Fault-Tolerant Computing

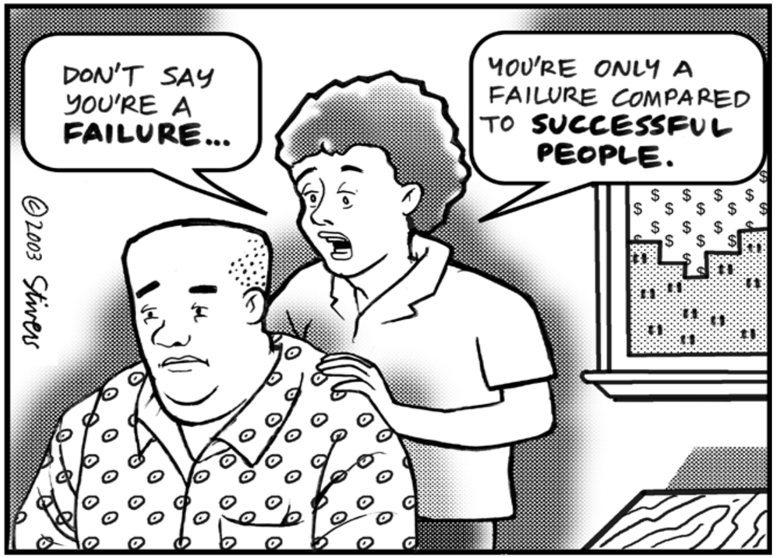
Dealing with High-Level Impairments

About This Presentation

This presentation has been prepared for the graduate course ECE 257A (Fault-Tolerant Computing) by Behrooz Parhami, Professor of Electrical and Computer Engineering at University of California, Santa Barbara. The material contained herein can be used freely in classroom teaching or any other educational setting.

Edition	**Released**	**Revised**	**Revised**
First	Nov. 2006		

Failure Confinement



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"My goal is to be a failure. If I reach my goal, I'll feel successful and if I don't reach my goal, I'll feel successful too!"

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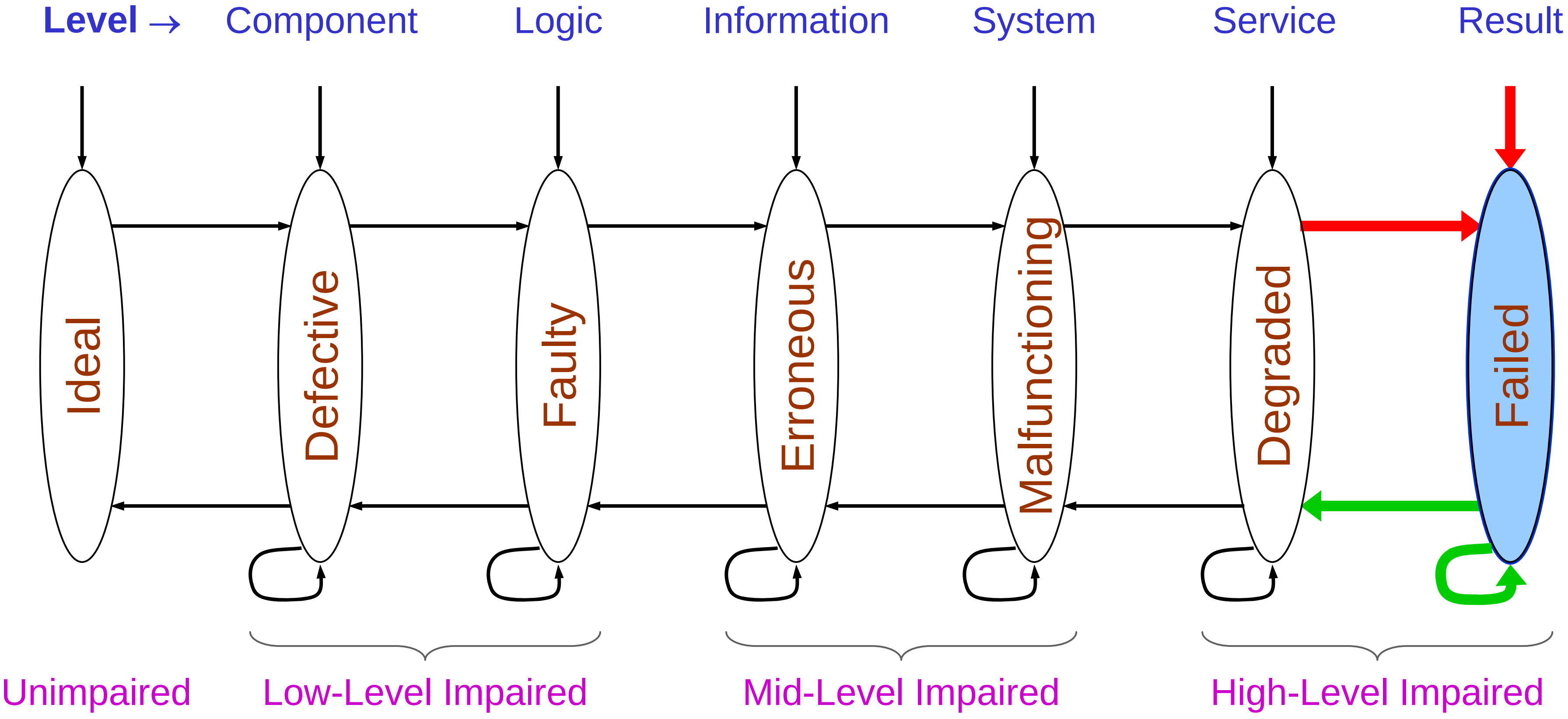
"Remember son, if at first you don't succeed, assemble a team of lawyers to shield all involved, convince your investors that failure is an essential component of success, create a network for spin control to trivialize any negative consequences, and try, try again."

Multilevel Model of Dependable Computing



Legend: Entry, Deviation, Remedy, Tolerance

Importance of Experimental Failure Data

- Indicate where effort is most needed
- Help with verification of analytic models

System outage stats (%)*	Hardware	Software	Operations	Environment
Bellcore [Ali86]	26	30	44	--
Tandem [Gray87]	22	49	15	14
Northern Telecom	19	19	33	28
Japanese Commercial	36	40	11	13
Mainframe users	47	21	16	16
Overall average	**30**	**32**	**24**	**14**

*Excluding scheduled maintenance

Tandem unscheduled outages

Power	53%
Communication lines	22%
Application software	10%
File system	10%
Hardware	5%

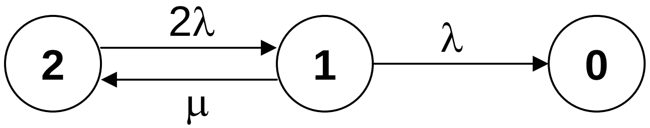
Tandem outages due to hardware

Disk storage	49%
Communications	24%
Processors	18%
Wiring	9%
Spare units	1%

Failure Data Used to Validate or Tune Models

- Indicate accuracy of model predictions (compare multiple models?)
- Help in fine-tuning of models to better match the observed behavior

Example: Two disks, each with MTTF = 50,000 hr, MTTR = 5 hr
Disk pair failure rate $\approx 2\lambda^2/\mu$
Disk pair MTTF $\approx \mu/(2\lambda^2)$
$= 2.5 \times 10^8$ hr = 285 centuries
In 48,000 years of observation (2 years × 6000 systems × 4 disk pairs),
35 double disk failures were reported $\Rightarrow$ MTTF $\approx$ 14 centuries



Problems with experimental failure data:
- Difficult to collect, while ensuring uniform operating conditions
- Logs may not be complete or accurate (the embarrassment factor)
- Assigning a cause to each failure not an easy task
- Even after collection, vendors may not be willing to share data
- Impossible to do for one-of-a-kind or very limited systems

Preparing for Failure

- Minimum requirement: accurate estimation of failure probability
- Putting in place procedures for dealing with failures when they occur

Failure probability = Unreliability
Reliability models are by nature pessimistic (provide lower bounds)
However, we do not want them to be too pessimistic

Risk	=	Frequency	×	Magnitude
Consequence / Unit time		Events / Unit time		Consequence / Event

Frequency may be equated with unreliability (failure probability)
Magnitude is estimated via economic analysis

Failure handling is often the most neglected part of the process
An important beginning: clean, unambiguous messages to operator/user
Listing the options and urgency of various actions is a good idea
Two way system-user communication (adding user feedback) helpful
Quality of failure handling affects the “Magnitude” term in risk equation

Very Small Probabilities: The Human Factor

Interpretation of data, understanding of probabilities, acceptance of risk

Risk of death / person / year

Influenza	1/5K
Struck by auto	1/20K
Tornado (US MW)	1/455K
Earthquake (CA)	1/588K
Nuclear power plant	1/10M
Meteorite	1/100B

Factors that increase risk of death by $1/10^6$ (deemed acceptable risk)

Smoking 1.4 cigarettes
Drinking 0.5 liter of wine
Biking 10 miles
Driving 300 miles
Flying 1000 miles
Taking a chest X-ray
Eating 100 steaks

US causes of death / 10^6 persons

Auto accident	210
Work accident	150
Homicide	93
Fall	74
Drowning	37
Fire	30
Poisoning	17
Civil aviation	0.8
Tornado	0.4
Bite / sting	0.2

Risk underestimation factors:

Familiarity, being part of our job, remoteness in time or space

Risk overestimation factors:

Scale (1000s killed), proximity

Believability and Helpfulness of Failure Warning

> “No warning system will function effectively if its messages, however logically arrived at, are ignored, disbelieved, or lead to inappropriate actions.” Foster, H.D., “Disaster Warning Systems,” 1987

Unbelievable failure warnings:

Failure event after numerous false alarms

Real failure occurring in the proximity of a scheduled test run

Users or operators inadequately trained (May 1960 Tsunami in Hilo, Hawaii, killing 61, despite 10-hour advance warning via sirens)

Unhelpful failure warnings:

Autos – “Check engine” indicator

Computer systems – “Fatal error” message

Engineering Ethics

Risks must be evaluated thoroughly and truthfully

IEEE Code of Ethics: As IEEE members, we agree to

1. accept responsibility in making decisions consistent with the safety, health and welfare of the public, and to disclose promptly factors that might endanger the public or the environment
6. maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations;
7. seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others

ACM Code of Ethics: Computing professionals must

minimize malfunctions by following generally accepted standards for system design and testing

give comprehensive and thorough evaluations of computer systems and their impacts, including analysis of possible risks

Speed of Failure Detection

Prompt failure detection is a prerequisite to failure confinement

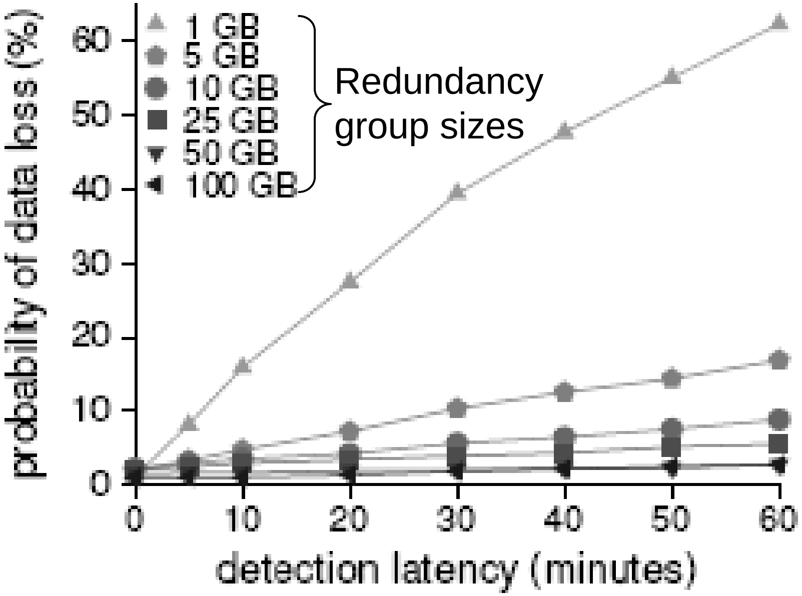
In many cases dealing with mechanical elements, such as wing flaps, reaction time of 10s/100s of milliseconds is adequate (reason: inertia)

In some ways, catastrophic failures that are readily identified may be better than subtle failures that escape detection

Example: For redundant disks with two-way mirroring, detection latency was found to have a significant effect on the probability of data loss

See: http://hpdc13.cs.ucsb.edu/papers/34.pdf

Failure detection latency can be made negative via "failure prediction" (e.g., in a storage server, increased error rate signals impending failure)



Fail-Safe Systems

Fail-safe: Produces one of a predetermined set of safe outputs when it fails as a result of “undesirable events” that it cannot tolerate

Fail-safe traffic light: Will remain stuck on red

Fail-safe gas range/furnace pilot: Cooling off of the pilot assembly due to the flame going out will shut off the gas intake valve

A fail-safe digital system must have at least two binary output lines, together representing the normal outputs and the safe failure condition

Reason: If we have a single output line, then even if one value (say, 0) is inherently safe, the output stuck at the other value would be unsafe

Two-rail encoding is a possible choice: **0**: 01, **1**: 10, **F**: 00, 11, or both

Totally fail-safe: Only safe erroneous outputs are produced, provided another failure does not occur before detection of the current one

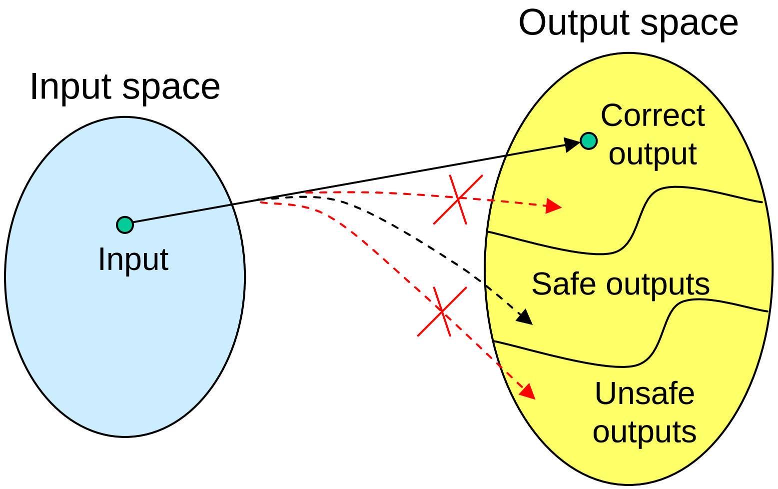
Ultimate fail-safe: Only safe erroneous output is produced, forever

Fail-Safe System Specification

Amusement park train safety system

Signal s_B when asserted indicates that the train is at beginning of its track (can move forward, but should not be allowed to go back)

Signal s_E when asserted indicates that the train is at end of its track (can go back, but should not move forward)



Is the specification above consistent and complete?

No, because it does not say what happens if $s_B = s_E = 1$; this would not occur under normal conditions, but because such sensors are often designed to fail in the safe mode, the combination is not impossible

Why is this a problem, though? (Train simply cannot be moved at all)

Completeness will prevent potential implementation or safety problems

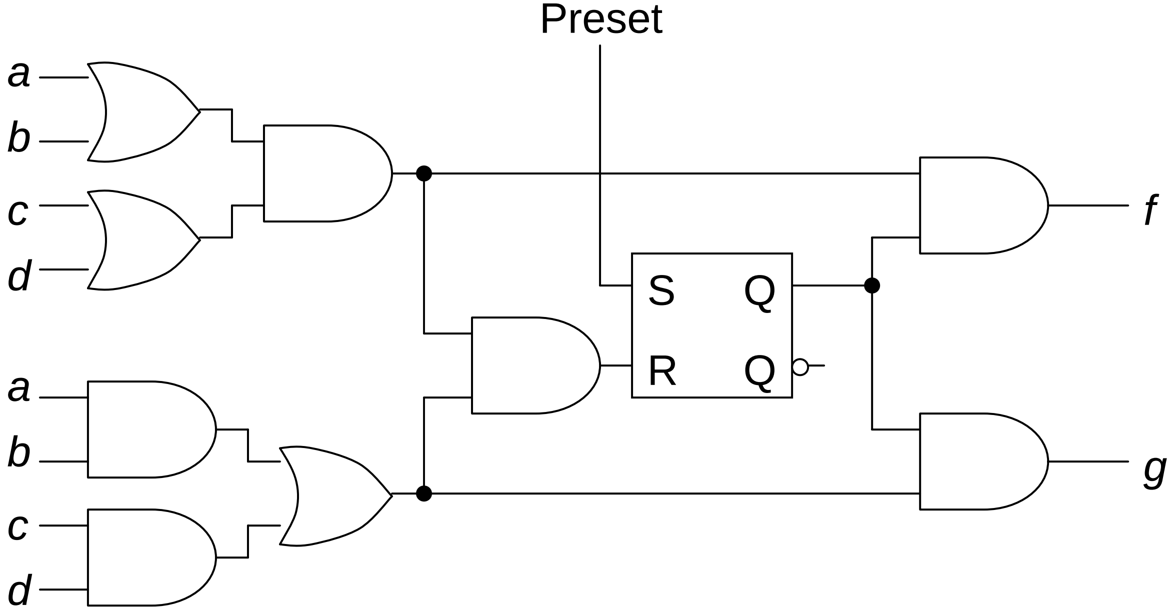
Fail-Safe 2-out-of-4 Code Checker

Input: 4 bits *abcd*, exactly 2 of which must be 1s

Output: *fg* = 01 or 10, if the input is valid
00 safe erroneous output
11 unsafe erroneous output

Codewords

a	*b*	*c*	*d*
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0



Output will become permanently 00 upon the first unsafe condition

Fail-Safe State Machines

Use an error code to encode states

Implement the next-state logic so that the machine is forced to an error state when something goes wrong

Possible design methodology:

Use Berger code for states, avoiding the all 0s state with all-1s check, and vice versa

Implement next-state logic equations in sum-of-products form for the main state bits and in product-of-sums form for the check state bits

The resulting state machine will be fail-safe under unidirectional errors

	Input	
State	x=0	x=1
A	E	B
B	C	D
C	A	D
D	E	D
E	A	D

State	Encoding
A	001 10
B	010 10
C	011 01
D	100 10
E	101 01

Hardware overhead for *n*-state machine consists of O(log log *n*) additional state bits and associated next-state logic, and a Berger code checker connected to state FFs

Principles of Safety Engineering

Principles for designing a safe system (J. Goldberg, 1987)

1. Use barriers and interlocks to constrain access to critical system resources or states
2. Perform critical actions incrementally, rather than in a single step
3. Dynamically modify system goals to avoid or mitigate damages
4. Manage the resources needed to deal with a safety crisis, so that enough will be available in an emergency
5. Exercise all critical functions and safety features regularly to assess and maintain their viability
6. Design the operator interface to provide the information and power needed to deal with exceptions
7. Defend the system against malicious attacks

Recovery from Failures

The recovery block scheme (originally developed for software)

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		

Computer system with manual backup may be viewed as a one-alternate recovery block scheme, with human judgment constituting the acceptance test

Instead of resorting to an alternate (hardware/software) module, one may reuse the primary one

This scheme is known as “retry” or time redundancy and is particularly effective for dealing with transient or soft failures

Fail-Stop and Failover Strategies

Fail-stop systems: Systems designed and built in such a way that they cease to respond or take any action upon internal malfunction detection

Such systems do not confuse the users or other parts of a distributed system by behaving randomly or, worse, maliciously upon failure

A subclass of fail-safe systems (here, stopping is deemed a safe output)

Failover: Upon failure detection, often of the fail-stop kind, requests and other tasks are redirected to a back-up system

Example – Failover on long-running connections for streaming media: all that is needed is to know the file being streamed, and current location within the file, to successfully switch over to a different server

Failover software is available for Web servers as part of firewalls for most popular operating systems

It monitors resources and directs requests to a functioning server

Failover features of Windows XP: http://msdn2.microsoft.com/en-us/library/ms686091.aspx