program can be automatically synthesized.

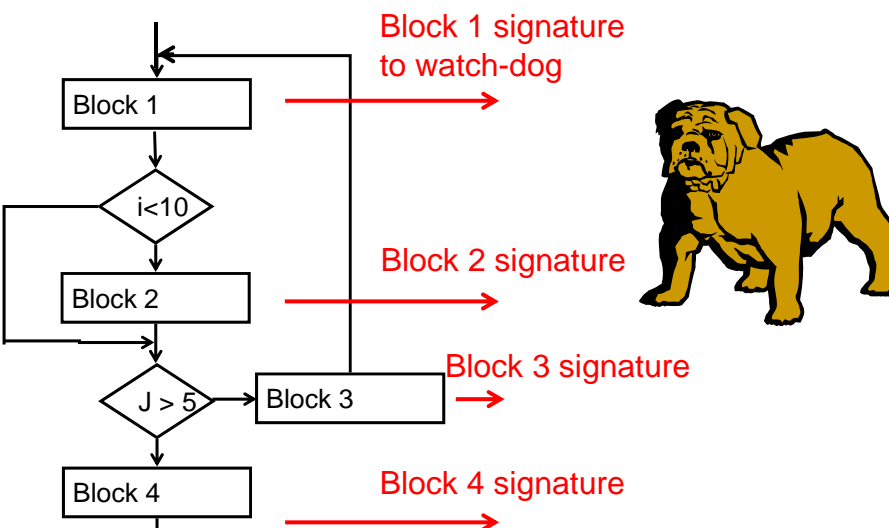
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Structural Integrity Check Example






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EDDI



- Error Detection by Duplicated Instructions
 - Intended for transient computation errors
- Duplicated Instructions
 - Master and shadow instructions
- Master and shadow results compared
 - Transient errors in computations detected
- Automated flow
- Performance overhead: 13%-111%
 - Super-scalar processors advantageous
 - No dependency between master & shadow


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EDDI Example



```

ADD R3, R1, R2           ; R3 ← R1 + R2
MUL R4, R3, R5           ; R4 ← R3 * R5
ST 0(SP), R4             ; store R4 in location
                        ; pointed by SP
                    
```



```

ADD R3, R1, R2           ; R3 ← R1 + R2   master
ADD R23, R21, R22       ; R23 ← R21 + R22 shadow
MUL R4, R3, R5           ; R4 ← R3 * R5   master
MUL R24, R23, R25       ; R24 ← R23 * R25 shadow
BNE R4, R24, ErrorHandler ; compare master and
                        ; shadow results
ST 0(SP), R4             ; store master result
ST offset(SP), R24       ; store shadow result
                    
```

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Heartbeats



- A common approach to detecting process and node failures in a distributed (networked) computing environment.
- Periodically, a monitoring entity sends a message (*a heartbeat*) to a monitored node or process and waits for a reply.
- If the monitored node does not respond within a predefined timeout interval, the node is declared as failed and appropriate recovery action is initiated.

Heartbeats: Issues



- The timeout period is pre-negotiated by the two parties or sometimes even hard-coded by the programmer
- The predefined timeout value cannot adapt to changes in network traffic or to load variability on individual nodes
- The monitored node is assumed to be healthy if it is able to respond to a heartbeat message
- Process/thread responding to the heartbeat message may operate correctly, while other processes/threads may be in a deadlock situation or operating incorrectly

Adaptive & Smart Heartbeat

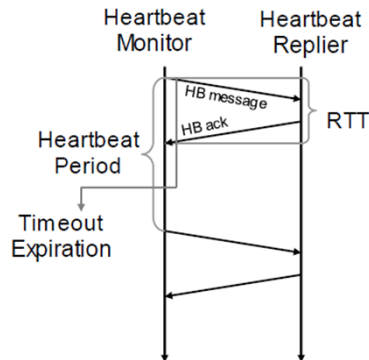


Adaptive heartbeat

- the timeout value used by the monitor process is not fixed but is periodically negotiated between the two parties to adapt to changes in the network traffic or node load.

Smart heartbeat

- the entity being monitored excites a set of predefined checks to verify the robustness of the entire process and only then responds to the monitoring process



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Consistency and Capability Checking



Capability Checking

- can be implemented as a hardware mechanism or can be part of the operating system (usually the case)
- access to objects (memory segments, I/O devices) is limited to users (processors or processes) with the proper authorization

Examples:

- virtual address management (MMU usually has a capability check)
- permission vs. activity; if these are not valid, there is an error trap
- password checking

Consistency Checks

- range check - confirms that a computed value is in a valid range, e.g., a computed probability must be in the range 0 to 1
- address checking - verifies that the address to accessed exists
- opcode checking - checks whether the instruction to be executed has one of defined (documented) opcodes
- arithmetic overflow and underflow

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Data Audits



- Widely used in the telecommunications industry
- A broad range of custom and ad hoc application-level techniques for detecting and recovering from errors in a switching environment (in particular in a database).
- Data-specific techniques deeply embedded in the application can provide significant improvement in availability
- Static and Dynamic Data Check
 - A corruption in static data region detected by computing a golden checksum of all static data at startup and comparing it with a periodically computed checksum (e.g., Cyclic Redundancy Code)
 - For dynamic data, the range of allowable values for database fields are often stored in the database system catalog. This information is used to perform a range check on the dynamic fields in the database.

Data Audits: Structural Checks



- The structure of the database is established by header fields that precede the data portion in every record of each table.
- Structural audit calculates the offset of each record header from the beginning of the database based on record sizes stored in system tables (all record sizes are fixed and known).
- The database structure (in particular, the alignment of each record and table within the database) is checked by comparing all header fields at computed offsets with expected values.

Data Audits



- **Semantic Referential Integrity Check**
 - Traces logical relationships among records in different tables to verify the consistency of the logical loops formed by the record(s)
 - Detects resource leaks
 - Corruption of key attributes in a database leads to lost records, i.e., records participating in semantic relationships disappear without being properly updated

Runtime Generated Assertions



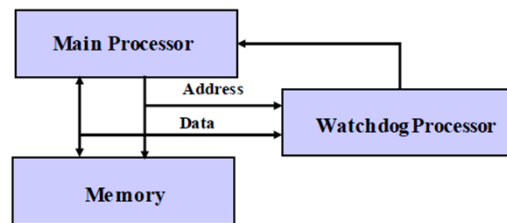
- **Goals**
 - Generate runtime assertions by monitoring the values of selected variables in a program
 - Use the monitored data to abstract out, via statistical pattern recognition techniques, the key relationships between the variables, separately and jointly, and to establish their probabilistic behavior
- **Approach**
 - Identify clusters of values traversed by different variables
 - Use this information to automatically generate runtime assertions capable of capturing abnormal behavior of an application due to hardware or software errors
 - Cross-check with other entities in the system their views on the state of selected variables
 - if a variable is globally accessible, then multiple entities (e.g., multiple execution threads) may have their own opinions about the correct value of the variable
 - can improve coverage and reduce false alarms

Control-flow Monitoring Using Signatures



■ Hardware Approaches

- Employ a Watchdog (a simple co-processor) to monitor behavior of a Main Processor
- Suitable for a single embedded applications with little or no caching
- Limited applicability in off-the-shelf systems, as require additional specialized resources, e.g., watchdog, pre-compiler.



Control-flow Monitoring Using Signatures



■ Hardware Approaches

■ Embedded Signature Monitoring

- Pre-computed signature embedded in the application program
- Recompile of existing programs
- Performance degradation of application

■ Autonomous Signature Monitoring

- Watchdog Processor stores pre-computed signature in the memory and mimics the control flow of application
- Watchdog Processor rather complex
- High memory overhead

Control-flow Monitoring Using Signatures



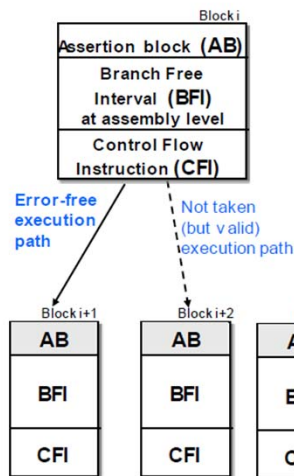
Software Approaches

- Software techniques partition the application into blocks, either in the assembly language or in the high-level language
- Appropriate instrumentation inserted at the beginning and/or end of the blocks
- The checking code is inserted in the instruction stream eliminating the need for a hardware watchdog processor
- Two classes of approaches
 - *non-preemptive* signature checking
 - *preemptive* signature checking

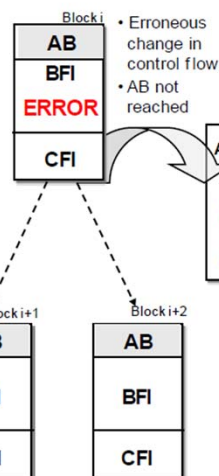
Problems with Control Flow Signatures



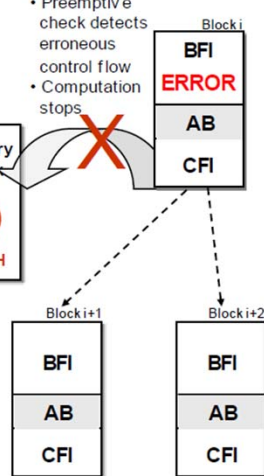
Correct execution



Incorrect execution without preemptive checking



Incorrect execution with preemptive checking



Preemptive Control Signatures (PECOS)

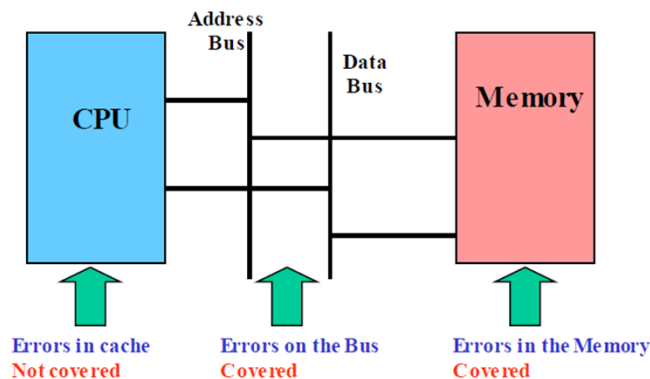


- PECOS determines the runtime target address and compares that against the valid addresses before the jump to the target address is made
 - executing instructions from an invalid target location is unlikely
- High-level control structure of Assertion Block
 1. Determine the runtime target address [= Xout].
 2. Extract the list of valid target addresses [= {X1,X2}].
 3. Calculate $ID := Xout * 1/P$,
 - where, $P = ![(Xout-X1) * (Xout-X2)]$
- Calculation of ID to raise a DIV-BY-ZERO exception in case of error
- Can handle single (jumps) or multiple (branches, calls, and returns) target addresses
- Assertion Block does not introduce any new control flow instruction

PECOS



- What Can We Cover with Preemptive Software Control Signature?



- **Solution:** Insert programmable error detection core into the CPU