Reliable Computing I

Lecture 2: Reliability Metrics

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Today’s Lecture

Definition, metrics, and terminology

fault-tol·er·ant  \f ölt-'täl(- ə)-rənt\  
adj : able to function in the  
absence of a major component
Goals of Fault Tolerant Systems

- How can we deal with problems?
- Option 1: Make problems less likely
  - Tough to do!
  - Testing and design for test (DFT) can help avoid physical defects
  - Careful design reviews can help to avoid design bugs
  - Training and practice can help to avoid operator error
- Option 2: Fail, but don’t corrupt anything
  - Example: ATM should shut down instead of passing out money
- Option 3: Transparently tolerate problems
  - Use hardware and/or software to mask fault effects
  - Key: use redundancy (a.k.a. spares or backups)
  - Example: having a co-pilot on an airplane
Reliable Computing System

- Correct outputs
  - Desired performance, power consumption
- Changing/varying environmental conditions
  - Power supply, radiation, noise
- Manufacturing process conditions
  - Defects, process variation
- Design errors
Reliability approaches

- **Fault avoidance**: eliminate problem sources
  - Remove defects: Testing and debugging
  - Robust design: reduce probability of defects
  - Minimize environmental stress: Radiation shielding etc
  - Impossible to avoid faults completely
    - Occurrence of failures minimized

- **Fault tolerance**: add redundancy to mask effect
  - Failures during system operation
  - Recovery & repair
  - Examples:
    - Error correction coding
    - Backup storage
    - Spare tire
# System View of Dependable Computing

<table>
<thead>
<tr>
<th>Applications</th>
<th>What can be provided in software and application itself?</th>
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<tbody>
<tr>
<td><strong>SIFT</strong></td>
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<tr>
<td>Application program interface (API)</td>
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<tr>
<td>Middleware</td>
<td></td>
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<tr>
<td>Reliable communications</td>
<td>What can be provided in the communication layer?</td>
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<tr>
<td>Operating system</td>
<td>What can be provided in the operating system?</td>
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<tr>
<td>Hardware</td>
<td>What can be provided in hardware to ensure fail-silent behavior of system components?</td>
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<tr>
<td>System network</td>
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<tr>
<td>Processing elements</td>
<td></td>
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<td>Memory</td>
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<td>Storage system</td>
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How to combine hardware and software fault tolerance techniques - (1) fast error detection in hardware, (2) high efficiency detection and recovery in software, How to assess whether the achieved availability meets system requirements.

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How do We Achieve the Objectives?

<table>
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<tr>
<th>Applications</th>
<th>Checkpointing and rollback, application replication, software voting (fault masking), process pairs, robust data structures, recovery blocks, N-version programming</th>
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<td>Reliable communications</td>
<td>CRC on messages, acknowledgment, watchdogs, heartbeats, consistency protocols</td>
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<td>Operating system</td>
<td>Memory management, detection of process failures, hooks to support software fault tolerance for application</td>
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<tr>
<td>Hardware</td>
<td>Error correcting codes, N_of_M and standby redundancy, voting, watchdog timers, reliable storage (RAID, mirrored disks)</td>
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Reliable Computing I: Lecture 2
Original definition of dependability (that stresses the need for justification of trust) states that: the dependability is the ability to deliver service that can justifiably be trusted.

The alternate definition (that provides the criterion for deciding if the service is dependable) states that: the dependability of a system is the ability to avoid service failures that are more frequent and more severe than is acceptable.
Dependable Systems

[Diagram showing the hierarchical structure of dependability with attributes, means, and impairments]

- Attributes:
  - Availability
  - Reliability
  - Maintainability
  - Safety
  - Security

- Means:
  - Validation
  - Fault Detection
  - Fault Removal
  - Procurement
  - Fault Prevention
  - Fault Tolerance

- Impairments:
  - Defects
  - Faults
  - Errors
  - Failures

[Note: Lap95: “Dependable computing: concepts, limits, challenges,” FTCS 1995]

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Intuitive Concepts

- Reliability – continues to work
- Availability – works when I need it
- Safety – does not put me in jeopardy
- Performability - combination of reliability & performance
  - “Graceful degradation”: loss of performance due to minor failures
- Maintainability - ease of repairing a system after failure
- Testability - ease of detecting presence of a fault
- **Survivability** – will the system survive catastrophic events?
Something is wrong…

- Defect
  - Distortion of the physical shape
- Fault
  - Logical model of defects
- Error
  - Incorrect signal values/state/information in computation
- Failure
  - Deviation from designed characteristics
  - Observed malfunction during operation
  - Loss of intended function
Something is wrong…

- **Latent fault**: which has not yet produced error
  - Faulty component will produce error only when used by a process.

- **Latent error**: which has not yet produced failure.
  - An infected person may not show symptoms of a disease.
Something is wrong...

- **Fault**: abstraction of physical defect or bug to structural level
- **Error**: effect of an physical defect, bug
- **Failure**: malfunction of the system, breakdown
What to do about faults?

Finding & identifying faults:
- Fault detection: is a fault there?
- Fault location: where?
- Fault diagnosis: which fault it is?

Automatic handling of faults
- Fault containment: blocking error flow
  - Fault masking: fault has no effect
- Fault recovery: back to correct operation
System Response to Faults

- **Error on output**: may be acceptable in non-critical systems if happens only rarely
- **Fault masking**: output correct even when fault from a specific class occurs
  - Critical applications: air/space/manufacturing
- **Fault-secure**: output correct or error indication
  - Retryable: banking, telephony, payroll
- **Fail safe**: output correct or in safe state
  - Flashing red traffic light, disabled ATM
Fault Cycle & Dependability Measures

Reliability:
a measure of the continuous delivery of service; 
$R(t)$ is the probability that the system survives (does not fail) throughout $[0, t]$; 
expected value: $MTTF$ (Mean Time To Failure)

Maintainability:
a measure of the service interruption 
$M(t)$ is the probability that the system will be repaired within a time less than $t$; 
expected value: $MTTR$ (Mean Time To Repair)

Availability:
a measure of the service delivery with respect to the alternation of the delivery and interruptions 
$A(t)$ is the probability that the system delivers a proper (conforming to specification) service at a given time $t$. 
expected value: $EA = MTTF / (MTTF + MTTR)$

Safety:
a measure of the time to catastrophic failure 
$S(t)$ is the probability that no catastrophic failures occur during $[0, t]$; 
expected value: $MTTCF$ (Mean Time To Catastrophic Failure)
Typical Recovery Latencies for a Hierarchical Fault Tolerant Design

Recovery Latency

- 10 s
- 1 s
- 100 ms
- 10 ms
- 1 ms
- 100 μs
- 10 μs
- 1 μs
- 100 ns
- 10 ns
- 1 ns

Recovery Level

- Hardware Concurrent Error Detection & Recovery
- Software Exception Handlers (Instruction Retry)
- Node Operating System (NOS)
- Network Management System (NMS)
- System Manager/Hardcore
First some probabilities…

- For each random variable $X$,
  - cumulative distribution function (CDF): $F(x) = P(X \leq x)$
    - Probability $P$ that event $X$ is less than or equal to value of $x$
  - Probability mass function (PMF): $F(x) = P(X = x)$
  - Probability density function (PDF): $f(x) = \frac{dF}{dx}$
    - Such that in general $P(a \leq x \leq b) = \int_{a}^{b} f(x) \, dx$
  - Mean or Expected value: $E[X] = \int_{-\infty}^{+\infty} x f(x) \, dx$
  - Variance: $\sigma_x^2 = E[(x - E[x])^2]$
Probability of Failure

- Random variable \( T \) is time to the next failure
  - Lifetime of a module (time until it fails)

\[ F(t) = \text{Prob} \{ T \leq t \} \]

- Probability that component will fail before or at time \( t \)

\[ f(t) = \frac{dF(t)}{dt}, \quad \int_0^\infty f(t)dt = 1, \quad f(t) \geq 0 \quad (\text{for all } t \geq 0) \]

- The momentary rate of probability of failure at time \( t \)

- \( F \) and \( f \) are related through:

\[ f(t) = \frac{dF(t)}{dt} \quad \quad \quad F(t) = \int_0^t f(s)ds \]
Reliability $R(t)$

- Probability that the system has been operating correctly and continuously from time 0 until time $t$, given that it was operating correctly at time 0
  
  $$R(t) = \text{Prob} \{ T > t \} = 1 - F(t)$$

- MTTF: Mean Time To Failure
  
  Expected value of the lifetime $T$
  
  $$MTTF = E[T] = \int_0^\infty t \cdot f(t) dt$$

  With $$\frac{dR(t)}{dt} = -f(t)$$ follows:

  $$MTTF = -\int_0^\infty t \cdot \frac{dR(t)}{dt} \cdot dt = -tR(t) \bigg|_0^\infty + \int_0^\infty R(t) \cdot dt = \int_0^\infty R(t) \cdot dt$$
**Failure Rate \( \lambda \)**

- Number of failures per time unit w.r.t. number of surviving components
  - Also known as hazard function, \( z(t) \)
  - \( \lambda(t) = z(t) = \frac{dF(t)/dt}{(1-F(t))} = \frac{f(t)}{R(t)} \)

- A module has a constant failure rate if and only if \( T \) has an exponential distribution
  
  \[
  R(t) = e^{-\lambda t}; \quad F(t) = 1 - e^{-\lambda t}; \quad R(0) = 1 \\
  f(t) = \lambda e^{-\lambda t}
  \]
Failure Rate $\lambda(t) = \lambda$

$MTTF = \int_0^\infty t \cdot \lambda e^{-\lambda t} dt = \int_0^\infty e^{-\lambda t} dt = \frac{1}{\lambda}$

Reliability

$R(t) = e^{-\lambda t}$
Availability

- **Availability A(t)**
  - Fraction of time system is operational during the interval [0,t]
  - Excludes time for recovery or repair

- **MTTR: Mean Time To Repair**

- **MTBF: Mean Time Between Failures**
  - \( MTBF = MTTF + MTTR \)

\[
A = \frac{E[\text{Uptime}]}{E[\text{Uptime}] + E[\text{Downtime}]} = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{MTBF}
\]
Other failure distribution models

- **Weibull distribution**
  - \( \alpha \) : shape parameter
    - \( \alpha < 1 \) : failure rate decreasing with time
    - \( \alpha = 1 \) : failure rate constant
    - \( \alpha > 1 \) : failure rate increasing with time
  - \( \lambda \) : scale parameter
  - PDF = \( f(t) = \alpha \lambda (\lambda t)^{\alpha-1} e^{-(\lambda t)^\alpha} \)
  - CDF = \( F(t) = 1 - e^{-(\lambda t)^\alpha} \)
  - Reliability = \( R(t) = e^{-(\lambda t)^\alpha} \)
Other failure distribution models

- Geometric distribution

  - Discrete times 0, 1, 2, …
  - Replacing $e^{-\lambda}$ by discrete probability $q$
  - Replacing $t$ by $n$

  - PMF $= f(n) = q^n - q^{n+1} = q^n(1 - q)$
  - CDF $= F(n) = 1 - q^n$
  - Reliability $= R(n) = q^n$

  - $\mu = \frac{1}{1-q}$, $\sigma = \frac{q^{1/2}}{1-q}$

- Discrete Weibull distribution
Maintainability

MTTR may be subdivided as follows

- Time needed to detect a fault and isolate the responsible components (diagnosis)
- Time needed to replace the faulty component
- Time needed to verify that the fault has been removed and the system is fully operational

Design for maintainability

- System design which supports efficient fault detection, isolation and repair
Performability

- Accomplishment levels \( L_1, L_2, \ldots, L_n \) defined in the application context
- Representing a level of quality of service delivered by the application
- E.g.: \( L_i \) indicates \( i \) system crashes during mission time
- Performability is a vector \((P(L_1), P(L_2), \ldots, P(L_n))\)
- \( P(L_i) \) : Probability that the system performs well enough that the application reaches level \( L_i \)