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Verification, Validation & Certification

Distributed Embedded Systems

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Where Are We Now?

- **Where we've been:**
  - How to build and analyze things
  - Testing – but that is only one way to evaluate how well something is built

- **Where we're going today:**
  - Validation, Verification & Certification – making sure it works
    - Largely this focuses on the design correctness part of dependability
    - It should also deal with failure modes and safety

- **Where we're going next:**
  - Economics
  - Test #1
  - Embedded networks
  - Mid-semester presentations
  - Dependable/safe/secure systems

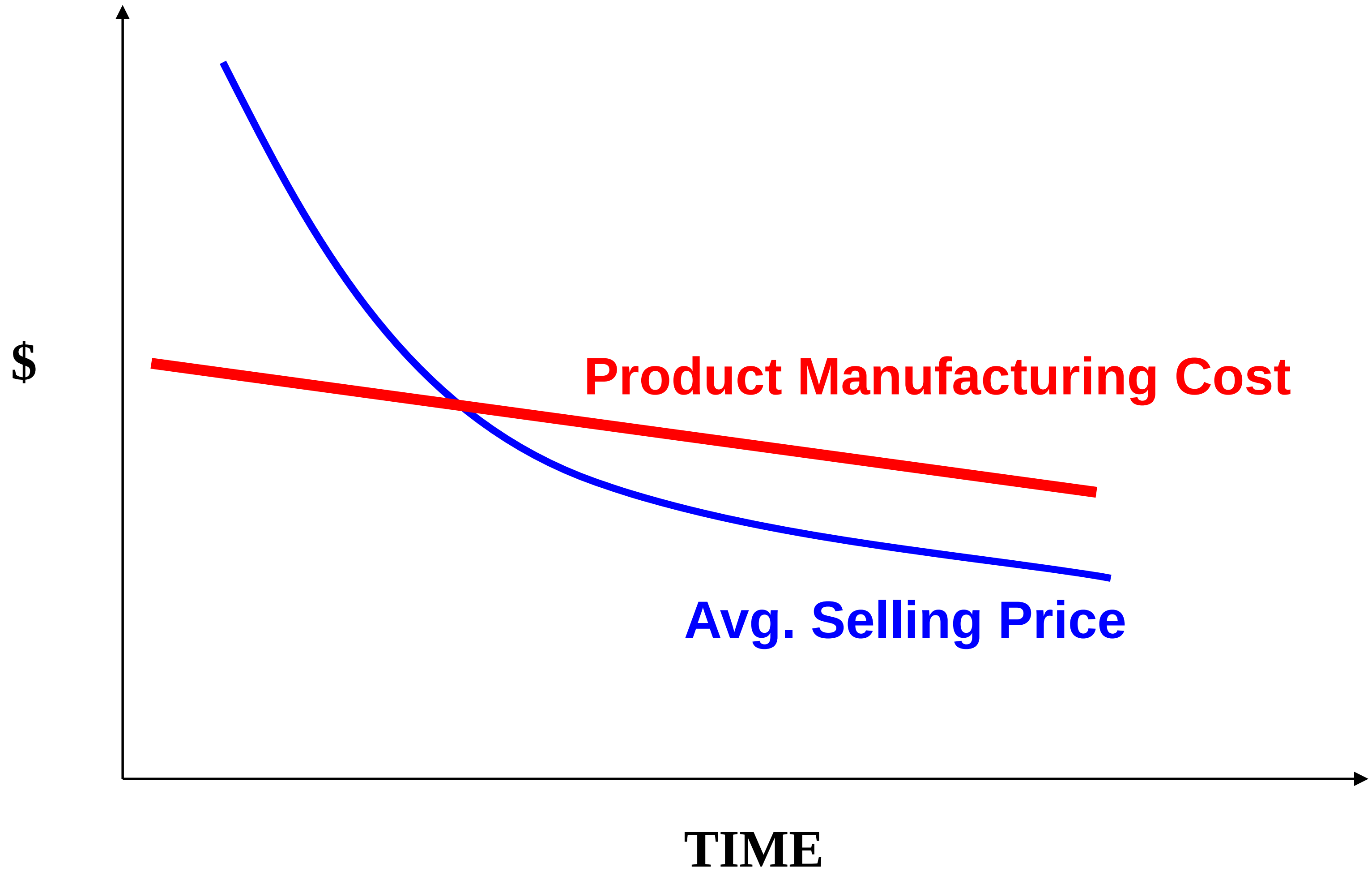
Preview

- **Three related concepts:**
  - Verification: making sure each design step does what it was supposed to do
  - Validation: making sure the end result satisfies requirements
  - Certification: a written guarantee that a system is acceptable for operational use

- **General Approaches**
  - Testing
  - Analysis
  - Certification strategies

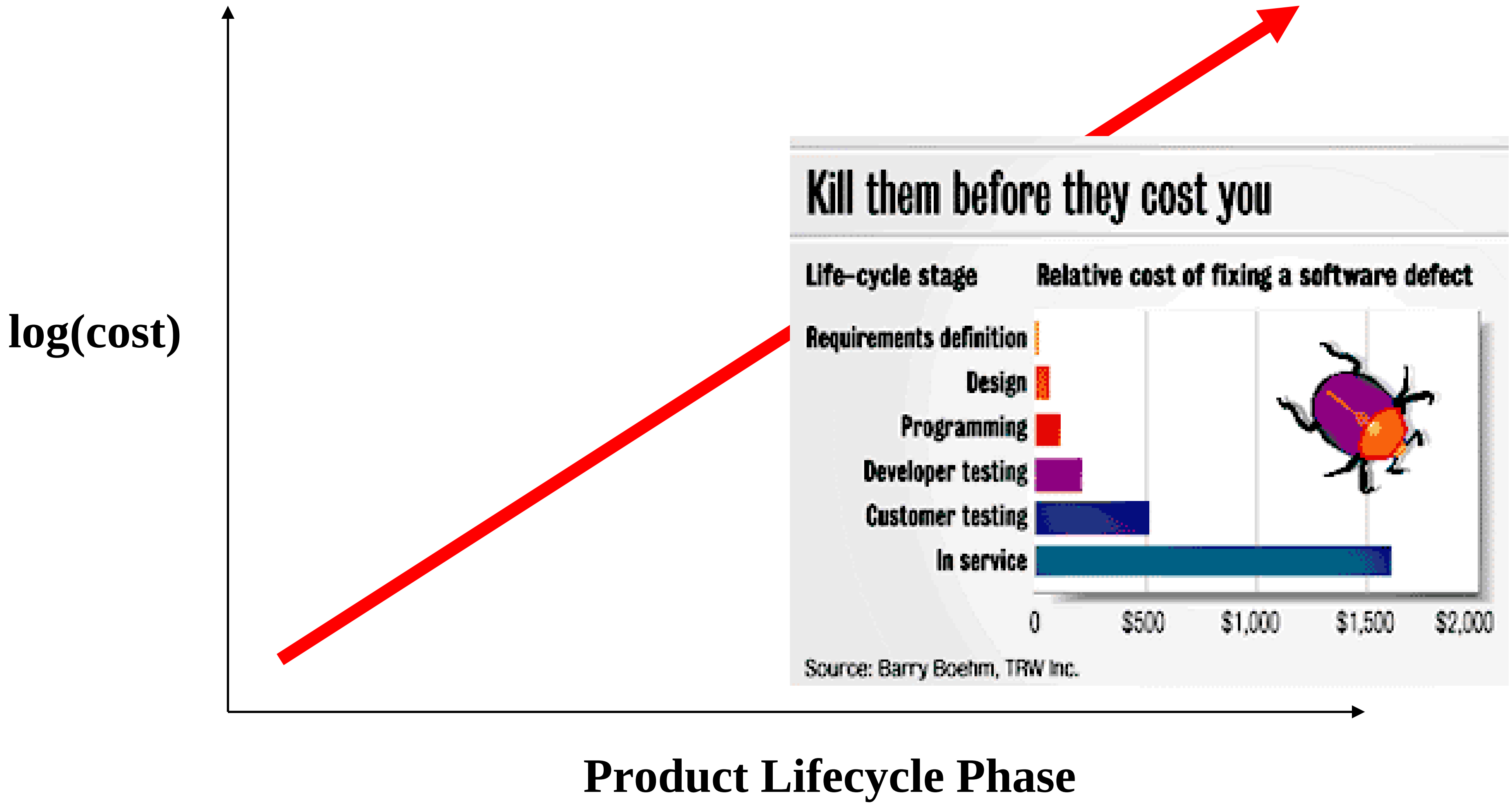
- **Areas of concern:**
  - Hardware correctness
  - Software correctness

Why Is Time To Market Important?



- **Profit window for consumer/commodity electronics may be 3 months**
  - Moral: Get it right the first time; use good process to improve your odds
  - Sometimes – make profits on services/software, not hardware items

What’s The Cost Of A Finding & Fixing A Defect?



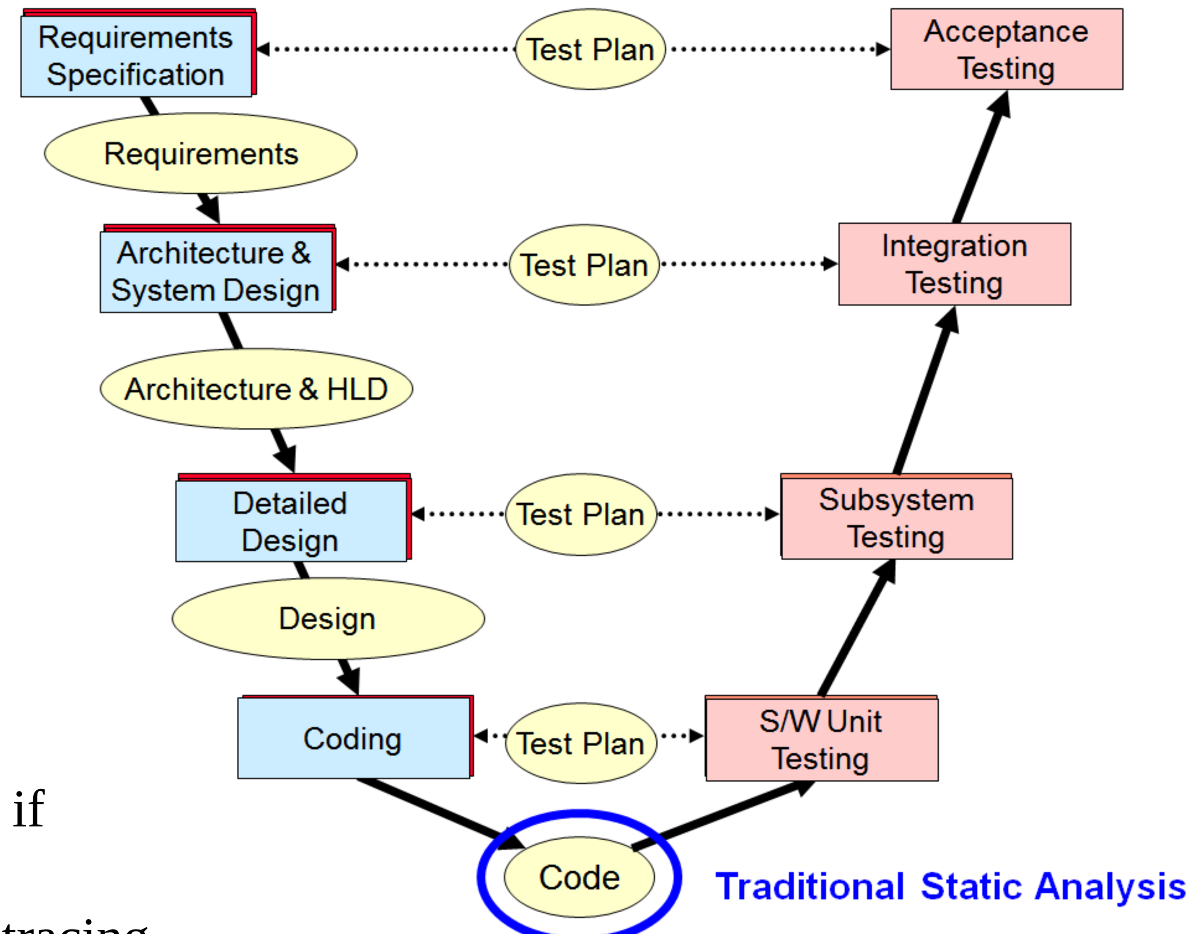
- **Get it right the first time if you can**
- **If you get it wrong, find out about it as soon as possible**

Is Speed The Key To Success?

- **A fast design process only helps if you get it right**
  - If you get it wrong, you get to spend more money fixing problems because you move further into the design before you find them!

Traceability

- **Traceability is checking to ensure steps fit together**
  - Starting point for most V&V
- **Forward Traceability:**
  - Next step in process has everything in current step
  - “Nothing got left out”
- **Backward Traceability**
  - Previous step in process provoked current step
  - “Nothing spurious included/no gold plating”
- **Traceability is an audit**
  - Doesn’t prove correctness if tracing is OK
  - But, problems are there if tracing fails



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Definitions

- **Verification:**
  - The process of evaluating a system or component to determine whether the **products of a given development phase satisfy the conditions imposed** at the start of that phase.
  - *Loosely:* forward traceability as design progresses
  - **"Did we build the product correctly?"**

- **Validation:**
  - The process of evaluating a system or component during or at the end of the development process to determine whether it **satisfies specified requirements**.
  - *Loosely:* backward traceability to requirements
  - **"Does the product do what it should?"**

- **Certification:**
  - A written guarantee that a system or component complies with its specified requirements and is **acceptable for operational use**.
  - **"Is an 3rd party happy enough with the product to stake his/her reputation on it?"**

- **Degree of required V/V/C often set by regulators (e.g., FAA)**

General Approaches To V/V/C

- **Testing**
  - Execute system to determine behavior
  - Inject intentional faults to determine system response
- **Analysis**
  - Determine if desirable properties hold true; if undesirable properties exist
  - Find inconsistencies among design phases
  - Determine if design rules have been followed
  - Scrutinize design and documents (reviews)
- **Process inspection**
  - Determine if process is appropriate for desired end result
  - Determine if process was adequately followed
- **Many techniques can be used for any of Verif., Valid., Cert.**
  - But, some techniques are better fits for a particular use

Testing Review/Summary

- **White-box testing ("structural testing")**
  - Look at program structure and design tests
    - e.g., 100% of branch path coverage (both sides of each branch)

- **Black-box testing ("functional testing")**
  - Test every item on the functional specification
  - Also, test for robustness/error handling

- **Levels of test**
  - Unit test – testing small pieces of code; done by programmer
  - Module/functional test – testing at API level; done by testing group
  - Integration test – testing pieces working together; done by testing group
  - Acceptance test – testing whole system; done by customer (or surrogate)
  - Beta test – letting a few customers use product before full production
  - Regression test – make sure changes haven't re-activated old bugs

Starting Points For Embedded Test Coverage

- **Below are example useful coverage metrics**
  - But remember from testing lectures – 100% coverage is not "100% tested"

- **Requirements coverage**
  - All requirements tested in every major operating mode
- **Scenario coverage**
  - All sequence diagrams tested (this is a form of system integration testing)
- **Statechart coverage**
  - All states visited
  - All arcs exercised
- **Code coverage**
  - Every statement in program executed (100% branch coverage)
  - Every exception handler exercised; every fault handler exercised
- **FMEA coverage**
  - FMEA = Failure Mode Effect Analysis (table predicting results of component faults)
  - Inject faults to see if FMEA correctly predicts system response

Things Other Than SW Get Tested Too!

- **Hardware testing**
  - "Shake & Bake" testing – temperature and vibration
  - STRIFE testing – stress + life – run just beyond hardware limits
    - E.g., 5% over-voltage and 5% over temperature
    - Components that fail are "weak", and likely to be field failure sources
  - Margin testing
    - E.g., increase clock speed until something breaks
    - See if there is enough design margin to account for component variation & aging
- **System-level testing (“execution” of human use of system)**
  - Usability tests
  - Check that maintenance can be performed within required time limits
  - Ensure that install & maintenance procedures work
- **Software gets stress tested … but nobody really knows what that means (in any rigorous way)!**

Cost To Certify An IEEE 802.16e Aircraft Radio

Environmental Conditions	Category and Requirement	Cost (Euro)
Temperature / Altitude	**DO-160E, Section 4, cat.A2**	1800
Temperature variation	**DO-160E, Section 5, cat. B**	1200
Humidity	**DO-160E, Section 6, cat. B**	5500
Operational shock and crash safety	**DO-160E, Section 7, cat B**	1700
Vibration	**DO-160E, Section 8, curve R**	5000
Explosion proofness	**DO-160E, Section 9, cat. X**	n/a
Waterproofness	**DO-160E, Section 10, cat. Y** (condensation)	600
Fluid susceptibility	**DO-160E, Section 11, cat. F**	1700
Sand and dust	**DO-160E, Section 12, cat. X** (cat X means n/a)	n/a
Fungus resistance	**DO-160E, Section 13, cat. F**	2000
Salt spray	**DO-160E, Section 14, cat. X**	n/a
Fire, Flammability	**DO-160 E, Section 26, Category C**	2000
Magnetic effect	**DO-160E, Section 15, cat. Z**	1000
Power supply	**DO-160E, Section 16, cat. [BZ]**	3000
Voltage spike	**DO-160E, Section 17, cat. A**	1000
Audio frequency conducted susceptibility	**DO-160E, Section 18, cat. Z**	1000
Induced signal susceptibility	**DO-160E, Section 19, cat. Z**	2000
Conducted susceptibility	**DO-160E, Section 20, cat. W**	3000
Radiated susceptibility	**DO-160E, Section 20, cat. G** 100 to 200 V/m SW/CW and **HIRF** 700 to 3500 V/m PM	6000
Conducted emission of radio frequency energy	**DO-160E, Section 21, cat. H**	1000
Radiated emission of radio frequency energy	**DO-160E, Section 21, cat. H**	2000
Lightning induced transient susceptibility	**DO-160E, Section 22 cat A3G33J33**	5000
Lightning direct effects	**DO-160E, Section 23, cat. X**	n/a
Icing	**DO-160E, Section 24, cat. X**	n/a
Electrostatic discharge	**DO-160E, Section 25, cat. A**	2000
Bonding	**MIL-STD 464, parag. 5**	1000
Manufacturer extra effort		**(person.day)**
Planning, follow-up, investigations, result analysis		140

Table 3: DO-160E Qualification Costs

Source:
Rockwell Collins
1/29/2009

Role Of Testing

- **Mostly for Validation:**
  - Unit test – does the unit behave as it should?
  - Acceptance test – if customer accepts product, that validates system is OK

- **Certification**
  - For narrow certification, can test a specific property
    - FCC certification that system does not emit too much RF interference
  - For broader certification, may need tests to give credibility to analyses
    - "Wing snap" test on Boeing 777 was used to demonstrate stress model accuracy
    - For X-by-Wire, might need tests to demonstrate models represent actual vehicle

Run-Time Instrumentation

- **Related idea is to perform some "tests" all the time**
  - Even in production units!
  - Everyday system usage forms the "workload"
  - Use a data recorder to catch and report problems for later analysis

- **Selected run-time "test" techniques**
  - Log actions and analyze logs
  - Assertions
    - e.g., `#assert  RPM < RedLineLimit`
    - Doesn't enforce this – just checks for when it happens
    - Throws an exception if assertion fails at run-time; good for monitoring invariants
  - Monitor system resources, e.g., memory exhaustion
  - Log all exceptions that occur
  - Detect loss of control loop closure
    - Commanded position too far from actual position for an actuator

Error Logs

- **Keep a run-time log of errors you encounter**

- **Helps detect bugs that escape into fielded products**
  - A robustly designed system will hide many bugs from the user…
    … so how to you know problems are happening?
    - For example, watchdog timer resets
    - For example, running control loops fast to tolerate occasional missed deadline
  - Permits early detection of problems that haven't been seen by customer
    - If a run-time error occurs, something is wrong with your design
  - What to log: system resets, run-time errors, assertion violations, hardware failures, non-computer failures (problems with the plant), operating conditions, time stamps

- **Protects software developers from blame**
  - "Product is acting weird; must be software"…
    … "Our error logs say it is a hardware problem; go harass them instead"

X-by-Wire Fault Injection

- **Assume that the safety case's fault hypothesis is: "Continues to operate despite an arbitrary single point fault"**
  - Then, it makes sense to test "arbitrary" faults
  - Hardware or software-based fault injection makes sense

- **Potential approaches to X-by-Wire fault injection:**
  - Test software that corrupts bits in memory
    - Used successfully in many areas
  - Radiation chamber
    - Used successfully to find problems with TTP
  - Network message fault injection
    - Corrupt or drop messages on network
  - Pin-level fault injection
    - Disturb electrical signals on circuit boards

[TTTech04]

Analysis

- **Examination of software & documentation**
  - No actual execution of real software
  - Very effective at finding defects in requirements, design, and software
- **Includes varying levels of tool / human involvement**
  - Ranges from complete static analysis by a compiler-like tool…
  - … to humans sitting in a conference room looking at requirements documents
- **Primary techniques we'll discuss:**
  - Traceability
  - Reviews
  - Static analysis
  - Model checking

  - Safety analysis (FTA/FMEA/etc.) –discussed in separate lecture

Refresher On Design Reviews

- **Design reviews are the most cost-effective way of preventing defects**
  - Think of it as V&V during design instead of after the fact

- **Simple version:**
  - Explain your software to someone else, going through it line by line
    - Explaining it out loud to yourself is helpful, but not good enough
    - Doing it via e-mail generally isn't good enough –
      too easy to sweep things under rug or miss subtleties

- **More industrial-strength design reviews**
  - Get a book on how to run design reviews
  - Convene a set of people do to a review in a fixed length of time
  - Have people study the code before the review; assign roles to reviewers
  - Have the presenter go through it and answer questions
  - Take corrective action; iterate reviews if necessary
  - Part of this is knowing what to review (checklist is recommended reading); part of it is having someone who knows how to run an effective review

Static Checking & Compiler Warnings

- **Static analysis looks at design or code to find problems**
  - E.g., look at statechart for states not connected to any other states
  - E.g., look at software for “dead code” – code that can’t be reached by any possible execution path
  - Can be done manually, but better to use tools if available

- **Example static analysis approaches:**
  - “Lint” / C compiler warning messages (and MISRA C style checkers)
    - Questionable syntax
    - Type checking errors
    - Bad practices
  - Tools to compute McCabe Cyclomatic Complexity
    - Simplistically, Cyclomatic Complexity is number of branches in a code module
    - High complexity means code is more failure prone and more difficult to test
  - More complex tools, such as finding possible memory leaks and unhandled exceptions
  - Always leave warnings turned on and ensure code compiles “clean”
    - This is basically a “free” design review – why would you ignore it???

2012 Coverity scan of open source software results:

- **Sample size: 68 million lines of open source code**
  - Control flow issues: 3,464 errors
  - Null pointer dereferences: 2,724
  - Resource leaks: 2,544
  - Integer handling issues: 2,512
  - Memory – corruptions : 2,264
  - Memory – illegal accesses: 1,693
  - Error handling issues: 1,432
  - Uninitialized variables: 1,374
  - Unintialized members: 918

- **Notes:**
  - Warning density 0.69 per 1,000 lines of code
  - Most open source tends to be non-critical code
  - Many of these projects have previously fixed bugs from previous scans

http://www.embedded.com/electronics-blogs/break-points/4415338/Coverity-Scan-2012?cid=Newsletter+-+Whats+New+on+Embedded.com

Model Checking

- **Model checking is a formal method for verifying finite-state concurrent systems**

- **Intuitive explanation:**
  - Start with a model of a system. Might be something like a statechart.
  - State an invariant that should apply:
    - E.g., “All network nodes eventually belong to a single group after a single error”
    - E.g., “Motor will not be commanded to run if any elevator doors are open”
  - Run a model checker, which explores all possible transitions through statechart
    - There are, in general, *many* transitions.
  - Model checker says one of two things:
    1. “I’ve looked at all possible execution paths, and what you say is guaranteed true”
    2. “I found a counter-example: here it is…”

(For more explanation, see: http://www.cs.cmu.edu/~modelcheck/tour.htm)

Applying Model Checking

- **Model checking is very good for proving pieces of systems correct**
  - Complexity is exponential with number of states
    - So it doesn't work with arbitrarily large systems; but technology improves yearly
  - OK for aspects of network protocols and small pieces of software

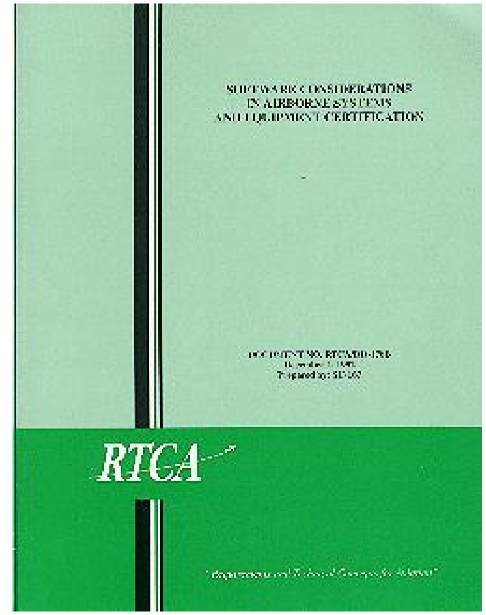
- **But, there are some cautions:**
  - Tests a model of design, not actual code. Software defects can still occur. Models might have errors, etc.
  - Requires specialized skills; not accessible to everyday engineers yet.
  - Model has underlying assumptions!
    - Assumptions are usually not true in all cases
    - Arguing that an assumption is "reasonable" is insufficient for 10^{-9} failure rates!
  - Scalability is always an issue – can't model check a whole car

  - The tricky part is knowing what properties to check!

Certification

- **Some Certifying Authority says that it is "good enough"**
  - Certification of individuals – licensed PE
  - Certification of organizations – ISO 9000; CMM Level 3
  - Certification of tools/methods – certified Ada compiler
  - Certified systems or products – UL-listed
- **May be process- or product-based**
  - UL labs – based on standardized tests of products
  - ISO 9000 – audit of process
  - … and lots of places in between
- **Certification may not be a warranty**
  - Warranty gives legal remedies; certification means it is up to some standard level of "goodness"
  - Certification simply places the reputation of the certifier at stake

Example: FAA Software Certification



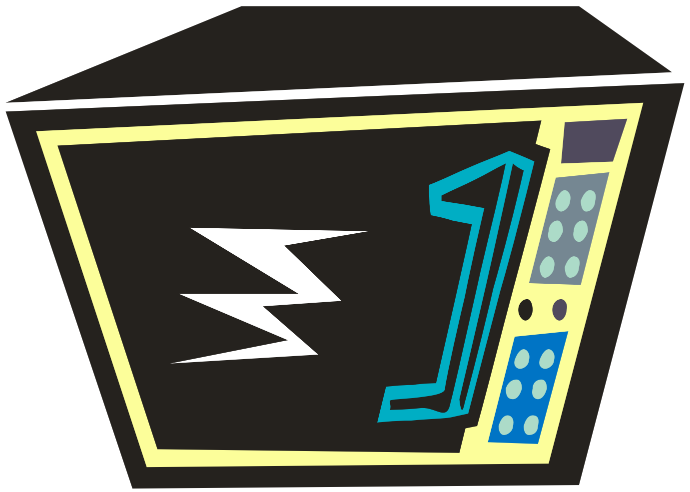
- **Based on RTCA/DO-178B**
  - Demonstrate that it satisfies requirements
  - Demonstrate there are no errors leading to catastrophic failure
  - (Newer version RTCS/DO-178C is recently out)

- **Verification:**
  - HW/SW integration testing
  - SW integration testing
  - Low-level testing
  - Requirements-based test coverage analysis
  - Structural coverage analysis

- **Alternate verification methods**
  - Formal methods
  - Exhaustive input testing

Example: UL 1998 for Software Components

- **Consumer electronics certification addresses software**
  - For software that replaces functions that previously had hardware protection
  - They want to see the software! Testing alone just isn't good enough
- **Requirements:**
  - Design for safety
  - Verification, Validation & Test
  - Change management
  - Software Risk Analysis



- **Risk traceability matrix**
  - FMEA-like table
- **Certification components:**
  - Electrical safety reviews + tests
  - Environmental stress tests
  - Software review – source code & some process documents

Quality

1994 Pentium FDIV bug:

- “We’ll replace the chip if you can prove the problem affects you”
- Eventually replaced chip for everyone who asked at cost of ~$500M

Hardware Correctness

- **Hardware testing is more manufacturing-centric**
  - Scan approaches
    - Scan paths to test flip-flops
    - Boundary scan to test chip-to-chip interconnects
  - Automatic test generation

- **But, what if the design is incorrect?**
  - The Pentium FDIV bug was a rude awakening
    - Math error in floating point division that affected only a few input values
    - Poor public relations resulted in demand for replacement chips ➔ cost ~$500M
    - But almost every CPU has bugs in it somewhere!
  - Isolate subsystems and test in isolation
  - Incorrect hardware design in many ways “feels” like a software problem…

  - And, in Jan 2011 … Intel found a bug with the Cougar Point support chip
    - Estimated $700M total cost

Software Correctness

- **This is a big can of worms**
  - In general, we can't prove software is correct (i.e., exactly meets the spec.)
  - Even if we can prove it's correct, we don't know if the specification is correct
  - So what we do is also include process (lectures on that coming up)

- **Software reliability – how many defects when it ships?**
  - Can be inferred by tracking bug detection rates (ship it when you stop finding bugs in testing)
  - Can be improved by better process
  - In general, current state of knowledge is:
    "keep testing until it takes a long time to find the next defect, then ship"

- **Software "field reliability" – does it fail in the field?**
  - Difficult problem; not a lot to say about this yet except that it is an issue
  - Components to software field reliability
    - Exposing design defects due to randomly occuring unusual events
    - Failures due to "code rot" and "resource leaks"

Configuration Management

- **Make sure that the hardware and software is actually the right stuff**
  - For example, compute a checksum or secure hash of the binary image
  - Make sure before you ship that you are shipping the right software version
  - Have a formal build process to make sure you ship a clean build
- **How can this go wrong?**
  - Someone leaves debug code in the final build
    - Watchdog timer accidentally turned off from single-step debugging
    - Back door factory access code left in (security problem)
  - Someone compiles with wrong version of libraries, source code, etc.
  - A virus gets into the build system and infects the built image …
- **Applies to hardware as well**
  - Want to make sure you know version and source for critical system components

Airbus A-380 bolt with part tracking information.
Size: 2 cm x 1 cm

What V&V Approaches Are We Using?

- **For the course elevator project, list V&V techniques:**

Challenge: Ultradependability

- **Ultradependable systems “never” fail**
  - But if they never fail, how can you know what the failure rate really is?

- **Can you test for ultradependability?**

1. How many tests to check all possible behaviors for this function:

   int32 MyProc(int32 A, int32 B, int32 C)

   – (who remembers this from last lecture?)

2. How long do you have to test to verify MTBF of 10^{-9}/hr?
   (This is a typical aircraft failure rate target

- Need to test longer than 10^9 hours and even then you didn’t test enough

- In fact, need to test between 3* and 10* MTBF to verify MTBF
  – 10* 10^9 hours = 1,141,000 years of testing

Ultradependability Approaches

- **Good process and lots of V&V**
  - Use good design methodology to reduce design defect rate
  - Use proven, “mature” components
    - But, be careful not to expose hidden limitations with new conditions
  - Test a large number of systems for a long time
    - Need completely failure-free operation during testing – even one failure can be too many for ultradependability
    - There is NO SUCH THING as a one-time failure… there are just situations waiting to re-occur in a different context
  - Use formal methods on tractable, high-risk pieces
  - Use fault injection to assess resiliency to problems that do happen

- **This is the approach taken by safety standards**

And Now, The Problem Gets Harder

- **Embedded Internet –**
  - Can someone hack into your car?

    …into your house?

    …into your digital wallet?

    …into your medication pump?

    …into your pacemaker?

    …into your train?
  - Security is now becoming part of the validation/verification/ certification picture
    - Static checkers are the first line of defense, but much more is required
    - Penetration testing helps, but much more is required.

Review

- **The Big Problem**
  - We need to ensure systems will really work, and we're on a tight deadline
  - BUT, there are proven techniques that can help!

- **Approaches:**
  - Design reviews to ensure designs are good before implementation
  - Verification: making sure each design step does what it was supposed to do
  - Validation: making sure the end result satisfies requirements
  - Certification: a written guarantee that a system is acceptable for operational use

- **In most embedded system companies, testing is the only real V&V**
  - BUT, testing isn't good enough for high-dependability / safe systems!
  - Need as many V&V techniques as possible
  - Ultimately, need a dependability case or safety case to be sure things are OK

  - Later lectures will describe more rigorous processes for critical systems