System Reliability and Metrics of Reliability

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What is Reliability?

- Probability of System ‘Survival’ $P[S](t)$ over time T.
- $P[S](t) = R(t) = 1 - Q(t)$
- A measure of the likelihood of no fault occurring.
- Related to system function and architecture.
- ‘All systems will fail, the only issue is when, and how frequently.’

System Reliability

- Hardware Reliability.
- Software Reliability.
- Reliability of interaction between hardware and software.
- Reliability of interaction between the system and the operator.

Hardware Reliability

- Component, PCB, interconnection reliability, and failure modes.
- Hard, transient & intermittent failures.
- Random failures - exponentially distributed.

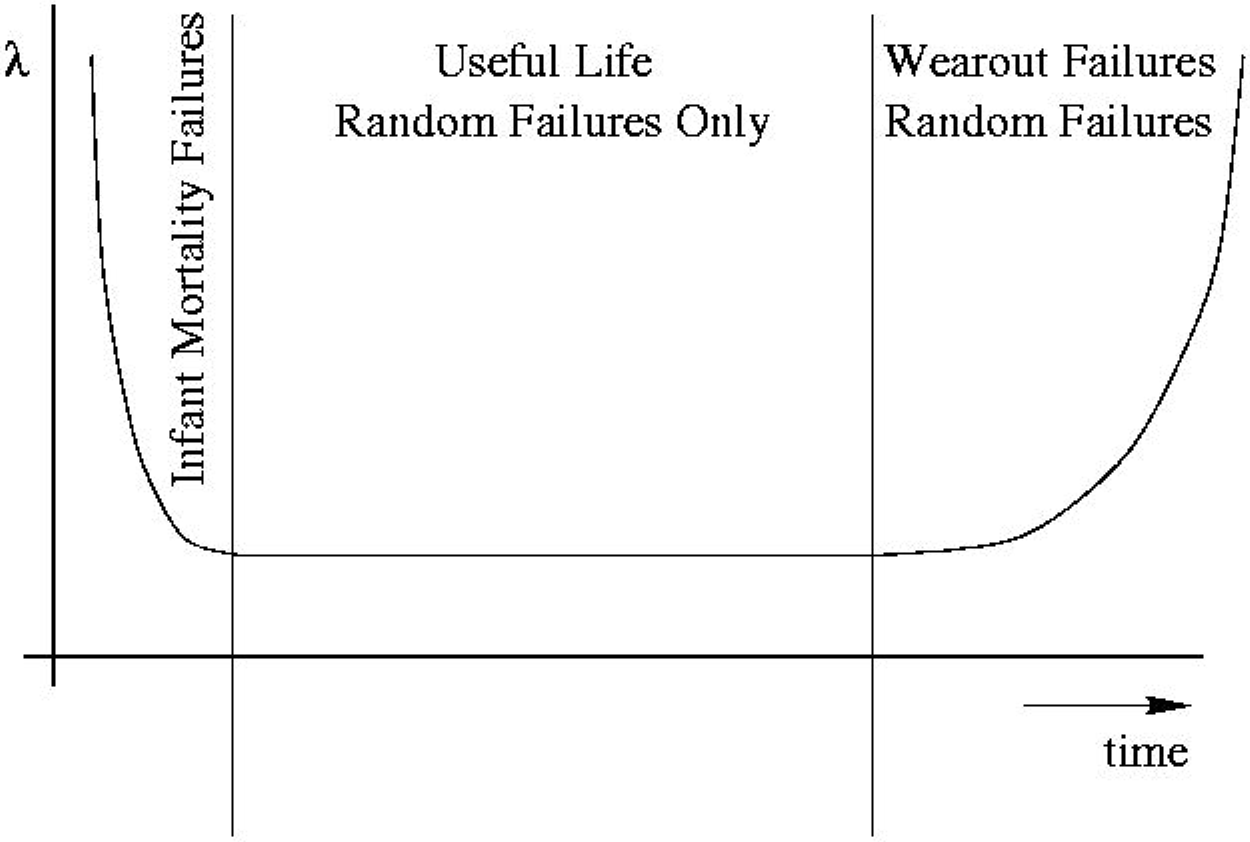
$$R(t) = \exp(-\lambda t)$$

- Wearout failures - normally distributed

$$R_w(t) = \frac{1}{\sigma\sqrt{2\pi}} \int \exp - \frac{1}{2} \left(\frac{T-\mu}{\sigma}\right)^2$$

- Infant Mortality

Bathtub Curve Diagram



Measures of Hardware Reliability

- MTBF = Mean Time Between Failures

$MTBF = 1/\lambda$ $\lambda = 1/MTBF$

- MTTR = Mean Time To Repair
- Temperature dependency of lambda - failure rates always increase at high operating temperatures.
- Voltage dependency of lambda - failure rates always increase at higher electrical stress levels.
- High stress - high lambda !

Lusser's Product Law

- Discovered during A4/V2 missile testing in WW2
- Superceded dysfunctional ‘weak link’ model
- Describes behaviour of complex series systems.
- Theoretical basis of Mil-Hdbk-217 and Mil-Std-756

$$R_s = \prod_{i=1}^{N} R_i$$

Serial Systems

- Failure of single element takes out system.
- Use LPL to quantify total lambda and P[S] for some T.

$$R_s = \prod_{i=1}^{N} R_i = \exp\left(- \sum_{i=1}^{N} \lambda_i t \right)$$

Parallel Systems

- Failure of single element is survivable, but P[S] reduced.

$$R_p = 1 - Q^N$$

- Used in aircraft flight control systems, Space Shuttle and critical control applications.

Complex Systems

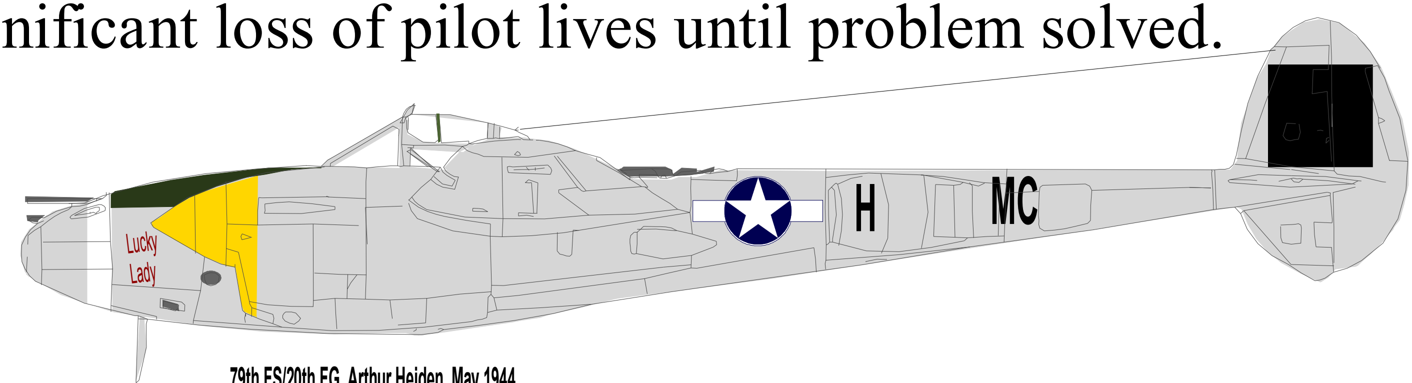
- Combine parallel and serial models.
- Required detailed analysis to determine R (t)
- Must analyse for dependencies.
- Must avoid Single Point of Failure (SPoF) items.
- The higher the complexity of the system, the higher the component reliability needed to achieve any given MTBF.

Example RAID Array (1999)

- N x 1 array with single fan and PSU
- Drive redundancy is OK, PSU or fan failures are SPoF.
- Problem fixed with redundant fans and PSU.
- No SPoF items - significantly improved reliability.

Example P-38 Twin Engine Fighter (1944)

- Electrical propeller pitch control, radiator and intercooler doors, dive flap actuators, turbocharger controls.
- Twin engine aircraft, only one generator on one of the engines.
- Loss of generator equipped engine - feather propeller, fail over to battery.
- Once battery flat, prop unfeathers, windmills, turbo runaway -> aircraft crashes.
- Problem fixed with dual generators, one per engine.
- Significant loss of pilot lives until problem solved.



79th FS/20th FG, Arthur Heiden, May 1944

Software vs Hardware Reliability

- Hardware failures can induce software failures.
- Software failures can induce hardware failures.
- Often difficult to separate H/W and S/W failures.
- Cannot apply physical models to software failures.
- Result is system failure.

Modes of Software Failure

- Transient Failure - incorrect result, program continues to run.
- Hard Failure - program crashes (stack overrun, heap overrun, broken thread).
- Cascaded Failure - program crash takes down other programs.
- Catastrophic Failure - program crash takes down OS or system -> total failure.

Types of Software Failure

- Numerical Failure - bad result calculated.
- Propagated Numerical Failure - bad result used in other calculations.
- Control Flow Failure - control flow of thread is diverted.
- Propagated Control Flow Failure - bad control flow propagates through code.
- Addressing Failure - bad pointer or array index.
- Synchronisation Failure - two pieces of code misunderstand each other's state.

Runtime Detection of Software Failures

- Consistency checks on values.
- Watchdog timers.
- Bounds checking.

Consistency Checking

- Can identify a bad computational result.
- Exploit characteristics of data to identify problems.
- Protect data structures with checksums.
- Parallel dissimilar computations for result comparison.
- Recovery strategy required.

Watchdog Timers

- Require hardware support to interrupt tasks or processes.
- Watchdog timer periodically causes status check routine to be called.
- Status check routine verifies that code is doing what it should.
- Can protect against runaway control flow.
- Recovery strategy required.

Bounds Checking

- Compare results of computation with known bounds to identify bad results.
- Requires *apriori knowledge* of bounds upon results.
- Cannot protect against bad results which have ‘reasonable’ values.
- Recovery strategy required.

Recovery Strategies

- Redundant data structures - overwrite bad data with clean data.
- Signal operator or log problem cause and then die.
- Hot Start - restart from known position, do not reinitialise data structures.
- Cold Start - reinitialise data structures and restart, or reboot.
- Failover to Standby System in redundant scheme (eg flight controls).

Case Studies

- Why Case Studies - explore how and why failures arise.
- Define the nature of the failure.
- Describe the result of the failure.
- Look at possible consequences of the failure.
- Try not to repeat other peoples' blunders.

Prototype Fighter Testing #1

- Test pilot selects wheels up while on the ground.
- Aircraft retracts undercarriage and falls to the ground.
- Immediate cause: software failed to scan the ‘undercarriage squat switch’.
- Reason: programmer did not know what a squat switch was for.
- Possible consequences: destroyed jet, dead pilot.

Prototype Fighter Testing #2

- Radar altimeter and barometric altimeter failed.
- Pilot notices altitude reading at 10 kft, yet aircraft at different altitude.
- Immediate cause: software default action on altimeter fail is set constant value.
- Reason: programmer did not understand how aircraft fly.
- Possible consequences: destroyed jet, dead pilot.

Prototype Fighter Testing #3

- Aircraft crossed equator on autopilot.
- Aircraft attempts to roll itself inverted.
- Immediate cause: navigation software failed to interpret sign change.
- Reason: unknown, programmer may have assumed operation only North of equator.
- Possible consequences: midair collision, destroyed jets, dead pilots.

Naval Cruiser Fire Control

- Late eighties Persian Gulf shootout with Iran.
- Forward missile launcher engaged to fire RIM-66 surface to air missile.
- Missile ejected off launcher.
- Missile engine does not ignite.
- Missile worth US$250k falls into ocean and sinks.

Naval Cruiser Fire Control

- Cause of fault initially unclear .
- Hardware is 100% fault free.
- Software operating normally with no fault status.
- Possible consequences serious since cruiser defends a carrier battle group from missile attacks.

Naval Cruiser Fire Control

- Repeated simulated and real launches on test ranges fault free.
- Fault eventually replicated when total CPU load extremely high.
- Conditions for fault extremely infrequent and difficult to replicate.
- Fault found to be relatively easy to fix once known.

Naval Cruiser Fire Control

- Cause of fault is use of switch state polling, rather than interrupts.
- Launcher rail uses position switch to sense when the missile is about to leave the rail.
- Once missile about to leave rail, ignition signal sent to ignite engine.
- Under heavy CPU load the frequency of switch state polling too low.
- Missile left rail before switch state sampled
- Software ‘thought’ the missile was still on the launch rail.

Ariane 501 Booster Prototype Loss

- New Ariane ‘5’ booster launched with payload of several satellites.
- Ariane 5 uses digital redundant multiple CPU flight control system.
- Soon after launch, travelling at about Mach 1, booster attempts 90 degree turn.
- Acceleration so large that booster breaks up and fuel explodes.
- Hundreds of millions of dollars worth of hardware lost.
- Major environmental hazard due to unburned toxic propellant spill.

Ariane 501 Booster Prototype Loss

- Flight control hardware recovered and found to be fault free.
- Flight control software cause of disaster.
- Code for new booster developed by reusing code from Ariane 4 design.
- Different system design caused code to believe vehicle was 90 degrees off course.
- Code attempts to correct non-existent trajectory error.
- Aerodynamic forces cause vehicle breakup.

Mariner Venus Probe Loss

- Flight control software failure.
- Expensive satellite and booster lost.
- Fault traced to broken Fortran DO loop.
- Typographical error in source code.

Typical Causes of Software Failures

- Programmer did not understand the system design very well.
- Programmer made unrealistic assumptions about operating conditions.
- Programmer made coding error.
- Programmers and hardware engineers did not talk to each other.
- Inadequate or inappropriate testing of code.

Dormant Fault Problem

- Statistical models used for hardware are irrelevant.
- Code may be operational for years with a fatal bug hidden somewhere.
- A set of conditions may one day arise which trigger the fault.
- If major disaster arises it may be impossible to recreate same conditions.

Complex System Problem

- Extremely complex system will be extremely difficult to simulate or test.
- Complexity may result in infeasible regression testing time.
- Components of system may interact in ‘unpredictable’ ways .
- Synchronisation failures may arise.
- Fault may be hidden and symptoms not easily detectable due complexity.

Coding for Reliability

- Problem must be well understood, especially conditions which may arise.
- Hardware can NEVER be trusted!
- Operating Systems can NEVER be trusted!
- Libraries can NEVER be trusted!
- Documentation can NEVER be trusted!
- Compilers can NEVER be trusted!

Coding for Reliability

- Design objectives must be understood.
- Each module should check the bounds on arguments.
- Each module should sanity check its results.
- Datastructures should be redundant or checksummed.
- Consistency checking should be used generously.
- Each module should be tested thoroughly before use.
- Recycled code should be tested thoroughly before use and well understood.

System Design for Reliability

- Design objectives must be understood.
- Redundancy should be used as appropriate.
- Failure modes and consequences should be understood.
- Each module should be tested thoroughly before use.
- Recycled modules should be tested thoroughly before use and understood.

Conclusions

- Deterministic proof of code reliability difficult or impossible.
- Regression testing may miss dormant faults or complex system faults.
- Human error by programmers and operators should be assumed.
- Hardware, operating systems, libraries, documentation and compilers may have hidden or unknown problems.
- Complexity introduces unexpected interactions.

Axioms to Memorise

- Murphy's Law applies 99% of the time (Vonada's Law)
- Simpler solutions are usually easier to prove correct (Occam's Razor)
- Paranoia Pays Off (Kopp's Axiom)