Software Fault Tolerance via Environmental Diversity

Keynote Talk

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Outline

- Motivation/Definitions
- Real System Examples
- Software Fault Classification
- Environmental Diversity
- Methods of Mitigation
- Conclusions
Pervasive Dependence on Computer Systems Implies the Need for High Reliability/Availability
Dependability—An umbrella term

- **Laprie**: Trustworthiness of a computer system such that reliance can justifiably be placed on the service it delivers.
Two of the Attributes of Dependability

- **Reliability**
  - Continuity of service, how long does system work w/o system failure

- **Availability**
  - Readiness of service, how frequently it fails and how quickly can it be repaired/restored/recovered
IFIP Working Group 10.4 (Laprie)

- **Failure** occurs when the delivered service no longer complies with the desired output.
- **Error** is that part of the system state which is liable to lead to subsequent failure.
- **Fault** (or **bug**), is adjudged or hypothesized cause of an error.

Faults are the cause of **errors** that may lead to **failures**

...... Fault ➔ Error ➔ Failure ......
Example Failures from High Tech companies

Mar. 2015, Gmail was down for 4 hours and 40 min.

Mar. 2015, Down for 3 hours affecting Europe and US

Dec. 2015, Microsoft Office 365 and Azure down for 2 hours

Sept. 2015, AWS DynamoDB down for 4 hours impacting among others Netflix, AirBnB, Tinder

Mar. 2015, Apple ITunes, App Stores long outage: 12 hours
More examples of real failures

Feb. 2017 - Amazon S3 service outage (almost 6 hours)

Jul. 2017 - Google Cloud Storage service outage (3 hours and 14 min.) - API low-level software defect

Jul. 2017 - Microsoft Azure service outage (4 hours) – Load Balancer Software bug

These examples indicate that even the most advanced tech companies are not offering high levels of dependability
More Recent Examples

- In Commercial aircrafts (Boeing 737 Max software problem)
  - Ethiopian Airlines Flight, March 2019, 149 people died
  - Lion Air Flight crash, Oct. 2018, 189 people died
- Air India’s passenger service system software, which looks after check-in, baggage and reservation, was down for more than 5 hours on April 27, 2019.
Software is a big problem

- Hardware fault tolerance, fault management, reliability/availability modeling relatively well developed
- System outages more due to software faults

Key Challenge:

Software reliability is one of the weakest links in system reliability/availability
Ensuring Software Reliability: Known Means

- Fault prevention or Fault avoidance
- Fault Removal
- Fault Tolerance
Reliable Software

- Fault prevention or Fault avoidance
  - Good software engineering practices
    - Requirement Elicitation (Abuse Case Analysis – TCS SSA)
    - Design Analysis / Review
    - Secure Programming Standard & Review
    - Secure Programming Compilation
    - Software Development lifecycle
    - Automated Code Generation Tools (IDE like Eclipse)
  - Use of formal methods
    - UML, SysML, BPM
    - Proof of correctness
    - Model Checking (SMART, SPIN, PRISM)

- Bug free code not yet possible for large scale software systems
- Yet there is a strong need for failure-free system operation
System outages and software

- The unstoppable cost increase of software failures
  - Brokerage $6,450,000 / h
  - Credit card authorization $2,600,000 / h
  - eCommerce $225,000 / h
  - Airline reservation $89,000 / h
  - ...

- Failures must be avoided through rigorous testing and fault removal as well as by fault tolerance against residual faults
Ensuring Software Reliability: Known Means

- Fault prevention or Fault avoidance
- Fault Removal
- Fault Tolerance
Reliable Software

- **Fault removal**
  - Can be carried out during
    - the specification and design phase
    - the development phase
    - the operational phase
  - Failure data may be collected and used to parameterize a software reliability growth model (SRGM) to predict when to stop testing

- Impossible to fully test and verify if software is fault-free
  
  “Testing shows the presence, not the absence, of bugs” - E. W. Dijkstra

- Software is still delivered with many bugs either because of inadequate budget for testing, very difficult to reproduce/detect/localize/correct bugs or inadequacy of techniques employed/known
Ensuring Software Reliability: Known Means

- Fault prevention or Fault avoidance
- Fault Removal
- Fault Tolerance
High Reliability/Availability:

Software is a big problem

Software fault tolerance is a potential solution to improve software reliability in lieu of virtually impossible fault-free software.
Software Fault Tolerance

Classical Techniques

- Design diversity
  - Recovery block
  - N-version programming
  - N-self check programming
- Data diversity
Software Fault Tolerance:

Classical Techniques
- Design diversity
  - Recovery block
  - N-version programming
  - N-self-check programming

Expensive $\rightarrow$ not used much in practice!

Yet there are stringent requirements for failure-free operation

Challenge: Affordable Software Fault Tolerance

A possible answer: Environmental Diversity
TAKE AWAY MESSAGE

- Complex systems (e.g., SDN, CPS, IoT) have a large amount of software. **Software failures are a major cause of undependability.**

- **Software failures during operation are a fact that we need to learn to deal with.** Traditional method of software fault tolerance based on design diversity is expensive and hence does not get used extensively.

- Software fault tolerance based on **inexpensive environmental diversity** should be exploited.

- The focus so far has been on **software faults**; we need to pay attention also to **failures** caused by software bugs and the recovery from these failures.

- Or, focus so far has been on software reliability; we need to pay attention to **software availability** as well.
Outline

- Motivation
- A Real System Example
- Software Fault Classification
- Environmental Diversity
- Methods of Mitigation
- Conclusions
REAL SYSTEM: SIP ON WEBSPHERE

IBM Implementation (around 2007)
High availability SIP Application Server Configuration on IBM WebSphere

More details in my PRDC 2008 and ISSRE 2010 papers

AS1 thru AS6 are Application Server
Proxy1's are Stateless Proxy Server
High availability SIP Application Server Configuration on IBM WebSphere

- Hardware configuration:
  - Two BladeCenter chassis; 4 blades (nodes) on each chassis
  - 1 chassis is sufficient from performance perspective

- Software configuration:
  - 2 copies of SIP/Proxy servers (1 sufficient for performance)
  - 12 copies of WebSphere Application Server (WAS or AS)
  - 6 copies sufficient for performance
  - Each WAS instance forms a redundancy pair (replication domain) with WAS installed on another node on a different chassis

- Fault Tolerance:
  - The system has both hardware redundancy
  - and software redundancy.
High availability SIP Application Server Configuration on IBM WebSphere

- **Software Redundancy**
  - Identical copies of SIP proxy used as backups (*hot spares*)
  - Identical copies of WebSphere Applications Server (WAS) used as backups (*hot spares*)
  - **Type of software redundancy** – (not design diversity) but replication of identical software copies
  - **Normal recovery after a software failure** – uses time redundancy
    - Restart software, reboot node or fail-over to a software replica; only when all else fails, a “software repair” is invoked
Software Fault Tolerance: New Thinking

Failover to an identical software replica (that is not a diverse version)
Both have the same bugs

Does it help?

If yes, why?

Thirty years ago this would be considered crazy!
Software Fault Tolerance: New Thinking

1. Have been Known to help in dealing with hardware transient faults

2. Do they help in dealing with failures caused by software bugs? Without fixing those bugs?

3. If yes, why?
Bugs are not all equal!

- **Fault triggers** make the difference
- Some bugs are “trivial”, and failures caused by them can be easily reproduced. So it is relatively easy to remove these bugs
- Others are “subtle”, and reproducing the failures caused by these bugs is challenging
  - Concurrency bugs
  - *Race conditions*
  - *Memory leaks*
  - *Hardware-related bugs affecting software*
  - ...
- These bugs have a significant impact in terms of the number of software failures and the resultant losses
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IFIP Working Group 10.4 (Laprie)

- **Failure** occurs when the delivered service no longer complies with the desired output.

- **Error** is that part of the system state which is liable to lead to subsequent failure.

- **Fault** (or bug) is adjudged or hypothesized cause of an error.

Faults are the cause of errors that may lead to failures.

-------- Fault → Error → Failure --------
A New Classification of Software Faults

Bohrbug: A fault that is easily isolated and that manifests consistently under a well-defined set of conditions, because its activation and error propagation lack complexity.

Example: A bug causing a failure whenever the user enters a negative date of birth

- Since they are easily found, Bohrbugs may hopefully be detected and fixed during the software testing phase.
- The term alludes to the physicist Neils Bohr and his rather simple atom model.
A New Classification of Software Faults

Mandelbug: A fault whose activation and/or error propagation are complex. Typically, a Mandelbug is difficult to isolate, and/or the failures caused by it are not systematically reproducible.

Example: A bug whose activation is scheduling-dependent:
- The residual faults in a thoroughly-tested piece of software are mainly Mandelbugs.
- The term alludes to the mathematician Benoît Mandelbrot and his research in fractal geometry.
- Sometimes called concurrency bugs or non-deterministic bugs, soft bugs or environment-dependent bugs; failures resulting from these bugs are sometimes called transient failures.
Mandelbug Complexity Factors

- Besides workload and internal state of the software system, its system-context (or operating) environment participates in determining whether a failure due to such a bug will occur.

- So a fault is a Mandelbug if its manifestation as a failure is subject to the following complexity factors:
  - Long time lag between fault activation and failure appearance
  - Operating environment dependence (OS resources, other applications running concurrently, hardware, network…)
  - Timing among submitted operations
  - Sequencing or ordering of operations

- A failure due to a Mandelbug thus may not recur upon the resubmission of the same workload if the operating environment has changed enough.
Aging-related bug := A fault that leads to the accumulation of errors either inside the running application or in its system-context environment, resulting in an increased failure rate and/or degraded performance.

Example:
- A bug causing memory leaks in the application
- Note that the aging phenomenon requires a delay between (first) fault activation and failure occurrence.
- Note also that the software appears to age due to such a bug; there is no physical deterioration
Bohrbug and Mandelbug are complementary antonyms. Aging-related bugs are a subtype of Mandelbugs.
Dealing with Mandelbugs

- Depending on the bugtype, appropriate strategies are needed
- **Traditional testing** tends to be ineffective for Mandelbugs; more suitable verification strategies are
  - Model checking
  - Combinatorial testing
  - Ratliff, Kuhn, Kacker, Lei & Trivedi, "The Relationship between Software Bug Type and Number of Factors Involved in Failures," *IEEE International Symposium on Software Reliability Engineering Workshops (ISSREW), 2016*
- Failures due to Mandelbugs can be **tolerated** by
  - Retrying failed operation, Restarting a process or Rebooting the VM
  - Failover to an identical replica
- Failures due to Aging-related bugs can be prevented by
  - Rejuvenation
  - **Handbook on Software Aging and rejuvenation**, Dohi, Trivedi & Avritzer (eds.), World scientific, 2020
Dealing with Software Failures

- We submit that a software fault tolerance approach based on retry, restart, reboot or fail-over to an identical software replica (not a diverse version) works because of a significant number of software failures are caused by Mandelbugs (environment-dependent bugs) as opposed to the traditional software bugs now known as Bohrbugs.
Examples of Mandelbugs in IT Systems

- Mandelbugs in IT Systems: “Recovery from failures due to Mandelbugs in IT systems,” Trivedi, Mansharamani, Kim, Grottke, Nambiar. PRDC 2011; IEEE TR, 2016 (Roberto Natella was added co-author for IEEE-TR paper)

- The selected TCS (Tata Consultancy Services) projects ranged across a number of business systems in the banking, financial, government, IT, pharmacy, and telecom sector
Mandelbug “Reproducibility”

(Failures due to) Mandelbugs are really hard to reproduce

- Conducted a set of experiments to study the environmental factors that affect the reproducibility of Mandelbugs in MySql
  - disk usage,
  - memory occupancy
  - Concurrency level
- High usage levels of environmental factors increases significantly failure occurrences due to Mandelbugs

Important Questions about these Bugs

- What fraction of bugs in real software systems are Bohrbugs, Mandelbugs and aging-related bugs
  - How do these fractions vary
    - over time
    - over projects, languages, application types,…
  - Need of Real Data
Fault Types in NASA Software

- This papers won the Test of Time Award at DSN 2020

<table>
<thead>
<tr>
<th>Project</th>
<th>LoC</th>
<th>% BOH</th>
<th>% NAM</th>
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Fault Types in Open-Source Systems


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Bug Types in Open-Source Systems: NAM classification

- **LAG**: there can be a time lag between the activation of the fault and the occurrence of a failure

- **ENV**: the activation and/or error propagation is influenced by the interactions of the software application with its system-internal environment

- **TIM**: the activation and/or error propagation is influenced by the timing of inputs and operations

- **SEQ**: the activation and/or error propagation is influenced by the sequencing (i.e., the relative order) of operations
Bug Types in Open-Source Systems: ARB classification

- **MEM**: ARBs causing the accumulation of errors related to memory management

- **STO**: ARBs causing the accumulation of errors that affect disk storage space

- **LOG**: ARBs causing leaks of “other logical resources”, that is, system-dependent data structures

- **NUM**: ARBs causing the accumulation of numerical errors

- **TOT**: ARBs in which the increase of the fault activation/error propagation rate with the total system run time is not caused by the accumulation of internal error states
## Examples of ARB/NAM

<table>
<thead>
<tr>
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<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MySQL</td>
<td>NAM/SEQ</td>
<td>“if you ‘alter table .. rename to ..’ on a table that has an active transaction open and UNIV DEBUG is defined, mysqld crashes”</td>
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<tr>
<td>Linux</td>
<td>NAM/LAG</td>
<td>”[The e1000 network driver at suspend/resume does not] explicitly free and allocate irq […] Restarting the network solved the problem”</td>
</tr>
<tr>
<td>HTTPD</td>
<td>NAM/ENV</td>
<td>“The error only occurs intermittently […] It behaves as if requests are being distributed (via round-robin or the like) and handled sometimes by a worker thread that is not properly initialized”</td>
</tr>
<tr>
<td>Axis</td>
<td>ARB/MEM</td>
<td>“Strings and char[]s are being leaked”</td>
</tr>
<tr>
<td>Linux</td>
<td>ARB/LOG</td>
<td>“In 2.6.35 and earlier, shutdown(2) will fully remove a socket. This does not appear to be true any more and is causing software to misbehave.”</td>
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<tr>
<td>HTTPD</td>
<td>ARB/S TO</td>
<td>“Apache child processes will die trying to write logs which have reached 2GB in size.”</td>
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Fault Types in Android


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Example of Mandelbug in Android

- **ENV**: On certain Android devices, performing the following operations in sequence could lead to a crash

  Open camera → Set flash ON → Take a picture
  → Set flash OFF → Take another picture.

  *(Caused by Environments)*
Fault Types in Linux Revisited


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Fault Types in Several Systems


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Software Faults and Mitigation Types

- The fault classification is not only theoretical, it has also practical implications.

- Each type of software fault may require different type of approach during development, testing, as well as during operations.
Outline

- Motivation
- Real System Examples
- Software Fault Classification
- Environmental Diversity
- Methods of Mitigation
- Conclusions
Software Fault Tolerance: New Thinking

- **Environmental Diversity** as opposed to Design Diversity

- Our claim is that this (retry, restart, reboot, failover to identical software copy) may well work since failures due to **Mandelbugs** are not negligible. We thus have an affordable software fault tolerance technique that we call **Environmental Diversity**
What is Environmental diversity?

- The underlying idea of Environmental diversity
  - Restart an application (without fixing the bus) and it most likely works -- Why?
    - because of the environment where the application is executed has changed enough to avoid the fault activation.
  - The environment is understood as
    - OS resources, other applications running concurrently and sharing the same resources, interleaving of operations, concurrency, or synchronization.

- This is Fault Tolerance since we do not necessarily fix the fault; fault caused a failure but this failure is dealt with by using time redundancy hence the user may not experience the failure again on retry.
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Bohrbugs: Remove

Software (OS, middleware, applications)

Bohrbugs

Debug/Test

Design diversity

Data diversity
Bohrbug: Remove

- Find and fix the bugs during testing
- Failure data collected during testing
- Calibrate a software reliability growth model (SRGM) using failure data; this model is then used for prediction
- Many SRGMs exist
  - Books by Lyu, Musa and several others
Methods of Mitigation: Mandelbugs

- Bohrbugs
  - Debug/Test
  - Design diversity
  - Data diversity
  - Retry operation
- Mandelbugs
  - Failover to standby
  - Restart Application
  - Reboot Node

Software (OS, middleware, applications)
Implications of Mandelbugs

- Can measure/model software availability
- Combined of software and hardware availability
- Need:
  - Develop methods of debugging and testing for environment-dependent bugs
  - Methods to determine environmental factors and their effects
  - Run-time control of environmental factors to avoid failure occurrences
  - Optimal recovery sequence after failure occurrence
  - Experimental methods to determine the nature software failure times including use of ALT
Determine Environmental Factors

There are two steps:

- **Step 1:** List all the possible environmental factors.
- **Step 2:** Determine the critical environmental factors that can affect the times to failure through:
  - Either *logically*, according to the failure mechanism
  - Or by *experimental method*, need Design of Experiments.
Determine Environmental Factors Step 1

- Five Categories of Candidate Environmental Factors:
  - Hardware resources
    - Physical memory, CPU, disk, network, I/O devices, buses, etc.
    - Connected firmware
  - Operating System kernel’s subsystems
    - OS memory management, device drivers, file-system, networking, process management, etc.
  - Concurrent software
    - Utility software, daemon processes, etc.
    - Application-level interacting software, middleware, etc.
  - Interfaces
    - Third-party library, open-source library, etc.
  - Others
Determine Environmental Factors
Step 2

- **Using logic.** Examples as follows:

  - **Data Race problem.** According to the OS theory, smaller the physical Resident-Set-Size memory, larger the number of concurrent users, and larger the number of CPU cores, larger the context switch frequency among threads; thereby increasing the race’s activation process. These three environmental factors are therefore critical ones. Details are in [Kun et al. TR 2019].

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Summary

- It is possible to enhance software availability during operation exploiting environmental diversity

- Multiple types of recovery after a software failure can be judiciously employed: restart, failover to a replica, reboot and if all else fails repair (patch)
TAKE AWAY MESSAGE

- Complex systems (e.g., SDN, CPS, IoT) have a large amount of software. **Software failures are a major cause of undependability.**

- **Software failures during operation are a fact that we need to learn to deal with.** Traditional method of software fault tolerance based on design diversity is expensive and hence does not get used extensively.

- Software fault tolerance based on **inexpensive environmental diversity** should be exploited.

- The focus so far has been on **software faults**; we need to pay attention also to **failures** caused by software bugs and the recovery from these failures.

- Or, focus so far has been on software reliability; we need to pay attention to **software availability** as well.
Thank you for your attention

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Key References

**Motivation**


- Network Troubleshooting, O. Kyas, Agilent Technologies , 2001

Key References

Real System


Fault Classification

- An Empirical investigation of fault triggers in Android operating system Android operating system, F. Qin, Z. Zheng, X. Li, Y. Qiao, K. S. Trivedi, PRDC 2017;
Key References

Environmental Diversity and Methods of Mitigation

- Understanding the impacts of influencing factors on time to a datarace software failures, K. Qiu, Z. Zheng, K.S. Trivedi, B. Yin, ISSRE 2017.
Extra Slides if Needed

- To answer questions about Heisenbugs vs. Mandelbugs
Jim Gray’s Definitions

- The terms “Bohrbug” and “Heisenbug” were first used in print by Jim Gray in 1985.
- “Bohrbugs, like the Bohr atom, are solid, easily detected by standard techniques, and hence boring.”
- “Most production software faults are soft. If the program state is reinitialized and the failed operation is retried, the operation will not fail a second time. … The assertion that most production software bugs are soft – Heisenbugs that go away when you look at them – is well known to systems programmers.” (Gray, 1985)
Based on Gray’s paper, researchers have often equated *Heisenbugs* with soft faults.

However, when Bruce Lindsay originally coined the term in the 1960s (while working with Jim Gray), he had a more narrow definition in mind.

“*Heisenbugs* as originally defined … are bugs in which clearly the system behavior is incorrect, and when you try to look to see why it’s incorrect, the problem goes away.” (Lindsay, 2004)

The term alludes to the physicist Werner Heisenberg and his Uncertainty Principle.
Heisenbug – Our Definition

**Heisenbug** := A fault that stops causing a failure or that manifests differently when one attempts to probe or isolate it.

- How can probing affect the bug?
  - Some debuggers initialize unused memory to default values, thus preventing failures due to improper initialization.
  - Trying to investigate a failure can influence process scheduling in such a way that a scheduling-related failure does not occur again.