Reliable Computing I

Lecture 9: Concurrent Error Detection

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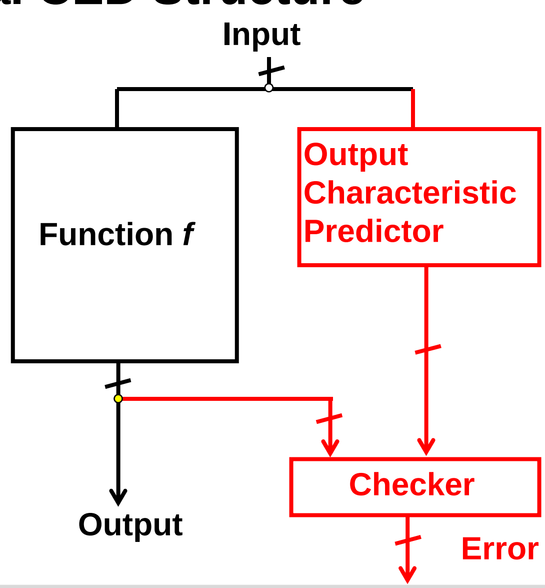
Today's Lecture

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

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"

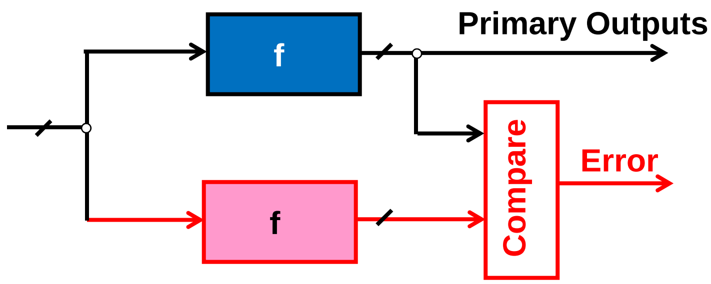
- Output itself
  - Duplication
- Output parity
  - Parity prediction
- Residue
  - Residue codes
- 1s or 0s count in output word
- Many others

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

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

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

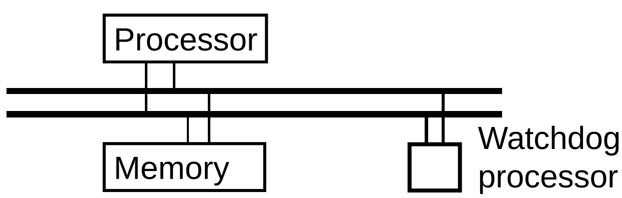
- NASA's Mars Pathfinder mission
  - mars rover uses a real-time preemptive multithreaded operating system
  - tasks scheduled based on priorities that reflect their relative urgency
- **Major failure event:** priority inversion between tasks with different priorities
  - system deadlock
- Watchdog timer 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

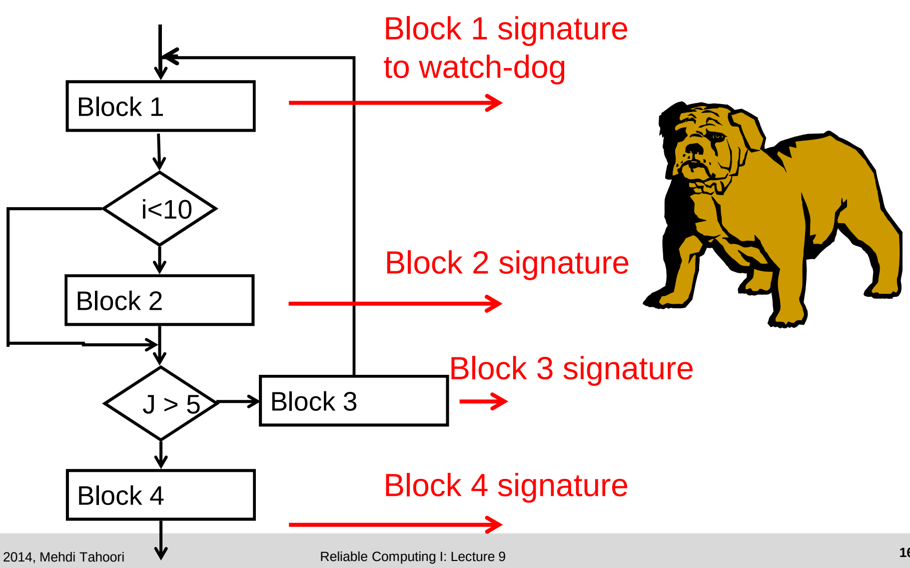
- Watchdog processor: “Simple” processor
  - Generalized version of watchdog timer
  - Program control flow checked
  - Assertion checks for computation errors
  - Can be integrated into the processor itself



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.

Structural Integrity Check Example



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

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
```

Heartbeats

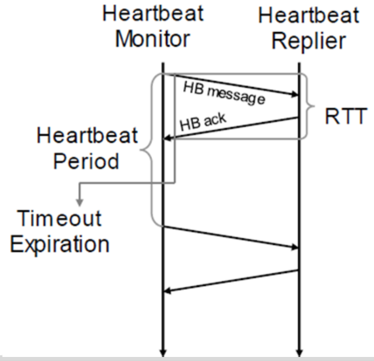
- A common approach to detecting process and node failures in a distributed (networked) computing environment.
- Periodically, a monitoring entity sends a message (*a heartbeat*) to a monitored node or process and waits for a reply.
- If the monitored node does not respond within a predefined timeout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



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

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

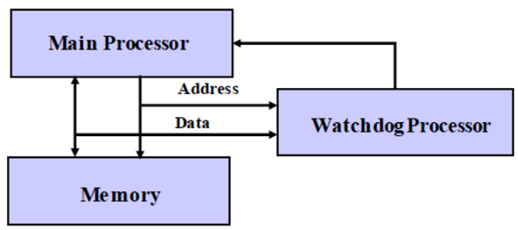
- Semantic Referential Integrity Check
  - Traces logical relationships among records in different tables to verify the consistency of the logical loops formed by the record(s)
  - Detects resource leaks
  - Corruption of key attributes in a database leads to lost records, i.e., records participating 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.



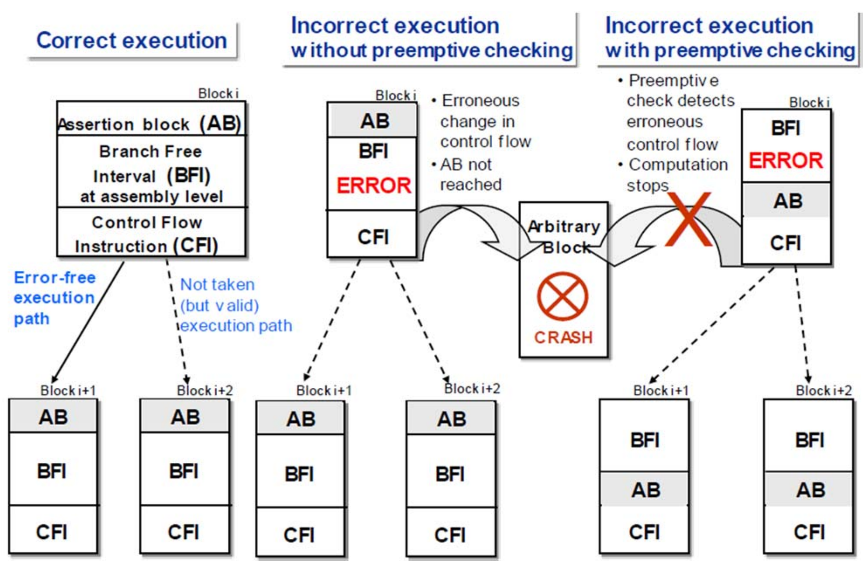
Control-flow Monitoring Using Signatures

- Hardware Approaches
  - **Embedded Signature Monitoring**
    - Pre-computed signature embedded in the application program
    - Recompilation 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

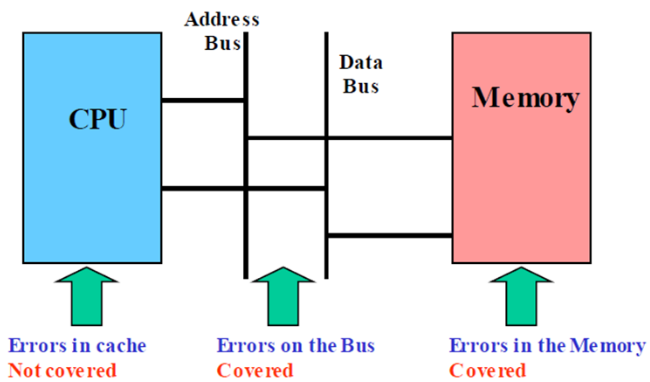


Preemptive Control Signatures (PECOS)

- 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

KIT – University of the State of Baden-Wuerttemberg and
National Laboratory of the Helmholtz Association