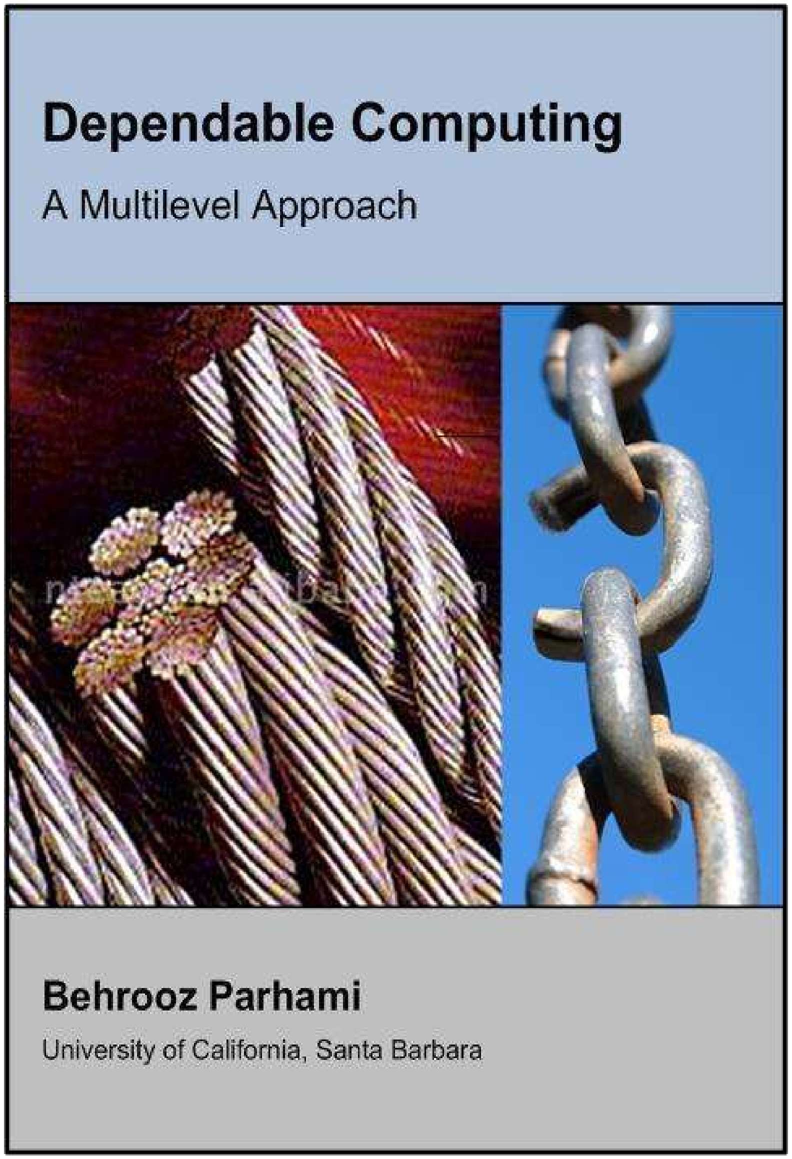
Dependable Computing

A Multilevel Approach

Behrooz Parhami

University of California, Santa Barbara

STRUCTURE AT A GLANCE

Part I — Introduction: Dependable Systems (The Ideal-System View)	Goals Models	1. Background and Motivation 2. Dependability Attributes 3. Combinational Modeling 4. State-Space Modeling
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Part VII — Failures: Computational Breaches (The Result-Level View)	Methods Examples	25. Failure Confinement 26. Failure Recovery 27. Agreement and Adjudication 28. Fail-Safe System Design

Appendix: Past, Present, and Future

About This Presentation

This presentation is intended to support the use of the textbook *Dependable Computing: A Multilevel Approach* (traditional print or on-line open publication, TBD). It is updated regularly by the author as part of his teaching of the graduate course ECE 257A, Fault-Tolerant Computing, at Univ. of California, Santa Barbara. Instructors can use these slides freely in classroom teaching or for other educational purposes. Unauthorized uses, including distribution for profit, are strictly prohibited.

Edition	Released	Revised	Revised	Revised	Revised
First	Sep. 2006	Oct. 2007	Nov. 2009	Nov. 2012	Nov. 2013
		Feb. 2015	Nov. 2015	Nov. 2018	Nov. 2019
		Nov. 2020			

21 Degradation Allowance

“Redundancy is such an ugly word. Let’s talk about your ‘employment crunch’.”

“I always give 110% to my job. 40% on Monday, 30% on Tuesday, 20% on Wednesday, 15% on Thursday, and 5% on Friday.”

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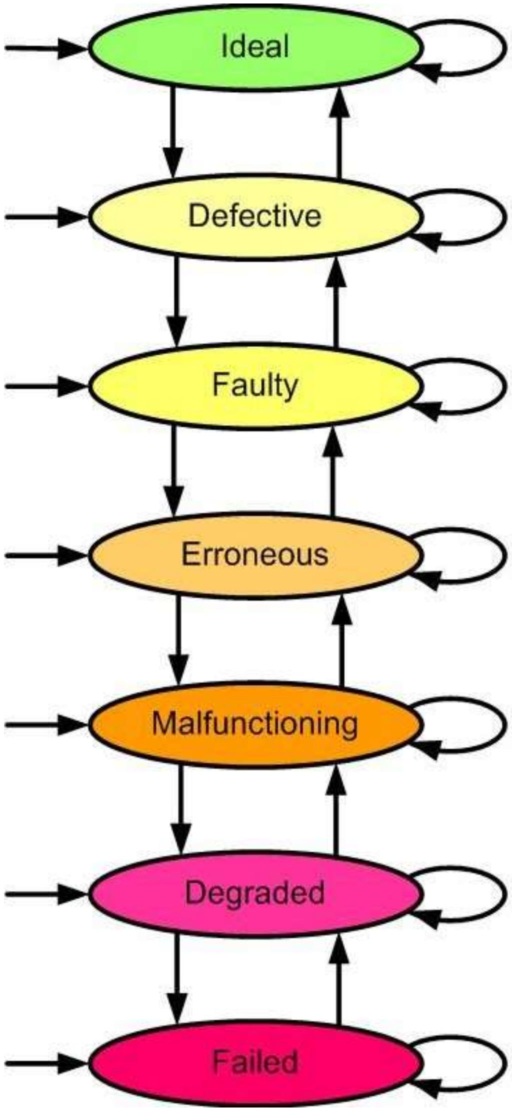
Appendix: Past, Present, and Future



21.1 Graceful Degradation

Terminology:	n.	Graceful degradation
	adj.	Gracefully degrading/degradable = fail-soft

Strategies for failure prevention

1. Quick malfunction diagnosis
2. Effective isolation of malfunctioning elements
3. On-line repair (preferably via hot-pluggable modules)
4. Avoidance of catastrophic malfunctions

Degradation allowance

Diagnose malfunctions and provide capability for the system to work without the modules which are malfunctioning

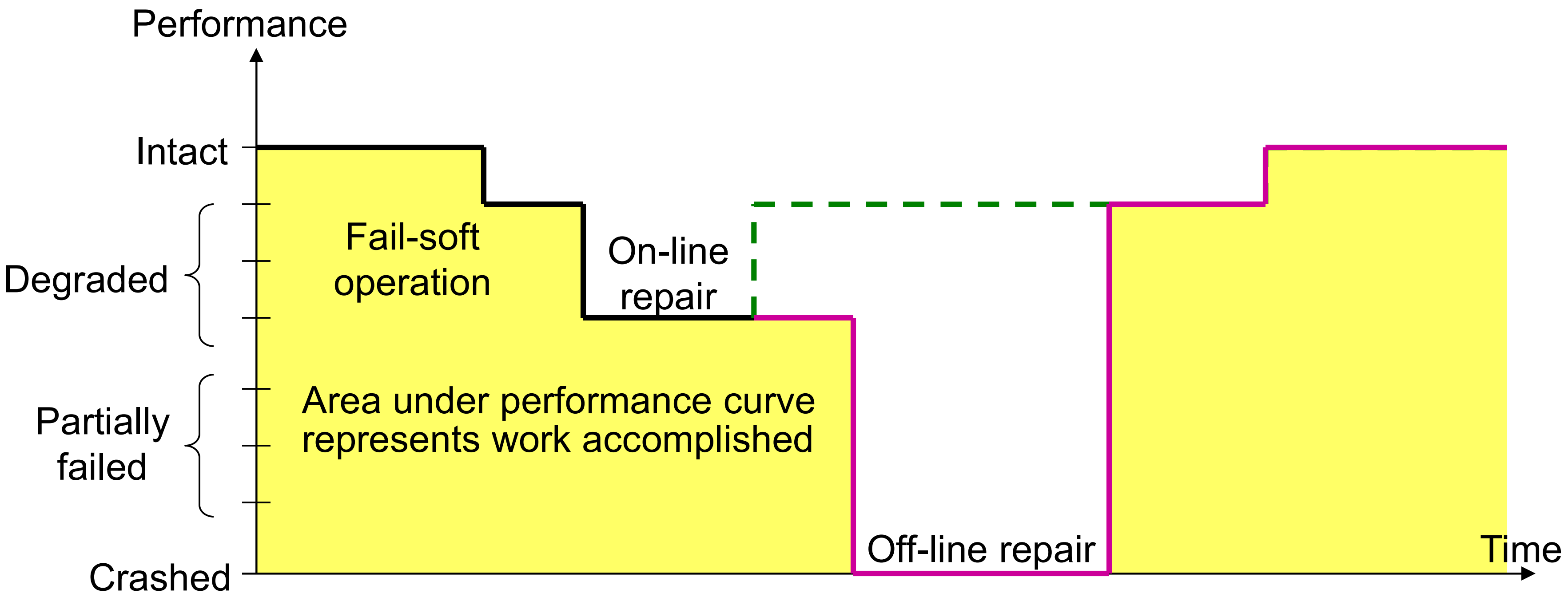
Degradation management

Adapt: Prioritize tasks and redistribute load
Monitor: Keep track of system operation in degraded mode
Reverse: Return system to the intact (or less degraded) state ASAP
Return: Go back to normal operation

Degradation Allowance Is Not Automatic

A car possessing extra wheels compared with the minimum number required does not guarantee that it can operate with fewer wheels

Performability of a Fail-Soft System

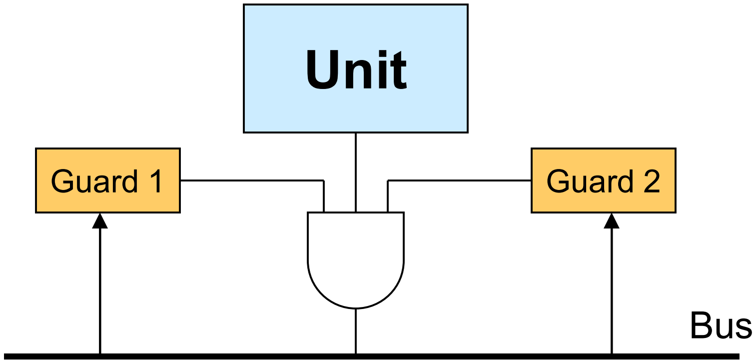


On-line repair: Done by removal/replacement of affected modules in a way that does not disrupt the operation of the remaining system parts

Off-line repair: Involves shutting down the entire system while affected modules are removed and replacements are plugged in

21.2 Diagnosis, Isolation, and Repair

Diagnose the malfunction



Remove the malfunctioning unit
- Update system (OS) tables
- Physical isolation?
- Initiate repair, if applicable

Create new working configuration
- Exclude processor, channel, controller, I/O device (e.g., sensor)
- Avoid bad tracks on disk, garbled files, noisy communication links
- Remove parts of the memory via virtual address mapping
- Bypass a cache or use only half of it (more restricted mapping?)

Recover processes and associated data
- Recover state information from removed unit
- Initialize any new resource brought on-line
- Reactivate processes (via rollback or restart)

Additional steps needed to return repaired units to operating status

21.3 Stable Storage

Storage that won’t lose its contents (unlike registers and SRAM/DRAM)

Possible implementation method: Battery backup for a time duration long enough to save contents of disk cache or other volatile memory

Flash memory

Combined stability & reliability can be provided with RAID-like methods

Malfunction-Stop Modules

Malfunction tolerance would be much easier if modules simply stopped functioning, rather than engage in arbitrary behavior

Unpredictable (Byzantine) malfunctions are notoriously hard to handle

Assuming the availability of a reliable stable storage along with its controlling s-process and (approximately) synchronized clocks, a *k*-malfunction-stop module can be implemented from *k* + 1 units

Operation of s-process to decide whether the module has stopped:

```
$R$ := bag of received requests with appropriate timestamps
if $|R| = k+1 \wedge$ all requests identical and from different sources $\wedge \neg stop$
then if request is a write
        then perform the write operation in stable storage
        else if request is a read, send value to all processes
else set variable $stop$ in stable storage to TRUE
```

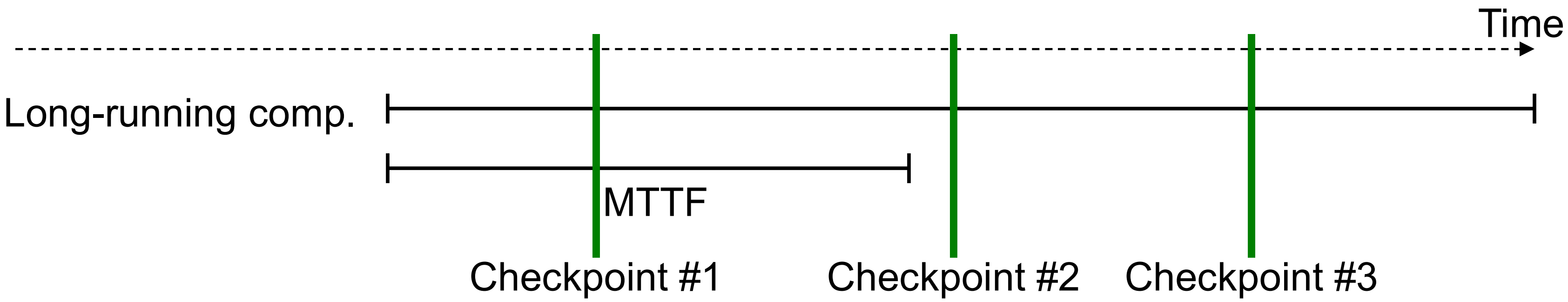
21.4 Process and Data Recovery

Use of logs with process restart

Impossible when the system operates in real time and performs actions that cannot be undone

Such actions must be compensated for as part of degradation management

21.5 Checkpointing and Rollback



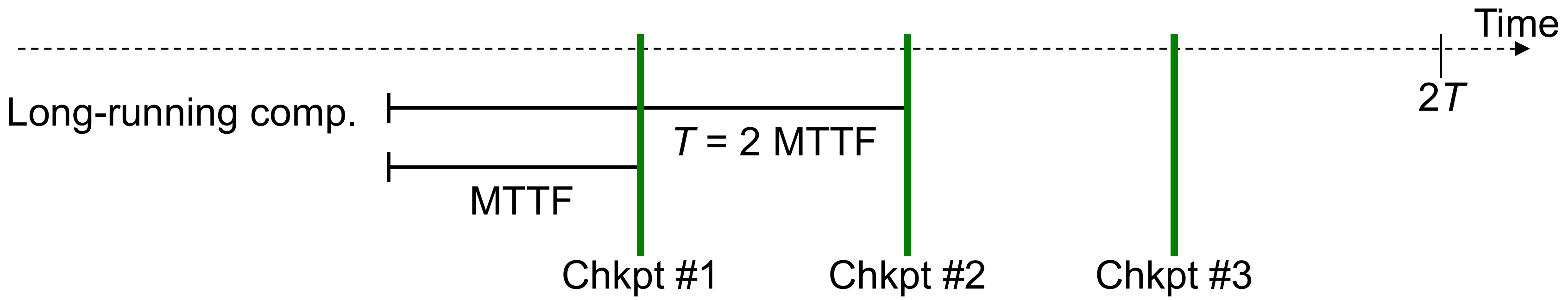
If MTTF is shorter than the running time, many restarts may be needed

Early computers had a short MTTF
It was impossible to complete any computation that ran for several hours

Checkpoints are placed at convenient points along the computation path (not necessarily at equal intervals)

Checkpointing entails some overhead
Too few checkpoints would lead to a lot of wasted work
Too many checkpoints would lead to a lot of overhead

Why Checkpointing Helps



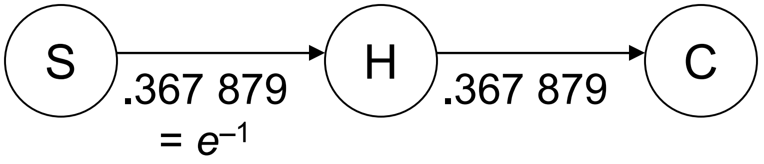
A computation's running time is T = 2 MTTF = $2/\lambda$. What is the probability that we can finish the computation in time $2T$:

a. Assuming no checkpointing

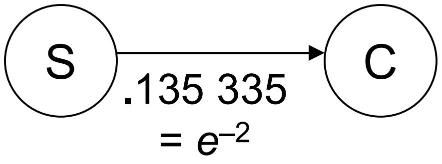
b. Assuming checkpointing at regular intervals of $T/2$

Ignore all overheads.

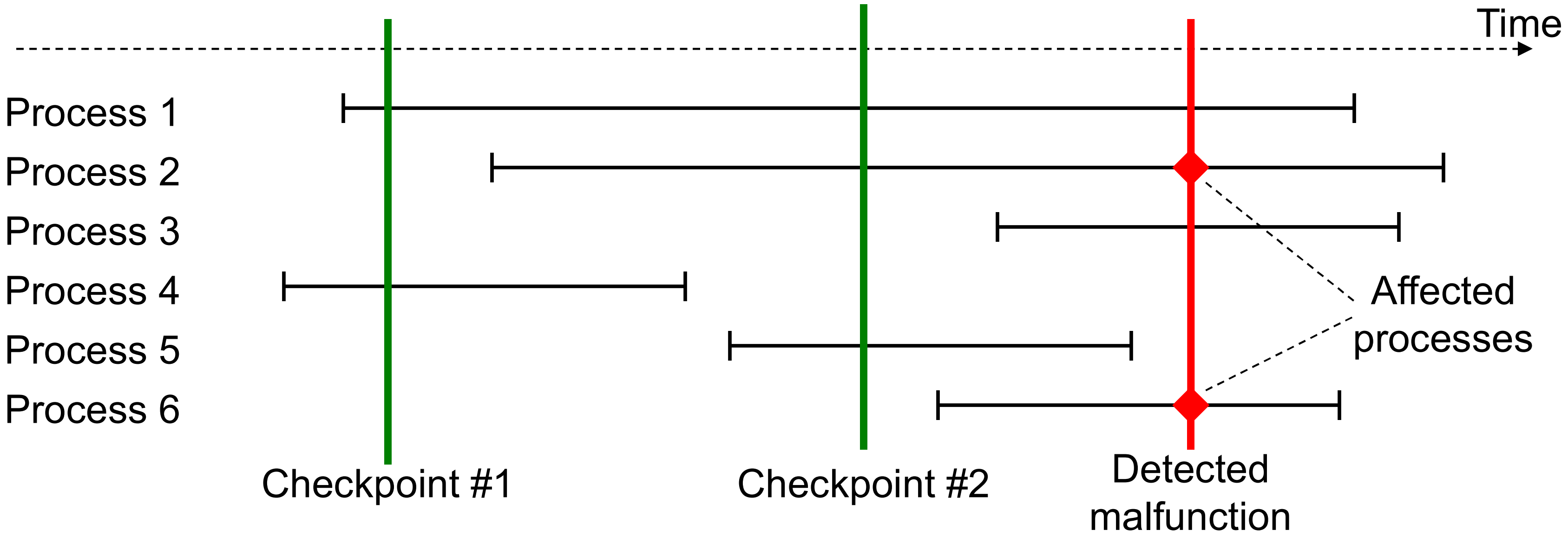
47% success probability



25% success probability



Recovery via Rollback



Roll back process 2 to the last checkpoint (#2)
Restart process 6

Rollback or restart creates no problem for tasks that do I/O at the end
Interactive processes must be handled with more care
  e.g., bank ATM transaction to withdraw money or transfer funds
  (check balance, reduce balance, dispense cash or increase balance)

Checkpointing for Data

Consider data objects stored on a primary site and *k* backup sites
(with appropriate design, such a scheme will be *k*-malfunction-tolerant)

Each access request is sent to the primary site
Read request honored immediately by the primary site
One way to deal with a write request:
  Update requests sent to backup sites
  Request is honored after all messages ack'ed

Alternative:
Primary site does
frequent back-ups

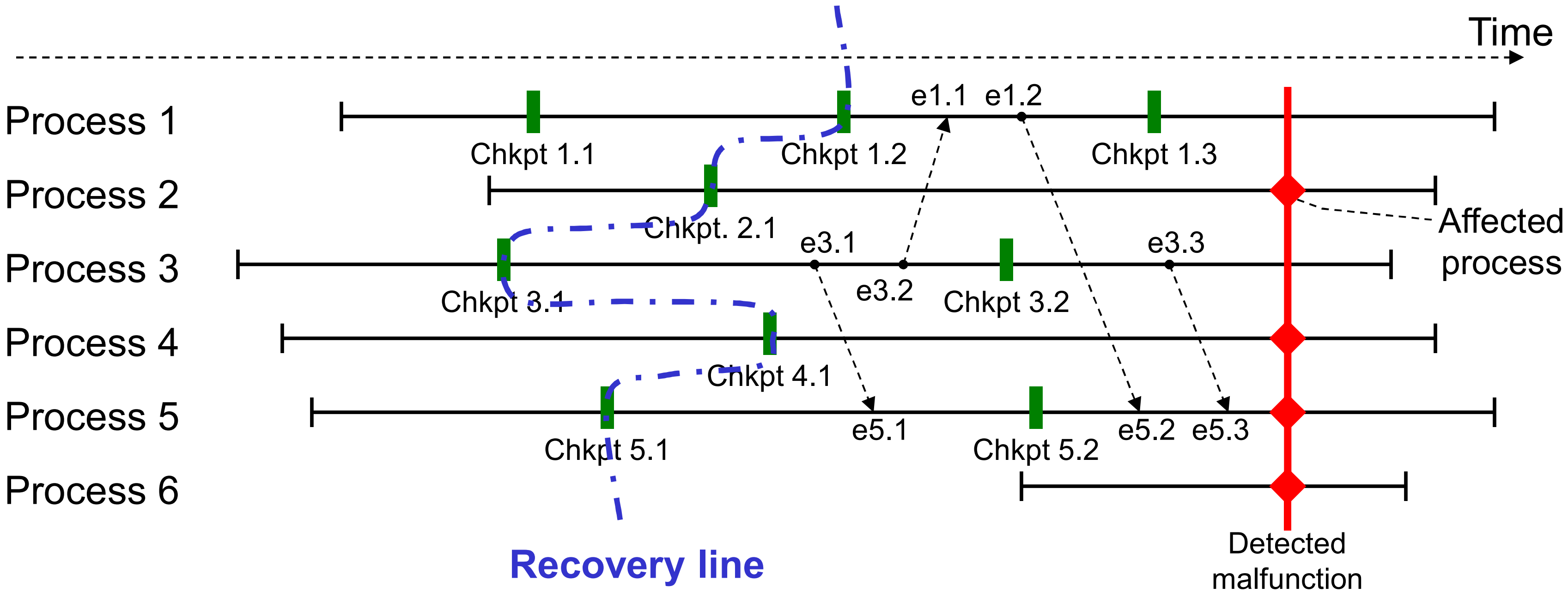
If one or more backup sites malfunction, service is not disrupted
If the primary site malfunctions, a new primary site is "elected"
  (distributed election algorithms exist that can tolerate malfunctions)

Analysis by Huang and Jalote:

	Time in state:
Normal state (primary OK, data available)	
Recovery state (primary site is changing)	
Checkpoint state (primary doing back-up)	↑fn of *k*
Idle (no site is OK)	↓fn of *k*

k	Availability
0	0.922
1	0.987
2	0.996
4	0.997
8	0.997

Asynchronous Distributed Checkpointing



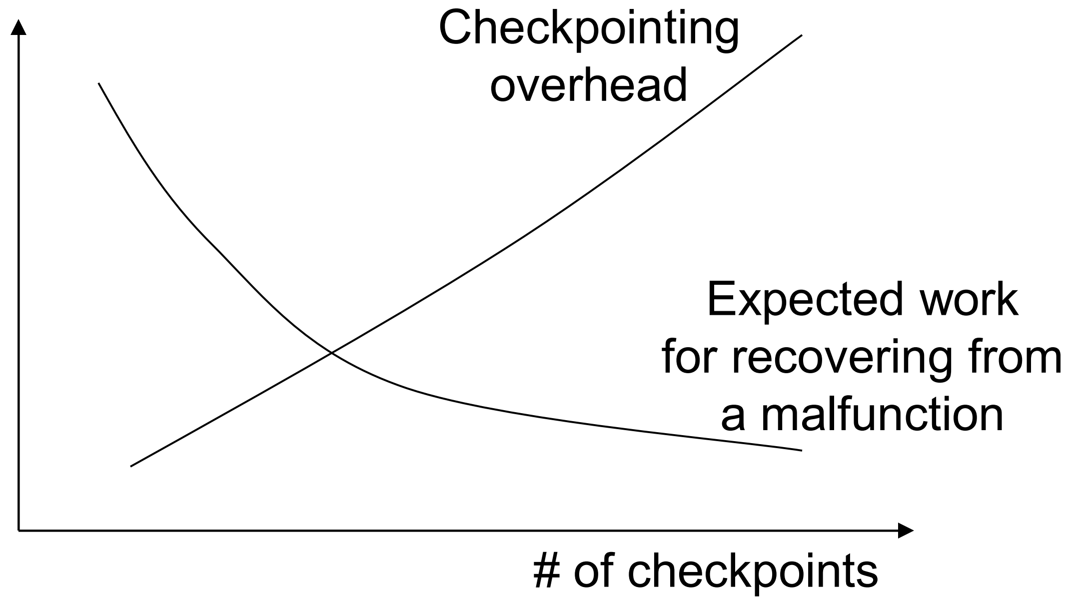
For noninteracting processes, asynchronous checkpoints not a problem

When one process is rolled back, other processes may have to be rolled back also, and this has the potential of creating a domino effect

Identifying a consistent set of checkpoints (*recovery line*) is nontrivial

21.6 Optimal Checkpoint Insertion

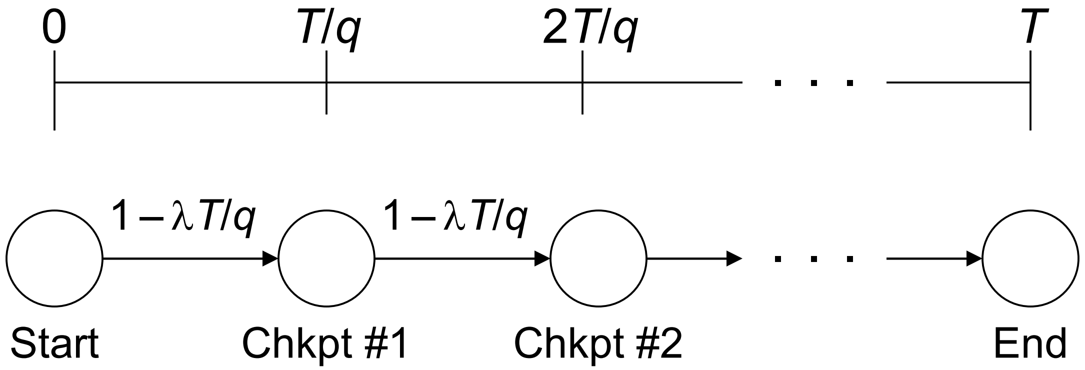
There is a clear tradeoff in the decision regarding checkpoints
Too few checkpoints lead to long rollbacks in the event of a malfunction
Too many checkpoints lead to excessive time overhead
As in many other engineering problems, there is a happy medium



Optimal Checkpointing for Long Computations

T = Total computation time without checkpointing
q = Number of computation segments; there will be $q - 1$ checkpoints
T_{cp} = Time needed to capture a checkpoint snapshot
λ = Malfunction rate

Discrete Markov model: Expected length of stay in each state $1/(1 - \lambda T/q)$, where time step is T/q



Computation time with checkpointing $T_{total} = T/(1 - \lambda T/q) + (q - 1)T_{cp}$

$$= T + \lambda T^2/(q - \lambda T) + (q - 1)T_{cp}$$

$$dT_{total}/dq = -\lambda T^2/(q - \lambda T)^2 + T_{cp} = 0 \quad \Rightarrow \quad q^{opt} = T(\lambda + \sqrt{\lambda/T_{cp}})$$

Example: $T = 200$ hr, $\lambda = 0.01$ / hr, $T_{cp} = 1/8$ hr

$q^{opt} = 200(0.01 + (0.01/0.25)^{1/2}) = 42$; $T_{total}^{opt} \approx 215$ hr

Warning: Model is accurate only when $T/q << 1/\lambda$

Elaboration on Optimal Computation Checkpoints

T = Total computation time without checkpointing (Example: 200 hr)
q = Number of computation segments; there will be $q - 1$ checkpoints
T_{cp} = Time needed to capture a checkpoint snapshot (Range: 1/8-10 hr)
λ = Malfunction rate (Example: 0.01 / hr)

Computation time with checkpointing $T_{total} = T + \overset{\text{Rollback}}{\lambda T^2/(q - \lambda T)} + \overset{\text{Checkpointing}}{(q - 1)T_{cp}}$

$dT_{total}/dq = -\lambda T^2/(q - \lambda T)^2 + T_{cp} = 0 \quad \Rightarrow \quad q^{opt} = T(\lambda + \sqrt{\lambda/T_{cp}})$
$d^2T_{total}/dq^2 = 2\lambda T^2/(q - \lambda T)^3 > 0 \Rightarrow$ Bowl-like curve for T_{total}, with a minimum

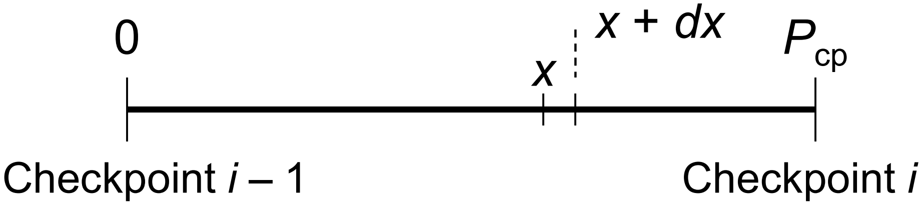
Example:

		q							
	T_{total}	4	6	8	10	20	30	40	50
T_{cp}	0	400	300	267	250	222	214	211	208
	1/8	400	301	267	251	225	218	215	214
	1/3	401	302	269	253	229	224	224	224
	1	403	305	274	259	241	243	250	257
	10	430	350	337	340	412	504	601	698

Optimal Checkpointing in Transaction Processing

P_{cp} = Checkpointing period
T_{cp} = Checkpointing time overhead (for capturing a database snapshot)
T_{rb} = Expected rollback time upon malfunction detection

Relative checkpointing overhead
$O = (T_{cp} + T_{rb}) / P_{cp}$



Assume that rollback time, given malfunction at time x, is $a + bx$
(b is typically small, because only updates need to be reprocessed)

$\rho(x)$: Expected rollback time due to malfunction in the time interval $[0, x]$

$\rho(x+dx) = \rho(x) + (a + bx)\lambda dx \Rightarrow d\rho(x)/dx = (a + bx)\lambda \Rightarrow \rho(x) = \lambda x(a + bx/2)$

$T_{rb} = \rho(P_{cp}) = \lambda P_{cp}(a + bP_{cp}/2)$

$O = (T_{cp}+T_{rb})/P_{cp} = T_{cp}/P_{cp} + \lambda(a + bP_{cp}/2)$ is minimized for: $P_{cp} = \sqrt{2T_{cp}/(\lambda b)}$

Examples for Optimal Database Checkpointing

$O = (T_{cp}+T_{rb})/P_{cp} = T_{cp}/P_{cp} + \lambda(a + bP_{cp}/2)$ is minimized for: $P_{cp} = \sqrt{2T_{cp}/(\lambda b)}$

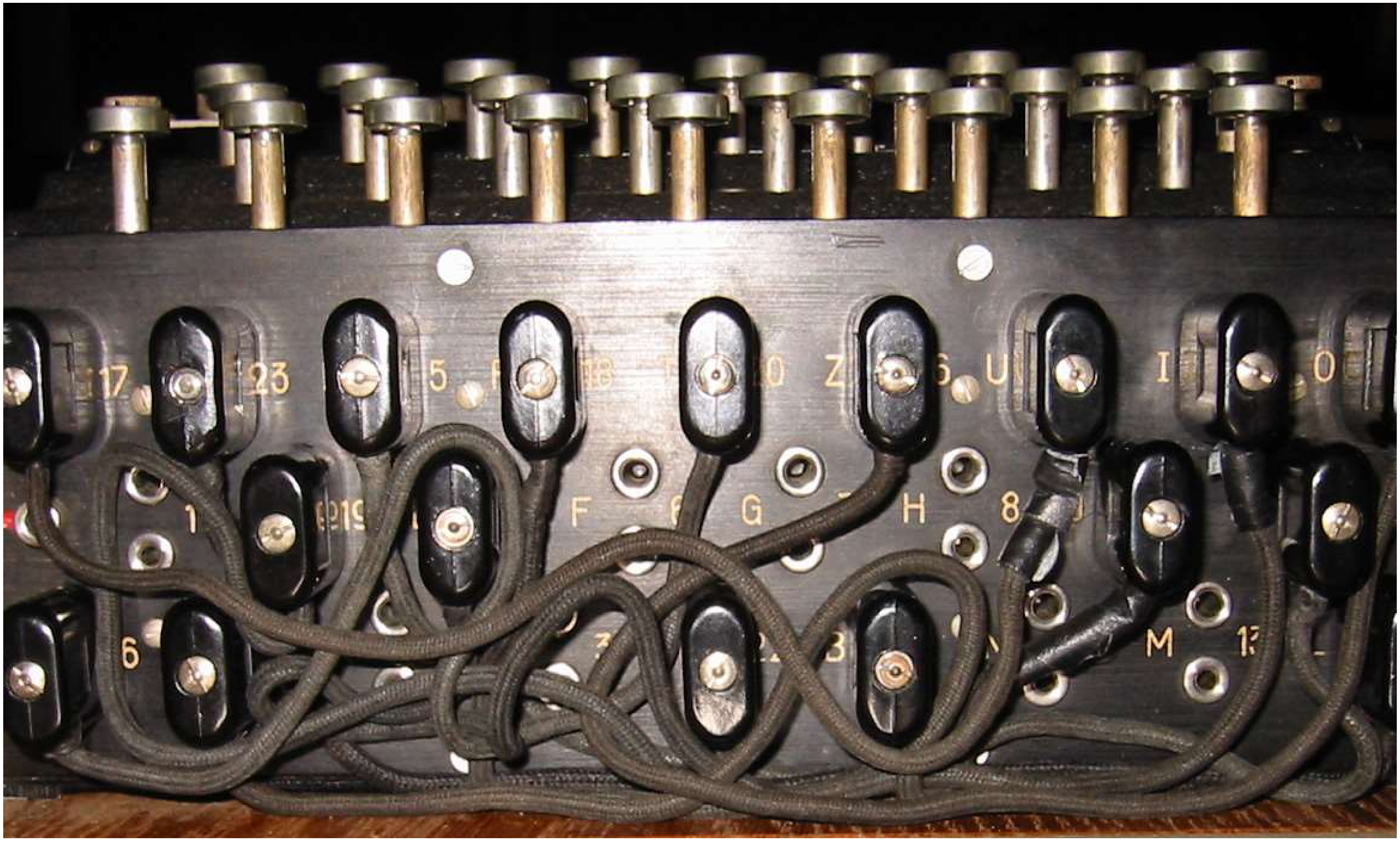
T_{cp} = Time needed to capture a checkpoint snapshot = 16 min
λ = Malfunction rate = 0.0005 / min (MTTF = 2000 min $\approx$ 33.3 hr)
$b = 0.1$

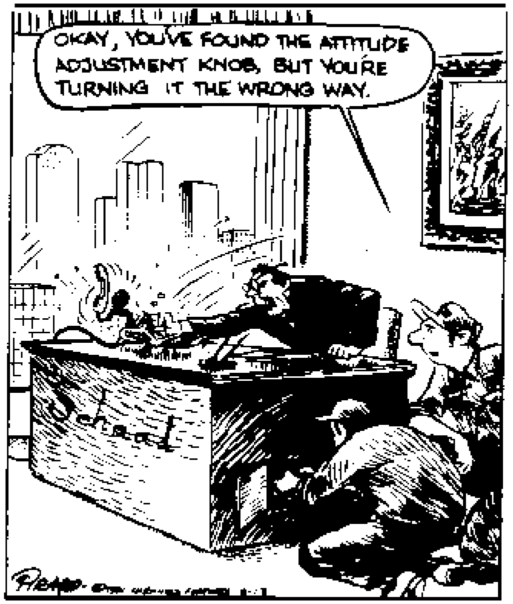
$P_{cp}^{opt} = \sqrt{2T_{cp}/(\lambda b)}$ = 800 min $\approx$ 13.3 hr

Suppose that by using faster memory for saving the checkpoint snapshots (e.g., disk, rather than tape) we reduce T_{cp} to 1 min

$P_{cp}^{opt} = \sqrt{2T_{cp}/(\lambda b)}$ = 200 min $\approx$ 3.3 hr

22 Degradation Management

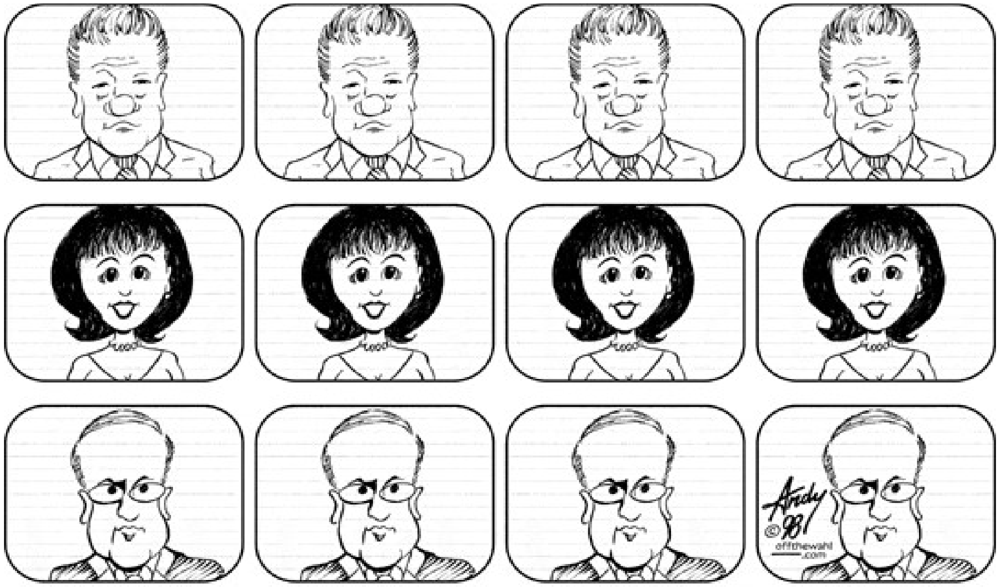




“.....and who's been messing with my desktop configuration?”

Wow! It works! My personalized configuration is up and running!

“Budget cuts.”



HONESTLY, WOULD HUMAN CLONING MAKE A DIFFERENCE?

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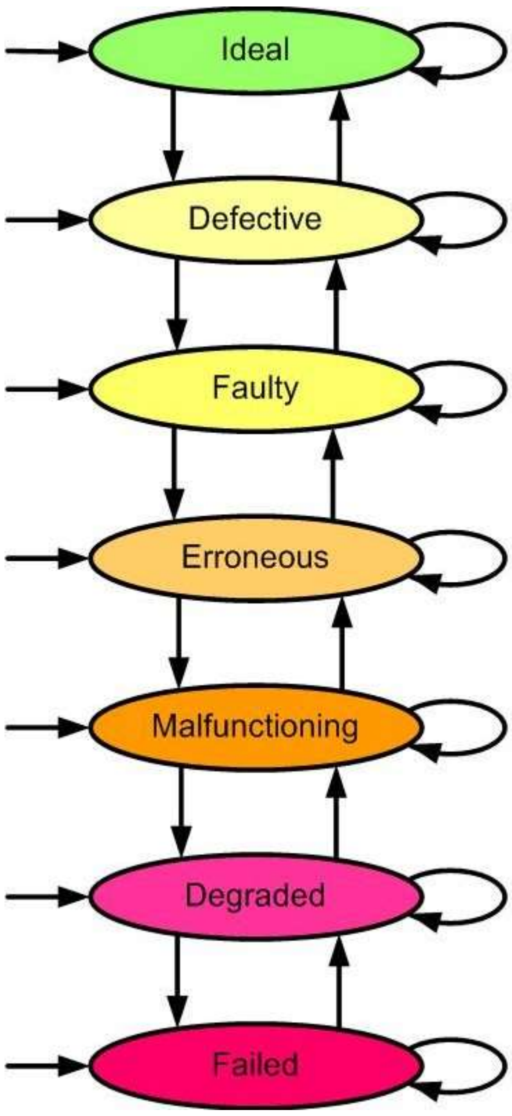
Appendix: Past, Present, and Future



22.1 Data Distribution Methods

Reliable data storage requires that the availability and integrity of data not be dependent on the health of any one site

Data Replication

Data dispersion

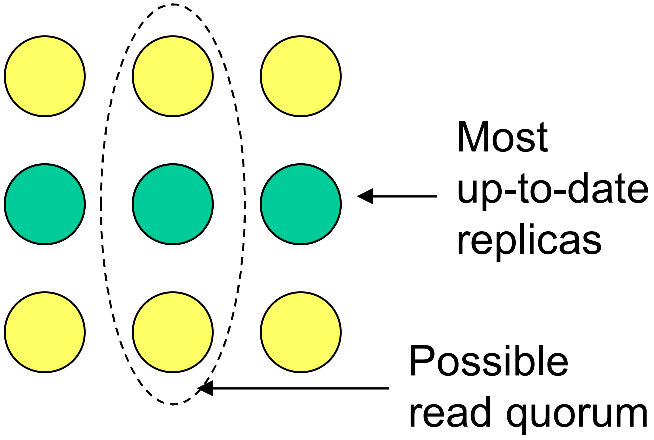
Data Replication

Resilient objects using the primary site approach

Active replicas: the state-machine approach
Request is sent to all replicas
All replicas are equivalent and any one of them can service the request
Ensure that all replicas are in same state (e.g., via atomic broadcast)

Read and write quorums

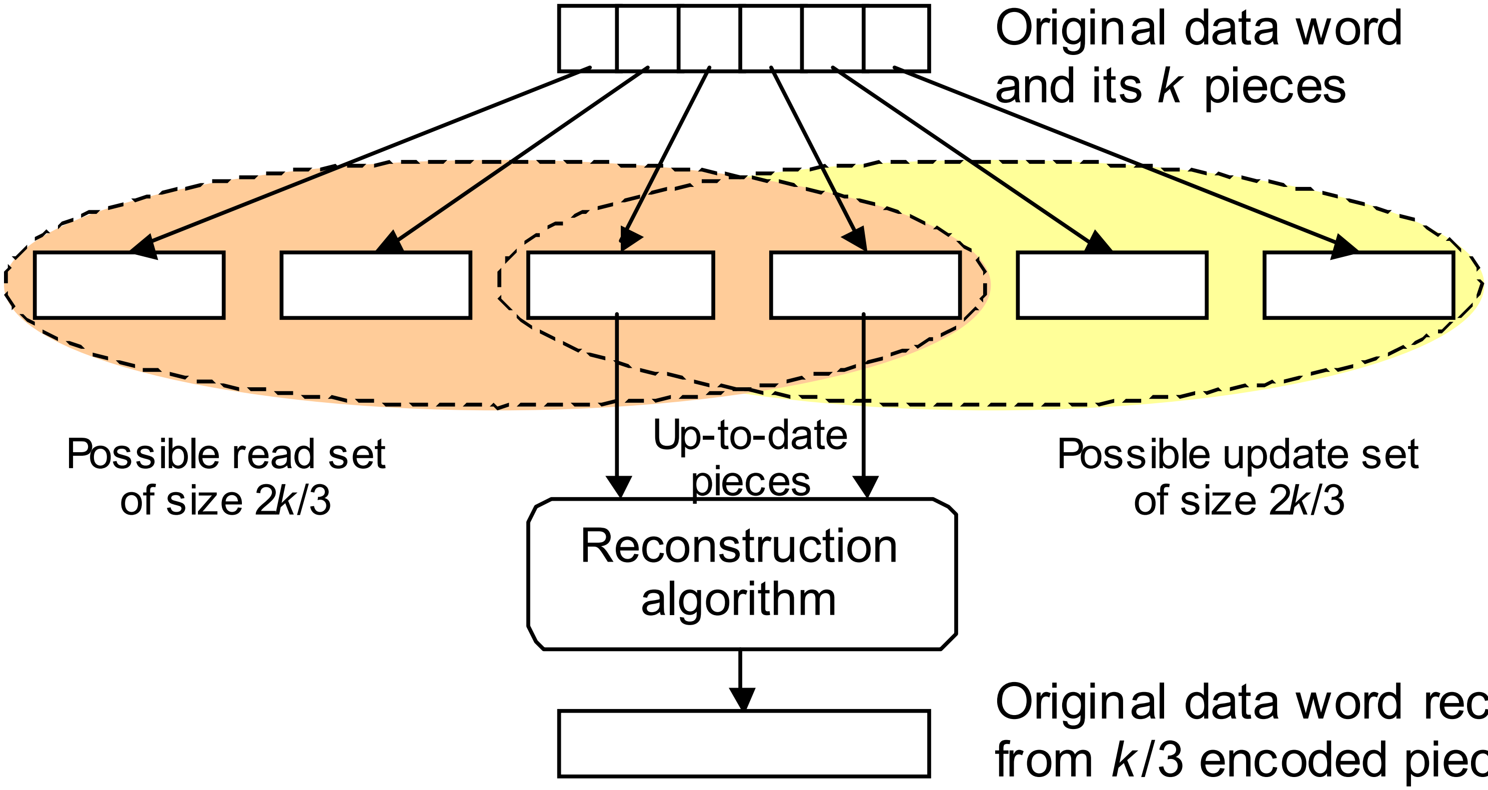
Example: 9 replicas, arranged in 2D grid
Rows constitute write quorums
Columns constitute read quorums
A read quorum contains the latest update



Maintaining replica consistency very difficult under Byzantine faults
Will discuss Byzantine agreement later

Data Dispersion

Instead of replicating data objects completely, one can divide each one into *k* pieces, encode the pieces, and distribute the encoded pieces such that any *q* of the pieces suffice to reconstruct the data



Original data word and its *k* pieces

The *k* pieces after encoding (approx. three times larger)

Possible read set of size 2*k*/3

Up-to-date pieces

Possible update set of size 2*k*/3

Reconstruction algorithm

Original data word recovered from *k*/3 encoded pieces

22.2 Multiphase Commit Protocols

The two generals problem: Two generals lead divisions of an army camped on the mountains on the two sides of an enemy-occupied valley

The two divisions can only communicate via messengers

We need a scheme for the generals to agree on a common attack time, given that attack by only one division would be disastrous

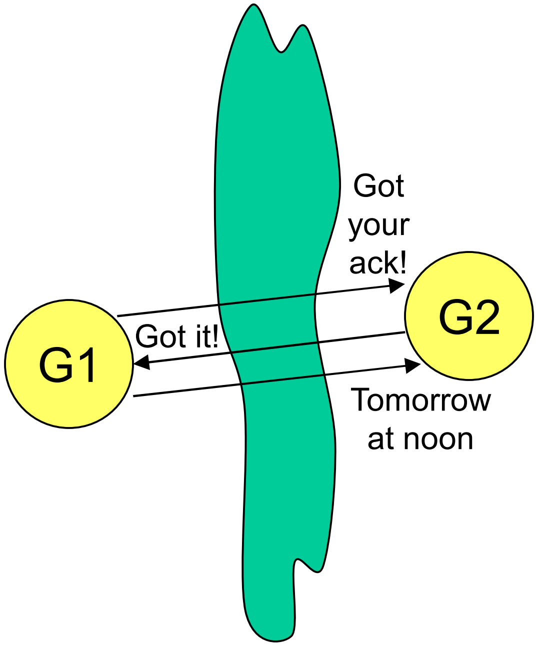
Messengers are totally reliable, but may need an arbitrary amount of time to cross the valley (they may even be captured and never arrive)

G1 decides on *T*, sends a messenger to tell G2

G2 acknowledges receipt of the attack time *T*

G2, unsure whether G1 got the ack (without which he would not attack), will need an ack of the ack!

This can go on forever, without either being sure



Maintaining System Consistency

Atomic action: Either the entire action is completed or none of it is done

One key tool is the ability to ensure atomicity despite malfunctions

Similar to a computer guaranteeing sequential execution of instructions, even though it may perform some steps in parallel or out of order

Where atomicity is useful:
Upon a write operation, ensure that all data replicas are updated
Electronic funds transfer (reduce one balance, increase the other one)

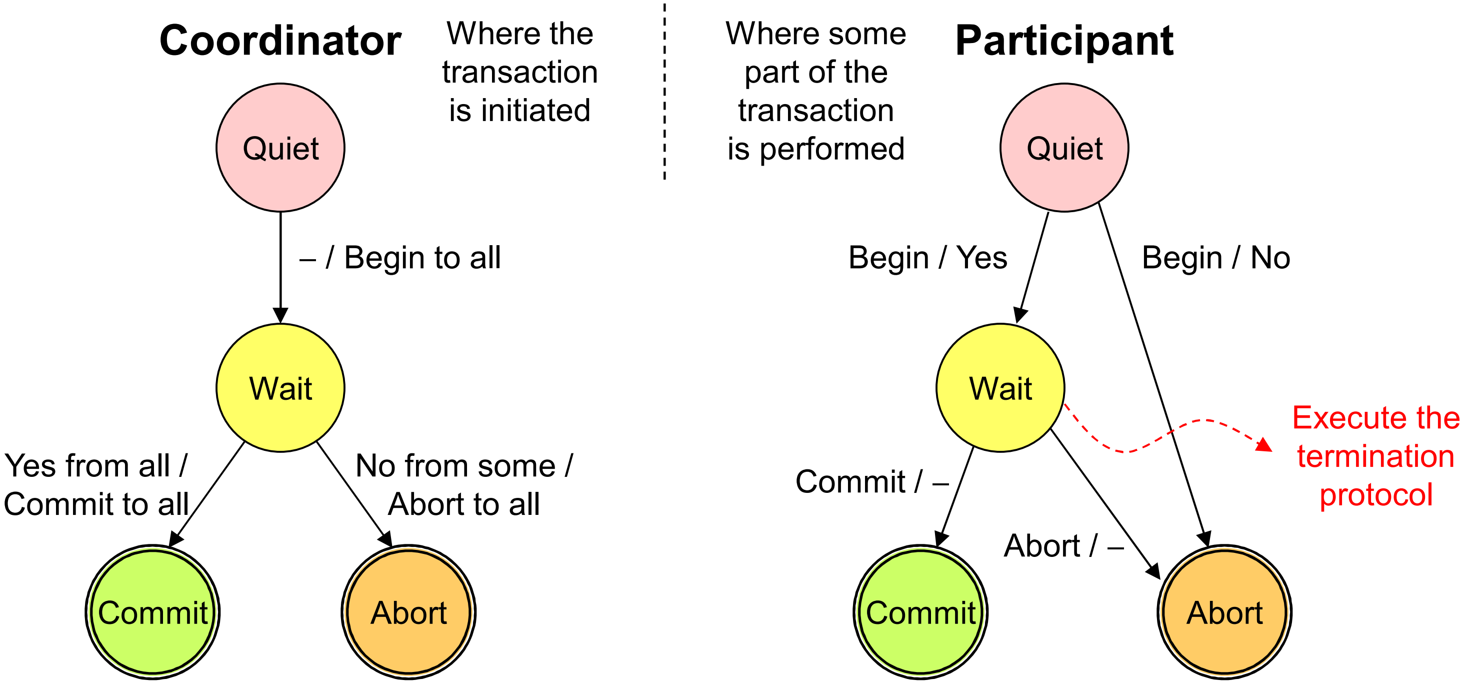
In centralized systems atomicity can be ensured via locking mechanisms

  Acquire (read or write) lock for desired data object and operation
  Perform operation
  Release lock

A key challenge of locks is to avoid deadlock (circular waiting for locks)

Two-Phase Commit Protocol

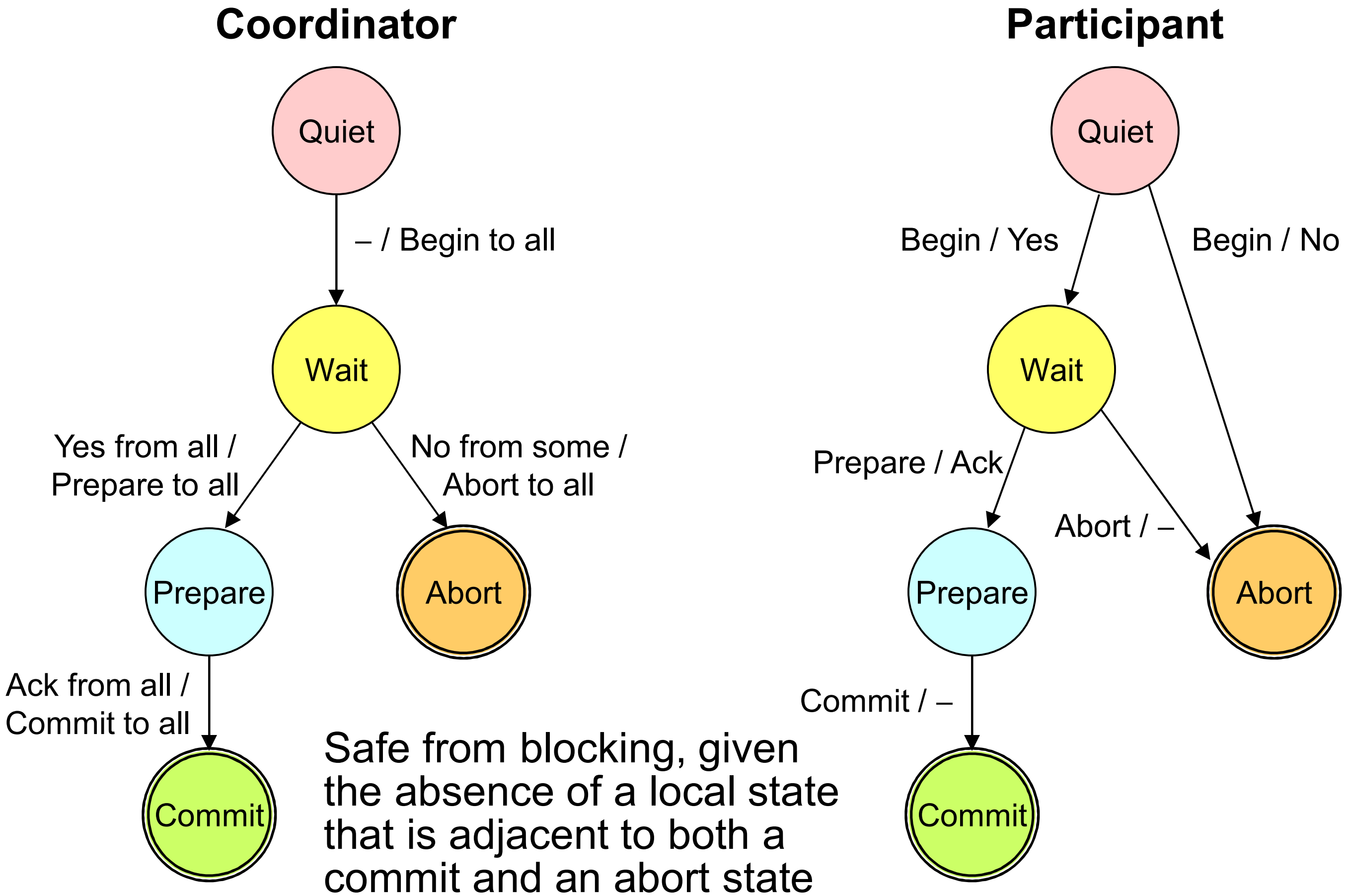
Ensuring atomicity of actions in a distributed environment



To avoid participants being stranded in the wait state (e.g., when the coordinator malfunctions), a time-out scheme may be implemented

Three-Phase Commit Protocol

Two-phase commit is a blocking protocol, even with timeout transitions



Safe from blocking, given the absence of a local state that is adjacent to both a commit and an abort state

22.3 Dependable Communication

Point-to-point message: encoding + acknowledgment + timeout

Reliable broadcast: message guaranteed to be received by all nodes

Forwarding along branches of a broadcast tree, with possible repetition (duplicate messages recognized from their sequence numbers)

Positive and negative acknowledgments piggybacked on subsequent broadcast messages (P broadcasts message m_1, Q receives it and tacks a positive ack for m_1 to message m_2 that it broadcasts, R did not receive m_1 but finds out about it from Q's ack and requests retransmit)

Atomic broadcast: reliable broadcast, plus the requirement that multiple broadcasts be received in the same order by all nodes (much more complicated to ensure common ordering of messages)

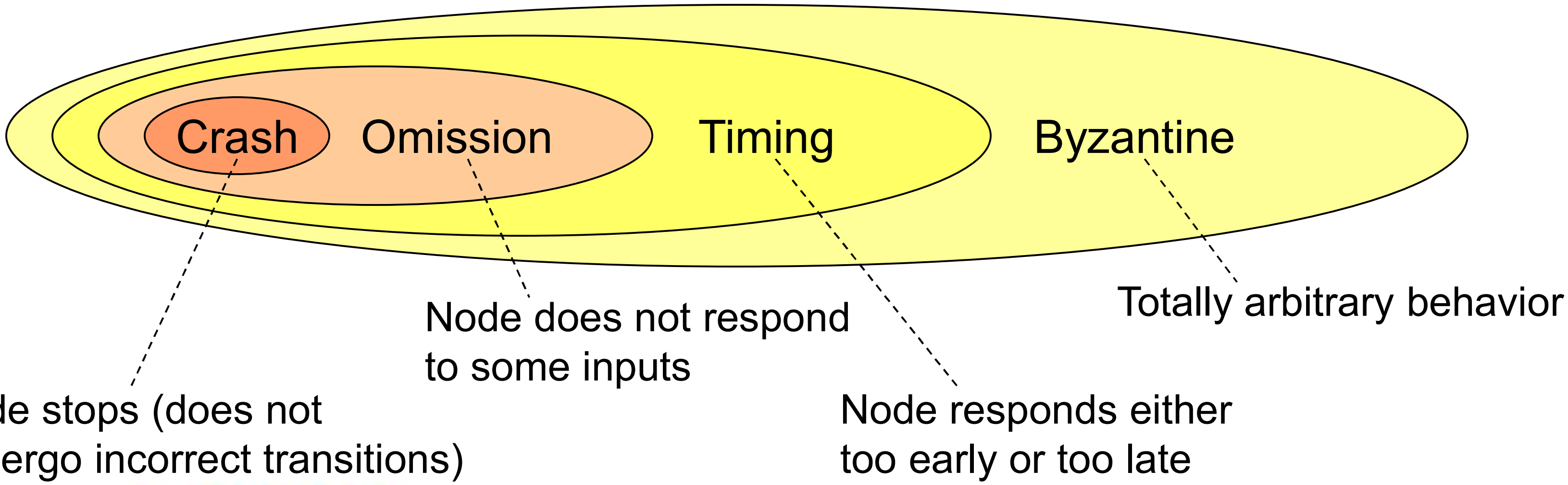
Causal broadcast: if m_2 is sent after m_1, any message triggered by m_2 must not cause actions before those of m_1 have been completed

22.4 Dependable Collaboration

Distributed systems, built from COTS nodes (processors plus memory) and interconnects, have redundancy and allow software-based malfunction tolerance implementation

Interconnect malfunctions are dealt with by synthesizing reliable communication primitives (point-to-point, broadcast, multicast)

Node malfunctions are modeled differently, with the more general models requiring greater redundancy to deal with



Node stops (does not undergo incorrect transitions)

Node does not respond to some inputs

Node responds either too early or too late

Totally arbitrary behavior

Malfunction Detectors in Distributed Systems

Malfunction detector: Distributed oracle related to malfunction detection

Creates and maintains a list of suspected processes

Defined by two properties: completeness and accuracy

Advantages:

Allows decoupling of the effort to detect malfunctions, e.g. site crashes, from that of the actual computation, leading to more modular design

Improves portability, because the same application can be used on a different platform if suitable malfunction detectors are available for it

Example malfunction detectors:

$\mathcal{P}$ (Perfect): strong completeness, strong accuracy (min required for IC)

$\Diamond\mathcal{S}$: strong completeness, eventual weak accuracy (min for consensus)

Reference: M. Raynal, “A Short Introduction to Failure Detectors for Asynchronous Distributed Systems,” *ACM SIGACT News*, Vol. 36, No. 1, pp. 53-70, March 2005.

Reliable Group Membership Service

A group of processes may be cooperating for solving a problem

The group's membership may expand and contract owing to changing processing requirements or because of malfunctions and repairs

Reliable multicast: message guaranteed to be received by all members within the group

ECE 254C: Advanced Computer Architecture – Distributed Systems (course devoted to distributed computing and its reliability issues)

22.5 Remapping and Load Balancing

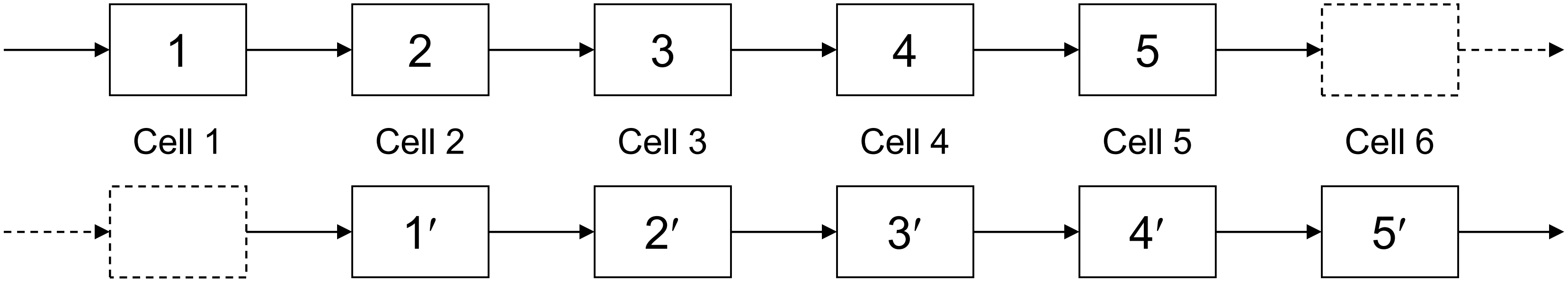
When pieces of a computation are performed on different modules, remapping may expose hidden malfunctions

After remapping, various parts of the computation are performed by different modules compared with the original mapping

It is quite unlikely that the same incorrect answers are obtained in the remapped version

Load balancing is the act of redistributing the computational load in the face of lost/recovered resources and dynamically changing computational requirements

Recomputation with Shift in Space

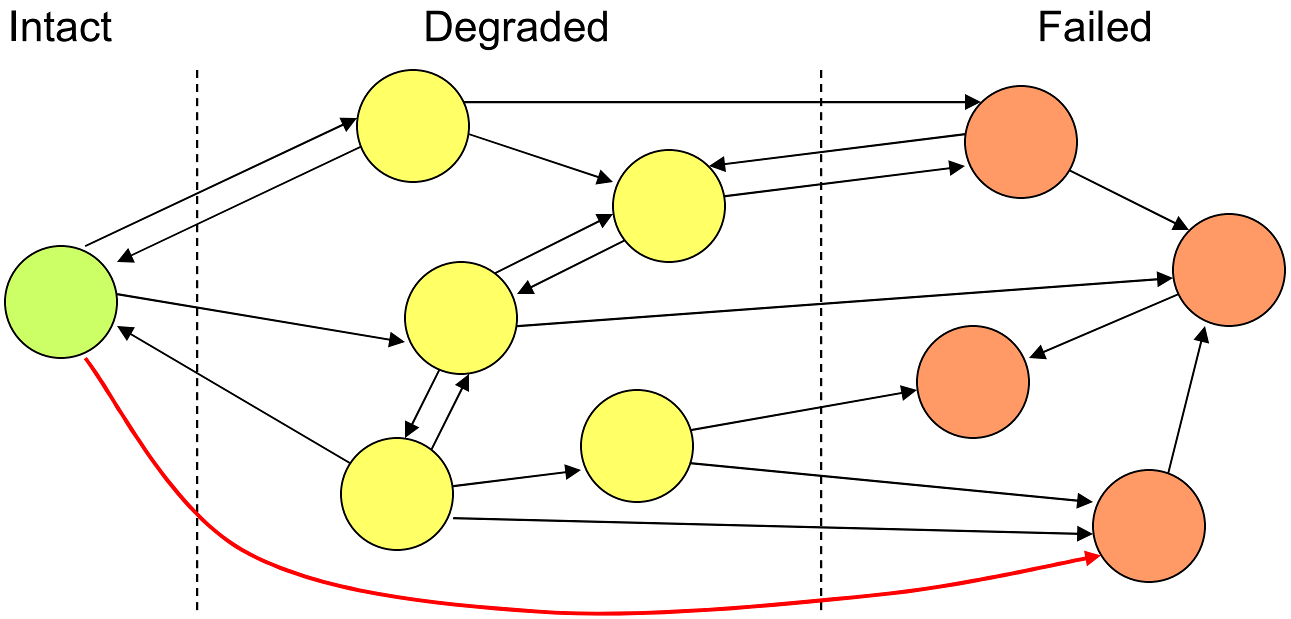


Linear array with an extra cell can redo the same pipelined computation with each step of the original computation shifted in space

Each cell *i* + 1 compares the result of step *i* that it received from the left in the first computation to the result of step *i* that it obtains in the second computation

With two extra cells in the linear array, three computations can be pipelined and voting used to derive highly reliable results

22.6 Modeling of Degradable Systems

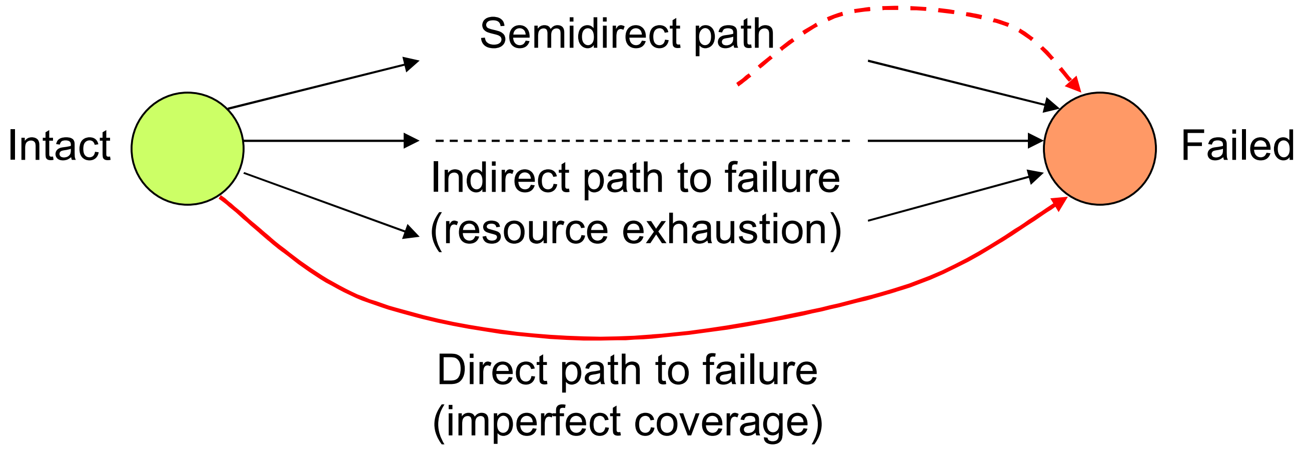


Catastrophic malfunction (to be avoided)

Reducing the probability of catastrophic malfunctions
Reduce the probability of malfunctions going undetected
Increase the accuracy of malfunction diagnosis
Make repair rates much greater than malfunction rates (keep spares)
Provide sufficient “safety factor” in computational capacity

Importance of Coverage in Fail-Soft Systems

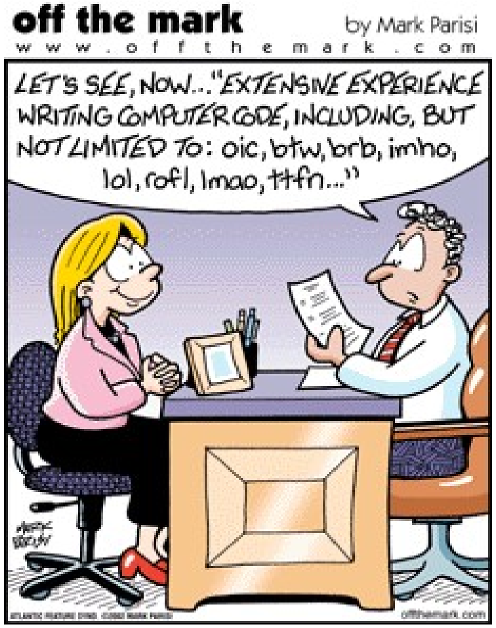
A fail-soft system can fail either indirectly, due to resource exhaustion, or directly because of imperfect coverage (analogous to leakage)

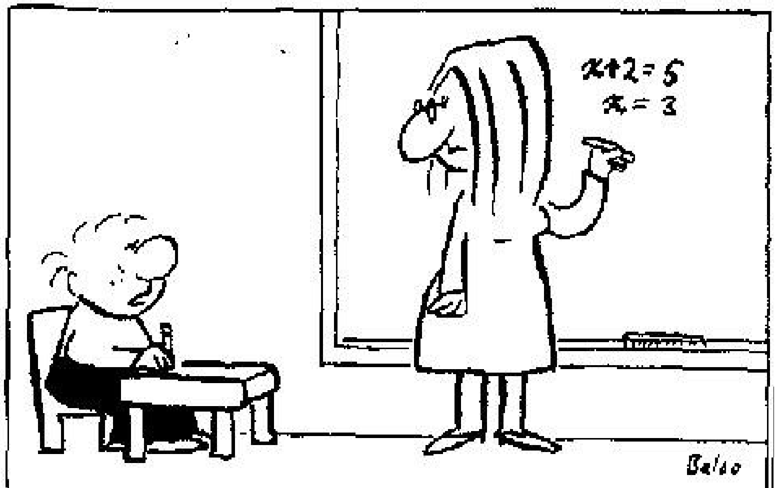


Providing more resources ("safety factor") lengthens the indirect path, thus slowing indirect failures but does nothing to block the direct path

Saturation effect: For a given coverage factor, addition of resources beyond a certain point would not be cost-effective with regard to the resulting reliability gain (same effect observed in standby sparing)

23 Resilient Algorithms





"Just a darn minute! Yesterday you said X equals two!"

STRUCTURE AT A GLANCE

Part I — Introduction: Dependable Systems (The Ideal-System View)	Goals Models	1. Background and Motivation 2. Dependability Attributes 3. Combinational Modeling 4. State-Space Modeling
Part II — Defects: Physical Imperfections (The Device-Level View)	Methods Examples	5. Defect Avoidance 6. Defect Circumvention 7. Shielding and Hardening 8. Yield Enhancement
Part III — Faults: Logical Deviations (The Circuit-Level View)	Methods Examples	9. Fault Testing 10. Fault Masking 11. Design for Testability 12. Replication and Voting
Part IV — Errors: Informational Distortions (The State-Level View)	Methods Examples	13. Error Detection 14. Error Correction 15. Self-Checking Modules 16. Redundant Disk Arrays
Part V — Malfunctions: Architectural Anomalies (The Structure-Level View)	Methods Examples	17. Malfunction Diagnosis 18. Malfunction Tolerance 19. Standby Redundancy 20. Robust Parallel Processing
Part VI — Degradations: Behavioral Lapses (The Service-Level View)	Methods Examples	21. Degradation Allowance 22. Degradation Management 23. Resilient Algorithms 24. Software Redundancy
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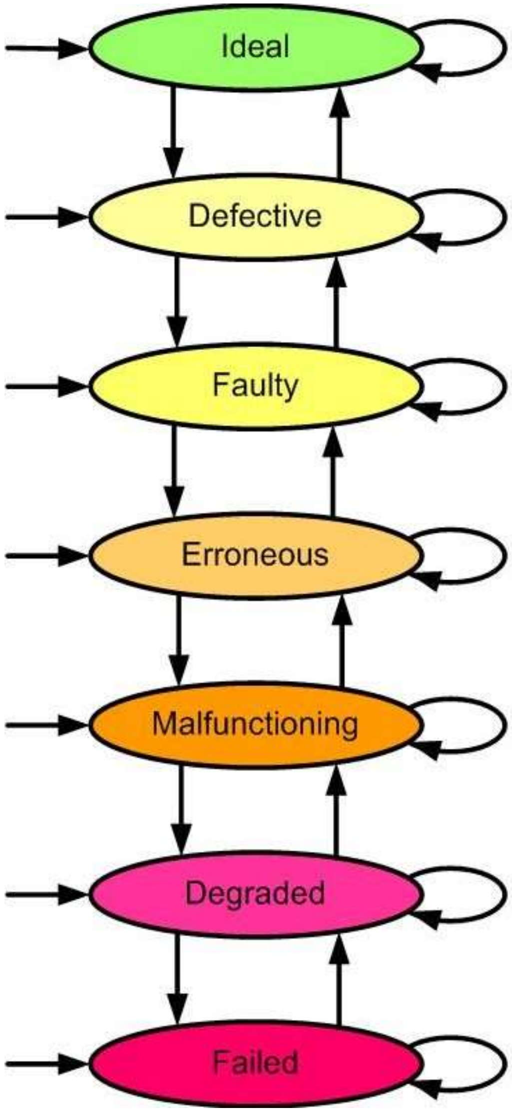
Appendix: Past, Present, and Future



23.1 COTS-Based Paradigms

Many of the hardware and software redundancy methods assume that we are building the entire system (or a significant part of it) from scratch

Some companies with fault-tolerant systems and related services:

ARM: Fault-tolerant ARM (launched in late 2006), automotive applications
Nth Generation Computing: High-availability and enterprise storage systems
Resilience Corp.: Emphasis on data security
Stratus Technologies: “The Availability Company”
Sun Microsystems: Fault-tolerant SPARC (ft-SPARC™)
Tandem Computers: An early ft leader, part of HP/Compaq since 1997

Question: What can be done to ensure the dependability of computations using commercial off-the-shelf (COTS) components?

A number of algorithm and data-structure design methods are available

Some History: The SIFT Experience

SIFT (software-implemented fault tolerance), developed at Stanford in early 1970s using mostly COTS components, was one of two competing "concept systems" for fly-by-wire aircraft control

The other one, FTMP (fault-tolerant multiprocessor), developed at MIT, used a hardware-intensive approach

System failure rate goal: 10^{-9}/hr over a 10-hour flight

SIFT allocated tasks for execution on multiple, loosely synchronized COTS processor-memory pairs (skew of up to 50 μs was acceptable); only the bus system was custom designed

Some fundamental results on, and methods for, clock synchronization emerged from this project

To prevent errors from propagating, processors obtained multiple copies of data from different memories over different buses (local voting)

Limitations of the COTS-Based Approach

Some modern microprocessors have dependability features built in:
Parity and other codes in memory, TLB, microcode store
Retry at various levels, from bus transmissions to full instructions
Machine check facilities and registers to hold the check results

According to Avizienis [Aviz97], however:
These are often not documented enough to allow users to build on them
Protection is nonsystematic and uneven
Recovery options are limited to shutdown and restart
Description of error handling is scattered among a lot of other detail
There is no top-down view of the features and their interrelationships

Manufacturers can incorporate both more advanced and new features, and at times have experimented with a number of mechanisms, but the low volume of the application base has hindered commercial viability

23.2 Robust Data Structures

Stored and transmitted data can be protected against unwanted changes through encoding, but coding does not protect the structure of the data

Consider, e.g., an ordered list of numbers
Individual numbers can be protected by encoding
The set of values can be protected by a checksum
The ordering, however, remains unprotected

Idea – Use a checksum that weighs each value differently: $(\Sigma j x_j) \bmod A$

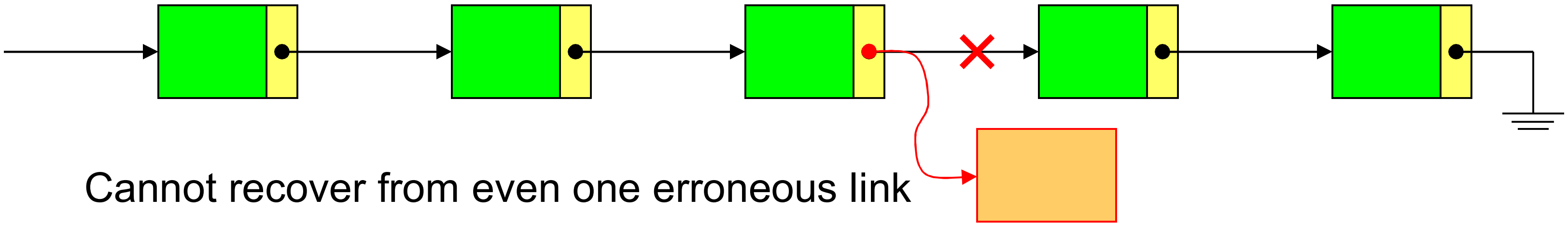
Idea – Add a “difference with next item” field to each list entry

x	x – y
y	y – z
z	. . .

Can we devise some general methods for protecting commonly used data structures?

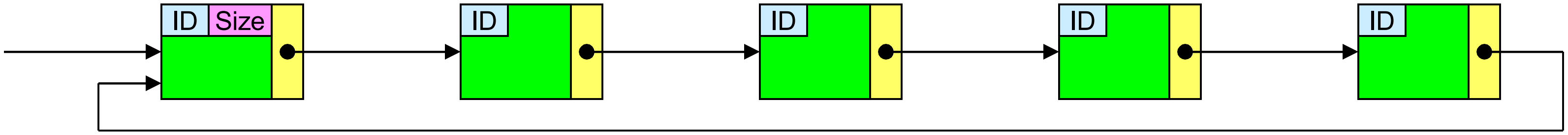
Recoverable Linear Linked Lists

Simple linked list: 0-detectable, 0-correctable

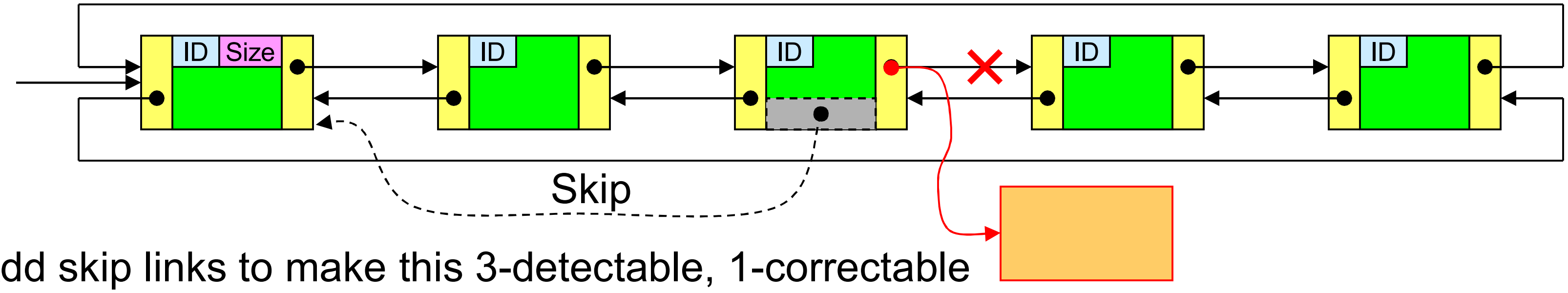


Cannot recover from even one erroneous link

Circular list, with node count and unique ID: 1-detectable, 0-correctable



Doubly linked list, with node count and ID: 2-detectable, 1-correctable



Add skip links to make this 3-detectable, 1-correctable

Other Robust Data Structures

Trees, FIFOs, stacks (LIFOs), heaps, queues

In general, a linked data structure is 2-detectable and 1-correctable iff the link network is 2-connected

Robust data structures provide fairly good protection with little design effort or run-time overhead

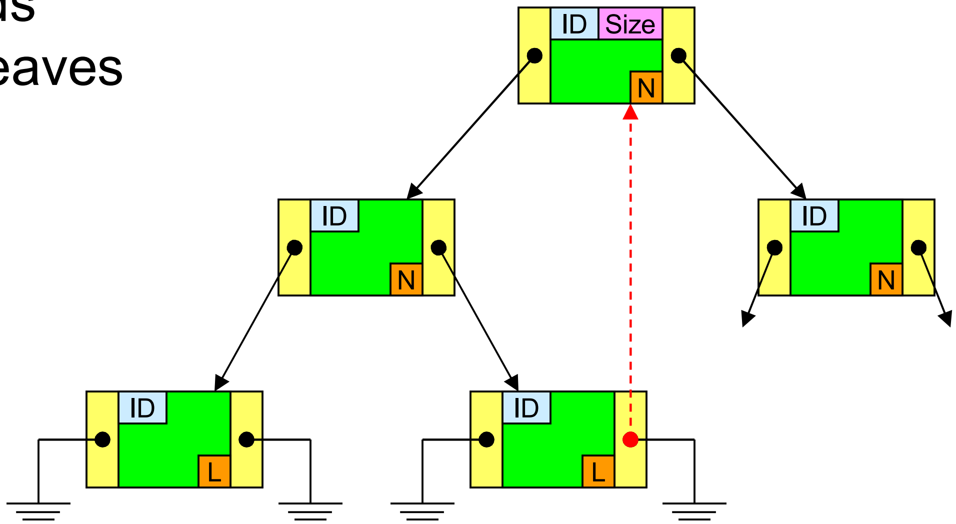
Audits can be performed during idle time
Reuse possibility makes the method even more effective

Robustness features to protect the structure can be combined with coding methods (such as checksums) to protect the content

Recoverable Binary Trees

Add "parent links" and/or "threads" (threads are links that connect leaves to higher-level nodes)

Threads can be added with little overhead by taking advantage of unused leaf links (one bit in every node can be used to identify leaves, thus freeing their link fields for other uses)



Adding redundancy to data structures has three types of cost:

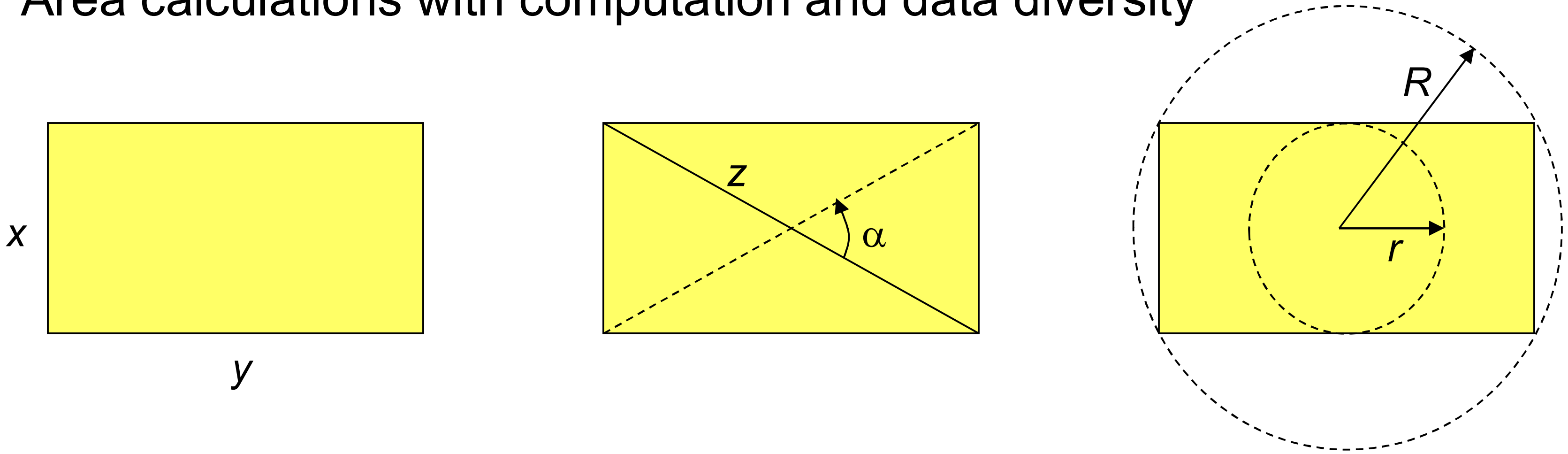
- Storage requirements for the additional information
- Slightly more difficult updating procedures
- Time overhead for periodic checking of structural integrity

23.3 Data Diversity and Fusion

Alternate formulations of the same information (input re-expression)

Example: The shape of a rectangle can be specified:
By its two sides x and y
By the length z of its diameters and the angle α between them
By the radii r and R of its inscribed and circumscribed circles

Area calculations with computation and data diversity



$A = xy$ $\qquad$ $A = \frac{1}{2} z^2 \sin \alpha$ $\qquad$ $A = 4r(R^2 - r^2)^{1/2}$

23.4 Self-Checking Algorithms

Error coding applied to data structures, rather than at the level of atomic data elements

Example: mod-8 checksums used for matrices

If $Z = X \times Y$ then $Z_f = X_c \times Y_r$

In M_f, any single error is correctable and any 3 errors are detectable

Four errors may go undetected

Matrix M

$$M = \begin{pmatrix} 2 & 1 & 6 \\ 5 & 3 & 4 \\ 3 & 2 & 7 \end{pmatrix}$$

Row checksum matrix

$$M_r = \begin{pmatrix} 2 & 1 & 6 & 1 \\ 5 & 3 & 4 & 4 \\ 3 & 2 & 7 & 4 \end{pmatrix}$$

Column checksum matrix

$$M_c = \begin{pmatrix} 2 & 1 & 6 \\ 5 & 3 & 4 \\ 3 & 2 & 7 \\ 2 & 6 & 1 \end{pmatrix}$$

Full checksum matrix

$$M_f = \begin{pmatrix} 2 & 1 & 6 & 1 \\ 5 & 3 & 4 & 4 \\ 3 & 2 & 7 & 4 \\ 2 & 6 & 1 & 1 \end{pmatrix}$$

Matrix Multiplication Using ABET

If $Z = X \times Y$ then
$Z_f = X_c \times Y_r$

$$X = \begin{pmatrix} 2 & 1 & 6 \\ 5 & 3 & 4 \\ 3 & 2 & 7 \end{pmatrix} \qquad Y = \begin{pmatrix} 1 & 5 & 3 \\ 2 & 4 & 6 \\ 7 & 1 & 5 \end{pmatrix}$$

46 + 20 + 42 = 108 = 4 mod 8

36 = 4 mod 8

$$\begin{pmatrix} 2 & 1 & 6 \\ 5 & 3 & 4 \\ 3 & 2 & 7 \\ 2 & 6 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 5 & 3 & 1 \\ 2 & 4 & 6 & 4 \\ 7 & 1 & 5 & 5 \end{pmatrix} = \begin{pmatrix} 46 & 20 & 42 & 36 \\ 39 & 41 & 53 & 37 \\ 56 & 30 & 56 & 46 \\ 21 & 35 & 47 & 31 \end{pmatrix}$$

Column checksum matrix for *X*

Row checksum matrix for *Y*

20 + 41 + 30 = 91 = 3 mod 8

35 = 3 mod 8

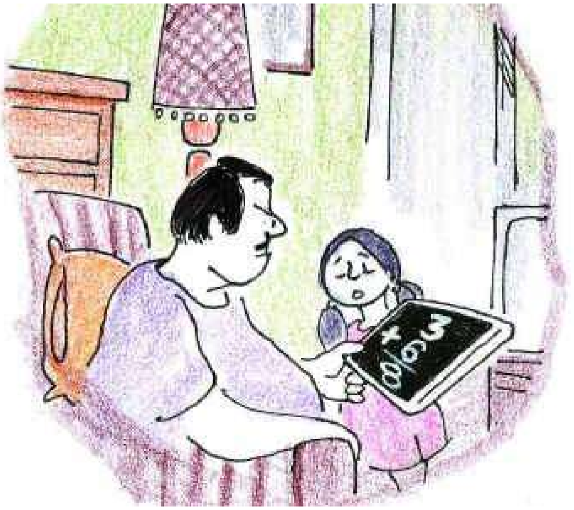
23.5 Self-Adapting Algorithms

This section to be completed

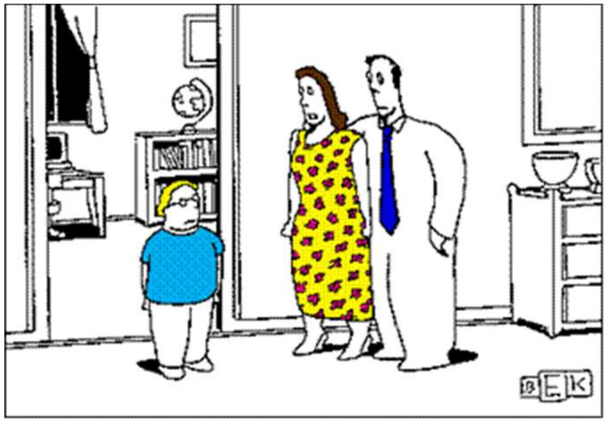
23.6 Other Algorithmic Methods

This section to be completed

24 Software Redundancy

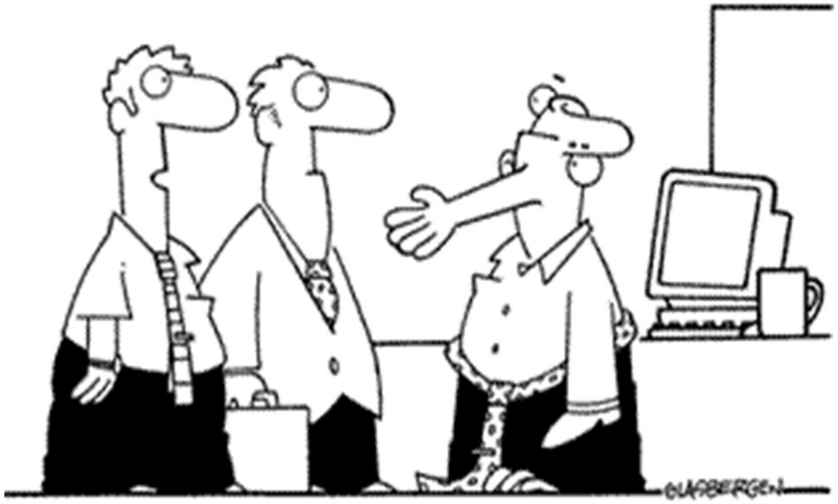


“Well, what’s a piece of software without a bug or two?”



“We are neither hardware nor software; we are your parents.”

“There’s nothing wrong with your personal finance software. You just don’t have any money.”



“That’s our CIO. He’s encrypted for security purposes.”

“I haven’t the slightest idea who he is.
He came bundled with the software.”

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Part II — Defects: Physical Imperfections (The Device-Level View)	Methods Examples	5. Defect Avoidance 6. Defect Circumvention 7. Shielding and Hardening 8. Yield Enhancement
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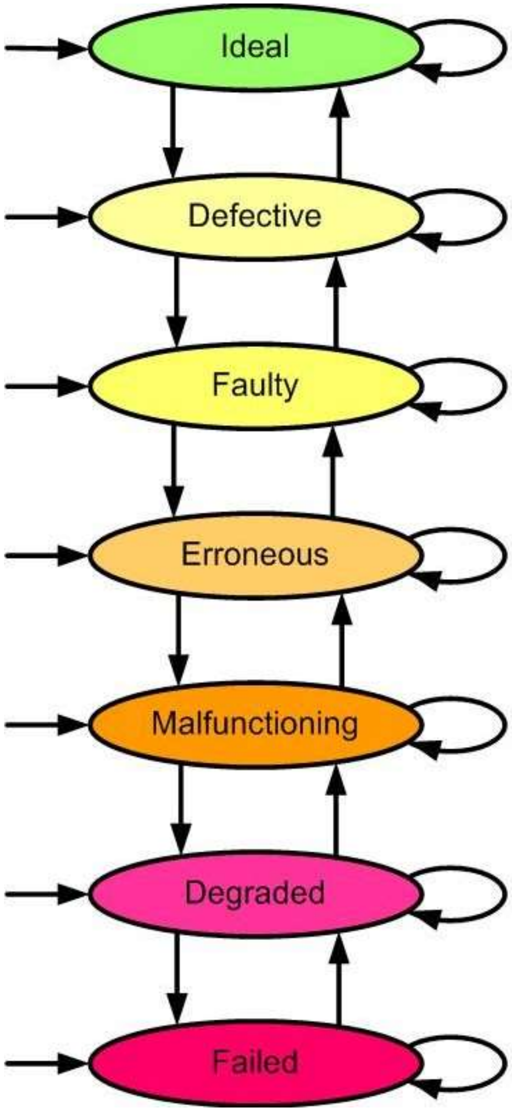
Appendix: Past, Present, and Future



24.1 Software Dependability

Imagine the following product disclaimers:

For a steam iron

There is no guarantee, explicit or implied, that this device will remove wrinkles from clothing or that it will not lead to the user’s electrocution. The manufacturer is not liable for any bodily harm or property damage resulting from the operation of this device.

For an electric toaster

The name “toaster” for this product is just a symbolic identifier. There is no guarantee, explicit or implied, that the device will prepare toast. Bread slices inserted in the product may be burnt from time to time, triggering smoke detectors or causing fires. By opening the package, the user acknowledges that s/he is willing to assume sole responsibility for any damages resulting from the product’s operation.

How Is Software Different from Hardware?

Software unreliability is caused predominantly by design slips, not by operational deviations – we use *flaw* or *bug*, rather than *fault* or *error*

Not much sense in replicating the same software and doing comparison or voting, as we did for hardware

At the current levels of hardware complexity, latent design slips also exist in hardware, thus the two aren't totally dissimilar

The curse of complexity

The 7-Eleven convenience store chain spent nearly $9M to make its point-of-sale software Y2K-compliant for its 5200 stores
The modified software was subjected to 10,000 tests (all successful)
The system worked with no problems throughout the year 2000
On January 1, 2001, however, the system began rejecting credit cards, because it "thought" the year was 1901 (bug was fixed within a day)

Software Development Life Cycle

Software flaws may arise at several points within these life-cycle phases

Project initiation	
Needs	
Requirements	
Specifications	
Prototype design	
Prototype test	Evaluation by both the developer and customer
Revision of specs	
Final design	
Coding	Implementation or programming
Unit test	Separate testing of each major unit (module)
Integration test	Test modules within pretested control structure
System test	
Acceptance test	Customer or third-party conformance-to-specs test
Field deployment	
Field maintenance	
System redesign	New contract for changes and additional features
Software discard	Obsolete software is discarded (perhaps replaced)

What Is Software Dependability?

Major structural and logical problems are removed very early in the process of software testing

What remains after extensive verification and validation is a collection of tiny flaws which surface under rare conditions or particular combinations of circumstances, thus giving software failure a statistical nature

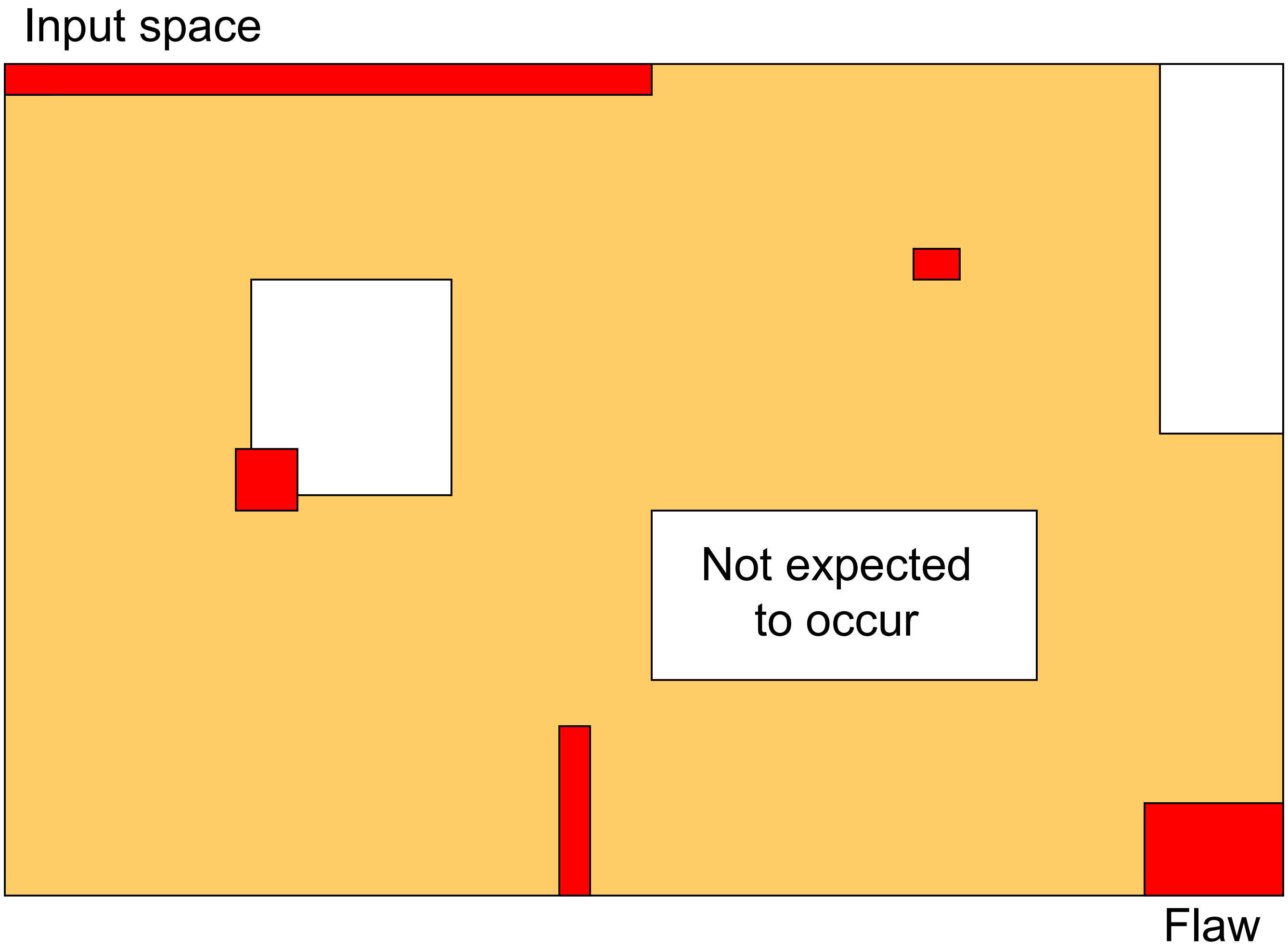
Software usually contains one or more flaws per thousand lines of code, with < 1 flaw considered good (linux has been estimated to have 0.1)

If there are *f* flaws in a software component, the hazard rate, that is, rate of failure occurrence per hour, is *kf*, with *k* being the constant of proportionality which is determined experimentally (e.g., $k = 0.0001$)

Software reliability: $R(t) = e^{-kft}$

The only way to improve software reliability is to reduce the number of residual flaws through more rigorous verification and/or testing

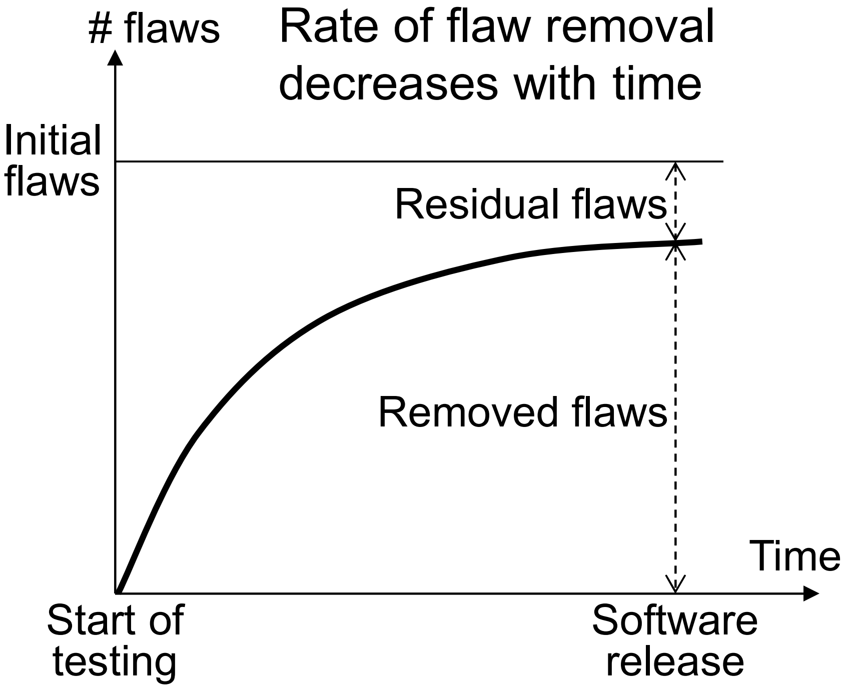
Residual Software Flaws



24.2 Software Malfunction Models

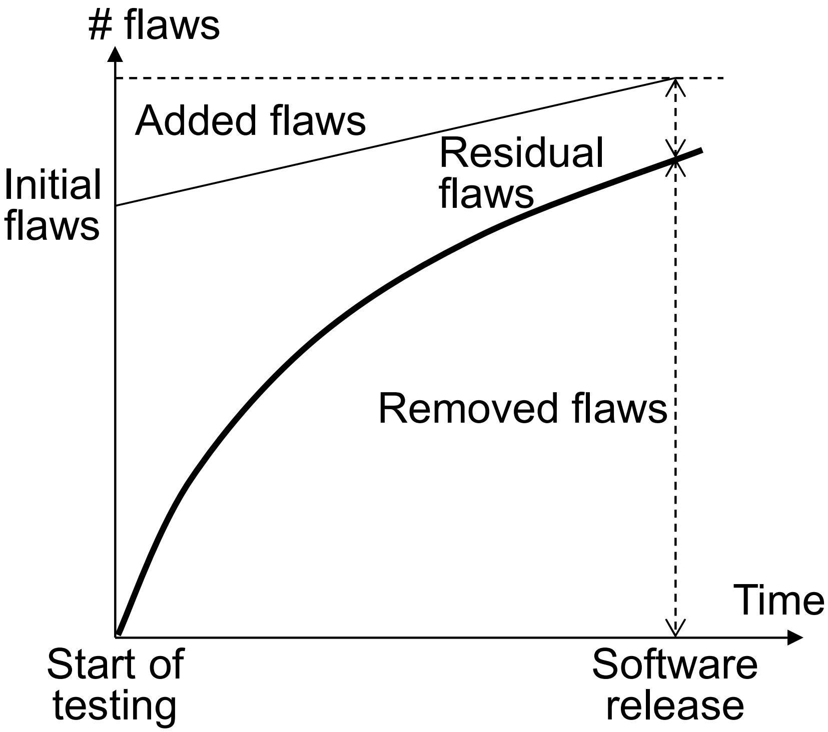
Software flaw/bug ⇒ Operational error ⇒ Software-induced failure

“Software failure” used informally to denote any software-related problem



Rate of flaw removal decreases with time

Removing flaws, without generating new ones



New flaws introduced are proportional to removal rate

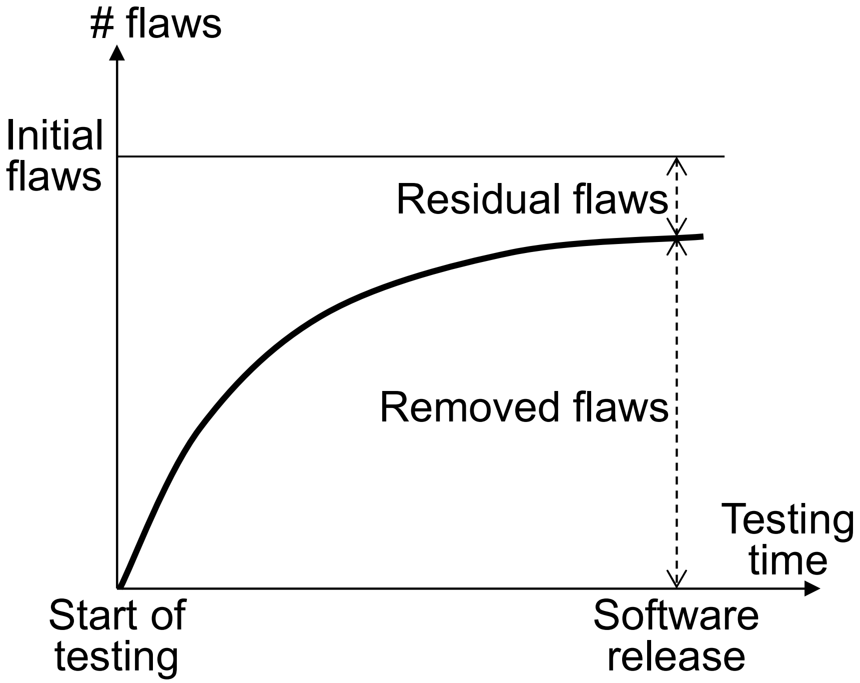
Software Reliability Models and Parameters

For simplicity, we focus on the case of no new flaw generation

Assume linearly decreasing flaw removal rate (F = residual flaws, τ = testing time, in months)

$dF(\tau)/d\tau = -(a - b\tau)$
$F(\tau) = F_0 - a\tau(1 - b\tau/(2a))$

Example: $F(\tau) = 130 - 30\tau(1 - \tau/16)$



Hazard function

$z(\tau) = k(F_0 - a\tau(1 - b\tau/(2a)))$

In our example, let $k = 0.000132$
$R(t) = \exp(-0.000132(130 - 30\tau(1 - \tau/16))t)$

Assume testing for τ = 8 months:

$R(t) = e^{-0.00132t}$

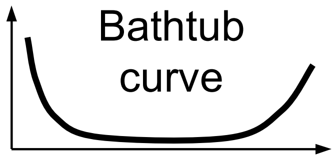
τ	MTTF (hr)
0	58
2	98
4	189
6	433
8	758

The Phenomenon of Software Aging

Software does not wear out or age in the same sense as hardware

Yet, we do observe deterioration in software that has been running for a long time

So, the bathtub curve is also applicable to software



Reasons for and types of software aging:

- Accumulation of junk in the state part (reversible via restoration)
- Long-term cumulative effects of updates (patches and the like)

As the software’s structure deviates from its original clean form, unexpected failures begin to occur

Eventually software becomes so mangled that it must be discarded and redeveloped from scratch

More on Software Reliability Models

Linearly decreasing flaw removal rate isn't the only option in modeling

Constant flaw removal rate has also been considered, but it does not lead to a very realistic model

Exponentially decreasing flaw removal rate is more realistic than linearly decreasing, since flaw removal rate never really becomes 0

How does one go about estimating the model constants?

- Use handbook: public ones, or compiled from in-house data
- Match moments (mean, 2nd moment, . . .) to flaw removal data
- Least-squares estimation, particularly with multiple data sets
- Maximum-likelihood estimation (a statistical method)

24.3 Software Verification and Validation

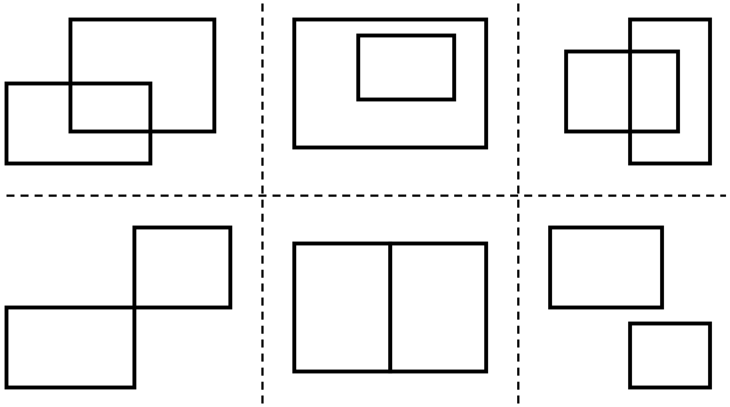
Verification: “Are we building the system right?” (meets specifications)

Validation: “Are we building the right system?” (meets requirements)

Both verification and validation use testing as well as formal methods

Software testing
Exhaustive testing impossible
Test with many typical inputs
Identify and test fringe cases

Example: overlap of rectangles



Formal methods
Program correctness proof
Formal specification
Model checking

Examples: safety/security-critical

Railway interlocking system
[Hlavaty 2001]

Cryptography device
[Kirby 1999]

Smart cards
[Requet 2000]

Automated lab analysis test equipment
[Bicarregui 1997]

Formal Proofs for Software Verification

Program to find the greatest common divisor of integers $m > 0$ and $n > 0$

```
input $m$ and $n$
$x := m$
$y := n$
while $x \neq y$
   if $x < y$
   then $y := y - x$
   else $x := x - y$
   endif
endwhile
output $x$
```

m and n are positive integers

x and y are positive integers, $x = m$, $y = n$

Loop invariant: $x > 0$, $y > 0$, $\gcd(x, y) = \gcd(m, n)$

$x = \gcd(m , n)$

Steps 1-3: "partial correctness"
Step 4: ensures "total correctness"

The four steps of a correctness proof relating to a program loop:

1. Loop invariant implied by the assertion before the loop (precondition)
2. If satisfied before an iteration begins, then also satisfied at the end
3. Loop invariant and exit condition imply the assertion after the loop
4. Loop executes a finite number of times (termination condition)

Software Flaw Tolerance

Flaw avoidance strategies include (structured) design methodologies, software reuse, and formal methods

Given that a complex piece of software will contain bugs, can we use redundancy to reduce the probability of software-induced failures?

The ideas of masking redundancy, standby redundancy, and self-checking design have been shown to be applicable to software, leading to various types of fault-tolerant software

"Flaw tolerance" is a better term; "fault tolerance" has been overused

Masking redundancy: N-version programming

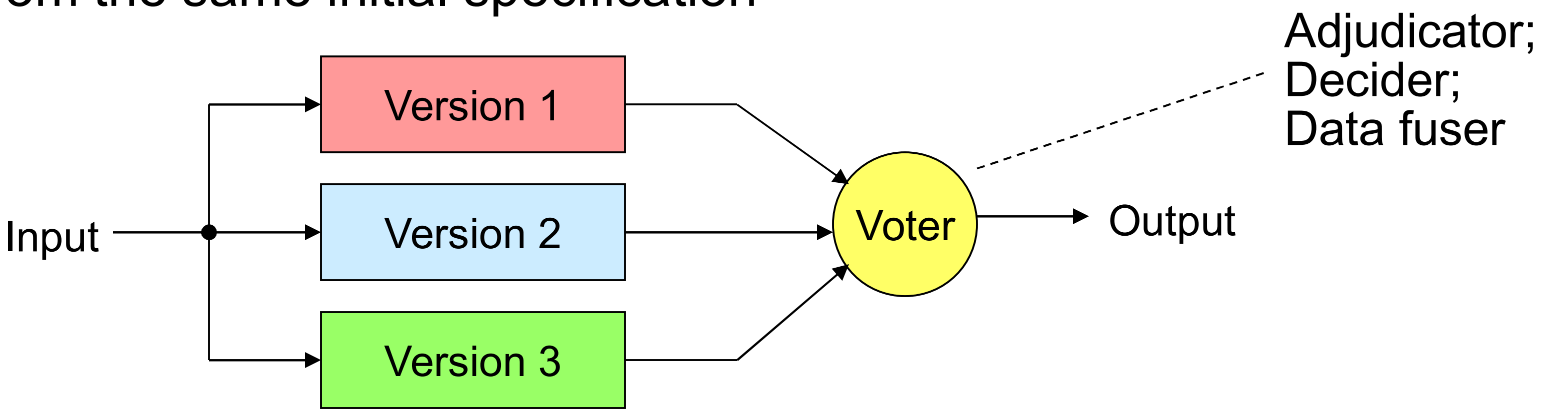
Standby redundancy: the recovery-block scheme

Self-checking design: N-self-checking programming

Sources: *Software Fault Tolerance*, ed. by Michael R. Lyu, Wiley, 2005
(on-line book at http://www.cse.cuhk.edu.hk/~lyu/book/sft/index.html)
Also, "Software Fault Tolerance: A Tutorial," 2000 (NASA report, available on-line)

24.4 N-Version Programming

Independently develop *N* different programs (known as "versions") from the same initial specification



The greater the diversity in the *N* versions, the less likely that they will have flaws that produce correlated errors

Diversity in:
Programming teams (personnel and structure)
Software architecture
Algorithms used
Programming languages
Verification tools and methods
Data (input re-expression and output adjustment)

Some Objections to N-Version Programming

Developing programs is already a very expensive and slow process; why multiply the difficulties by *N*?	Cannot produce flawless software, regardless of cost
Diversity does not ensure independent flaws (It has been amply documented that multiple programming teams tend to overlook the same details and to fall into identical traps, thereby committing very similar errors)	This is a criticism of reliability modeling with independence assumption, not of the method itself
Imperfect specification can be the source of common flaws	Multiple diverse specifications?
With truly diverse implementations, the output selection mechanism (adjudicator) is complicated and may contain its own flaws	Will discuss the adjudication problem in a future lecture

Reliability Modeling for N-Version Programs

Fault-tree model: the version shown here is fairly simple, but the power of the method comes in handy when combined hardware/software modeling is attempted

Probabilities of coincident flaws are estimated from experimental failure data

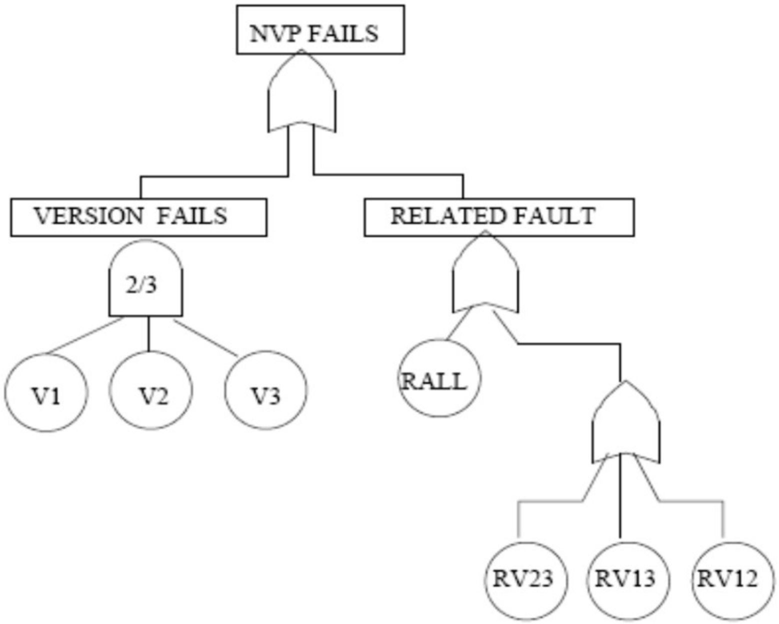
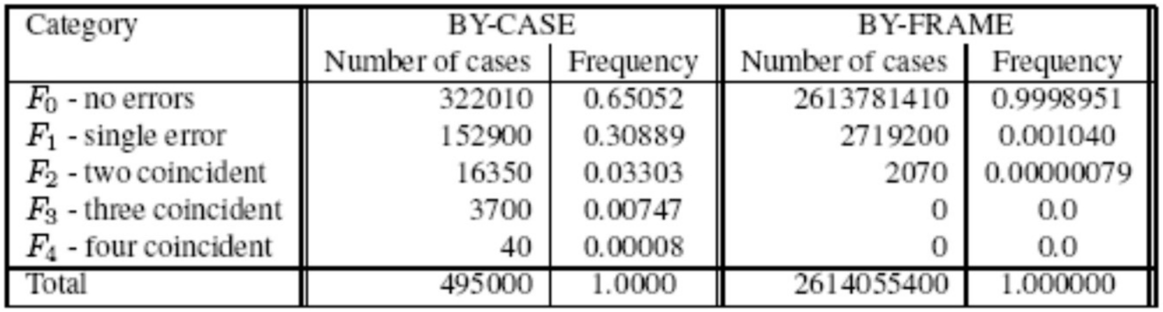


Table 5.6 Error characteristics for four-version configurations



Category	BY-CASE		BY-FRAME	
	Number of cases	Frequency	Number of cases	Frequency
F_0 - no errors	322010	0.65052	2613781410	0.9998951
F_1 - single error	152900	0.30889	2719200	0.001040
F_2 - two coincident	16350	0.03303	2070	0.00000079
F_3 - three coincident	3700	0.00747	0	0.0
F_4 - four coincident	40	0.00008	0	0.0
Total	495000	1.0000	2614055400	1.000000

Source: Dugan & Lyu, 1994 and 1995

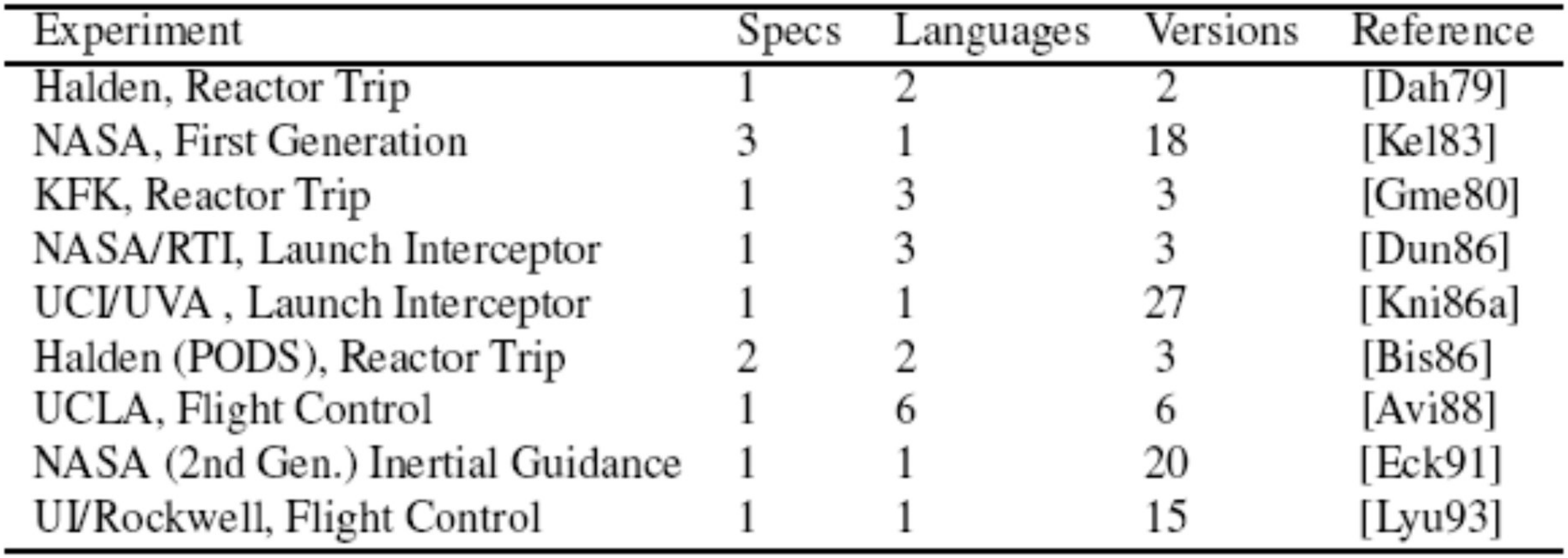
Applications of N-Version Programming

Back-to-back testing: multiple versions can help in the testing process

B777 flight computer: 3 diverse processors running diverse software

Airbus A320/330/340 flight control: 4 dissimilar hardware/software modules drive two independent sets of actuators

Some experiments in N-version programming



Experiment	Specs	Languages	Versions	Reference
Halden, Reactor Trip	1	2	2	[Dah79]
NASA, First Generation	3	1	18	[Kel83]
KFK, Reactor Trip	1	3	3	[Gme80]
NASA/RTI, Launch Interceptor	1	3	3	[Dun86]
UCI/UVA , Launch Interceptor	1	1	27	[Kni86a]
Halden (PODS), Reactor Trip	2	2	3	[Bis86]
UCLA, Flight Control	1	6	6	[Avi88]
NASA (2nd Gen.) Inertial Guidance	1	1	20	[Eck91]
UI/Rockwell, Flight Control	1	1	15	[Lyu93]

Source: P. Bishop, 1995

24.5 The Recovery Block Method

The software counterpart to standby sparing for hardware

Suppose we can verify the result of a software module by subjecting it to an acceptance test

ensure	*acceptance test*	e.g., sorted list
by	*primary module*	e.g., quicksort
else by	*first alternate*	e.g., bubblesort
⋮		⋮
else by	*last alternate*	e.g., insertion sort
else fail		

The acceptance test can range from a simple reasonableness check to a sophisticated and thorough test

Design diversity helps ensure that an alternate can succeed when the primary module fails

The Acceptance Test Problem

Design of acceptance tests (ATs) that are both simple and thorough is very difficult; for example, to check the result of sorting, it is not enough to verify that the output sequence is monotonic

Simplicity is desirable because acceptance test is executed after the primary computation, thus lengthening the critical path

Thoroughness ensures that an incorrect result does not pass the test (of course, a correct result always passes a properly designed test)

Some computations do have simple tests (inverse computation)
Examples: square-rooting can be checked through squaring, and roots of a polynomial can be verified via polynomial evaluation

At worst, the acceptance test might be as complex as the primary computation itself

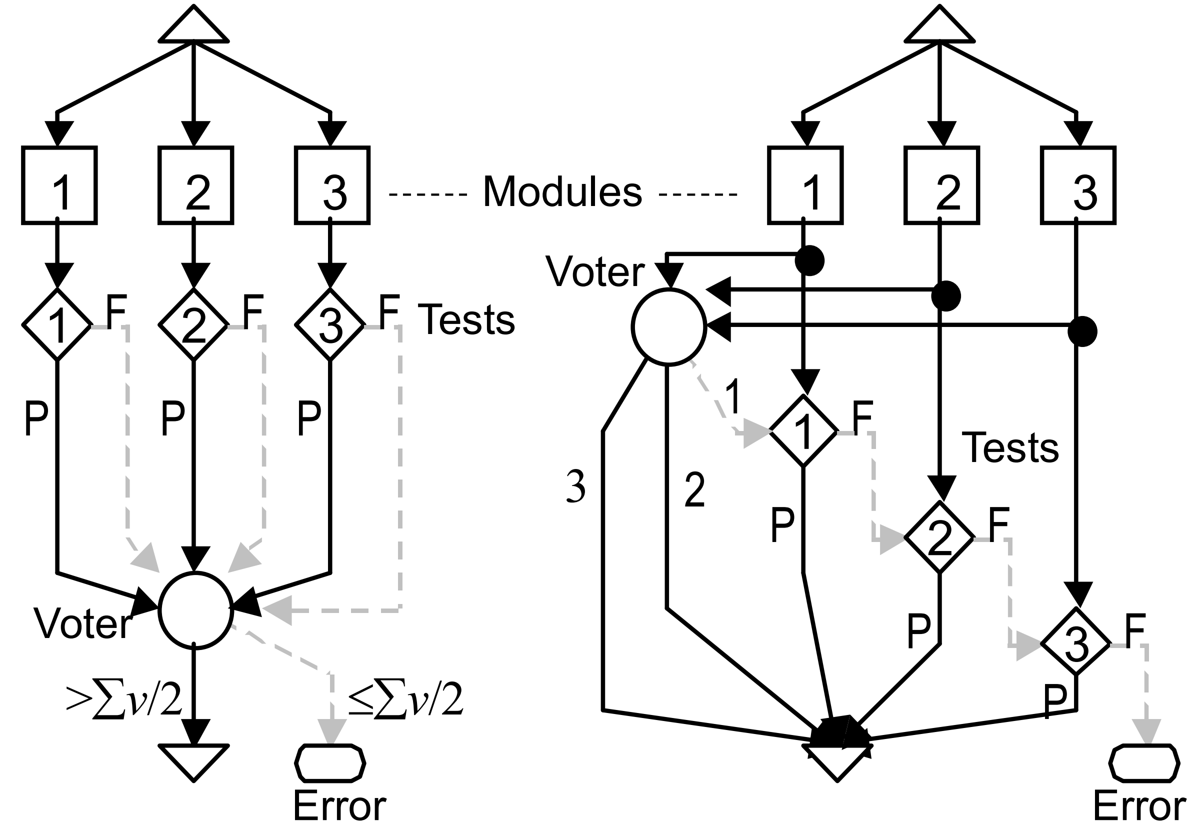
24.6 Hybrid Software Redundancy

Recoverable N-version block scheme = N-self-checking program

Voter acts only on module outputs that have passed an acceptance test

Consensus recovery block scheme

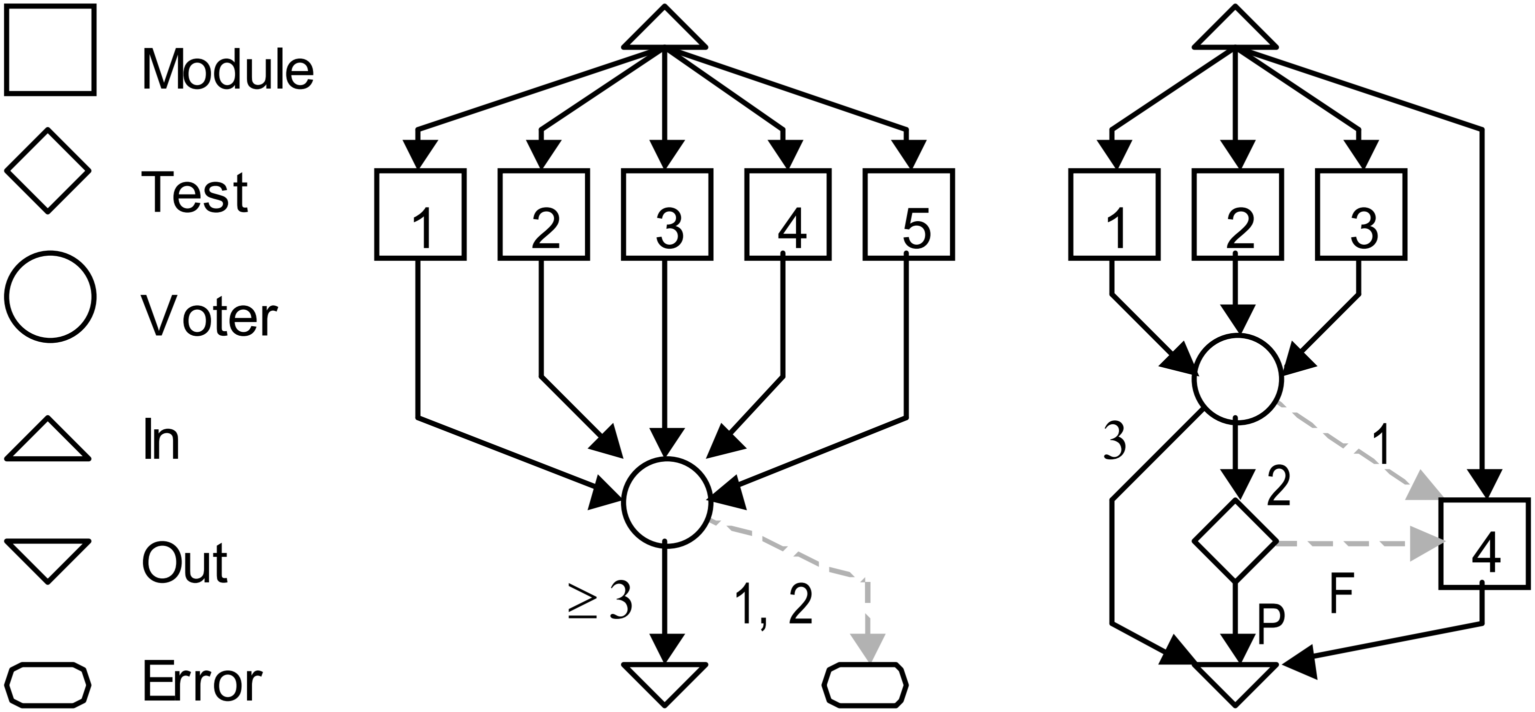
Only when there is no majority agreement, acceptance test applied (in a prespecified order) to module outputs until one passes its test



(a) RNVB / NSCP (b) CRB

Source: Parhami, B., "An Approach to Component-Based Synthesis of Fault-Tolerant Software," *Informatica*, Vol. 25, pp. 533-543, Nov. 2001.

More General Hybrid NVP-AT Schemes



(a) Legend (b) 5VP (c) ALT1

Source: Parhami, B., “An Approach to Component-Based Synthesis of Fault-Tolerant Software,” *Informatica*, Vol. 25, pp. 533-543, Nov. 2001.