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Dependability and fault tolerance

Loeng 4
Risk reduction. Testing

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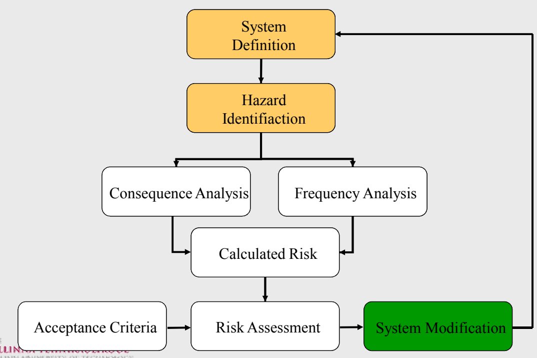
Important

- Draft of the report (incl. introductory presentation of the topic):
  - March 15
  - Drafts also by e-mail, after the meeting

Lecture Outline

- Risk Reduction & Design
- Test Economics
- Types of Testing
- Testing coverage

Hazard and Risk Analysis Process



Risk Reduction Procedures

- Four main categories of risk reduction strategies, given in the order that they should be applied:
  - Hazard Elimination
  - Hazard Reduction
  - Hazard Control
  - Damage Limitation
- Only an approximate categorisation, since many strategies belong in more than one category

Hazard Ellimination

- Before considering safety devices, attempt to eliminate hazards altogether
  - use of different materials, e.g., non-toxic
  - use of different process, e.g., endothermic reaction
  - use of simple design
  - reduction of inventory, e.g., stockpiles in Bhopal
  - segregation, e.g., no level crossings
  - eliminate human errors, e.g., for assembly of system use colour coded connections

Design Principles

- Familiar
  - use tried and trusted technologies, materials techniques
- Simple
  - testable (including controllable and observable)
  - portable (no use of sole manufacturer components compiler dependent features)
  - understandable (behaviour can easily be from implementation)
  - deterministic (use of resources is not random)
  - predictable (use of resources can be predicted)
  - minimal (extra features not provided)

Design Principles (cont.)

- Structured design techniques
  - defined notation for describing behaviour
  - identification of system boundary and environment
  - problem decomposition
  - ease of review
- Design standards
  - limit complexity
  - increase modularity
- Implementation standards
  - presentation and naming conventions
  - semantic and syntactic restrictions in software

Classes of System Failure

- Random (physical) failures
  - due to physical faults
  - e.g., wear-out, aging, corrosion
  - can be assigned quantitative failure probabilities
- Systematic (design) failures
  - due to faults in design and/or requirements
  - inevitably due to human error
  - usually measured by integrity levels
- Operator failures
  - due to human error
  - mix of random and systematic failures

Nature of Random Failures

- Arise from random events generated during operation or manufacture
- Governed by the laws of physics and cannot be eliminated
- Modes of failure are limited and can be anticipated
- Failures occur independently in different components
- Failure rates are often predictable by statistical methods
- Sometimes exhibit graceful degradation
- Treatment is well understood

Treating Random Failures

- Random failures cannot be eliminated and must be reduced or controlled
- Random failures can be mitigated by:
  - predicting failure modes and rates of components
  - applying redundancy to achieve overall reliability
  - performing preventative maintenance to replace components before faults arise
  - executing on-line or off-line diagnostic checks

Nature of Systematic Failures

- Ultimately caused by human error during development, installation or maintenance
- Appear transient and random since they are triggered under unusual, random circumstances
- Systematic and will occur again if the required circumstances arise
- Failures of different components are *not* independent
- Difficult to predict mode of failure since the possible deviations in behaviour are large
- Difficult to predict the likelihood of occurrence

Treating Systematic Failures

- In theory, design failures can be eliminated
- In practice, perfect design may be too costly
- Focus the effort on critical areas
  - identify safety requirements using hazard analysis
  - assess risk in system and operational context
- Eliminate or reduce errors using quality development processes
  - verify compliance with safety requirements
  - integrate and test against safety requirements

Design Faults

- Design faults are much more difficult to deal with than random (degradation) faults because:
  - They are hard to anticipate
  - Their effects are hard to predict
  - Component failure semantics tend to be undefined
- This makes all forms difficult to tolerate, especially software faults

Common Design Faults

- All forms of software:
  - System software
  - Application software
  - Embedded software (firmware)
- All forms of computing hardware:
  - Hardware design faults now dominate
  - Degradation faults used to dominate
- Power supply systems
- Component interconnection wiring

Design Diversity

- Idea:
  - Design faults are “aspects” of design
  - Different designs, different faults
  - Produce multiple designs—independent level.
  - Operate in parallel at execution time
- Applies to all types of design fault
- Can be configured using many system architectures, like NMR, TMR, etc.

Hazard Reduction

- Reduce the likelihood of hazards
- Use of barriers, physical or logical
  - Lock-ins
  - Lock-outs
  - Interlocks
- Failure minimization
  - Redundancy
  - Recovery

Forms of Redundancy

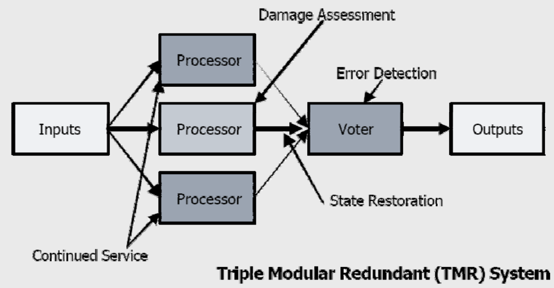
- Hardware redundancy
- Software redundancy
- Information redundancy
- Temporal (time) redundancy

- Design diversity, for hardware/software
  - Develop different implementations of the same hardware/software component
  - Called N-version programming
  - Then apply static or dynamic redundancy

Hardware Redundancy

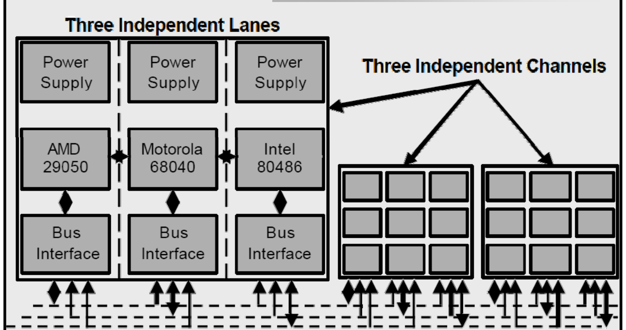
- Static redundancy
  - Component (at least) triplicated
    - Triple Modular Redundancy (TMR), N-Modular Redundancy (NMR)
  - Voting element used to remove effects of single failure
  - Loss Of Unit Implies:
    - Removal Or Containment
    - Service Provided By Those That Remain
- Dynamic redundancy
  - Component has a mirror that is invoked when fault occurs
  - Cold or Hot Standby, spares
  - Loss Of Unit Implies:
    - Removal Or Containment
    - Introducing Standby Unit

Fault Tolerant System Example



Risk of single-point failure

B777 Primary Flight Computer Architecture



N Modular Redundancy

- Independent development of modules
- This is what Boeing did with N = 3 for processors
- Operation:
  - Parallel—forward error recovery
  - Serial—backward error recovery
- In software with forward error recovery, referred to as N-version programming
- In software with backward error recovery, referred to as recovery block

B777 PFC CPUs

- Problem:
  - Processors often (essentially always) contain design faults, need to deal with them
  - 777 channel is a TMR system
- Three manufacturers, three designs
- Are these designs different?
- How would you measure the difference?
- What metric is there for design diversity?

Redundancy

- Software redundancy, e.g. N-version programming
- Information redundancy, e.g., checksums, cyclic redundancy codes, error correcting codes
- Hybrid redundancy

N-Version Programming

- NMR for software
- Practical issues:
  - Cost of development, team separation
  - Resources during execution
  - Different execution times for different versions
  - Different but similar output values
  - Different but valid output values (multiple correct solutions)

N-Version Programming

- Performance:
  - Assumed statistical independence
  - If not independent, then no lower bound
  - Common specification defects
  - Common implementation (design) faults
- Problem compounded by comparison checking during testing

Hybrid Redundancy

- N-S modular redundancy with "S" spares
- As members of the N-S fail, spares switched in
- Able to tolerate up to N-2 failures
- Spares may be unpowered:
  - Saves power
  - Unpowered units much more reliable than powered
  - Attention required to infant mortality
- Clearly applicable to:
  - Long-duration systems
  - Systems with no repair opportunity

Space Shuttle Computer System

- Uses combination of
  - Redundancy, fault detection and design diversity
- Hardware voting on sensors and actuators
- Five identical computers
  - During critical stages, four computers work in NMR with voting for fault detection
  - Fifth computer performs non-critical functions, e.g. comm.
- Fault tolerance
  - Tolerates failure of two computers
  - In case of third failure, crew/ground control decide which computer wins
  - Fifth computer can take over control, uses different software

Recovery

- Can reduce failures by recovering after error detected but before component or system failure occurs
- Recovery can only take place after detection of error
  - Backward recovery
  - Forward recovery

Error Detection

- Based on check that is independent of implementation of the system
  - coding - parity checks and checksums
  - reasonableness - range and invariants
  - reversal - calculate square of square root
  - diagnostic - hardware built-in tests
  - timing - timeouts or watchdogs

Error Detection (cont.)

- Timing of error detection important
  - early error detection can be used to prevent propagation
  - late error detection requires a check of the entire activity of system
- Checking may be in several forms
  - monitor, acting after a system function, checking outputs after production but before use
  - kernel, encapsulating (safety-critical) functions in a subsystem that allows all inputs to and outputs from the kernel to be checked

Backward Recovery

- Corrects errors through reversing previous operations
- Return system to a previous known safe state
- Allows retry
- Requires checkpoints or saved states (and the expenses involved with producing them)
- Rollback usually impossible with real-time system

Forward Recovery

- Corrects errors without reversing previous operations, finding safe (but possibly degraded) state for system
  - data repair, use redundancy in data to perform repairs
  - reconfiguration, use redundancy such as backup or alternate systems
  - coasting, continue operations ignoring (hopefully transient) errors
  - exception processing, only continue with selection of (safetycritical) functions
  - failsafe, achieve safe state and cease processing
    - use passive devices (e.g., deadman switch) instead of active devices (e.g., motor holding weight up)

Hazard Control

- Detect and control hazard before damage occurs
- Reduce the level or duration of the hazard
- Hazard control mechanisms include:
  - Limiting exposure: reduce the amount of time that a system is in an unsafe state (e.g. don't leave rocket in armed state)
  - Isolation and containment
  - Fail safe design

Damage Limitation

- In addition to eliminating hazards or employing safety devices, consider
  - warning devices
  - procedures
  - training
  - emergency planning
  - maintenance scheduling
  - protective measures

Architectural Design

- Suitable architectures may allow a high integrity system to be built from lower integrity components
  - combinations of components must implement a safety function independently
  - overall likelihood of failure should be the same or less
  - be wary of common failure causes
- Apportionment approaches can be quantitative and/or qualitative
  - quantitative: numerical calculations
  - qualitative: judgement or rules of thumb

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Fault Tolerance

Basics

- Computing systems are characterized by five fundamental properties:
  - functionality
  - usability
  - performance
  - cost
  - dependability

Faults

- Faults are there!
- Either prevent, **tolerate**, remove or forecast
- We need redundancy
  - System that is more complex than needed for performing the required task

Means to Achieve Dependability

- Fault prevention
  - Good design processes, avoid design flaws
  - Good procedures for runtime faults
- Fault tolerance
  - Fault detection
  - Redundancy
  - Diversity
- Fault removal
  - Verification and validation during design
  - Corrective/preventive action during maintenance
- Fault forecasting
  - Simulation, modelling, prediction
  - Analysis based on history statistics

Fault Tolerance

- Automobile:
  - Spare Tires
  - Dual Braking Systems
- Power Supplies:
  - UPS/battery backup
  - Power-fail interrupts
- Multiple engines on aircraft
- Emergency lighting in buildings
- Tape backups of disk files
- Checkpoint/restart of long-running programs
- Parity and SECDED in computer memories

Faults

- Random faults (Degradation faults)
  - Arise during operation
  - Usually hardware component failure
- Systematic faults (Design Faults)
  - mistakes in the spec
  - mistakes in the hardware
  - mistakes in the software

Faults

- Faults are either permanent, transient or intermittent
- Design faults are always permanent
- Dealing with faults:
  - During development: fault avoidance & removal
  - During operation: fault tolerance & detection

Hardware Faults

- Use of fault models
- Decomposition into modules
  - Gates, transistors, etc
- Connection faults
  - Single stuck-at model, bridging model (shorts), stuck-open
- Used to model hardware faults
  - Design testing schemes for digital circuits
  - Fault removal coverage usually less than 100%
  - Guard against physical defects, not design faults
- In safety critical systems
  - Combined with Failure Modes and Effects Analysis (FMEA)
  - Need fault avoidance by verification…

Other Faults

- Hardware design and specification faults
  - Few fault models available
  - Many faults cannot be modelled
  - System must meet the spec, but spec might be incorrect as well
  - Spec errors may manifest as either hardware or software failures
  - Use of formal methods (formal spec. languages, automata theory, formal verification, model checking, etc.)

Software Faults

- Bugs:
  - Software spec faults
  - Coding faults
  - Logical errors within calculations
  - Stack overflows or underflows
  - Uninitialized variables
- No random failures and it does not degrade with age
- Always systematic
- Exhaustive testing almost impossible
- Must be tolerated

SW Testing - i.e. Verification

- Verification:
  - SW testing
  - formal verification
- Functional and structural testing
- Path testing, transaction flow testing, data-flow testing, domain testing, mutation testing etc.

Fault Detection Techniques

- Functionality checking
  - march test
- Consistency checking
  - range checking, overflow
- Signal comparison
- Information redundancy
  - checksums, cyclic redundancy codes, error correcting codes
- Monitoring techniques
  - Loopback testing
  - Power supply monitoring

Watchdog Timer

- An inexpensive method of error detection
- Process being watched must reset the timer before the timer expires, otherwise the watched process is assumed as faulty
- Watchdog timers only detect errors which manifest themselves as a control-flow error such that the system does not continue to reset the timer
- Only processes with relatively deterministic runtimes can be checked, since the error detection is based entirely on the time between timer resets

Heartbeats

- A common approach to detecting process and node failures in a distributed (networked) computing environment.
- Periodically, a monitoring entity sends a message (a heartbeat) to a monitored node or process and waits for a reply.
- If the monitored node does not respond within a predefined timeout interval, the node is declared as failed and appropriate recovery action is initiated.
- Adaptive or smart

System Testing

HW Testing SW Testing

HW/SW Testing
(system testing)

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Software Testing

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Programmers are in a race with the Universe to create bigger and better idiot-proof programs.

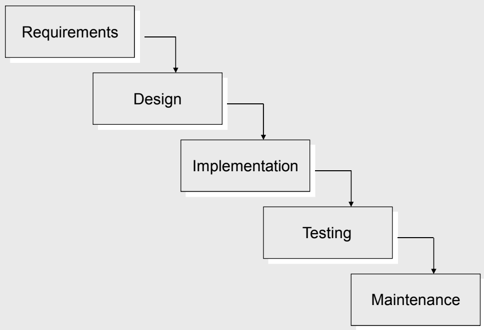
While the Universe is trying to create bigger and better idiots.

So far the Universe is winning

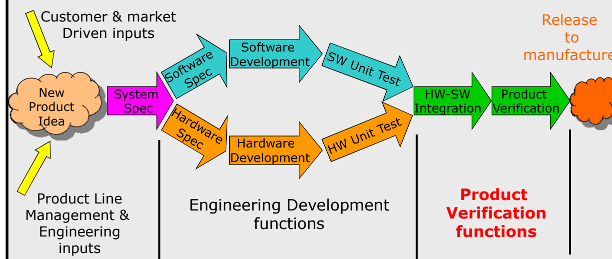
Software Testing Topics

- Test Economics
- Types of Testing
- Testing coverage

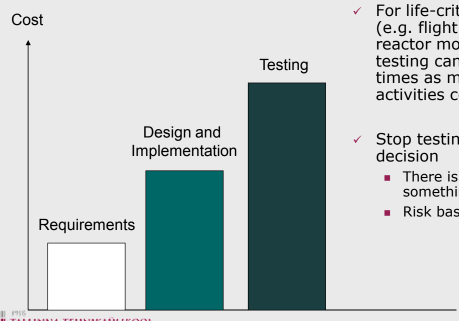
Software Life Cycle



The Product Development Cycle

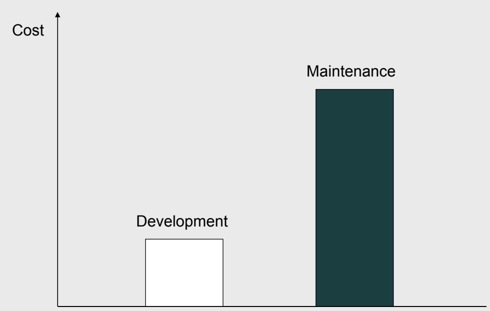


Software Development Costs



- For life-critical software (e.g. flight control, reactor monitoring), testing can cost 3 to 5 times as much as all other activities combined.
- Stop testing is a business decision
  - There is always something more to test
  - Risk based decision

Software Life Cycle Costs



Software Qualities

- Correctness
- Reliability (dependability)
- Robustness
- Safety
- Security (survivability)
- Performance
- Productivity
- Maintainability, portability, interoperability, …

Software Verification and Validation

- Verification
  - Are we building the product right?
  - Process-oriented
    - Does the product of a given phase fulfill the requirements established during the previous phase?
- Validation
  - Are we building the right product?
  - Product-oriented
    - Does the product of a given phase fulfill the user's requirements?

Techniques for V&V

- ✓ Static
  - Collects information about a software without executing it
    - Reviews, walkthroughs, and inspections
    - Static analysis
    - Formal verification
- ✓ Dynamic
  - Collects information about a software with executing it
    - Testing: finding errors
    - Debugging: removing errors

Static Analysis

- ✓ Control flow analysis and data flow analysis
  - Extensively used for compiler optimization and software engineering
- ✓ Examples
  - Unreachable statements
  - Variables used before initialization
  - Variables declared but never used
  - Variables assigned twice but never used between assignments
  - Variables used twice with no intervening assignment
  - Possible array bound violations

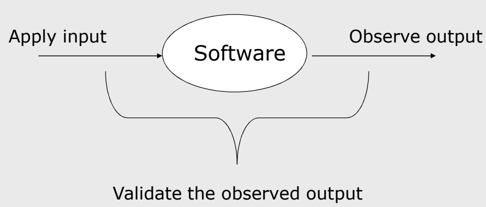
Formal Verification

- ✓ Given a model of a program and a property, determine whether the model satisfies the property based on mathematics
- ✓ Examples
  - Safety
    - If the light for east-west is green, then the light for south-north should be red
  - Liveness
    - If a request occurs, there should be a response eventually in the future

Introduction to Testing

- ✓ Debugging and testing are not the same thing!
- ✓ Testing is a systematic attempt to break a program.
  - Correct, bug-free programs by construction are the goal but until that is possible (if ever!) we have testing.
  - Since testing is basically **destructive** in nature, it requires that the tester discard *preconceived* notions of the *correctness* of the software to be tested

Testing



Is the observed output the same as the expected output?

Software Testing Fundamentals

- ✓ Testing objectives include
  - Testing is a process of executing a program with the intent of finding an error.
  - A **good** test case is one that has a high probability of finding an as yet undiscovered error.
  - A **successful** test is one that uncovers an as yet undiscovered error.

Limitations of Testing (I)

- To test all possible inputs is impractical or impossible

```
int foo(int x) {
    y = very-complex-computation(x);
    write(y);
}
```

- To test all possible paths is impractical or impossible

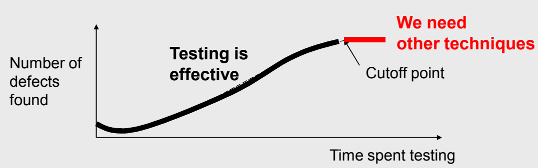
```
int foo(int x) {
    for (index = 1; index < 10000; index++)
        write(x);
}
```


Limitations of Testing (II)

- Dijkstra, 1972
  - Testing can be used to show the presence of bugs, but never their absence
- Goodenough and Gerhart, 1975
  - Testing is successful if the program fails
- The (modest) goal of testing
  - Testing cannot guarantee the correctness of software but can be effectively used to find errors (of certain types)

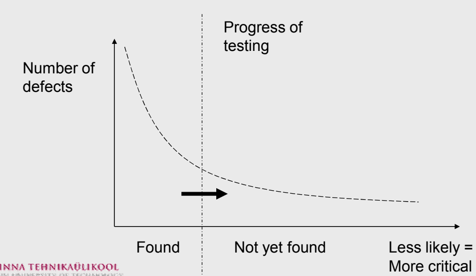
Economics of Testing (I)

- The characteristic S-curve for error removal



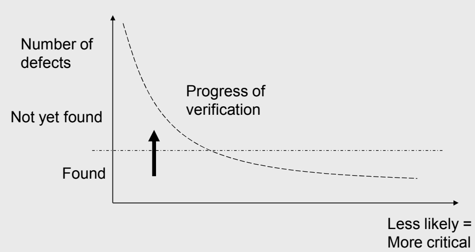
Economics of Testing (II)

- Testing tends to intercept errors in order of their probability of occurrence



Economics of Testing (III)

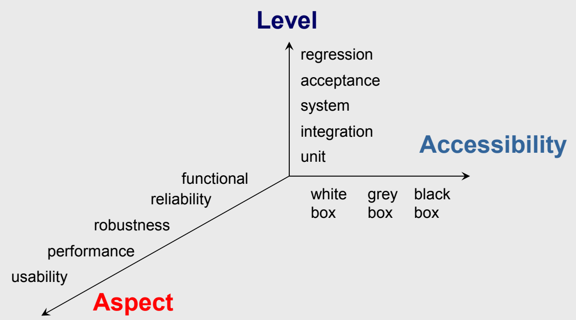
- Verification is insensitive to the probability of occurrence of errors



Fundamental Questions in Testing

- When can we stop testing?
  - Test coverage
- What should we test?
  - Test generation
- Is the observed output correct?
  - Test oracle
- How well did we do?
  - Test efficiency
- Who should test your program?
  - Independent V&V

Types of Testing



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Questions?