Paranoid Programming

Techniques for Constructing Robust Software

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"The action cannot be completed because Unknown is busy."
$\mu$$Word, when opening this document.

Attitude Adjustment

Stratus sells Continuous Availability (CA) computers

Customers expect CA computers to run 24 hours per day, 365 days per year

Software errors are a leading cause of system downtime

Software quality and robustness are especially important

Prime Directive

Code written for Continuously Available systems should

- **Work correctly regardless of input, system load, or state**
  - **Not be the source of system failure through action or inaction**
- **Contain and not propagate errors**
  - **Properly diagnose and reject all bad input**
  - **Recover from errors and bad state**
  - **Make the consequence of the error proportional to its severity**
- **Log significant events for later debugging**
- **Evolve compatibly over time**

It should be *paranoid*!

Paranoid Programming Course

This presentation outlines some techniques for developing paranoid code

- Based on intensive one-day course taught at Stratus

Course Objectives

- Understand the effects of other people's hardware and software faults on computer system dependability
- Acquire a tool kit of software construction techniques to help reduce the occurrence of failures due to other people's hardware and software faults
- Be able to implement these techniques effectively on current and planned projects

Course Outline

- Nature and Significance of the Problem
- Terminology and Buzzwords
- Software Techniques for Tolerating Errors
  - General Framework and Observations
  - Checkpoint and Rollback
  - State Rejuvenation
  - Recovery Block
  - Process Pairs
  - MultiVersion Programming
  - Process Groups
  - Robust Data Structures
  - Structure Marking
  - Control Flow Monitoring
  - Programming in a High-Availability Environment
- Techniques for Reducing Bugs
  - Maintaining a Ship and Debug Version
  - Assertions
  - Designing Error-Resistant Interfaces
  - Avoiding Memory Theft
  - Making the Compiler Work for You
  - Avoiding Risky Coding Style
  - Error Handling and Reporting Principles
  - Concurrent Programming
  - Testing
  - Inspections

NATURE AND SIGNIFICANCE OF THE PROBLEM

Causes of Outages

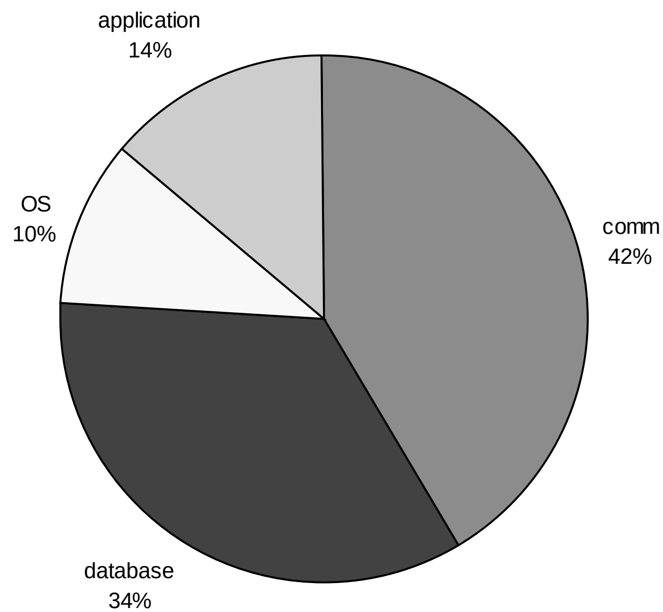
	Non-Fault Tolerant Systems	Fault Tolerant Systems
Hardware	50%	8%
Software	25%	65%
Communications / Environment	15%	7%
Operations / Procedures	10%	10%

Software-induced outages dominate hardware-induced outages in fault tolerant systems

Procedural and operations-induced outages are significant

From "Dependable Computing: Concepts, Limits, Challenges," by J. C. Laprie, FTCS-25.

Sources of Outage-Inducing Software Flaws: Tandem 1989



For Tandem, most outage-inducing software flaws are in communications and database software

From "A Census of Tandem System Availability Between 1985 and 1990," by Jim Gray

Tandem Guardian Software Halts by Cause

Fault Category	%	%
Incorrect computation	3	3
Data fault	12	12
Data definition fault	3	3
Missing operations:		20
Uninitialized pointers	6	
Uninitialized nonpointers	4	
Not updating data structures on occurrence of certain events	6	
Not telling other processes on the occurrence of certain events	4	
Side effect of code update	4	4
Unexpected situation:		29
Race/timing problem	14	
Errors with no defined error-handling procedures	4	
Incorrect parameters or invalid calls from user processes	3	
Not providing routines to handle legitimate but rare operational scenarios	8	
Microcode defect	4	4
Others	10	10
Unable to classify	15	15

20% of halts caused by missing operations

29% were caused by unanticipated situations

Tandem Guardian Software Halts by Severity

Many software halts take down more than one processor

Fault Severity	%
Single Processor Halt	79%
Multiple Processor Halt	18%
Halt during Reboot	1%
Unable to Classify	2%

Most software halts are caused by known bugs

Fault Type	%
First Occurrence	24%
Recurrence	61%
Unidentified	15%

Analysis of Tandem Error Logs

What process was running just prior to halt?

Active Process	Cause Breakdown	%	%
Interrupt Handler	process control	5%	41%
	memory management	2%	
	message system	14%	
	processor control	1%	
	hardware-related	16%	
	unknown	2%	
System monitor	memory management	4%	4%
Memory Manager	process control	31%	32%
	memory management	1%	
All Other Privileged Processes	process control	1%	14%
	memory management	1%	
	communication product	8%	
	TMF	1%	
	tape process	1%	
	unknown	1%	
Unknown	hardware-related	7%	9%
	message system	2%	

Interrupt handling and memory management code seem to be particularly troublesome

- **Touches hardware and is highly concurrent**

Fault Propagation in the UNIX OS

Lee and Iyer injected 500 simulated hardware and software faults into SunOS 4.1.2 kernel

Results of hardware fault injection:

		System Failure		Multiple User Application Failure	No	error
Fault Type	Without Self-Reboot	With Self-Reboot	System Hang		Fault Avoided	> 20 Mins. Latency
Memory fault in text segment	0.02	0.22	0.02	0	0.06	0.68
Memory fault in data segment	0.02	0.14	0	0.08	0.18	0.58
Bus fault on address line	0	0.82	0	0.1	0.06	0.02
Bus fault on data line	0	0.76	0	0.1	0.14	0
CPU fault in registers	0	0.66	0	0	0.34	0

Most injected hardware faults in SunOS 4.1.2 either caused reboot or were never detected

BUT

Memory faults in text segment caused a system hang...very bad

Fault Propagation in the UNIX OS, cont'd

Results of software fault injection:

	System	Failure	Multiple User Application Failure	No	Error
Fault Type	With Self-Reboot	System Hang		Fault Avoided	> 20 Mins. Latency
Uninitialized pointer	0.46	0	0	0	0.54
Misassigned pointer	0.4	0	0	0	0.6
Missing condition check	0.22	0	0.02	0.2	0.56
Incorrect condition check	0.26	0	0	0.12	0.62
Uninitialized / misassigned pointer data	0.26	0.02	0.06	0.06	0.6

Most injected software faults in SunOS 4.1.2 either caused reboot or were never detected

BUT

Pointer faults caused a system hang

VOS 1992 Crash Data

63% of all VOS crashes occurred around hardware events

- 30% occurred around maintenance events
- 33% occurred around other events

A hardware event is

- When the hardware is not in a normal running state (e.g., booting or power-fail)
- Some unusual event is happening with a piece of hardware
- Hardware maintenance is occurring

Tandem Integrity NonStop/UX Field Data

Modules containing panic-inducing faults

Module	%
Device Drivers (async, ethernet, etc.)	31
Memory Subsystem	16
Streams Mechanism	12
Process Management	6
Machine-Dependent VM Code	8
Shutdown / Boot Process	8
Filesystem	10
I/O Subsystem	3
Mirror Driver	1
Interrupt Handling	1
Diagnostic / Integration	3
MIDAS (monitoring facility)	1

Tandem Integrity NonStop/UX Field Data

Programming errors causing panic-inducing faults

Programming Error	%
Pointer made NULL and later used	17
Pointer assigned to wrong location	9
Stale pointer left from before	2
Missing check for an exception	26
Incorrect algorithm or code placement (includes major algorithm mistakes)	26
Unaligned data structures	4
Memory allocation / deallocation	11
Unneccesary code left in the OS	4

Summary of Empirical Data

Software-induced outages increasingly dominate hardware-induced outages

For Tandem, most outage-inducing software flaws are in comm and DB software

20% of Tandem Guardian halts caused by something somebody forgot to do

29% of Tandem Guardian halts caused by situations somebody didn’t anticipate

18% of Tandem Guardian faults take down more than 1 processor

61% of Tandem Guardian faults are caused by known bugs

Most Tandem Guardian halts occurred during interrupt handling (41%) and memory management (32%) code

Summary of Empirical Data

Most injected hardware and software faults in SunOS 4.1.2 either caused reboot or were never detected, but some memory and pointer faults caused system hangs

63% of 1992 VOS crashes occurred around hardware events

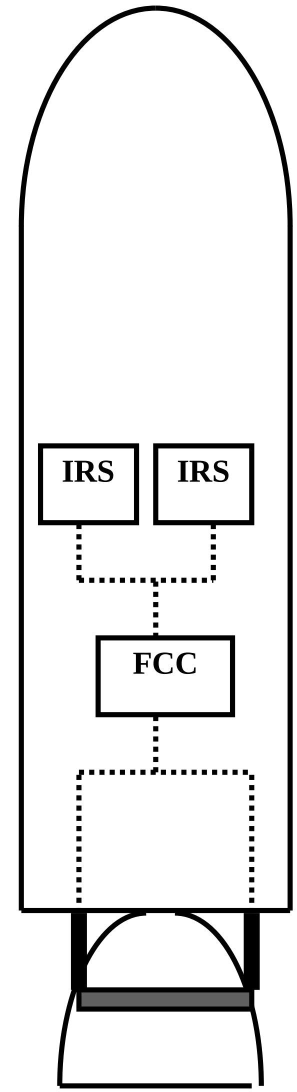
Ariane 501 Crash

4 June 1996 maiden flight of Ariane 5

40 secs into flight, Flight Control Computer (FCC) commands nozzle actuators to hard over position

Ariane 5 undergoes aero breakup and subsequent destruction

DM 1200 million down the drain



Ariane 501 Causal Factors

- Inertial Reference System (IRS) informed FCC the missile is flying sideways
  - IRS emitted diagnostic information to FCC
  - This was interpreted as attitude data
- Both Primary and Backup IRS failed
  - Unhandled exception due to overflow when converting 64-bit float to 16-bit integer in IRS horizontal velocity calibration code
    - Other conversions were protected by exception handlers
    - No justification for omitting protection for this variable
  - IRS cal code reused from Ariane 4
    - Continues to run after liftoff in case of short launch hold
    - Not needed in flight for Ariane 4
    - Not needed at all for Ariane 5
    - Ariane 5 horizontal velocity >> Ariane 4

Ariane 501 Causal Factors

Error not excited during test

- IRS cal code not tested under Ariane 5 trajectory
- Not flight critical

Spec says halt IRS when unhandled exception

- Assumed random hardware faults only
- Assumed software is perfect

Ariane 501 Lessons

IRS-FCC interface was insufficiently robust

Fault model incomplete: did not include SW errors

Error handling requirements not appropriate for common-mode SW errors

Critical assumptions were not documented, justified, or reviewed

New operational conditions violated design-time assumptions of re-used software

Gratuitous functionality does not go away just because it is no longer needed

Testing under realistic operational conditions was omitted

Software Error Genesis

Design Errors

- 60-65% of all SW faults introduced here
- Incomplete, missing, inadequate, inconsistent, unclear requirements
- Requirements not fitting physical models
- Correction cost is 10X cost of correcting coding errors

Implementation Errors

- 35-40% of all SW faults introduced here
- # errors proportional to
  - Size of code
  - Number of paths through code

TERMINOLOGY AND BUZZWORDS

Dependability

Property of a computing system which allows justifiable reliance to be placed upon delivered service

Means for achieving dependability

- fault prevention: writing bug-free code
- fault removal: testing and fixing bugs
- fault forecasting: predicting and avoiding failures
- fault tolerance: tolerating failures as they occur

Quantifications of dependability are numerous

- Reliability, availability, N-fail/op, ...

A system can be dependable without being fault tolerant

A system can be fault tolerant without being dependable

† These definitions are based on the International Federation of Information Processing Working Group 10.4 document "Dependability: Basic Concepts and Terminology," Anderson et. al., December 1990.

Failure

Deviation of delivered service from specification

failure domain

- **value - the value of the delivered service does not comply with the specification**
- **timing - the timing of the delivered service does not comply with the specification**

failure perception

- **consistent - all users have identical perceptions of the failure**
- **inconsistent - users have different perceptions of the failure**

failure severity

- **benign - failure consequences are of same order of magnitude as benefit of service delivery**
- **catastrophic - failure consequences are incommensurably greater than benefit of service delivery**

Error

Corruption of system state liable to lead to failure

- Latent - not recognized by detection mechanism
- Detected - recognized by detection mechanism

Example

- Corrupted contents of RAM in text area

Fault

Adjudged or hypothesized cause of error(s)

- Active - capable of producing an error
- Dormant - incapable of producing an error

Physical Fault Models

- Stuck-at
- Inversion
- Symmetric / asymmetric
- Permanent / intermittent / transient

Software Fault Models

- Bohrbugs: permanent; Heisenbugs: transient

These are all subsets of “Byzantine faults”:

- Arbitrary (even malicious) fault manifestations

Fault Occurrence and Error Processing Behavior

There are several steps involved in handling faults correctly

Not all systems go through all steps

The name of the game is to prevent faults from causing failures

time ↓

fault arrival and error production

error propagation

error manifestation

error compensation

error detection

fault diagnosis

error processing - recovery

fault passivation - reconfiguration

Error Compensation

Also known as fault masking

Possible when system state contains enough redundancy to enable delivery of error-free service from erroneous internal state

Needed when glitch-free service delivery is required

May be all that is needed for some mission regimes

Does not imply error detection, error recovery, or fault passivation

Examples

- N-modular redundancy with voting for general-purpose computation
- Error correcting codes for data transmission and storage
- Averaging effect of many signal processing algorithms

Error Containment Region

Errors should not propagate past error containment region boundaries

Errors which do so can result in system failure

Hardware Examples

- Voting plane
- Decoder at memory output
- Decoder at bus interface
- Voting actuator

Software Examples

- Software voter
- Recovery Block acceptance test
- Data structure integrity check
- Control flow check

Error Manifestation Boundary

Faults are detected via error manifestation

Error manifestation boundaries should be defined

Error detection mechanisms reside at error manifestation boundaries

Errors should be quickly flushed to error manifestation boundaries to expedite detection, diagnosis, and recovery

- **The sooner the error is detected, the easier recovery will be**
- **“Fix it so it breaks”**

Error Detection

The use of error detection mechanisms at Error Manifestation Boundaries to determine the existence of errors

- proactive: go out hunting for errors
- reactive: wait for errors to happen

Facilitates subsequent error recovery, fault diagnosis, and fault passivation

Examples

- Syndrome attached to voter/comparator
- Parity on memory fetches
- Block codes on data transmissions

Error Processing - Recovery

The process of returning the system to an acceptable physical and computational state

Explicit recovery operations may or may not be required

- Depends on how well error propagation can be controlled
- Depends on whether state information is stored redundantly
- Depends on temporal constraints

Recovery is essentially a semantic process

- Must consider the physics of the system in order to subdue erratic behavior
- Corrective action must not aggravate any transient already caused by the failure

Error Recovery

Computational state must be corrected

- If state information is stored stably then a valid copy can be retrieved in a straightforward manner
- If only a single copy of state information existed then the system state has to be reconstructed
- Internal parameters with limited history can be reinitialized to a known state if the resulting transient is not too great (e.g., digital filter values)

Fault Diagnosis

The identification of the fault location or ambiguity group

Enables fault passivation

Fault diagnosis issues

- **Coverage with respect to a class of faults**
- **Assuring that all participants arrive at consistent diagnoses**
- **Ambiguity group localization**
- **Verification and validation of coverage**
- **Intrusiveness**
- **Physical and temporal overhead**
- **Fault classification: permanent, transient, etc.**

Fault Passivation (Reconfiguration)

Reconfiguration is the process of

- Isolating a failed element so it no longer has any influence on system behavior
- Reassigning the function of the failed element to a good element or group of elements

Isolation and reassignment may be

- Logical – there are multiple sources for a parameter and the bad one is simply ignored
- Electrical – removing power from the failed element or switching in a replacement element
- Physical – elements are separated by a reconfiguration actuator

Fault Passivation (Reconfiguration)

Reconfiguration can be automatic or initiated by a human operator

- Since a substantial proportion of outages are due to maintenance and procedural errors, automatic means are preferred

Reconfiguration/recovery must be completed quickly to prevent failure due to near-coincident faults

Fault Containment Region

A *fault containment region* is a bounded group of components or functionality

An arbitrary fault inside a region cannot propagate across the boundary to cause another region to fail or to misbehave in any way

Conversely, faults outside the region cannot physically affect proper operation inside the region

However, errors (the effects of faults) may propagate to other regions

Proper organization of fault containment regions is critical to achieving fault tolerance

A physical fault containment region requires, (1) electrical isolation, (2) independent clocking, (3) independent power, (4) physical isolation

Coverage

Numerical quantification of the effectiveness of a fault tolerance technique

Different coverage numbers will apply to different phases of fault and error handling

Example

- Effectiveness of a fault tolerance technique with respect to a class of faults
  - Detection coverage of stopping faults
  - Tolerance coverage of babbling faults
  - Tolerance coverage of Byzantine faults

Coverage

Can be expressed probabilistically

- Probability of detecting stopping faults
- Probability of tolerating babbling faults

Can be determined empirically in some cases

Can <u>not</u> be determined empirically in most cases

SOFTWARE TECHNIQUES FOR TOLERATING FAILURES

General Observations and Implementation Principles

Define success criteria for the function you are developing

- Safety (what must never happen)
- Liveness (what must always happen)

Understand your environment, expected failure modes, and acceptable error handling

- What do you do when you can’t go on?
- Examples: single node (best-effort), cluster (fail-fast)

Select proactive or reactive technique

- Proactive techniques search for or attempt to predict errors
- Reactive techniques wait for errors to occur

General Observations and Implementation Principles

Define error containment boundaries

- **Partition application so a portion can be down without entire application being down**

Define error manifestation boundaries and detection mechanisms

- **At least based on safety and liveness; preferably based on application specific checks**
- **Always check inputs and outputs**
- **Always check return values and error codes**
- **Balance overhead with detection coverage**

Define error handling actions appropriate to safety, liveness, and environmental requirements

- **Log significant events for later debugging**
- **Fail loudly, don’t fail silent...those who come after will thank you**
- **Don’t assume HW or SW are operating correctly**

General Observations and Implementation Principles

Test all error detection and recovery code

- It is important but not core to central functionality; no revenue $ tied to it
- It gets implemented last
- It gets tested least
- It is hard to test
- It is invoked under periods of maximum system stress

In telecom applications (e.g., 5ESS)

- 50% LOC on core functionality
- 50% LOC on error handling
- This is an appropriate mix for critical applications

Human error-making patterns are repetitive - categorize and log your errors and periodically review them

Rollback and Recovery

A menagerie of techniques

- Checkpoint and Rollback
- Recovery Blocks
- Process Pairs
- Transactions…

Overall Idea

- Save snapshot of correct state somewhere
- Do work, logging inputs and events
- Check for errors
- If error,
  - Roll back or restore process(es) to state snapshot
  - Optionally, inculcate nondeterminism
  - Replay the computation
- Else

Checkpoint and Rollback

A reactive technique

Applicability

- Where cost of failure is an annoyance
- Soft HW and (primarily) SW failures
- Works on nonredundant or redundant architecture
- Where you have time to retry a computation
- When you can identify checkpoints in your application

Checkpoint and Rollback Critical Assumptions

Errors can be detected

Checkpoints can be identified and efficiently copied to stable storage

Inputs and events can be logged

Computation can be replayed

Replay is deterministic with respect to applied inputs

Replayer can access checkpointed data

Rollback can be confined to a small number of processes, or interprocess interactions can be replayed or are idempotent

Checkpoint / Rollback Approach (1)

- **Develop error detection mechanisms**
  - **Internal to application: code- or structure-based self checks**
  - **External to application: probes, signals, null messages to app, heartbeats, ...**
- **Determine data to be checkpointed**
  - **Transparent to application**
    - **Compile-time**
    - **Run time: checkpoint all volatile state, checkpoint dirty data**
  - **Visible to application**
    - **Allocate data to be checkpointed to appropriate region: ISIS, libft, ...**
  - **Must be stored in stable storage**
  - **Must be accessible to process that is performing the retry**

Checkpoint / Rollback Approach (2)

Determine events to be logged and replayed

- Messages
- Events
- Transactions

Determine checkpoint times; options are:

- Transparent to application
  - Based on elapsed time
  - Based on message arrival
  - Based on amount of dirtied state
- Visible to application
  - Based on critical function invocation / exit

Figure out how you are going to replay the computation

Figure out what you are going to do if error is persistent

Example: Tandem HATS / AT&T "libft" Technology[1]

watchd: distributed watchdog daemon

- Monitors registered application processes on primary and backup nodes for crash or hang; also monitors nodes
- Sends null message or signal to primary every T seconds, or awaits heartbeats
- If no response and primary node is unfailed, restarts process on primary
- If primary node is failed, restarts process on backup node
- Uses checkpoint data and message logs to replay computation

[1] Also check out http://www.cs.utk.edu/~plank/ckp.html and http://warp.dcs.st-andrews.ac.uk/warp/systems/checkpoint/source.html

Example: AT&T "libft" Technology

libft: set of reusable UNIX library calls for checkpointing and message-logging

- Allows app programmer to designate variables to be checkpointed via "critical()" call
- Allows app programmer to trigger checkpoints via "checkpoint()" call
- Permits logging of received and transmitted messages on primary and backup nodes for replaying, via "ftread()" and "ftwrite()" calls
- Can reorder message arrivals in attempt to avoid Heisenbugs

nDFS: n-Dimensional File System

- Provides replicated stable storage to allow backups access to checkpointed data

Checkpoint and Rollback Cost Effectiveness

Development Cost

- **Based on AT&T libft experience, can insert watchd/libft/nDFS in existing telecom apps quickly (weeks)**
- ***Using portable watchd/libft/nDFS library - didn't have to write difficult checkpointing code from scratch***

Run time cost (no faults)

- **<14% for libft checkpointing approach**

Effectiveness

- **On the order of 90% coverage of non-design errors**
- **AT&T reports highly effective at tolerating certain known bugs that they can't afford to fix**

Checkpoint / Rollback Advantages

Works, mostly

AT&T has had success in tolerating faults it can't afford to fix

Runtime overhead acceptably low: say 15%

Not all-or-nothing: can use judiciously in critical functions and integrate seamlessly

Checkpoint / Rollback Disadvantages

Defining checkpoint data and intervals is tricky

Checkpoint / rollback algorithms in concurrent systems are exceedingly complex and potentially slow

- Must establish recovery lines and avoid domino rollback

Irreducible overhead for checkpointing: processing, comm, storage

Efficient techniques are not transparent; transparent techniques are not efficient

Fault model is moderately weak

- Only as good as error detection means
- Doesn't work for persistent software errors
- Error detection coverage is critical but usually neglected

Checkpoint placement and frequency are critical: price / performance tradeoff must be made

Could require double the run time to handle faults

State Rejuvenation

A proactive technique: use it to avoid failures

Applicability

- **Where long-running processes gradually degrade system state due to**
  - **Memory leaks, memory caching, weak memory reuse, memory fragmentation, unreclaimed resources, bitrot, ...**
- **Where processes use canned (or old) code whose source can't be modified**

Critical Assumptions

- **No need to detect errors...you get them before they get you**
- **Checkpoint data can be identified and copied to stable storage**
- **Can generate checkpoint and restart scheme that lets you pick up where you let off**
- **Rollback can be confined to a small number of processes**

State Rejuvenation Example

Buggy Subroutine

```
#define MEG (1024*1024)
unmodifiable_call(arguments)
{
/* initialization */
        if(ptr1 = malloc(MEG)) == NULL) exit(1);
        if(ptr2 = malloc(MEG)) == NULL) exit(2);
/* incredibly complex control flow */
        free(ptr1);
/* more incredibly complex control flow */
        free(ptr2);
}
```

Without State Rejuvenation

```
main()
{
while(1)
        {
        new_state = unmodifiable_call(some_arguments);
        write_output(new_state);
        }

}
```

With State Rejuvenation

```
main()
{
int i = 0;
while(1)
        {
        new_state = unmodifiable_call(some_arguments);
        write_output(new_state);
        if(i++ % REJUV_PERIOD == 0)
                {
                flush_outputs()
                checkpoint()
                rollback()
                }
        }
}
```

State Rejuvenation Cost Effectiveness

Development and maintenance cost

- **Somewhat less than checkpointing, since don’t have to design general purpose error detection and recovery techniques**

Run time cost

- **Same as checkpointing; on the order of 15%**
- **Runtime cost is predictable since you determine how often to rejuvenate**

Effectiveness

- **Has been shown to be very effective when applicable: memory leaks, etc.**
- **Can sometimes reduce execution time by aggregating fragmented state**
- **Can run during slack times to minimize performance impact**

Issues with State Rejuvenation

Limited applicability

- Essentially a boutique solution

Has most of checkpointing / rollback’s problems:

- Tricky to define checkpoint data
- Must empirically determine how often to rejuvenate
- Not transparent
- Serious difficulties in multiprocessing systems

Best used sparingly when you know that you have a longevity flaw

Recovery Block

A reactive technique

Applicability

- Where cost of failure is severe
- Where must deliver service at all costs
- Soft HW and (primarily) SW failures
- Typically, nonredundant architecture
- Where you have time to retry a computation

Recovery Block Critical Assumptions

Faults are soft and primarily due to software errors

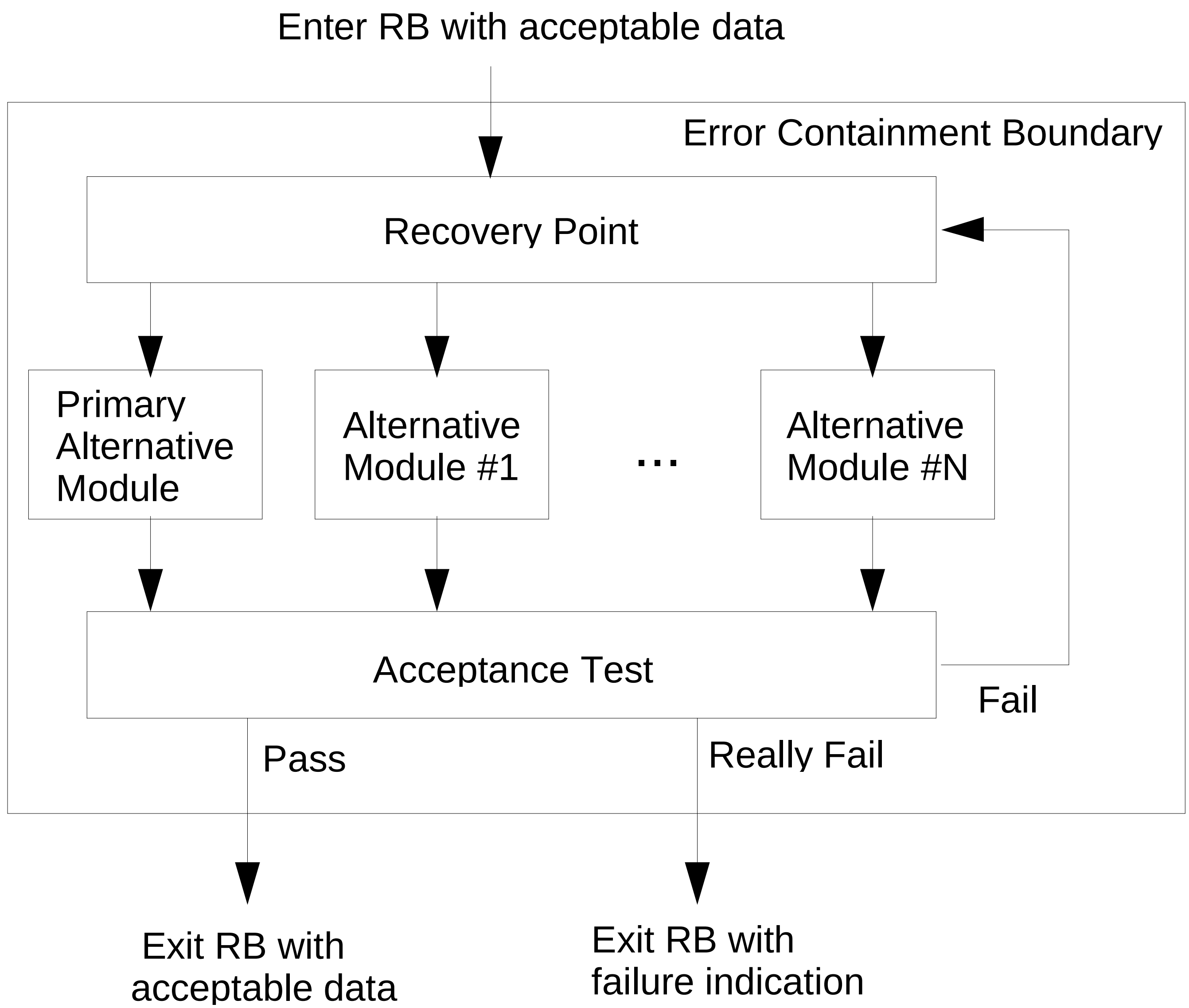
Software errors could be design or, more probably, coding errors

Faults do not cause app or system to crash

Faults can be corrected by retrying alternate version of code

Replica execution is deterministic

Recovery Block Flowchart



Example: Memory Allocation

Recovery Point

- State of pointer chains to be modified by allocation routine

Try block 1

- Allocate from heap 1

Try block 2

- Allocate from heap 2

Acceptance test

- Sum of allocated block sizes == requested size == size of free list decrement?
- Free / used pointer chains connected?

If fail, restore pointer chains from recovery point and retry

If error, perform error handling appropriate for the function and environment

Recovery Block Cost Effectiveness

Development and maintenance cost

- **Approximately 60% increment for 2 try blocks**

Run time cost (no faults)

- **Typically in the 10-20% range**
- **Fujitsu reports 50% run time overhead for recovery block-protected UNIX system calls**
- **At least 2X in presence of faults**

Effectiveness

- **Approximately 90% coverage of non-design errors**

Recovery Block Advantages

Works, mostly

Makes you figure out what the code is supposed to do by writing acceptance tests

Makes you think of at least two ways of solving the problem

Makes you figure out what you should do if your routine fails

Runtime overhead acceptably low: say 15%

Not all-or-nothing: can use judiciously in critical functions and integrate seamlessly

Recovery Block Disadvantages

Acceptance tests are critical

- **Single point of failure and a source of irreducible overhead**
- **SW errors in boundary code occur significantly more often than in main routine**
- **Price/performance tradeoff must be made: where and how often to place acceptance tests**

Expensive

- **At least two copies of code must be constructed, tested, supported, etc.**

Requires additional storage for input conditions to allow retries to commence

Could require double the run time to handle faults

Recovery Block Disadvantages

Fault model is weak

- **Poorly tolerates design faults, hardware failures, OS crashes, app crashes**

How to construct recovery point

- **Sufficient data must be saved to enable retry**

How to construct different try blocks

- **How many copies to be developed**
- ***Could use same code if trying to tolerate Heisenbugs and can inculcate nondeterminism***

What to do when all tests fail

- **Remember: context dictates actions when you can't go on**

Multiprocessing systems suffer from domino rollback: avoidance is complex

Process Pairs

A reactive technique

Applicability

- **Hard or soft HW and SW failures**
- **Loosely coupled redundant architecture; fail fast hardware optional**
- **Message-passing interprocess communication**
- **Works best for transaction-oriented applications**

Critical assumptions

- **Processes and hardware are fail-fast**
- **Errors can be corrected by re-executing same code in another environment**
- **No single points of failure in architecture**

Overall Approach

Construct *fail-fast* processes

- Either function correctly or detect a fault, signal failure, and stop
- Both hardware and software may be designed to be fail fast
- Fail fast processes may be constructed on non-fail-fast hardware

Enforce fault and error containment

- No shared state; processes communicate via message passing
- This prevents a process from corrupting state on its local processor
- It also facilitates construction of process pairs

Two process pair types prevail

- Checkpoint / restart / message
- Persistent

Checkpoint / Restart / Message Process Pairs

Primary performs the work

Secondary listens for "I'm alive" messages

In checkpoint / restart scheme, primary logs state updates to stable storage accessible to secondary

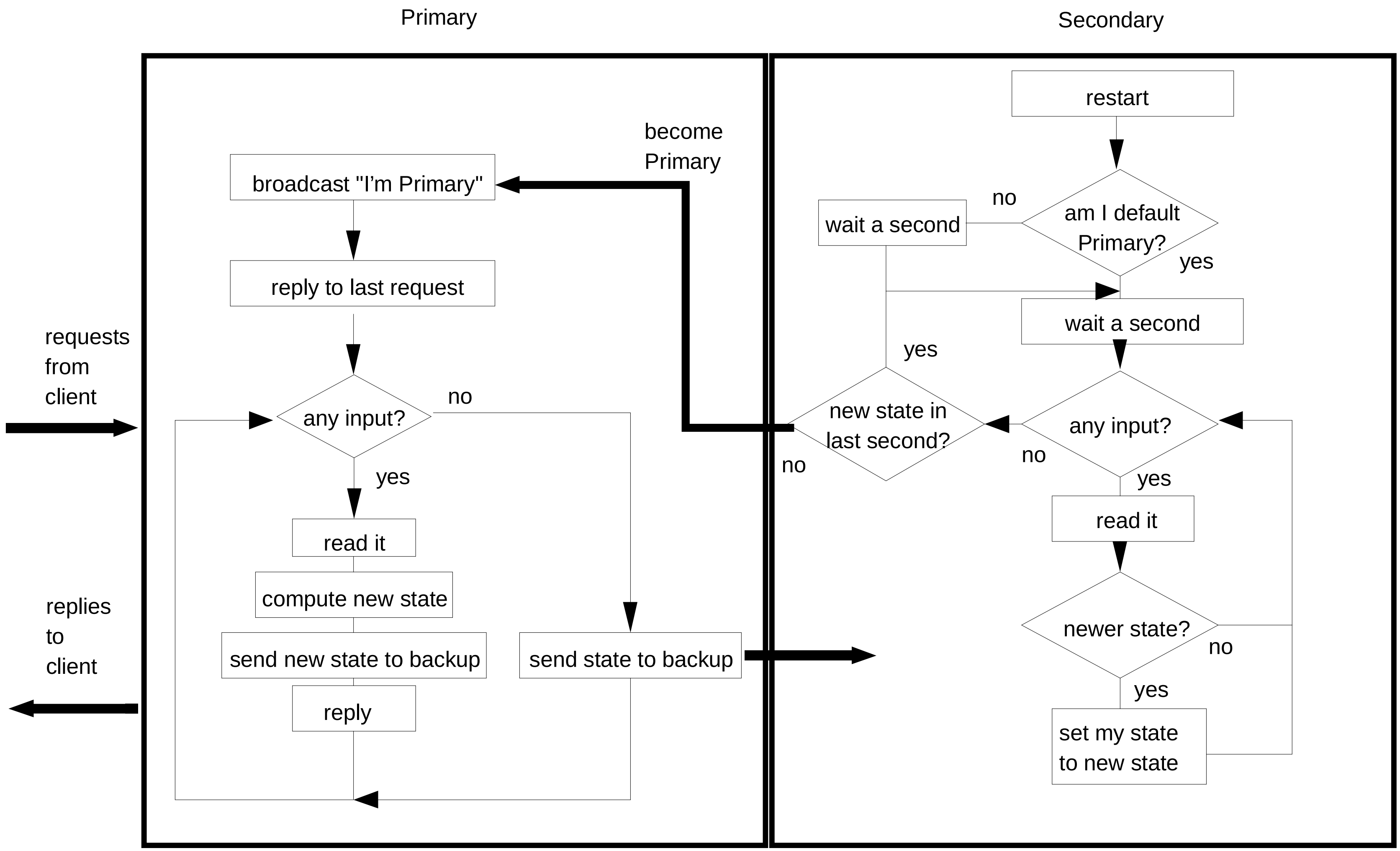
In checkpoint / message scheme, state updates are piggybacked on (and may supplant) "I'm alive" messages

When secondary detects failure of primary, secondary refreshes state either from stable storage or from message log

Secondary then picks up processing where primary left off

"...it is the authors' [Jim Gray and Andreas Reuter] experience that everyone who has written [a process pair] thinks that it is the most complex and subtle program they have ever written."

Checkpoint / Restart / Message Example



Persistent Process Pairs

Suitable for transaction-based applications

Works in conjunction with transaction monitor

- TM can undo partial transactions

Primary executes ACID transactions

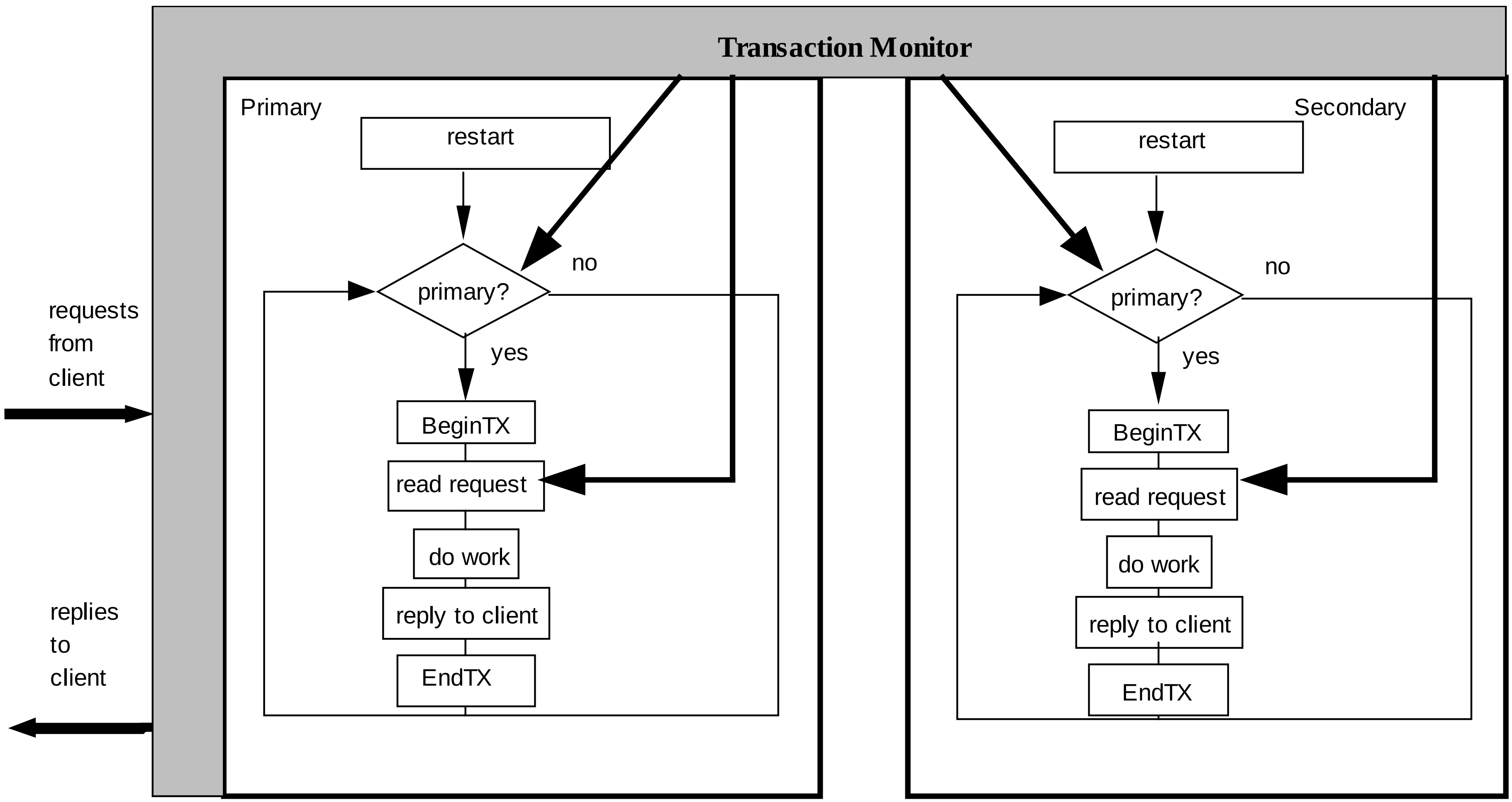
- BeginTransaction
  - code, code, code
- EndTransaction or AbortTransaction

Amnesiac secondary (or TM or OS) listens for “I’m alive” messages

When primary fails-fast, TM undoes any transactions in progress and resubmits them (as well as subsequent client traffic) to the amnesiac secondary

Persistent process pairs provided as a primitive by NonStop operating system

Persistent Pair Example-with OS Support



Advantages

Extremely successful in Tandem OLTP applications

Persistent process pairs relatively easy to program

Fault model is moderately strong: tolerates hardware, OS, and app failures

High coverage (>90%) of hardware and software (including OS) faults

Does not consume too much performance at backup site: about 10% runtime overhead can be achieved

Disadvantages

Checkpoint / restart / message process pairs difficult to construct without significant toolkit or infrastructure investment

Must use checkpoint / restart / message process pairs in a non-transaction-based application

Must develop error detection checks and signaling techniques to make a process fail-fast

Works best on fail-fast hardware

Works best on message-passing interprocess communication

Works best on loosely coupled distributed hardware architecture

Multiversion Software

Applicability

- Fast real-time critical applications where no dropout is acceptable: aerospace, nuclear, ground transportation
- Where cost of failure is severe
- Tolerates soft or hard faults, whether in HW or SW (primarily oriented towards tolerating SW coding faults)

Critical assumptions

- Specification contains no flaws (omissions, inconsistencies, ambiguities)
- Independent programming teams don't make the same mistakes
- Requires loosely synchronous redundant architecture
- Replica execution is deterministic

Multiversion Software Development Steps

Develop specification

- Constraining enough to allow version comparison
- Flexible enough to allow diversity

Develop version voter

- Plurality voting
- Approximate voting

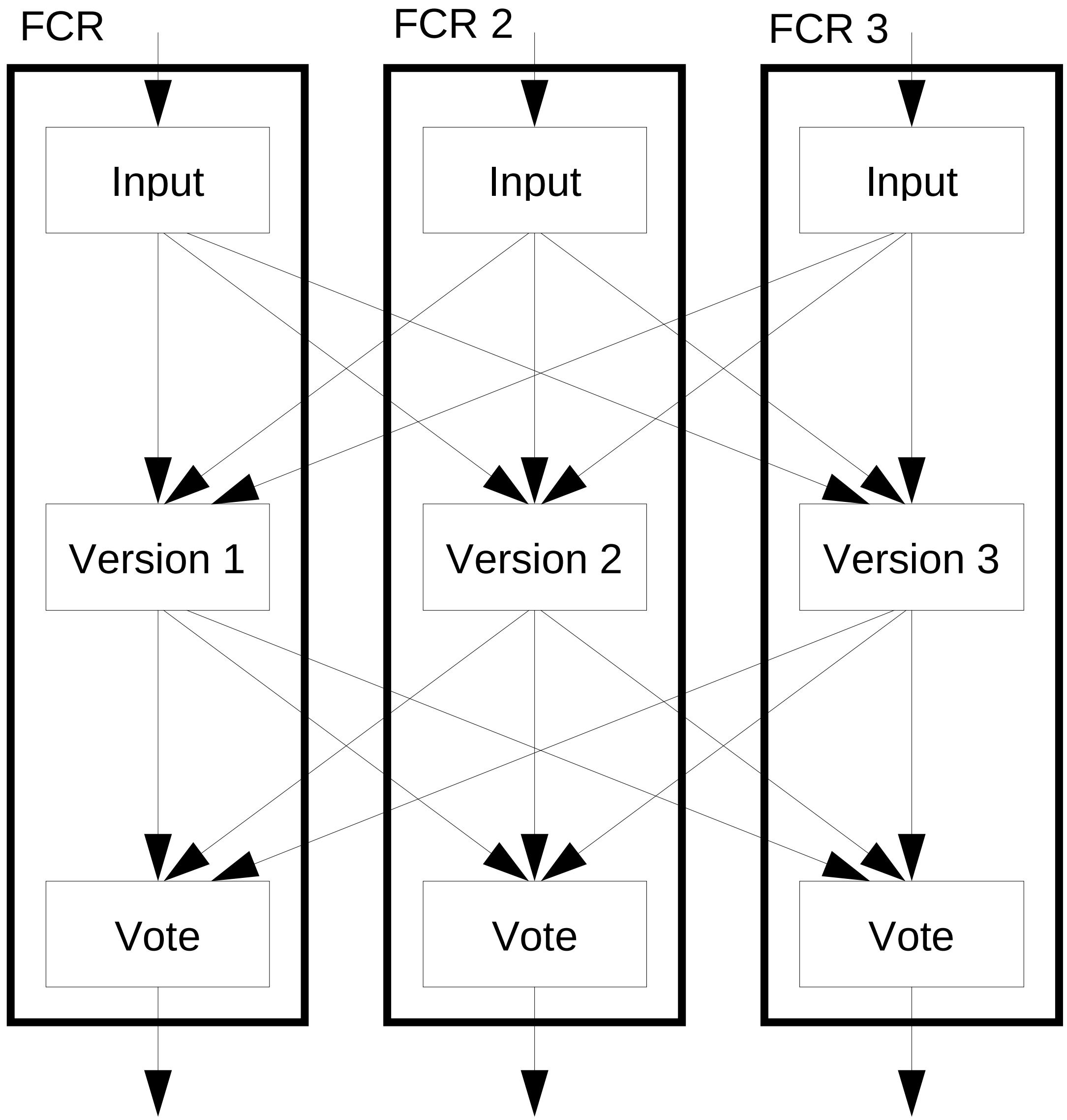
Generate diverse programs

- Give specification to three or more independent programming teams
- Random or enforced diversity

Run diverse versions on independent hardware

Perform periodic voting of version outputs

Multiversion Software Flowchart



MultiVersion Software Cost

Development and maintenance cost

- **About 2.26 times the cost of single version for three versions**

Run time overhead

- **On the order of 10 to 25%**
- **Same in presence of faults**

Hardware overhead

- **At least 3X**

MultiVersion Software Effectiveness

Case 1: Aircraft autoland control law experiment

Version	*LOC*	*# errors*	*error prob*
ada	2256	0	0
c	1531	568	.00011
modula-2	1562	0	0
pascal	2331	0	0
prolog	2228	680	.00013
t	1568	680	.00013

Category	*3 versions: probability*	*5 versions: probability*
No errors	.9998409	.9997807
Single errors in one version	.0001305	.0001915
Two distinct errors in multiple versions	.000002048	.000002275
Two coincident errors in multiple versions	.00002652	.00002210
Three Errors in multiple versions	0	.000003413

Case 2: Leveson, et al, found that code-based self-checks were far more effective than multiversion programming at finding programming errors

Multiversion Software Issues

Specification management

- **Make sure all teams are using same spec**

Version construction

- **Ensure diversity**

Version resolution

- **Voter construction is critical from detection and performance viewpoint**
- **You get monstrosities like "approximate thresholding plurality voters"**
- **When is bitwise agreement meaningful?**
- **Placement and frequency of voting**

Multiversion Software Issues

Version synchronization

- Requires fault tolerant synchronization mechanism

Version recovery

- Bring faulted version to same state as nonfaulty versions

Cross-channel exchange of input and output data

- Consumes bandwidth

Multiversion Software Advantages

Makes you figure out what the code is supposed to do by writing spec and voter

Helps validate and clarify the specification

Fault model is strong

Approved by Your Government for flight- and safety-critical systems

Constant execution time and no dropouts in presence of faults

Effective at coping with a few bad programs (if most versions are good)

Multiversion Software Disadvantages

Specifications DO contain flaws (omissions, inconsistencies, ambiguities)

Independent programmers DO make the same mistakes

Less effective when all programs are uniformly reliable: the hard stuff is hard for everybody

Versions may not agree in absence of faults due to roundoff error, non-commutativity, etc. ==> complex voters

Expensive: at least three copies of code must be developed and maintained

Requires 3X redundant hardware architecture plus interchannel communications network

Process Groups

Deterministic processes are replicated on multiple computing nodes of a distributed system

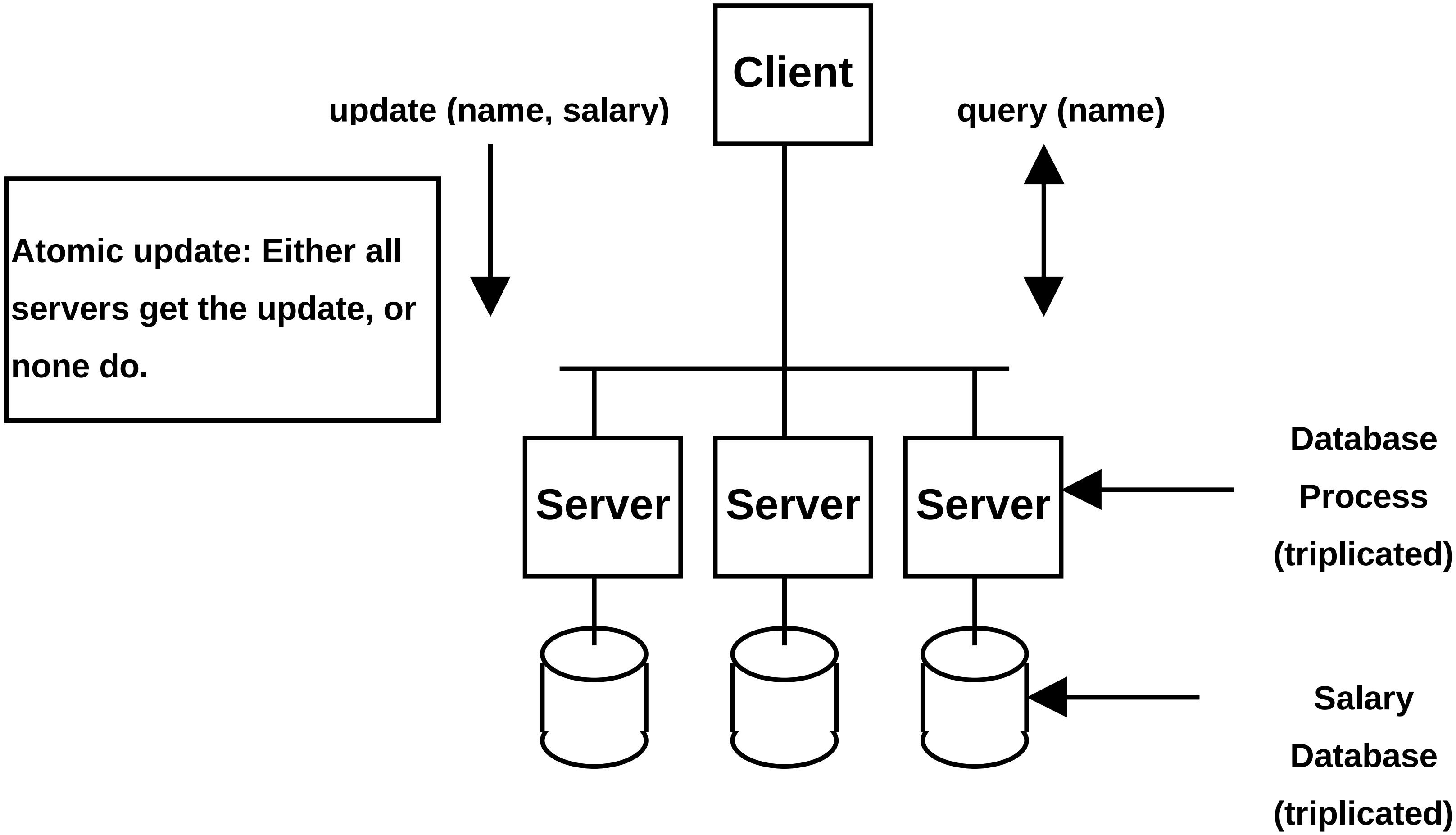
- The service provided by the replicated processes can be "continuously" available when some of the replicas fail
- Every replica has a copy of the common state
- State updates occur in the same order on all replicas
- Client communicates with a group address, not a single process address

Client and server process application code must execute group membership and communication calls

Client and server process application code must execute group membership and reliable multicast algorithms

- global, atomic, causal, fifo, hierarchical, and other broadcasts
- Virtual synchrony used to ensure consistency of group view

Process Groups Example: Database Server



Process Groups Example: Server Code; ISIS Lingo

```
#include "isis.h"
#define UPDATE 1
#define QUERY 2
main() {
    isis_init(0);
    isis_entry(UPDATE, update, "update");
    isis_entry(QUERY, query, "query");
    pg_join("salary_DB", PG_XFER,
    send_state, rcv_state, 0);
    isis_mainloop(0);
}

update(mp)
register message *mp; {
    char name[32]; int salary;
    msg_get(mp, "%s, %d", name, &salary);
    set_salary(name, salary);
}
```

```
query(mp)
register message *mp; {
    char name[32]; int salary;
    msg_get(mp, "%s", name);
    salary = get_salary(name);
    reply(mp, "%d", salary);
}
send_state() {
struct sdb_entry *sp;
for (sp = head(sdp); sp != tail(sdb); sp = sp-
>s_next)
    xfer_out("%s, %d", sp->s_name, sp-
    >s_salary);
}
rcv_state()
register message *mp; {
    update (mp);
}
```


Process Groups Example: Client Code

```
#include “isis.h”
#define UPDATE 1
#define QUERY 2
address *server
main() {
        isis_init(0);
        server = pg_lookup(“salary_DB”);
        pc_client(server);
        …
        …do client work: calls to update and
        get_salary…
        …
}

update(name, salary)
char *name; int salary;  {
        abcast(server, UPDATE, “%s,%d”, name,
        salary, 0);
}

get_salary(name)
char *name; {
        int salary;
        fbcast(server, QUERY, “%s”, name, 1,
        “%d”, &salary);
        return(salary);
}
```


Process Group Advantages and Disadvantages

Advantages

- Tolerates hardware, operating system, and some application failures
- Works over widely distributed heterogeneous systems
- Not all-or-nothing - can be deployed for critical services only

Disadvantages

- Not application transparent
- Does not support mutually preemptible threads very well
- Hierarchical groups not supported well
- Performance may be low
- Fault model is weak: usually fail-stop
- Error detection latency may be a few seconds

Robust Data Structures

A proactive technique

- **Use to seek out and destroy errors before they cause failures**
- **A number of techniques is available**
- ***We will use linked lists to demonstrate the concept***

Intended to achieve

- **Semantic integrity: the data's meaning is uncorrupted**
- **Structural integrity: the data's organization is correct**
- ***We will discuss structural integrity techniques today***

Robust Data Structures

Applicability

- Critical data structures having a clearly defined and regular structure
- Most highly developed for linked lists and trees

Critical Assumptions

- Data structures can be fitted with redundancy
- Execution time is available to audit and correct data structures
- Storage is available to store essential redundant information

Robust Data Structures Approach

Robust data structures contain redundant data which allow erroneous changes to be detected and corrected by checks

Checks may perform on-line error detection and correction

- Overhead and effectiveness are functions of data structure access frequency

Detection / correction programs (audits) may be used

- Overhead may be tuned based on performance considerations
- Checks may be run during slack time

Robust Data Structures Approach

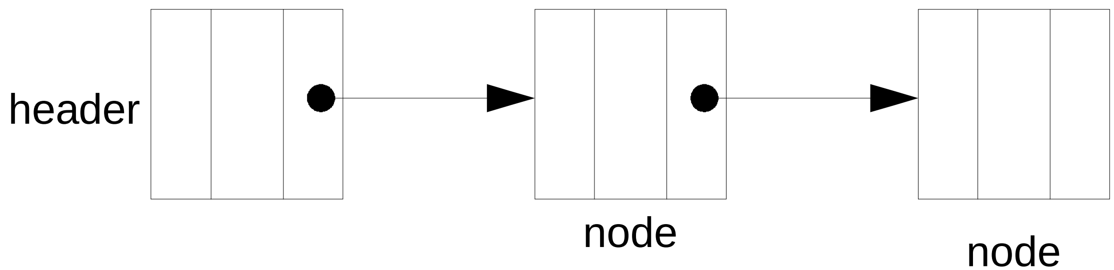
Robust data structures are classified as N-detectable and M-correctable

- N-detectable: all sets of N or fewer changes to structure can be detected
- M-correctable: all sets of M or fewer changes to structure can be corrected

Changes are defined to be arbitrary (malicious) modifications to the data structure

Example: Linked List

Nonrobust design

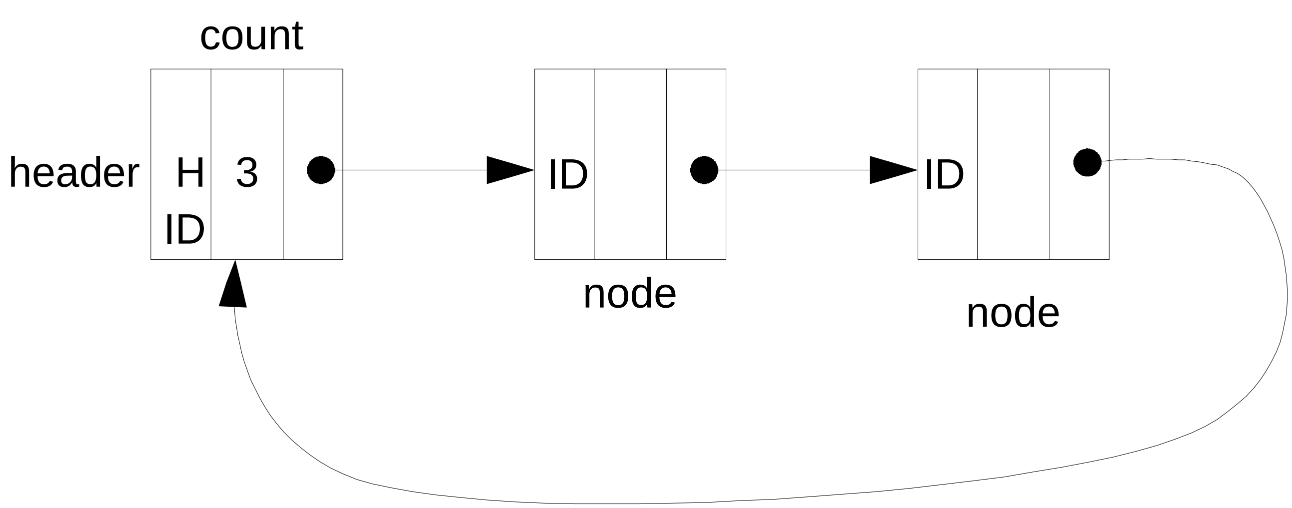


0-detectable, 0-correctable

Robust Linked List Design 1

Robustness additions

- **Store count of number of nodes**
- **Add unique structure identifier field to each node**
- **Link end of list to header**

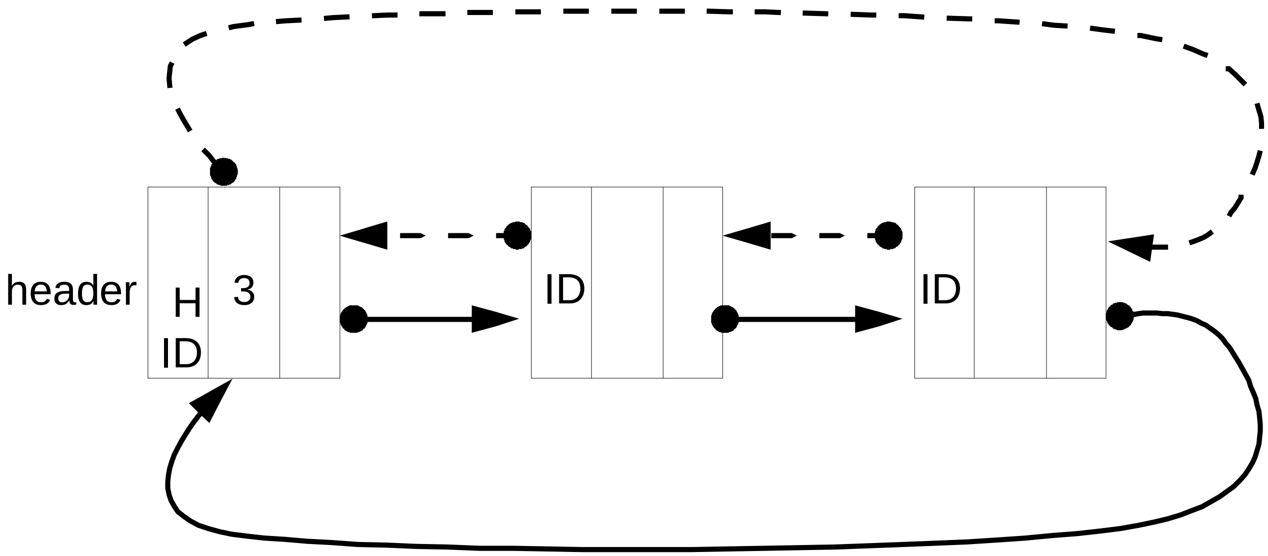


1-detectable, 0-correctable

Robust Linked List Design 2

Robustness addition

Add pointer from successor to predecessor node

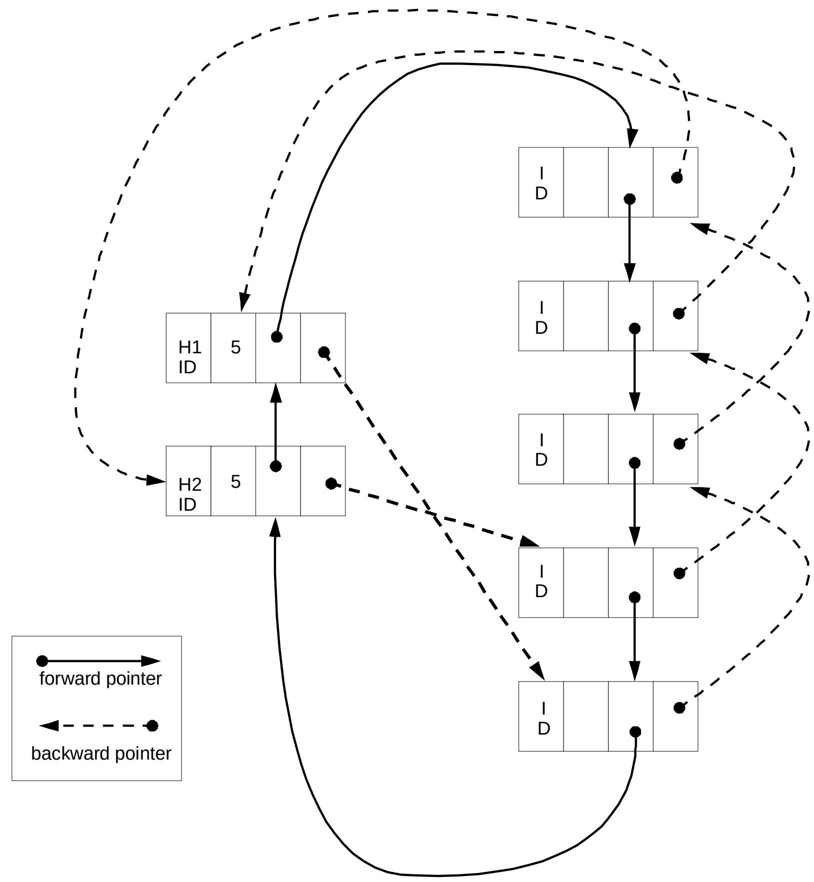


2-detectable, 1-correctable

Robust Linked List Design 3

Robustness addition

Add pointer from successor to predecessor's predecessor node



3-detectable, 1-correctable

Code to Correct Errors in Design 2 Linear Linked List (1)[2]

```
correctlist (void *H) {
  void *P, *prevP;
  int J = 0 ;
  prevP = H;
  P = H->next
  /* Scan main body of data structure */
  while ( P != H) {
    J++;
  if( (P->prev == prevP) && (p->ID == H->ID ) {
      /* This node looks OK */
      prevP = P;
      P = P->next
      }
    else {
    /* We have a problem */
      if( backscan(H, P, prevP) == CORRECTED_ERROR )
      return (CORRECTED_ERROR);
      else
      return (UNCORRECTED_ERROR);
      }
  } /* Done scanning main body of data structure */
```

```
  /* Now examine header of data structure */
  if( (H->prev != prevP) || !correct(ID(H))) {
  /* An error */
    if( backscan(H, P, prevP) == CORRECTED_ERROR)
      return(CORRECTED_ERROR);
    else
      return(UNCORRECTED_ERROR);
  } /* end if */
  /* Lastly, check count field in header */
  if( H->numnodes != J) {
  /* An error */
    H->numnodes = J;
    return(CORRECTED_ERROR);
    }
/* No Errors */
return(NO_ERRORS);
} /* end of correctlist */
```

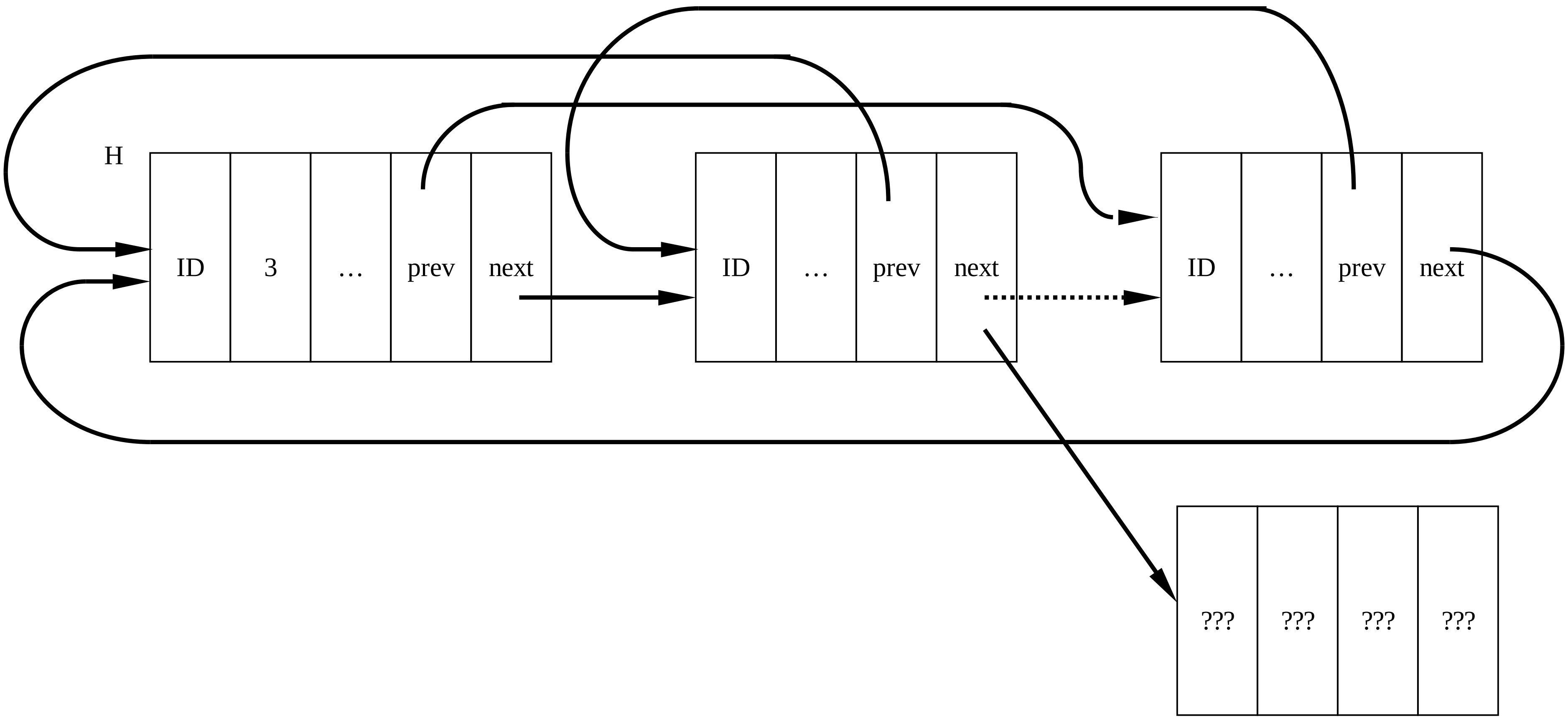
[2] Adapted from D. Taylor et. al., “Redundancy in Data Structures: Improving Software Fault Tolerance,” *IEEE Trans. Software Eng.*, Nov. 1980.

Code to Correct Errors in Design 2 Linear Linked List (2)

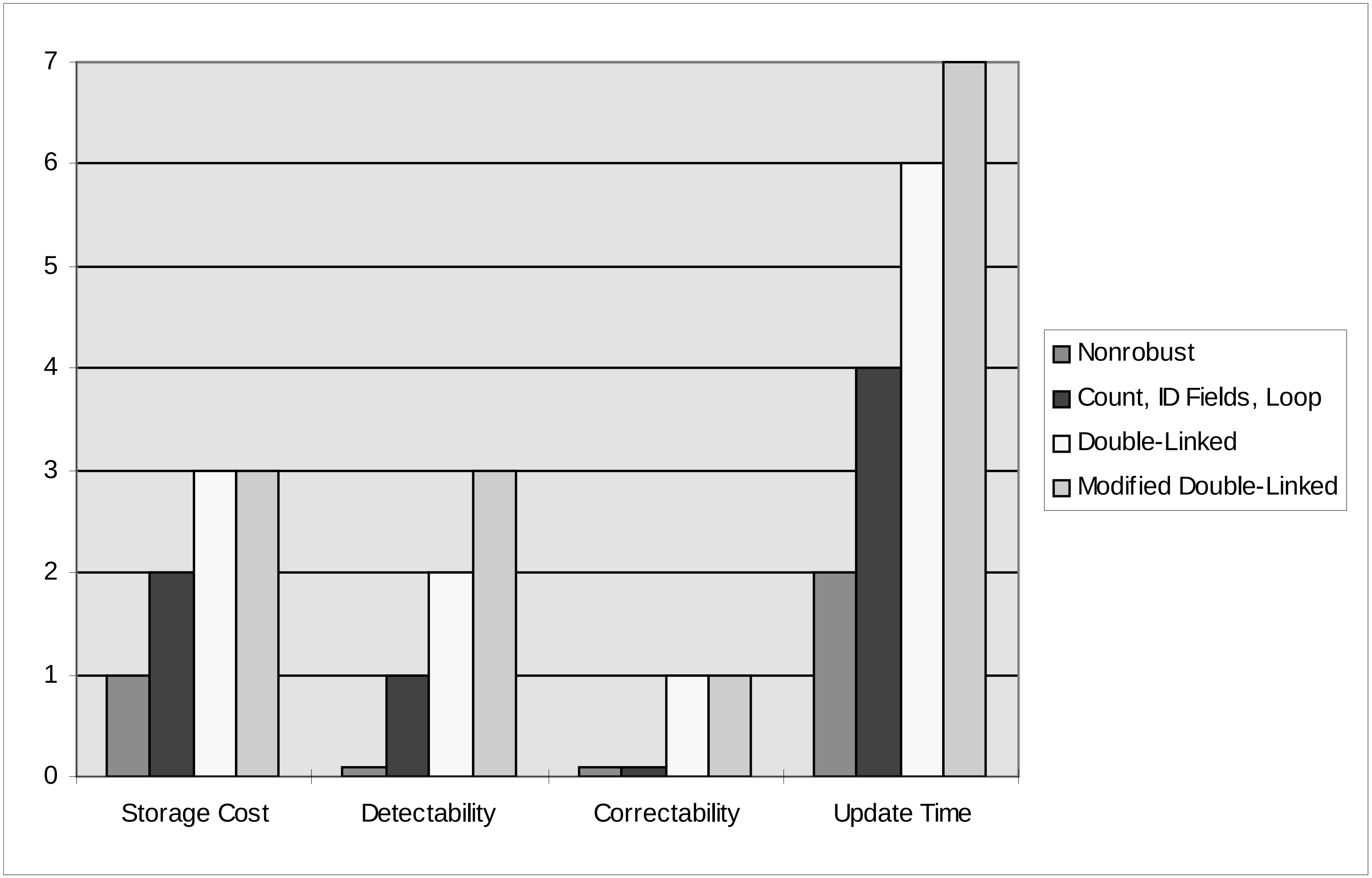
```
backscan (void *H, void *P, void *prevP) {
  void *Q, *prevQ;
  int J = 0;
  prevQ = H;
  Q = H->prev
  while( J++ < H->numnodes) {
    if( (Q->next == prevQ) && (Q->ID == H->ID) ) {
      prevQ = Q;
      Q = Q->prev;
      }
    else {
      if( repair(P, prevP, Q, prevQ) == CORRECTED_ERROR)
        return (CORRECTED_ERROR);
      else
        return (UNCORRECTED_ERROR);
  } /* end of while */
} /* end of backscan */
```

```
repair (void *P, void *prevP, void *Q, void *prevQ) {
  if( (P == Q) && (P->ID != H->ID) ) {
    P->ID = H->ID;
    return(CORRECTED_ERROR);
    }
  else if ( P == prevQ) {
    Q->prev = prevP;
    return(CORRECTED_ERROR);
    }
  else if( prevP == Q) {
    P->next = prevQ;
    return(CORRECTED_ERROR);
    }
  else
    return(UNCORRECTED_ERROR);
} /* end of repair */
```

Linear Linked List Correction Example



Cost Effectiveness of Linked List Designs



Other Robust Data Structure Techniques

Other techniques are available in the literature

Structural techniques for popular data structures

- **Trees, stacks, fifos, heaps, queues, etc.**
- **In general, a linked data structure is 2-detectable and 1-correctable iff the pointer network is bi-connected**

Content-based techniques

- **Checksums, encodings**

Robust Data Structure Cost Effectiveness

Development Cost

- **Not too bad, especially if can reuse code for common data structures (e.g., linked list manipulation / audit code)**

Run Time Cost

- **Not excessive, especially if can run audits during slack times**
- **Techniques can be selected / designed / tuned for low run time overhead**

Effectiveness

- **Highly effective at ferreting out and correcting structural flaws**
- ***Leveson et al found code-based self-checks far more effective than multiversion programming***
- **Less effective at tolerating semantic flaws**

Issues with Robust Data Structures

Not a transparent technique

Relevant to a limited (but significant) class of errors

- Best at errors which corrupt the structure of the data

Data structure auditing / correction code is subtle, complex, difficult to program, and prone to programming errors

Not for the squeamish

Structure Marking

<u>Add</u> TYPE, SIZE, VERSION, and OWNER to data structure

TYPE: Unique number for each different structure

SIZE: in bytes

VERSION: Changed whenever structure declaration changes

OWNER: Unique ID of owner

TYPE SIZE VERSION … …structure data… … OWNER

<u>Set</u> them when the structure is instantiated

<u>Check</u> them before using structure instance

```
RunAssert( (s.TYPE == STYPE) &&
           (s.SIZE == SSIZE) &&
           (s.VERSION == SVERSION3) &&
           (s.OWNER == uid) );
```

<u>Clear</u> or 0xdeadbeef them when the structure is deallocated

```
s.TYPE = s.SIZE = s.VERSION = s.OWNER = 0xdeadbeef;
```

Structure Marking Tips

Don't use common values (0, 1) for TYPE

OWNER must be independent of structure contents; can be UID, least significant bits of clock, etc.

Can find OWNER at sizeof(augmented structure) - sizeof(OWNER field)

Can use sizeof() to generate SIZE field

Don't use common values for VERSION

VERSION field helps find integration errors

VERSION field can be used as parameter to procedure to indicate which version of structure to return; eases compatible evolution

Obvious applicability to object-oriented systems; set up the markings in constructors; check them in the methods

Can augment robust data structures with structural marking

Structure Marking Effectiveness

Protects against

- **Clobbered data: wild stores, bit rot, data overruns**
- **Programming errors: logic errors, incorrect calls, using data after freeing or before allocating**
- **System integration errors: notices cases where programs are unable to handle the data they are passed**

Not so effective against

- **Design and compiler errors: wrong algorithm or compiler bug can produce perfect structure with incorrect contents**

Experience

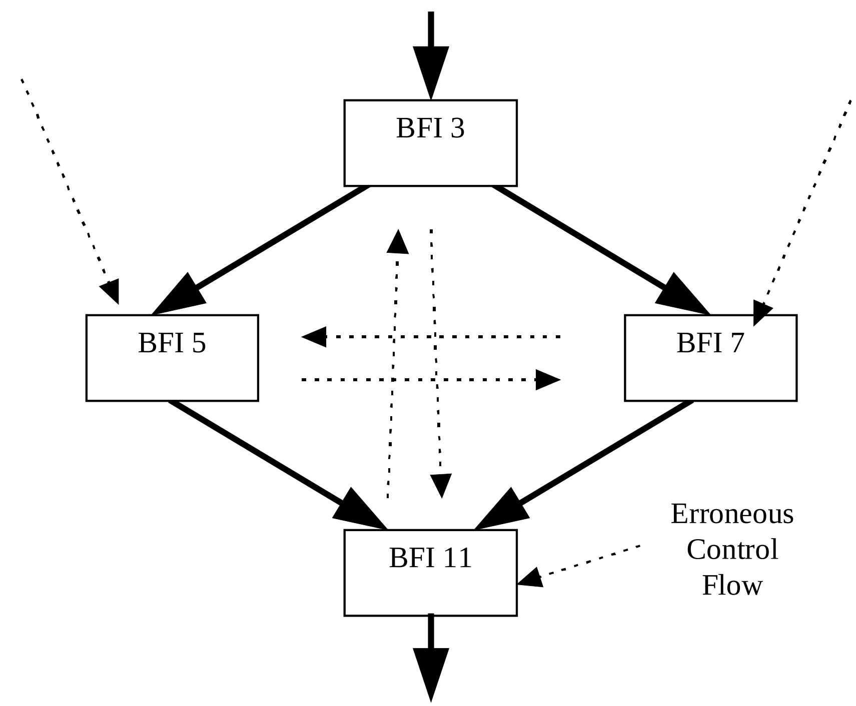
- **Highly successful in MULTICs**
- **Performance overhead quite low**

Control Flow Monitoring

A technique to ensure that control flow goes through intended paths

Example:

```
/* beginning of monitored code */
… BFI 3…
if (swizzle) {
…BFI 5…
}
else {
…BFI 7…
}
…BFI 11…
/* end of monitored code */
```



(BFI = Branch-Free Interval)

Control Flow Monitoring using ECCA

Enhanced Control Flow Checking using Assertions (ECCA)

Assign each BFI a prime ID called BID	Assign each BFI a value for NEXT = product of all possible next BIDs
#define BID 3 **… BFI 3…** **if (swizzle) {** ***#define BID 5*** **…BFI 5…** **}** **else {** ***#define BID 7*** **…BFI 7…** **}** ***#define BID 11*** **…BFI 11…**	***#define BID 3*** ***#define NEXT 5*7*** **… BFI 3…** **if (swizzle) {** ***#define BID 5*** ***#define NEXT 11*** **…BFI 5…** **}** **else {** ***#define BID 7*** ***#define NEXT 11*** **…BFI 7…** **}** ***#define BID 11*** **…BFI 11…**

Control Flow Monitoring using ECCA

Add land mines: now there is now way to get through the BFIs incorrectly	The final touch: now there is no way to get out of an incorrectly entered BFI
#define BID 3	*#define BID 3*
*#define NEXT 5*7*	*#define NEXT 5*7*
… BFI 3…	… BFI 3…
id =NEXT;	*id =NEXT;*
if (swizzle) {	if (swizzle) {
#define BID 5	*#define BID 5*
#define NEXT 11	*#define NEXT 11*
id = BID / ((!(id%BID)) ; / check for illegal entry */*	*id = BID / ((!(id%BID)) * (id%2)); /* check */*
…BFI 5…	…BFI 5…
id = NEXT; / only update id when done with BFI */*	*id = NEXT+ !!(id - BID);*
}	}
else {	else {
#define BID 7	*#define BID 7*
#define NEXT 11	*#define NEXT 11*
id = BID / ((!(id%BID)) ; / check for illegal entry */*	*id = BID / ((!(id%BID)) * (id%2)); /* check */*
…BFI 7…	…BFI 7…
id = NEXT;	*id = NEXT+ !!(id - BID);*
}	}
#define BID 11	*#define BID 11*
id = BID / ((!(id%BID)) ; / check for illegal entry */*	*id = BID / ((!(id%BID)) * (id%2)); /* check */*
…BFI 11…	…BFI 11…

Example

```
#define NEXT 5*7
… BFI 3…
id = NEXT+ !!(id - BID);

if (swizzle) {

/* if legal entry, id = 5*7 */
/* if illegal entry, id != 5*7, probably */
#define BID 5
#define NEXT 11
/* check for illegal entry */

id = BID / ( (!(id%BID)) * (id%2) );

 /* if legal entry, would get id = 5 / (( !(35%5)) = 5 / ((!0)) = 5 / 1 = 5 */
/* if illegal entry, would get id = 5 / (( !(id%5)) = 5 / ((!1)) = 5 / 0 = divide by zero error */

…BFI 5…

/* if exit out of BFI 5 before id = NEXT, will get caught at next illegal entry check with wrong id */

id = NEXT+ !!(id - BID); /* only update id when done with BFI */

} /* end of BFI 5 */
```

This term checks that BFI5 was legally entered from BFI 3.

This term checks that the previous BFI was not illegally entered after its entry check.

This term declares that the only valid next BFI is BFI 11.

This clobbers the id if BFI 5 was entered somewhere in its middle.

Control Flow Monitoring using ECCA

ECCA: Assertion Version

```
#define BID 3
… BFI 3…
#define NEXT 5*7
id =NEXT+ !!(id - BID);
if (swizzle) {
#define BID 5
RunAssert  (  (!(id%BID)) * (id%2) );  id = BID;
…BFI 5…
#define NEXT 11
id = NEXT+ !!(id - BID);
}
else {
#define BID 7
RunAssert  (  (!(id%BID)) * (id%2) );  id = BID;
…BFI 7…
#define NEXT 11
id = NEXT+ !!(id - BID);
}
#define BID 11
RunAssert  (  (!(id%BID)) * (id%2) );  id = BID;
…BFI 11…
```


Control Flow Monitoring using ECCA

Advantages

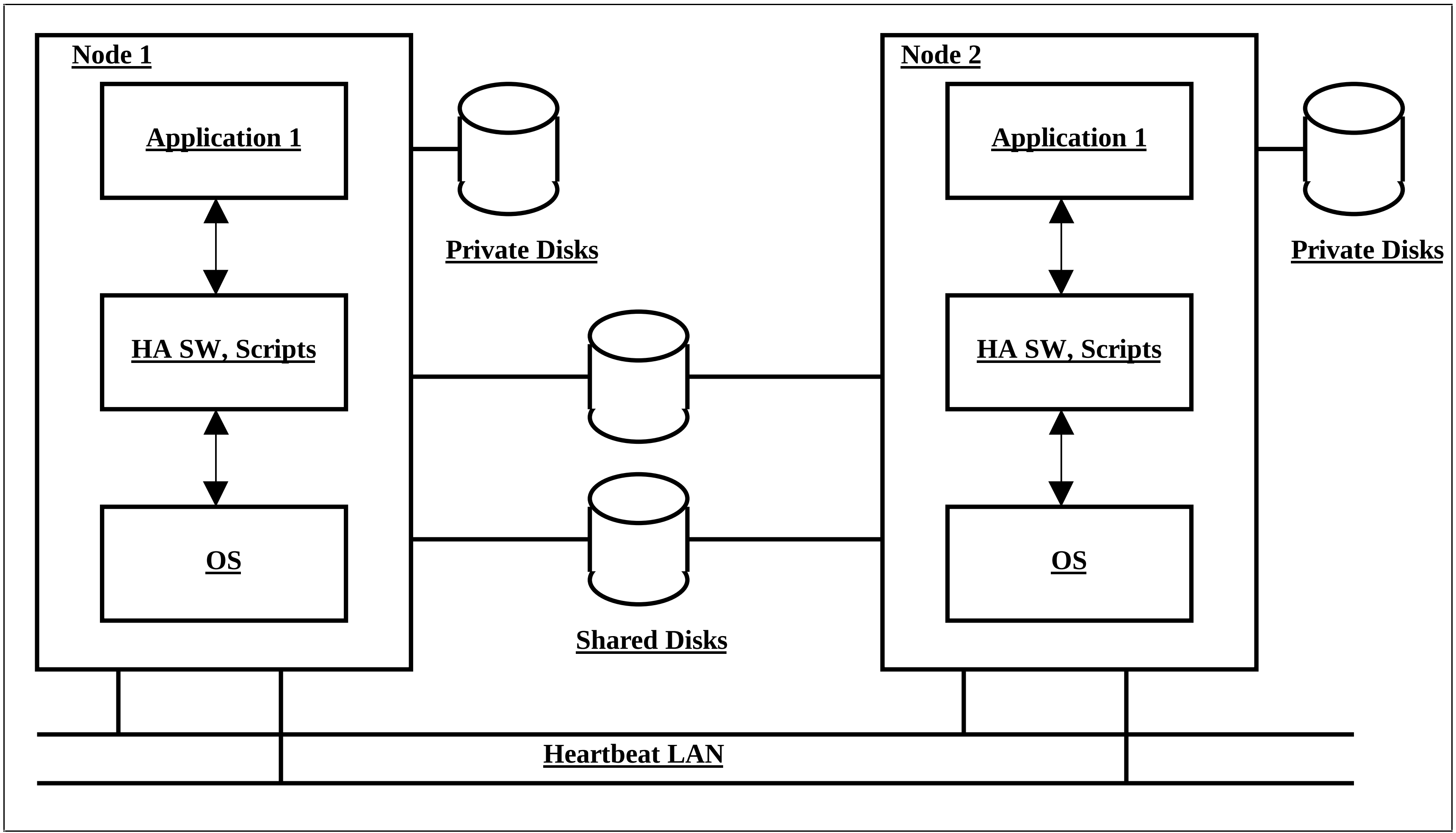
- **Detects all single and most double control flow errors**
- **Preprocessor can be easily implemented**
- **Low overhead if BFI is large**
- **Can easily add assertions**
- **Can turn on for debugging and off for shipping**

Disadvantages

- **Must modify source code**
- **High overhead if BFI is small**

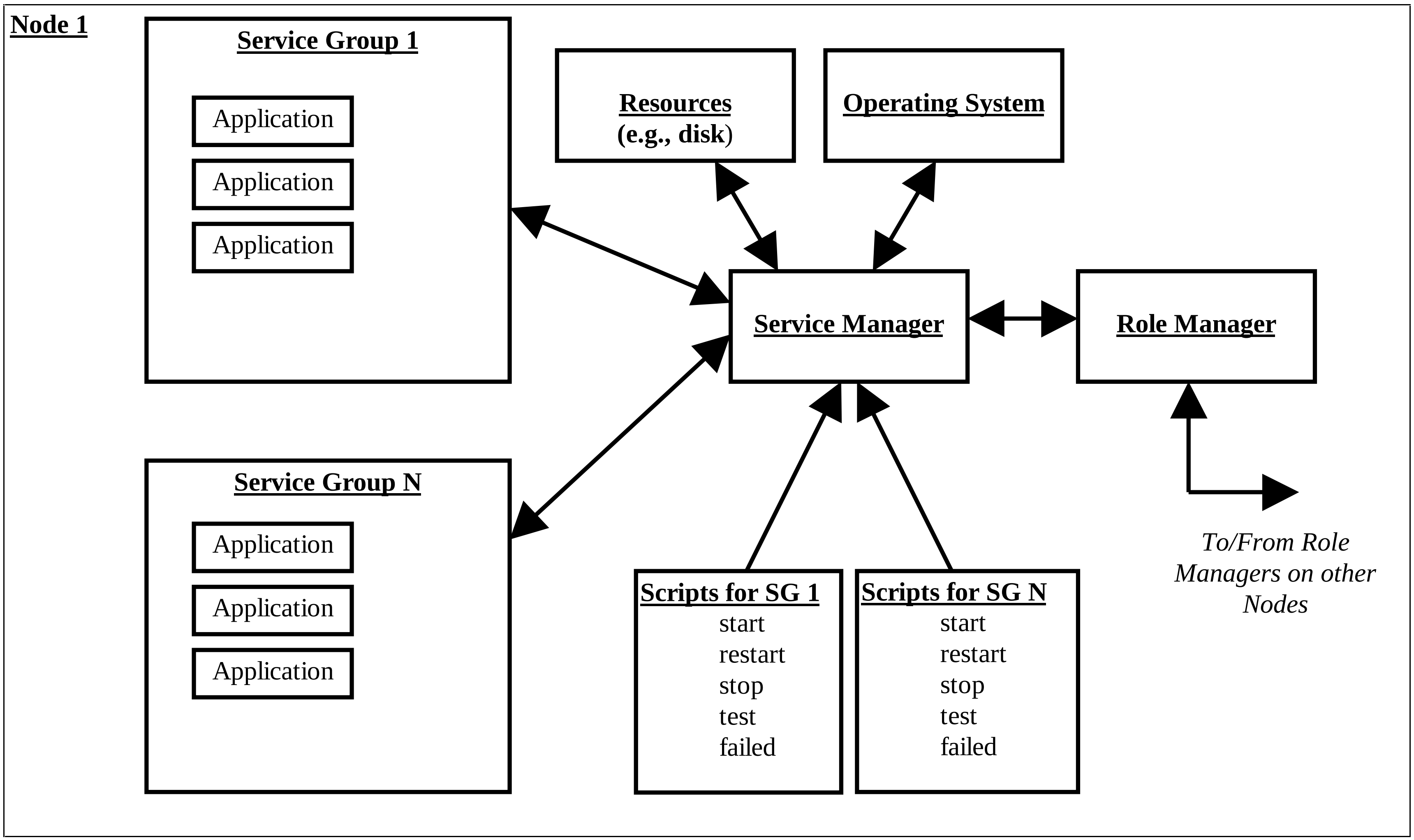
Programming for a High-Availability Cluster Environment

Typical Configuration



Programming for a High-Availability Cluster Environment

Functional Architecture (Qualix lingo)



Key Strategies

Automating application operation

Maximizing speed of application failover

Design for application migration

Insulate users from failover

Design applications to detect and recover from faults

Automating Application Operation

Application should be started or stopped without operator or user intervention

Define application startup and shutdown procedures

- No operator intervention
- Report startup/shutdown to HA monitor
- Don’t let shutdown accidentally cause failover

Maximize Speed of Application Failover

Replicate code and data on multiple nodes if possible

On shared disk, use raw volumes that do not require fsck

On shared disk, use journalled file system

Minimize data loss upon failure

- Minimize in-memory volatile data
- Use restartable transactions
- Use checkpoints

Run active-active

Design for Application Migration

Avoid system-specific information

- **Each application should have its own IP#**
- **Each application should have its own “hostname”**
- **Let DNS do the work**
- **Avoid SPU Ids or MAC addresses**
- **Avoid uname(2)**
- **Bind to a fixed port - don’t let the system choose one for you**
- **Bind to a relocatable IP#**
- **Call bind() before connect() to ensure the use of the relocatable IP#**

Design for Application Migration

Give each application its own volume group

- **Volume groups are units of migration**
- **If two applications use the same volume group, they <u>must</u> migrate together**

Avoid file locking if possible

- **Local locks will be unknown to recovered application - could cause problems**
- **Remote NFS locks will be unknown to recovered application and may never be released**

Insulate Users from Failover

Try to require no user intervention to reconnect

- Design client software to try to reconnect automatically
- Use transaction processing monitor or message queueing software to distribute, retry, and enqueue transactions

Minimize re-entry of data

- Restartable transactions and checkpointing

Minimize impact of failure

- Design for reserve capacity to minimize performance degradation upon failure

Handling Application Failures

Modularize applications and make components tolerate each others' failure

Attempt local restart of application components

Use techniques described in this course to detect and tolerate application failures

Developing "Bug-Free" Code

Observation

- **Cost to fix increases 10X for each stage (design, unit test, system test, released) that bug discovery and correction is delayed**

Therefore we want to

- **Find bugs as early and as easily as possible**
- **Find bugs automatically with minimal effort**
- **Minimize the skill required to catch and fix bugs**

Maintain a Ship and Debug Version

Maintain a ship and a debug version of the code

- **Debug version designed to catch bugs**
- **Ship version designed to run quickly and reliably**

Debug version

- **#ifdef DEBUG … #endif**
- **Debug version must behave exactly the same as the ship version**
- **Don’t apply ship constraints to debug version**
- **Trade size and speed for error detection**

Ship version

- **Use defensive programming techniques previously described**
- **Use run time assertions**

Use Assertions

Three categories of assertions

- **Compiler assertions: CompileAssert**
- **Debug time assertions: DebugAssert**
- **Run time assertions: RunAssert**

Assertions are used to provide compile-time or run-time checking of design-time assumptions

General structure

- **Assert (expression that should be true)**

Failed assertions cause compilation or runtime error

Compile-Time Assertions

Objective

- **Verify design-time assumptions at compile-time**
- **Especially useful when maintenance programmer unknowingly violates design assumptions**

Usage

```
...
char buffer[BUFSIZE];
...
CompilerAssert ( ISPOWER2 ( sizeof(buffer)));
```

A mechanization of CompilerAssert

```
#define CompilerAssert(exp) extern char _CompilerAssert [ (exp)
? 1 : -1 ]

#define ISPOWER2 (x) (!((x)&((x)-1)))
```

Debug Time Assertions

Debug time assertions are used to provide debug time checking of design-time assumptions

Use debug time assertions to catch bugs

- Validate function arguments and outputs
- Catch undefined behavior
- Audit data structures, logs, etc.
- Validate that the results of debug-only redundant algorithm are identical

Debug assertions MUST NOT

- Disturb memory
- Initialize data
- Have ANY side effects

Debug Time Assertions

Usage: Should be true for execution to proceed

```
void func (int nValue)
{
        DebugAssert(nValue>0)
                {
                …guarded code…
                }
}
```

Definitions:

#define DebugAssert(exp) if (!(exp)) { \
 ReportError(__FILE__, __LINE__); \
 return(FALSE); \
 }\
 else
	ReportError(char *strFILE, unsigned uLINE)
	 {
	 fflush(stdout);
	 fprintf(stderr, “Assertion failure: file %s, line %d\n”, strFILE, uLINE);
	 fflush(stderr);
	 exit(1);
	 }

Debug Time Assertion Tips

Debug time assertions are <u>not</u> used to catch errors that can occur in practice

Example:

```
char *strdup (char *str)
{
char *strnew;

/* CORRECT: tests for illegal condition that should never occur.*/
DebugAssert(str != NULL);

strnew = (char *)malloc(strlen(str)+1);

/* WRONG: tests for error condition what will occur in practice and should be handled. */
DebugAssert(strnew !=NULL);
…
```

Debug Time Assertion Tips

Debug-time assertions MUST NOT

- **disturb memory**
- **initialize data**
- **have ANY side effects**

WRONG:	**RIGHT:**
`DebugAssert ((x/=2) > 0);`	`x/=2;` `DebugAssert ((x) > 0);`

Assertion Tips

Comment your assertions: what bug are they checking for, what should the programmer try instead

The programmer that fires your assertion may assume the assertion is erroneous, otherwise

Example of commented assertion

```
/* Do source and destination blocks overlap? Use memmove. */
DebugAssert( (pbTo >= pbFrom + size) || (pbFrom >= pbTo + size));
```

Example of assert.h from SunOS /usr/include

```
# ifndef NDEBUG
# define _assert(ex)    {if (!(ex)){(void)fprintf(stderr,"Assertion failed: file \"%s\", line
%d\n", __FILE__, __LINE__);exit(1);}}
# define assert(ex)     _assert(ex)
# else
# define _assert(ex)
# define assert(ex)
# endif
```


Design Error-Resistant Interfaces

In safety critical systems, most accidents occur due to interface errors

Assume that:

- **Your functions will be called with erroneous arguments**
- **Your error codes will be ignored**
- **Functions you call will produce errors**

Design Error-Resistant Interfaces

Use strong function prototypes

WRONG:

```
void *memchr ( const void *pv, int ch, int size);
/* easy for caller to swap character and size args without compiler warning */
```

RIGHT:

```
void *memchr ( const void *pv, unsigned char ch, size_t size);
/* no way, now. */
```

Design Error-Resistant Interfaces

Don’t bury error codes in return values: make it hard to ignore them

WRONG:	RIGHT:

char c:
….
c=getchar();
if (c == EOF)
{ end of file processing }
else
{ character processing }
…
	char c:
	...
	BOOL fgetchar (char *pch) /* function prototype */
	…
	if(fgetchar (&c))
	{c has character}
	else
	{EOF and c is unchanged}

Design Error-Resistant Interfaces

Don’t write multipurpose functions

- Complex code paths are hard to test
- It is hard to validate all input argument combinations using assertions
- Egregious example: realloc

Use simple functions

- Simple function names
- Simple code paths
- Make each input and output represent exactly one type of data
- Easy for caller to understand simple functions
- Easier to validate arguments using rigid assertions

Design Error-Resistant Interfaces

Make code intelligible at the point of call

Document calling example and emphasize potential hazards

Encourage programmer to cut and paste your recommended usage

Example

```
/* realloc (void *pv, size_t size)
* typical use:
* void *pvnew; //  used to protect pv if realloc fails
* pvNew = realloc(pv, sizeNew);
* if (pvNew != NULL) {
* //success…update pv
* pv = pvNew;
* }
* else
* \\failure – don't destroy pv with the NULL pvNew
* /
void *realloc(void *pv, size_t size)
…
```

Design Error-Resistant Interfaces

Don't pass data in global or static memory

- **Callers up or down the calling chain may be using or may clobber the data**

Don't use caller's input buffers as a workspace

- **You don't really know how big they are or whether you can modify them**

Use assertions to validate function arguments

Avoid Boolean arguments

- **Easy to forget what "TRUE" means**
- **Easy for a fault to toggle TRUE and FALSE (NORAD fault)**

Avoid Memory Theft

Don’t reference memory you don’t own or have freed

- Especially memory-mapped I/O

Don’t reference memory that you think you have locked but don’t

- This gave the SVR4 MP porters fits

Techniques

- 0xdeadbeef and 0xfeedbabe memory
- Use robust data structures and structure marking
- Perform BOTH allocation and deallocation on same side of interface

Make the Compiler Work for You

- Enable all optional compiler warnings, including “require prototypes for all functions”
- Enable subscript range checking where possible
  - Leave on in ship code if possible
- Use lint
- Tolerate no compiler warnings
- Turn off all compiler optimizations in debug version to facilitate single-stepping through code
  - There are probably more bugs in your code than in the compiler
  - However, gcc optimization does provide some additional error checking for “uninitialized variable” and “return without value” errors

Avoid Risky Coding Style

Use well-defined data types: rely only on what the ANSI standard specifically guarantees to be portable

char	**0 .. 127**
signed char	**-127 .. 127**
unsigned char	**0 .. 255**
	Unknown size, but no smaller than 8 bits
short	**-32767 .. 32767**
signed short	**-32767 .. 32767**
unsigned short	**0 .. 65535**
	Unknown size, but no smaller than 16 bits
int	**-32767 .. 32767**
signed int	**-32767 .. 32767**
unsigned int	**0 .. 65535**
	Unknown size, but no smaller than 16 bits
long	**-2147483647 .. 2147483647**
signed long	**-2147483647 .. 2147483647**
unsigned long	**0 .. 2147483647**
	Unknown size, but no smaller than 32 bits
int i : n	**0 .. $(2^{(n-1)} -1)$**
signed int i : n	**$-(2^{(n-1)} -1)$ .. $(2^{(n-1)} -1)$**
unsigned int i : n	**0 .. $(2^{(n-1)} -1)$**
	Unknown size, but at least n bits

Avoid Risky Coding Style

Look for underflows and overflows of variables

Avoid risky idioms

Don’t mix operator types

- If you must, use ( )’s to enforce precedence and type
- If you have to look up precedence in the manual, use ( )’s

Write boring code that is legible by the average programmer

Tight C does not guarantee efficient machine code; it does guarantee subsequent confusion

- We read code more often than we write it

Try Hungarian Notation

Makes it possible to identify types as you read the code without seeing the variable declaration

a	array
f	boolean flag
b	byte
ch	char
dw	dword
h	handle
l	long
lp	long pointer
n	int
p	pointer
w	word

Variable name = prefix + Descriptive name

Examples: pchTo, phObjHandle, pbNew, phObjHandle->length

Software Development Hygiene

Single-step through every code path of all new or modified code

- Focus on data flow and state transformations

Don’t clean up old code unless absolutely necessary

Don’t implement nonstrategic or unnecessary features

Don’t implement “free” features

Don’t implement unnecessary flexibility

Error Handling and Reporting Principles

Always check for error codes returned by procedures and functions

Use common, gathered cleanup paths

Ensure that locks are released and memory is deallocated before calling error handling routine that may exit

Keep recovery code simple (remember the VOS outage data?)

Concurrent Programming

Concurrent programming is difficult to get right and difficult to debug

Don’t use concurrency unless you have to

Identify the benefits of concurrency before you use it

Avoid gratuitous nondeterminacy; it’s going to be hard enough to debug already

Don’t confuse semaphores with condition variables

Concurrent Programming

Learn concurrent programming from a good book

- **Concurrent Programming, Andrews**
- **Concurrent Systems, Bacon**
- **Multithreaded Programming with Windows NT, Pham and Garg**

Use or build a library of standard concurrent programming primitives

- **Semaphores, monitors / condition variables**
- **Ad hoc devices are almost certainly buggy, offer incomplete semantics, or are very hard to use**

Testing

People are optimists and test to show that code does work

Most programmers quit testing when 60% of the code has been tested

Write and test code in small chunks as they are completed

Try to test under conditions that approximate reality

Fix bugs as you find them, not later

Use code coverage tool to grade testing effectiveness

Test all error handling and recovery (remember the VOS outage data?)

- It doesn’t get used very often
- It doesn’t get used unless there is already a problem
- It is hard to test

Eliminate Random Behavior, at Least in Debug Version

Force bugs to be reproducible

- **0xfeedbabe newly allocated memory**
- **0xdeadbeef newly deallocated memory**

Make sure routines can be made to produce same output for same input so regression testing will work

- **Be able to freeze dates, timestamps, random numbers, etc.**

Augment data structures with auditable structures and logs

- **Be careful to ensure that logs and auditing do not cause behavior of debug version to differ from ship version**
- **Unless you want to use auditable data structures in the ship version**

Inspections

Inspection definition:

- **Group evaluation of a work product for the purpose of finding defects**

Inspections are:

- **Formal: Well-defined roles, responsibilities, and procedures**
  - **Documented in Stratus SED-2014, *Work Product Inspection Procedure***
- **Flexible: Applicable to all types of work products**
  - **Specs, designs, code, test plans, …**
- **Economical: Allow defects to be uncovered and removed early in the process when they are easier and cheaper to fix**
- **Efficient: Structured nature of inspections ensures that time is spent productively**

Inspections

Inspections are NOT:

- **Brainstorming sessions to find solutions to problems**
- **Performance review of author of the inspected work product**

Inspection Process (1)

Planning

- **Identify author, moderator, recorder, inspectors and allocate their time**

Setup

- **Distribute materials and book the room**

Preparation

- **Inspectors review work product and record all defects**
- **1:1 to 2:1 ratio preparation time to meeting time is appropriate**

The Meeting

- **Walk through work product and record / classify defects and issues**
- **4 possible outcomes: approved, not approved, conditional approval, and inspection incomplete**

Inspection Process (2)

Reporting

- **Written and distributed by moderator summarizing the inspection**

Rework

- **Author owns all defects and is responsible for addressing each**

Verification

- **If conditionally approved, verifier is appointed to confirm that defects have been addressed**

Analysis

- **Analyze results to see if process can be improved**
- **Provide statistics to show effectiveness of the process, provide planning data, demonstrate quality achievements, demonstrate productivity gains, etc.**
- **Can lead to checklist updates, process changes, documentation changes, training plans, etc.**

Inspection Productivity

IBM, 1975

Inspecting test plans, test designs, and test cases reduced unit test time by up to 85%

Imperial Chemical Industries, 1982

Program maintenance effort was 0.6 minutes/line/year for inspected code, 7 minutes/line/year for uninspected code

ICL, 1986

1.58 person-hours cost to find defect in inspection, 8.47 person-hours cost to find detect in test

Stratus Continuum Languages Group, 1995

Inspection time / total project time = 10%

64% of all defects were found in inspection

Total inspection cost = cost of fixing 61 field bugs

Many More Techniques are Available

Process Improvements

Formal Specification and Verification

Structured exception handling

...

These techniques can be added to future courses as needed

Feel free to call on me at any time during your career at Stratus for consultation on using paranoid programming in your jobs

Recommended Reading

Your course papers

Software Fault Tolerance, by Michael Lyu, Ed.

Safeware, by Nancy Leveson

Safer C, by Les Hatton

Proceedings of the IEEE Fault Tolerant Computing Symposia

C Traps and Pitfalls, by Andrew Koenig

Writing Solid Code, by Steve Maguire

www.rstcorp.com

List of Course Papers

"Fault Tolerance in Commercial Computers," D. Siewiorek, *IEEE Computer*, July 1990.

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"Ariane 5 Flight 501 Failure Report by the Inquiry Board," J. Lions, July 1996, http://www.esrin.esa.it/htdocs/tidc/Press/Press96/ariane5rep.html.

"Dependable Computing and Fault Tolerance: Concepts and Terminology," J.-C. Laprie, *Proceedings of the 15th International Symposium on Fault Tolerant Computing*, June 1985.

"Software Implemented Fault Tolerance: Technologies and Experience," Y. Huang and C. Kintala, *Proceedings of the 23rd International Symposium on Fault Tolerant Computing*, June 1993.

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"System Structure for Software Fault Tolerance," B. Randell, *IEEE Transactions on Software Engineering*, Vol. 1, No. 2, February 1990.

"Why Do Computers Stop and What Can Be Done About It?," J. Gray, Tandem Computers Technical Report 85.7, June 1985.

"Fault Tolerance by Design Diversity: Concepts and Experiments," A. Avizienis and J. Kelly, *IEEE Computer*, August 1984.

"The N-Version Approach to Fault Tolerant Software," A. Avizienis, *IEEE Transactions on Software Engineering*, December 1985.

"Redundancy in Data Structures: Improving Software Fault Tolerance," D. Taylor et. al., *IEEE Transactions on Software Engineering*, November 1980.

"A Compendium of Robust Data Structures," J. P. Black et. al., *Proceedings of the 11th International Symposium on Fault Tolerant Computing*, June 1991.

"Design of a Portable Control-Flow Checking Technique," Z. Alkhalifa and V. Nair, *Proceedings of the High Assurance Systems Engineering Workshop*, August 1997.

"Designing Highly Available Cluster Applications," J. Foxcroft, *Proceedings of the 1996 InterWorks Conference*, http://www.interworks.org/conference/IWorks96/sessions/apps4HAabs.html.

