ECE 60872: Fault-Tolerant Computer System Design

Software Fault Tolerance

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Some material based on ECE442 at the University of Illinois taught by Profs. Ravi Iyer & Zbigniew Kalbarczyk

Outline

- **Definition and Motivation for Software Fault Tolerance**
- **Process pairs**
- **Robust data structures**

What is Software Fault Tolerance?

- Three alternative definitions

1. Management of faults originating from defects in design or implementation of software components
2. Management of hardware failures in software
3. Management of network failures

- We will follow the classical definition (1) due to Avizienis in 1977

Motivation for Software Fault Tolerance

- Usual method of software reliability is fault avoidance using good software engineering methodologies
- Large and complex systems ⇒ fault avoidance not successful
  - Rule of thumb fault density in software is 10-50 per 1,000 lines of code for good software and 1-5 after intensive testing using automated tools
- Redundancy in software needed to detect, isolate, and recover from software failures
- Hardware fault tolerance easier to assess
- Software is difficult to prove correct

HARDWARE FAULTS	**SOFTWARE FAULTS**
1. Faults time-dependent	**Faults time-invariant**
2. Duplicate hardware detects	**Duplicate software not effective**
3. Random failure is main cause	**Complexity is main cause**

Consequences of Software Failure

- General Accounting Office reports $4.2 million lost annually due to software errors
- Launch failure of Mariner I (1962)
- Destruction of French satellite (1988)
- Problems with Space Shuttle and Apollo missions
- SS7 (signaling system) protocol implementation - untested patch (mistyped character) (1997)
- Therac 25 (overdose of medical radiation 1000’s of rads in excess of prescribed dosage)
- Toyota Prius recall (2004) due to bug in embedded code

Difficulties

- Improvements in software development methodologies reduce the incidence of faults, yielding fault avoidance
- Need for test and verification
- Formal verification techniques, such as proof of correctness, can be applied to rather small programs
- Potential exists of faulty translation of user requirements
- Conventional testing is hit-or-miss. “Program testing can show the presence of bugs but never show their absence,” - Dijkstra, 1972.
- There is a lack of good fault models for software defects

Forms of Software Testing

- Exhaustive testing of reasonable sized applications is impossible
- Approach is to define equivalence classes of inputs so that only one test case from each class suffices
- Techniques proposed include
  - Path testing
  - Branch testing
  - Interface testing
  - Special values testing
  - Functional testing
  - Anomaly analysis
- Studies have shown path testing and interface testing while difficult to design afford good coverage for large number of applications

Approaches to Software Fault Tolerance

- **ROBUSTNESS**: The extent to which software continues to operate despite introduction of invalid inputs.

  Example: 1. Check input data
  =>ask for new input
  =>use default value and raise flag
  2. Self checking software

- **FAULT CONTAINMENT**: Faults in one module should not affect other modules.

  Example: Reasonable checks
  Watchdog timers
  Overflow/divide-by-zero detection
  Assertion checking

- **FAULT TOLERANCE**: Provides uninterrupted operation in presence of program fault through multiple implementations of a given function

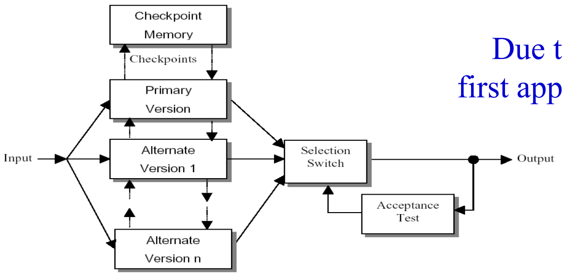
Temporal Redundancy

- Reexecution of a program when error is encountered
- Error may be faulty data, faulty execution or incorrect output
- Reexecution will clear errors arising from temporary circumstances
- Examples: Noisy communication channel, Full buffers, Power supply transients, Resource exhaustion in multiprocess environment
- Provides fault containment
- Possible to apply to applications with loose time constraints

Multi-Version Software Fault Tolerance

- Use of multiple versions (or “variants”) of a piece of software
- Different versions may execute in parallel or in sequence
- Rationale is that multiple versions will fail differently, i.e., for different inputs
- Versions are developed from common specifications
- Three main approaches
  - Recovery Blocks
  - N-version Programming
  - N Self-Checking Programming

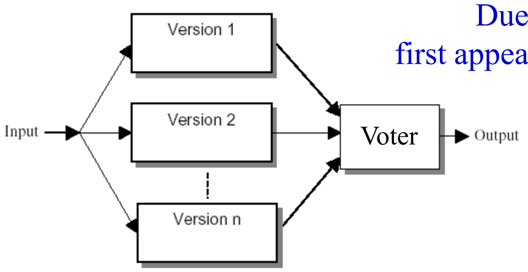
Recovery Blocks



Due to Brian Randell,
first appeared in ToSE 1975

- Checkpoint and restart approach
  - Try a version, if error detected through acceptance test, try a different version
  - Ordering of the different versions according to reliability
- Checkpoints needed to provide valid operational state for subsequent versions
- Acceptance test could be on output or embedded in code

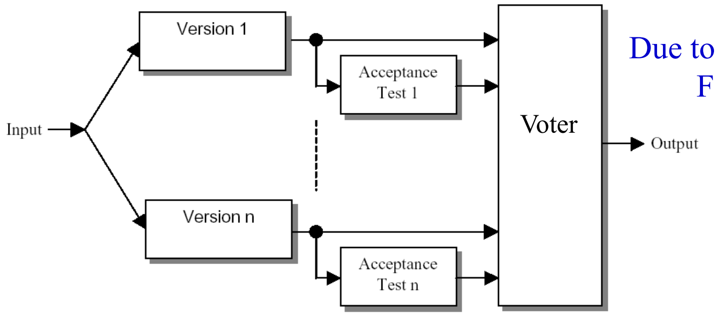
N-Version Programming



Due to Al Avizienis,
first appeared in CompSAC 1977

- All versions designed to satisfy same basic requirement
- Decision of output comparison based on voting
- Different teams build different versions to avoid correlated failures

N Self-Checking Programming



Due to J. C. Laprie, FTCS 87

- Multiple software versions with structural variations of RB and NVP
- Use of separate acceptance tests for each version

Reliability Analysis of Multi-Version Approaches

- Three postulates of software development:

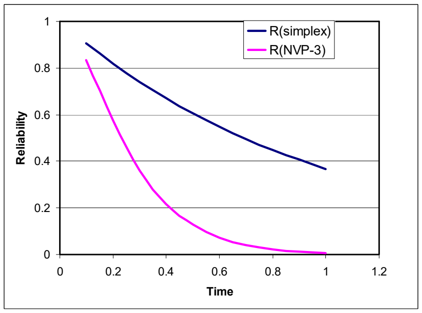
P1: Complexity Breeds Bugs: Everything else being equal, the more complex the software project is, the harder it is to make it reliable.

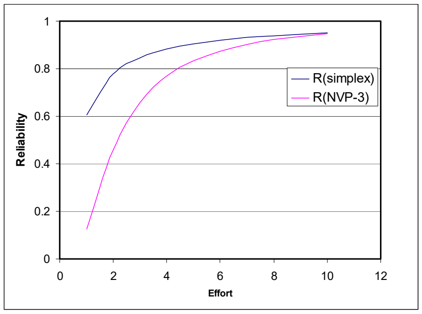
P2: All Bugs are Not Equal: You fix a bunch of obvious bugs quickly, but finding and fixing the last few bugs is much harder, if you can ever hunt them down.

P3: All Budgets are Finite: There is only a finite amount of effort (budget) that we can spend on any project. That is, if we go for n version diversity, we must divide the available effort n-way.

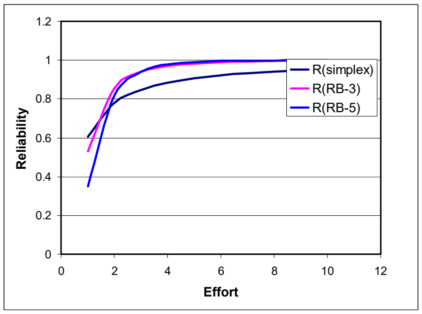
- $R(t) = e^{-\lambda t}$
- Failure rate $\lambda \propto 1/\text{Effort (E)}$
- Failure rate $\lambda \propto \text{Complexity (C)}$

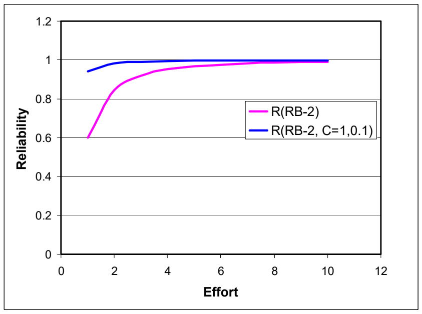
Reliability of NVP vs. single version





Reliability of RB vs. Simplex





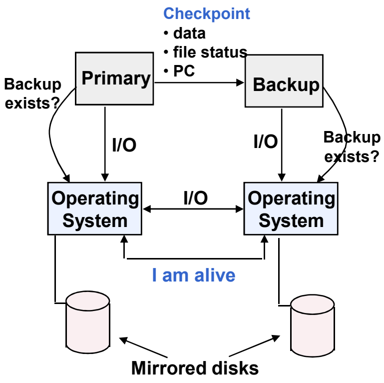
Process Pairs

- Used in HP Himalaya servers as part of their NonStop Advanced Architecture
- Bragging rights of the architecture
  - Run the majority of credit and debit card systems in N.America
  - More than US$3 billion of electronic funds transfers daily
  - Run many of the E911 systems in North America
- Primary and backup processes on two different processors
- Primary process executes actively
  - Backup process is kept current by periodically sending state of primary process
- Processors execute fail-stop failure
  - When processor failure detected, backup takes over

Process Pairs

- **Applicability**
  - Permanent and transient hardware and software failures
  - Loosely coupled redundant architectures
  - Message passing process communication
  - Well suited for maintaining data integrity in a transactional type of system
  - Can be used to replicate a critical system function or user application
- **Assumptions**
  - Hardware and software modules design to *fail-fast*, i.e., to rapidly detect errors and subsequently terminate processing
  - Errors can be corrected by re-executing the same software copy in changed environment

Process Pairs Mechanism in Tandem Guardian OS



1. The application executes as *Primary*
2. *Primary* starts a *Backup* on another processor
3. Duplicated file images are also created
4. *Primary* periodically sends checkpoint information to *Backup*
5. *Backup* reads checkpoint messages and updates its data, file status, and program counter
   - the checkpoint information is inserted in the corresponding memory locations of the *Backup*
7. *Backup* loads and executes if the system reports that *Primary* processor is down
   - the error detection is done by *Primary* OS or
   - *Primary* fails to respond to *"I am alive"* message
8. All file activities by *Primary* are performed on both the primary and backup file copies
9. *Primary* periodically asks the OS if a *Backup* exists
   - if there is no *Backup*, the *Primary* can request the creation of a copy of both the process and file structure

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Evaluation of Process-Pairs

- Done for Tandem's Guardian OS Studied Tandem Product Report (TPR) which are used to report product failures
- Problem classified as software fault only after analysts have pinpointed the cause
- Classes of software faults (not exhaustive)
  - Incorrect computation (3%)
  - Data fault (15%)
  - Missing operation (20%)
  - Side effect of code update (4%)
  - Unexpected situation (29%)
  - Microcode defect (4%)

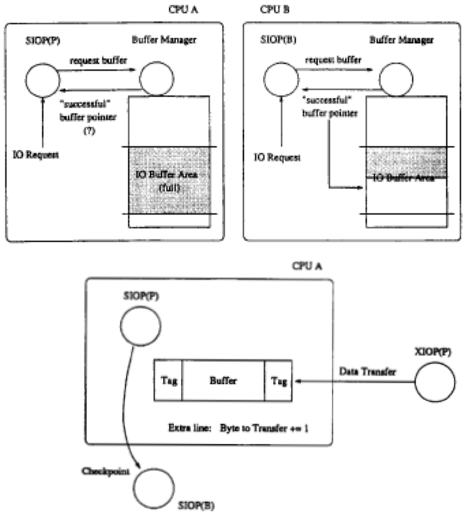
Results from Evaluation

- Out of total software failures, 138 out of 169 (82%) caused single processor halt (recoverable). This is a measure of the software fault tolerance of the system.
- Reasons for multiple processor fault
  - Same fault as in the primary: 17/28 (60%)
  - Second fault during job recovery: 4/28 (14.3%)
  - Second halt is not related to process pairs: 4/28 (14.3%)

Results from Evaluation

- Reasons for uncorrelated software fault
  - Backup reexecutes same task, but same fault not exercised: 29%.
    - Different memory state
    - Race or timing related problem
  - Example:
    - Privileged process on primary requests a buffer
    - Because of high user activity on primary, buffer exhaustion
    - Bug in buffer management routine and returns “success”
    - Primary privileged process uses uninitialized buffer pointer and causes processor halt
    - Backup process served the request after takeover
    - But buffer was available on the backup processor

Figure for Cases of Software Fault Tolerance



Results from Evaluation

- Reasons for uncorrelated software fault
  - Backup does not reexecute failed request on takeover: 20%.
    - Processor monitoring task
    - Interactive task
  - Effect of error latency: 5%
    - Task that caused the error finished before detection
    - Example: I/O process for copying buffer from source to destination.
    - Copied an additional byte overwriting buffer tag.
    - No problem in data transfer.
    - The successful data transfer was checkpointed but not the corrupted buffer tag
    - Problem surfaces later when buffer manager verifies buffer.
    - No problem when reexecuting on backup.

Results from Evaluation

- Process pairs with checkpointing and restart recovers from 75% of reported software faults that result in processor failures
- The complexity of process pairs introduces some faults
  - 16% of single processor halts were failures of backup processes
- Counter-intuitive result since same software run on both processors
- Loose coupling between processors, long error latency, operation using checkpoints and not lock-step
- Are process triples better than process pairs?

Process Pairs
Advantages & Disadvantages

Advantages

- Extremely successful in Tandem OLTP applications
- Tolerates hardware, operating system, and application failures
- High coverage (> 90%) of hardware and software faults
- The backup does not significantly reduce the performance

- **Disadvantages**
  - Necessity of error detection checks and signaling techniques to make a process fail-fast
  - Process pairs are difficult to construct for non-transaction-based applications

Robust Data Structures

- The goal is to find storage structures that are robust in the face of errors and failures
- What do we want to preserve?

Semantic integrity - the data meaning is not corrupted

Structural integrity - the correct data representation is preserved

Focus on techniques for preserving the structural integrity

Robust Data Structures (cont.)

- A robust data structure contains *redundant data* which allow *erroneous changes* to be detected, and possibly corrected
  - a change is defined as an elementary (e.g., as single word) modification to the encoded (data structure representation on a storage medium) form of a data structure instance
  - structural redundancy
    - a stored count of the numbers of nodes in a structure instance
    - identifier fields
    - additional pointers

Robust Data Structures (cont.)

- Consider data structure which consists of ***a header*** and a set of ***nodes***
  - the header contains
    - pointers to certain nodes of the instance or to parts of itself
    - counts
    - identifier fields
  - a node contains
    - data items
    - structural information: pointers and node type identifier fields
- Error detection and correction
  - in-line checks may be introduced into normal system code to perform error detection and possibly correction, during regular operation

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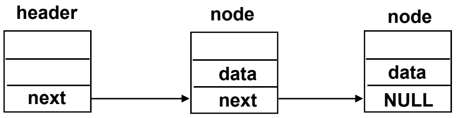
Link Lists

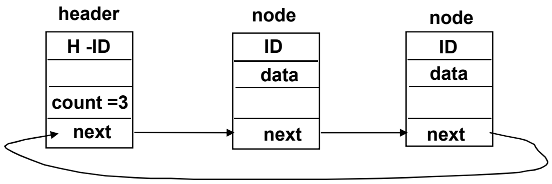
- Non-robust data structure
  - in each node store a pointer to the next node of the list
  - place a null pointer in the last node



0-detectable and 0-correctable
changing one pointer to NULL can reduce any list to empty list

Robust Data Structures
Single-Linked List Implementation

- Additions for improving robustness
  - an identifier field to each node
  - replace the NULL pointer in the last node by a pointer to the header of the list
  - stores a count of the number of nodes



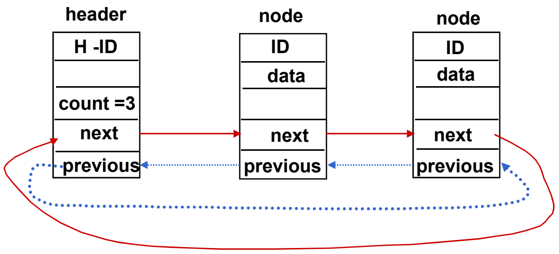
1-detectable and 0-correctable

•change to the count can be detected by comparing it against the number of nodes found by following pointers

•change to the pointer may be detected by a mismatch in count number or the new pointer points to a foreign node (which cannot have a valid identifier)

Robust Data Structures
Double-Linked List Implementation

- Additions for improving robustness
  - a pointer added to each node, pointing to the predecessor of the node on the list

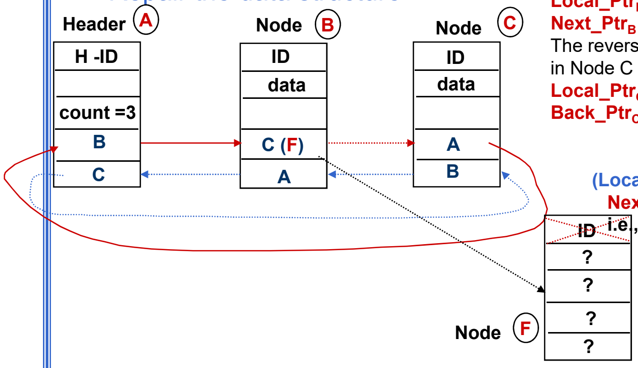


2-detectable and 1-correctable

the data structure has two independent, disjoint sets of pointers, each of which may be used to reconstruct the entire list

Error Correcting in Double-Linked List

- *Scan the list in the forward direction* until an identifier field error or forward/backward pointer mismatch is detected
- When this happens *scan the list in the reverse direction* until a similar error is detected
- Repair the data structure



The forward scan detects a mismatch
in Node B and sets
Local_Ptr_B = B (local node's pointer)
Next_Ptr_B = F (pointer to the next node)
The reverse scan detects a mismatch
in Node C and sets
Local_Ptr_C = C (local node's pointer)
Back_Ptr_C = B (pointer to the previous node)

Correction
(Local_Ptr_B == Back_Ptr_C) ⇒
Next_Ptr_B := Local_Ptr_C
i.e., (Next_Ptr_B = C)

Application of Robust Data Structures for Semantic Error Checking

- Application to checking index corruption in B-trees
- See class presentation

Robust Data Structures

Concluding Remarks

- Commonly used techniques for supporting robust data structures
  - techniques which preserve structural integrity of data
    - binary trees, heaps, fifos, queues, stacks
    - linked data structures
  - content-based techniques
    - checksums, encoding
- Limitations
  - not transparent to the application
  - best in tolerating errors which corrupt the structure of the data (not the semantic)
  - increased complexity of the update routines may make them error prone
  - erroneous changes to the data structure may be propagated by correct update routines
  - faulty update routines may provoke correlated erroneous changes to several fields

References

- “11 of the most costly software errors in history” Raygun, Jan 2022.
- D. K. Pradhan, ed., “Fault Tolerant Computer System Design”, Chapter 7: Fault Tolerance in Software
- Multi-version software
  - Lui Sha, “Using Simplicity to Control Complexity,” IEEE Software, Jul/Aug 01, pp. 20-28.
  - Wilfredo Torres-Pomales, “Software Fault Tolerance: A Tutorial,” Technical Report: NASA-2000-tm210616, 2000.
- Process pairs
  - Inhwan Lee, R.K. Iyer: “Software dependability in the Tandem GUARDIAN system”, IEEE Transactions on Software Engineering, May 1995.
- Robust data structures
  - David J. Taylor, David E. Morgan, James P. Black: “Redundancy in Data Structures: Improving Software Fault Tolerance.” TSE 6(6): 585-594 (1980)
  - K. Fujimura, P. Jalote, “Robust search methods for B-trees”, FTCS-18, June 1988.