Fault-Tolerant Computing

Software Design Methods
About This Presentation

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<table>
<thead>
<tr>
<th>Edition</th>
<th>Released</th>
<th>Revised</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>Nov. 2006</td>
<td>Nov. 2007</td>
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</table>
Software Reliability and 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.”
Multilevel Model of Dependable Computing

Legend:
- Entry
- Deviation
- Remedy
- Tolerance

Level → Component Logic Information System Service Result

Ideal Defective Faulty Erroneous Malfunctioning Degraded Failed

Unimpaired Low-Level Impaired Mid-Level Impaired High-Level Impaired

Nov. 2007 Software Reliability and Redundancy B. Parhami Slide 5
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

Project initiation
Needs
Requirements
Specifications
Prototype design
Prototype test
Revision of specs
Final design
Coding
Unit test
Integration test
System test
Acceptance test
Field deployment
Field maintenance
System redesign
Software discard

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

Evaluation by both the developer and customer

Implementation or programming

Separate testing of each major unit (module)

Test modules within pretested control structure

Customer or third-party conformance-to-specs test

New contract for changes and additional features

Obsolete software is discarded (perhaps replaced)
What Does Software Reliability Mean?

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

Input space

Flaw

Not expected to occur
Software Error Models

Software flaw/bug $\Rightarrow$ Operational error $\Rightarrow$ Software-induced failure

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

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 ($F = \text{residual flaws}$, $\tau = \text{testing time, in months}$)

$$\frac{dF(\tau)}{d\tau} = -(a - b\tau)$$

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

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 $\tau = 8$ months:

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

<table>
<thead>
<tr>
<th>$\tau$</th>
<th>MTTF (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>58</td>
</tr>
<tr>
<td>2</td>
<td>98</td>
</tr>
<tr>
<td>4</td>
<td>189</td>
</tr>
<tr>
<td>6</td>
<td>433</td>
</tr>
<tr>
<td>8</td>
<td>758</td>
</tr>
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</table>
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, 2\textsuperscript{nd} moment, . . .) to flaw removal data
• Least-squares estimation, particularly with multiple data sets
• Maximum-likelihood estimation (a statistical method)
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 \( n \)
\[
\begin{align*}
  x &:= m \\
  y &:= n \\
  \text{while } x \neq y \\
  &\quad \text{if } x < y \\
  &\quad\quad y := y - x \\
  &\quad\text{else } x := x - y \\
  &\text{endif} \\
\end{align*}
\]

output \( x \)

\( m \) and \( n \) are positive integers

\( x \) and \( y \) are positive integers, \( x = m, y = n \)

\textit{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

N-Version Programming: The Idea

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)
<table>
<thead>
<tr>
<th>Objection</th>
<th>Counterpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developing programs is already a very expensive and slow process; why multiply the difficulties by (N)?</td>
<td>Cannot produce flawless software, regardless of cost</td>
</tr>
<tr>
<td>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)</td>
<td>This is a criticism of reliability modeling with independence assumption, not of the method itself</td>
</tr>
<tr>
<td>Imperfect specification can be the source of common flaws</td>
<td>Multiple diverse specifications?</td>
</tr>
<tr>
<td>With truly diverse implementations, the output selection mechanism (adjudicator) is complicated and may contain its own flaws</td>
<td>Will discuss the adjudication problem in a future lecture</td>
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</tbody>
</table>
N-Version Programming: Reliability Modeling

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

<table>
<thead>
<tr>
<th>Category</th>
<th>BY-CASE</th>
<th>BY-FRAME</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of cases</td>
<td>Frequency</td>
</tr>
<tr>
<td>$F_0$ - no errors</td>
<td>322010</td>
<td>0.65052</td>
</tr>
<tr>
<td>$F_1$ - single error</td>
<td>152900</td>
<td>0.30889</td>
</tr>
<tr>
<td>$F_2$ - two coincident</td>
<td>16350</td>
<td>0.03303</td>
</tr>
<tr>
<td>$F_3$ - three coincident</td>
<td>3700</td>
<td>0.00747</td>
</tr>
<tr>
<td>$F_4$ - four coincident</td>
<td>40</td>
<td>0.00008</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>495000</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

Source: Dugan & Lyu, 1994 and 1995
N-Version Programming: Applications

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

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Specs</th>
<th>Languages</th>
<th>Versions</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Halden, Reactor Trip</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>[Dah79]</td>
</tr>
<tr>
<td>NASA, First Generation</td>
<td>3</td>
<td>1</td>
<td>18</td>
<td>[Kei83]</td>
</tr>
<tr>
<td>KFK, Reactor Trip</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>[Gme80]</td>
</tr>
<tr>
<td>NASA/RTI, Launch Interceptor</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>[Dun86]</td>
</tr>
<tr>
<td>UCI/UVA, Launch Interceptor</td>
<td>1</td>
<td>1</td>
<td>27</td>
<td>[Kni86a]</td>
</tr>
<tr>
<td>Halden (PODS), Reactor Trip</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>[Bis86]</td>
</tr>
<tr>
<td>UCLA, Flight Control</td>
<td>1</td>
<td>6</td>
<td>6</td>
<td>[Avi88]</td>
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<tr>
<td>NASA (2nd Gen.) Inertial Guidance</td>
<td>1</td>
<td>1</td>
<td>20</td>
<td>[Eck91]</td>
</tr>
<tr>
<td>UI/Rockwell, Flight Control</td>
<td>1</td>
<td>1</td>
<td>15</td>
<td>[Lyu93]</td>
</tr>
</tbody>
</table>

Source: P. Bishop, 1995
Recovery Block Scheme: The Idea

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

\[
\begin{align*}
\text{ensure by} & \quad \text{acceptance test} \\
\text{primary module by} & \quad \text{first alternate} \\
\vdots & \\
\text{else by} & \quad \text{last alternate} \\
\text{else fail} & \\
\end{align*}
\]

\[
\begin{align*}
\text{e.g., sorted list} \\
\text{e.g., quicksort} \\
\text{e.g., bubblesort} \\
\vdots \\
\text{e.g., insertion sort}
\end{align*}
\]

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
Recovery Blocks: 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.
Combined NVP and Acceptance Testing

**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

More General Hybrid NVP-AT Schemes

(a) Legend

- Module
- Test
- Voter
- In
- Out
- Error

(b) 5VP

(c) ALT1