

Lecture 8
Overview of software testing

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- Testing in general
- Unit testing
- Coverage criteria
- System testing
- Some slides borrowed from the course "Testing, Debugging, Verification" at Chalmers

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Overview

- Ideas and techniques of testing have become essential knowledge for all software developers.
- Expect to use the concepts presented here many times in your career.
- Testing is not the only, but the primary method that industry uses to evaluate software under development.

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Overview (2)

- Testing field is HUGE
 - Many different approaches, many different opinions
 - Creating an exhaustive overview is a futile endeavour
- This lecture will cover some of the most important/common notions, in particular w.r.t. embedded systems

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Correctness

- Software is called **correct** if it complies with its specification
 - Spec. might be *implicit* or *explicit*, *formal* or *informal*, *declarative* or *imperative*, etc.
 - Often: spec. is a set of requirements and/or use cases
- Software that violates spec. contains **bugs/defects**

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Validation vs. Verification

- **Validation:** assessment whether program has intended behaviour (this can mean: check whether chosen *requirements* are correct or consistent)
- **Verification:** assessment whether program complies to specification/requirements

The V&V of software engineering

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Validation vs. Verification (2)

- Testing is the most common approach to V&V
- Testing is form of **dynamic V&V**
 - Works through concrete execution of software
- Alternatives:
 - Static V&V: model checking, etc.
 - Code inspection/reviews

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Faults, errors, failures

- **Fault:** abnormal condition or defect in a component (software or hardware)
- **Error:**
 - deviation from correct system state caused by a fault
 - human mistake when using the system
- **Failure:** observably incorrect behaviour of system, caused by a fault

Many different definitions exist!

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Fault/failure example

```
for (;;) {
  if (GPIO_ReadInputData(SwitchPin)) {
    ++count;
  } else if (count != 0) {
    GPIO_WriteBit(GPIOA, ON1Pin, Bit_RESET);
    GPIO_WriteBit(GPIOA, ON2Pin, Bit_RESET);
    count = 0; 0
  }

  if (count == 10) // 0.2 seconds
    GPIO_WriteBit(GPIOA, ON1Pin, Bit_SET);
  else if (count == 100) { // 0.2 + 1.8 seconds
    GPIO_WriteBit(GPIOA, ON1Pin, Bit_RESET);
    GPIO_WriteBit(GPIOA, ON2Pin, Bit_SET);
  }

  vTaskDelayUntil(&lastWakeupTime,
    PollPeriod / portTICK_RATE_MS);
}
```

Software fault: wrong RHS

Error: variable has wrong value

Failure: wrong value on pin, rockets are launched

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Testing consists of ...

- designing test inputs
- running tests
- analysing results

- Done by **test engineer**
- Each of the steps can be automated

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Test engineers vs. developers

- In practice, often different people
- Various opinions on this ...

Your opinion?

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Opinion 1 (Glenford J. Myers, ...)

- Programmer should avoid testing his/her own program (misunderstanding of specs carry over to testing)
- A programming organisation should not test its own programs
→ Conflict of interest

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Opinion 2 (Kent Beck, Erich Gamma, ...)

- **Test-driven development:** Developers create tests *before* implementation
- Test cases are **form of specification**
- Re-run tests on all incremental changes

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What is testing good for? Bit of philosophy ...

Boris Beizer's levels of test process maturity

- **Level 0:** Testing = debugging
- **Level 1:** Purpose of testing: show that software works
- **Level 2:** Purpose of testing: show that software does not work
- **Level 3:** Purpose of testing: reduce risk due to software
- **Level 4:** Testing is mental discipline to develop high-quality software

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Level 0: testing = debugging

- Naïve starting point: debug software by writing test cases and manually observing the outcome
- No notion of *correctness*
- Does not help much to develop software that is reliable or safe

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Level 1: show that software works

- Correctness is (almost) impossible to achieve
- Danger: you are subconsciously steered towards tests likely to not fail the program
- What do we know if no failures? good software? or bad tests?
- No strict goal, no real stopping rule, no formal test technique

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Level 2: show that software doesn't work

- Goal of testing is to find bugs
- Puts testers and developers into an adversarial relationship
- What if there are no failures?
- Practice in most software companies

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Level 3: reduce risk

- Correct software is not achievable
- Evaluate potential risks incurred by software, minimise by
 - writing software appropriately
 - testing guided by risk analysis
- Testers + developers cooperate

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Level 4: testing as mental discipline

- Learn from test outcomes to improve development process
- Quality management instead of just testing
- V&V guides overall development
- Compare with spell checker: purpose is not (only) to find mistakes, but to improve writing capabilities

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Categories of testing

Overview

- Acceptance testing
- **System testing**
- Integration testing
- **Unit testing**
- *Orthogonal dimension:* regression testing

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Unit testing

- Assess software units with respect to **low-level unit design**
 - E.g., pre-/post-conditions formulated for individual functions
- As early as possible during development

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Integration testing

- Assess software with respect to **high-level/architectural design**
- Focus on interaction between different modules
- Normally done after unit/module testing

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System testing

- Assess software with respect to **system-level specification**
 - Could be overall requirements, or more detailed specification
 - Testing by observing externally visible behaviour (no internals)
→ Black-box approach
- Usually rather late during development (but also applied to early versions of complete system)

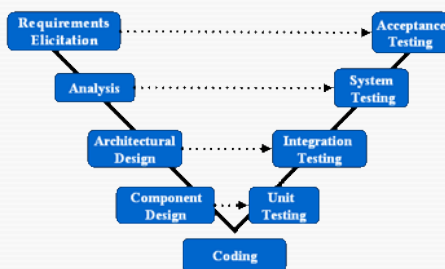
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Acceptance testing

- Assess software with respect to **user requirements**
- Can be done either by system provider or by customer (prior to transferring ownership)
- Late in development process

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Testing w.r.t. V model



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Regression testing

- Testing that is done after changes in the software.
- *Purpose:* gain confidence that the change(s) did not cause (new) failures.
- Standard part of the maintenance phase of software development.
- *Ideally:* every implemented feature is covered (preserved) by regression tests
- *Often:* regression tests are written as reaction to found bugs

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Unit testing

Structure of a unit test case

- **Step 1:** Initialisation
E.g., prepare inputs
 - **Step 2:** Call functions of implementation under test (IUT)
 - **Step 3:** Decision (oracle) whether the test succeeds or fails
- Preferable for many reasons:
Tests can be re-run easily;
Correct behaviour is described formally
- Steps can be performed *manually or automatically*

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Unit testing example

- Suppose we want to test this function:

```
void sort(int *array) { ... }
```

- An executable **test case**:

```
int testSort(void) {  
    int a[] = { 3, -1, 5 };  
  
    sort(a);  
  
    return (a[0] <= a[1] &&  
            a[1] <= a[2]);  
}
```

} Initialisation
} IUT invocation
} Oracle, return true if test succeeded

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Test oracles

- Oracles are often independent of particular test case
- Can sometimes be derived mechanically from unit specification
- Oracle is essential for being able to run tests automatically
- Common special case:
Oracle just compares unit outputs with desired outputs

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Sets and suites

- **Test set:** set of test cases for a particular unit
- **Test suite:** union of test sets for a number of units

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Automated, repeatable testing

- By using a tool you can automatically run a large collection of tests
- The testing code can be integrated into the actual code (side-effect: documentation)
- After debugging, the tests are rerun to check if failure is gone
- Whenever code is extended, all old test cases can be rerun to check that nothing is broken (regression testing)

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Automated, repeatable testing (2)

- Supported by unit testing frameworks (also called **test harness**): e.g., "xUnit"
 - SUnit: SmallTalk
 - JUnit: Java
 - CppUnit: C++
- One of the most common commercial frameworks: C++Test, Parasoft → can be integrated with MDK-ARM

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Construction of test suites

- **Black-box** (specification-based)
 - Derive test suites from external descriptions of the software, including specifications, requirements, design, and input space knowledge
- **White-box** (implementation-based)
 - Derive test suites from the source code internals of the software, specifically including branches, individual conditions, and statements
- Many approaches in between (e.g., **model-based**)

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Test suite construction is related to *coverage criteria*

- Tests are written with a particular goal in mind
 - Exercise program code thoroughly (white-box); or
 - Cover input space thoroughly (black-box)

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Assessing quality of test suites: coverage criteria

(used not only for unit testing)

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Common kinds of coverage criteria

- Control-flow graph coverage
 - Logic coverage
 - Input space partitioning
 - Mutation coverage
- } Structural coverage
- In embedded software, it is often **required** to demonstrate coverage
 - E.g., DO-178B (avionics standard), level A requires some level of MC/DC coverage

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Input space partitioning

- Based on **input domain modelling (IDM)**: abstract description of input space
 - Input space partitioned into blocks (sets of input values)
 - Values of each block are equivalent w.r.t. some characteristic
- **Coverage criteria:** has each block been covered by test cases?

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Interface-based IDM

- Characteristics derived from signature, datatypes
- E.g., for integer inputs:
 - interesting blocks are zero, positive, negative, maximum number, etc.

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Functionality-based IDM

- Characteristics derived from intended program functionality
- E.g., different expected program outputs

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Example: triangle classification

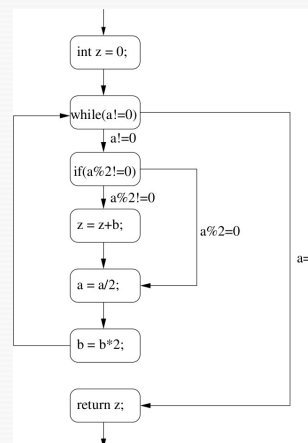
- Consider program

```
typedef enum { Scalene,  
              Isosceles,  
              Equilateral,  
              Invalid } TriType;  
  
TriType determineType(int length1,  
                     int length2,  
                     int length3) {...}
```

Which test inputs would you choose?

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Control-flow graphs (CFGs)



```
int mult(int a, int b){  
    int z = 0;  
    while ( a != 0 ) {  
        if ( a % 2 != 0 ) {  
            z = z+b;  
        }  
        a = a /2;  
        b = b *2;  
    }  
    return z;  
}
```

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Common notions in CFGs

- **Execution Path:** a path through a CFG that starts at the entry point and is either infinite or ends at one of the exit points
- **Path condition:** a path condition PC for an execution path p within a piece of code c is a condition that causes c to execute p if PC holds in the prestate of c
- **Feasible execution path:** path for which a satisfiable path condition exists

Examples!

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Statement coverage (SC)

(a kind of CFG coverage)

- A test suite TS **achieves SC** if for every node n in the CFG there is at least one test in TS causing an execution path via n
- Often quantified: e.g., 80% SC

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Branch coverage (BC)

- A test suite TS **achieves BC** if for every edge e in the CFG there is at least one test in TS causing an execution path via e.
- BC subsumes SC

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Path coverage (PC)

- A test suite TS **achieves PC** if for every execution path ep of the CFG there is at least one test in TS causing ep
- PC subsumes BC
- PC cannot be achieved in practice
 - number of paths is too large (for mult example, $\approx 2^{31}$)
 - paths might be infeasible

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Decision coverage (DC)

(a kind of logic coverage)

- **Decisions** $D(p)$ in a program p : set of *maximum* boolean expressions in p

- E.g., conditions of `if`, `while`, etc.

- But also other boolean expressions:

```
A = B && (x >= 0);
```

Precise definition is subject of many arguments: only consider decisions that program branches on?

(`B && (x >= 0)`) is a decision, `B` and `(x >= 0)` are not

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Decision coverage (DC) (2)

- **NB:** multiple occurrences of the same expression are counted as different decisions!

E.g.

```
if (x >= 0) { ... }
// ...
if (x >= 0) { ... }
```

Two decisions

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Decision coverage (DC)

- For a given decision d , DC is satisfied by a test suite TS if it contains at least one test where d evaluates to false, and one where d evaluates to true (might be the same test)
- A test suite TS **achieves DC** for a program p if it achieves DC for every decision d in $D(p)$

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DC example

- Consider decision $((a < b) \ || \ D) \ \&\& \ (m \geq n * o)$

- **Inputs to achieve DC?**

TS achieves DC if it triggers executions

```
a = 5, b = 10, D = true, m = 1, n = 1, o = 1
and
a = 10, b = 5, D = false, m = 1, n = 1, o = 1
```

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Condition coverage (CC)

- **Conditions** $C(p)$ in a program p : set of *atomic* boolean expressions in p

- e.g., in the decision

```
((a < b) || D) && (m >= n * o)
```

the conditions are

```
(a < b), D, and (m >= n * o)
```

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Condition coverage (CC) (2)

- For a given condition c , CC is satisfied by a test suite TS if it contains at least one test where c evaluates to false, and one where c evaluates to true (might be the same test)

- A test suite TS **achieves CC** for a program p if it achieves CC for every condition c in $C(p)$

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CC example

- Consider all the conditions in $((a < b) \ || \ D) \ \&\& \ (m \geq n * o)$

- **Inputs to achieve CC?**

TS achieves CC if it triggers executions

```
a = 5, b = 10, D = true, m = 1, n = 1, o = 1
and
```

```
a = 10, b = 5, D = false, m = 1, n = 2, o = 2
```

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Modified condition decision coverage (MC/DC)

- For a given condition c in decision d , MC/DC is satisfied by a test suite TS if it contains one test where c evaluates to false, one test where c evaluates to true, d evaluates differently in both, and the other conditions in d evaluate identically in both.

- For a given program p , MC/DC is satisfied by TS if it satisfies MC/DC for all c in $C(p)$

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MC/DC example

- Consider the condition $(a < b)$ in $((a < b) \ || \ D) \ \&\& \ (m \geq n * o)$

- TS achieves MC/DC if it triggers executions

$a = 5, b = 10, D = \text{false}, m = 1, n = 1, o = 1$
and

$a = 10, b = 5, D = \text{false}, m = 8, n = 2, o = 3$

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Bottom line

- Value of any kind of structural/logic coverage is arguable
- But demonstration is often required

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Further reading

- “Introduction to Software Testing,” Paul Ammann and Jeff Offutt;
<http://www.cs.gmu.edu/~offutt/softwaretest/>

System testing

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Overview

- No longer consider software units, but system as a whole
- Again, many different variants:
 - Stress testing
 - Usability testing
 - Performance testing
 - ...

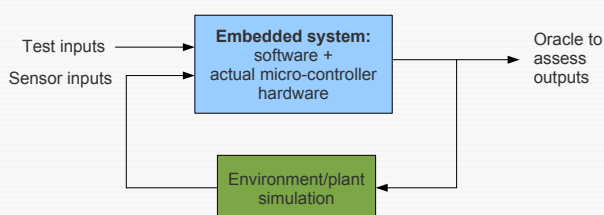
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Testing embedded systems

- Embedded systems are reactive: need **stream** of test inputs
- Realistic environment needed:
 - Either actual environment (latest stage of testing)
 - Or a simulation of the environment (cheaper, faster)
- Important setups for embedded systems: **hardware-in-the-loop**, **software-in-the-loop**

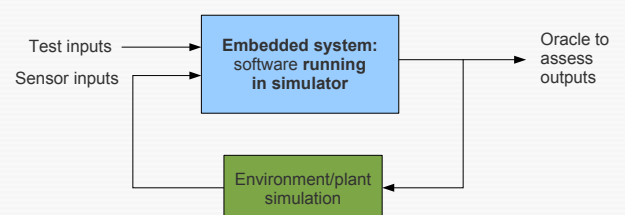
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Hardware-in-the-loop (HIL)



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Software-in-the-loop (SIL)



→ Compare with elevator lab!

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HIL + SIL

- Not only test inputs, but also environment simulation has to be chosen by test engineer
 - What if simulation is not realistic?
 - Possible variations of environment can/should be included in simulation
 - Often developed in high-level languages like Matlab/Simulink
 - See “Model-based ...” course