Softwaretechnik / Software-Engineering

Lecture 16: Testing & Review

2015-07-13

Prof. Dr. Andreas Podelski, **Dr. Bernd Westphal**

Albert-Ludwigs-Universität Freiburg, Germany

Contents of the Block "Quality Assurance"

(i) **Introduction and Vocabulary**
- correctness illustrated
- vocabulary: fault, error, failure
- three basic approaches

(ii) **Formal Verification**
- Hoare calculus
- Verifying C Compiler (VCC)
- over- / under-approximations

(iii) **(Systematic) Tests**
- systematic test vs. experiment
- classification of test procedures
- model-based testing
- glass-box tests: coverage measures

(iv) **Runtime Verification**

(v) **Review**

(vi) **Concluding Discussion**
- Dependability

Sergio: WFA
Daniel: Salvo
Jochen: Ultimate

Introduction	L 1:	20.4., Mo
	T 1:	23.4., Do
Development Process, Metrics	L 2:	27.4., Mo
	L 3:	30.4., Do
	L 4:	4.5., Mo
	T 2:	7.5., Do
	L 5:	11.5., Mo
Requirements Engineering	-	14.5., Do
	L 6:	18.5., Mo
	L 7:	21.5., Do
	-	25.5., Mo
	-	28.5., Do
	T 3:	1.6., Mo
	-	4.6., Do
	L 8:	8.6., Mo
	L 9:	11.6., Do
	L 10:	15.6., Mo
	T 4:	18.6., Do
Architecture & Design, Software Modelling	L 11:	22.6., Mo
	L 12:	25.6., Do
	L 13:	29.6., Mo
	L 14:	2.7., Do
	T 5:	6.7., Mo
Quality Assurance	L 15:	9.7., Do
	L 16:	13.7., Mo
Invited Talks	L 17:	16.7., Do
	T 6:	20.7., Mo
~~Wrap Up~~	L 18:	23.7., Do

Contents & Goals

Last Lecture:
- Completed the block "Architecture & Design"

This Lecture:
- **Educational Objectives:** Capabilities for following tasks/questions.
  - What can we conclude from the outcome of tools like VCC?
  - What is an example for not a test, non-systematic test, systematic test?
  - Given a test case and a software, is the outcome successful or unsuccessful?
  - How many test cases are necessary for exhaustive testing of a given software?
- **Content:**
  - The Verifying C Compiler (VCC)
  - Systematic test, test case, test suite
  - Testing notions
  - Coverage measures

The Verifying C Compiler

VCC

- The **Verifying C Compiler** (VCC) basically implements Hoare-style reasoning.
- **Special syntax**: $\{p\}\ S\ \{q\}$ $\{p\}\ f\ \{q\}$
  - `#include <vcc.h>`
  - `_(requires p)` — pre-condition, p is a C expression
  - `_(ensures q)` — post-condition, q is a C expression
  - `_(invariant expr)` — looop invariant, $expr$ is a C expression
  - `_(assert p)` — intermediate invariant, p is a C expression
  - `_(writes &v)` — VCC considers **concurrent** C programs; we need to declare for each procedure which global variables it is allowed to write to (also checked by VCC)
  - **Special expressions**:
    - `\thread_local(&v)` — no other thread writes to variable v (in pre-conditions)
    - `\old(v)` — the value of v when procedure was called (useful for post-conditions)
    - `\result` — return value of procedure (useful for post-conditions)

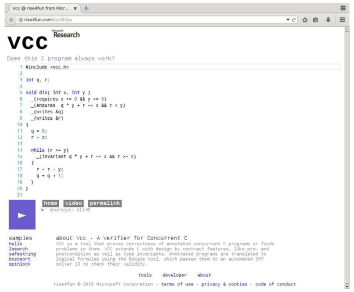
VCC Syntax Example

```
#include <vcc.h>

int q, r;

void div( int x, int y )
  _(requires x >= 0 && y >= 0)
  _(ensures q * y + r == x && r < y)
  _(writes &q)
  _(writes &r)
{
  q = 0;
  r = x;
  while (r >= y)
  _(invariant q * y + r == x && r >= 0)
  {
    r = r - y;
    q = q + 1;
  }
}
```

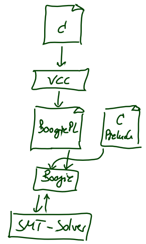
$$DIV \equiv q := 0;\ r := x;\ \textbf{while}\ r \geq y\ \textbf{do}\ r := r - y;\ q := q + 1\ \textbf{do}$$

$$\{x \geq 0 \land y \geq 0\}\ DIV\ \{q \cdot y + r = x \land r < y\}$$

VCC Web-Interface



VCC Architecture

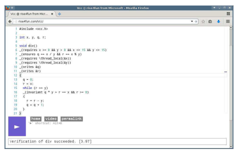


$\{p\}\ x := x - y\ \{q\}$

VCC Features

- For the exercises, we use VCC only for **sequential, single-thread programs**.
- VCC checks a number of **implicit assertions**:
  - **no arithmetic overflow** in expressions (according to C-standard),
  - **array-out-of-bounds access**,
  - **NULL-pointer dereference**,
  - and many more.
- VCC also supports:
  - **concurrency**: different threads may write to shared global variables; VCC can check whether concurrent access to shared variables is properly managed;
  - **data structure invariants**: we may declare invariants that have to hold for, e.g., records (e.g. the length field l is always equal to the length of the string field str); those invariants may **temporarily** be violated when updating the data structure.
  - and much more.
- Verification **does not always succeed**:
  - The backend SMT-solver may not be able to discharge proof-obligations (in particular non-linear multiplication and division are challenging);
  - In many cases, we need to provide **loop invariants** manually.

Interpretation of Results



- VCC says: "**verification succeeded**

  We can **only conclude** that the tool —
  under its interpretation of the C-standard,
  under its platform assumptions (32-bit), etc.
  — "thinks" that it can prove $\models \{p\}\ DIV\ \{q\}$. Can be due to an error in the tool!

  Yet we can ask **for a printout of the proof** and check it manually (hardly possible in practice) or with other tools like interactive theorem provers.

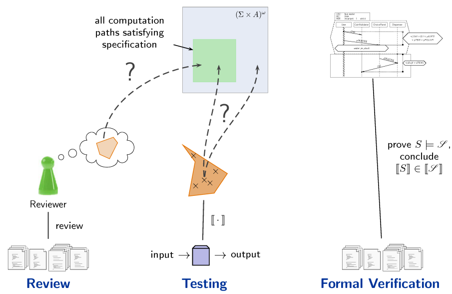
  Note: $\models \{\mathit{false}\}\ f\ \{q\}$ **always holds**
  — so a mistake in writing down the pre-condition can provoke a **false negative**.

- VCC says: "**verification failed**
  - One case: "timeout" etc. — completely inconclusive outcome.
  - The tool **does not provide counter-examples** in the form of a computation path.

    It (only) gives **hints on input values** satisfying p and causing a violation of q.

    May be a **false negative** if these inputs are actually never used.
    Make pre-condition p stronger, and try again.

Recall: Three Basic Directions



Testing

Quotes On Testing

"Testing is the execution of a program with the goal to discover errors."
G. J. Myers, 1979

"Testing is the demonstration of a program or system with the goal to show that it does what it is supposed to do."
W. Hetzel, 1984

"Software can be used to show the presence of bugs, but never to show their absence!"
E.W. Dijkstra, 1970

Rule-of-thumb: (fairly systematic) tests discover half of all errors.
(Ludewig and Lichter, 2013)

Tests vs. Systematic Tests

Test — (one or multiple) execution(s) of a program on a computer with the goal to find errors. (Ludewig and Lichter, 2013)

(Our) Synonyms: Experiment, 'Rumprobieren'.

Not (even) a test (in the sense of this weak definition):

- any inspection of the program,
- demo of the program,
- analysis by software-tools, e.g. for values of metrics,
- investigation of the program with a debugger.

Systematic Test — a test with

- (environment) conditions are defined or precisely documented,
- inputs have been chosen systematically,
- results documented and assessed according to criteria that have been fixed before.

(Ludewig and Lichter, 2013)

In the following: **experiment** := test — **test** := systematic test.

More Formally: Test Case

- A **test case** T is a set of pairs $\{(In_1, Soll_1), \dots\}$ consisting of
  - a (description of a) finite **input** sequence In_i (pairwise different in T),
  - a (description of a) finite set of **expected** computation path $Soll_i$.

Examples:

- $T_1 = (\text{FILLUP}, \text{C50}; \text{water\_button\_on})$ (shorthand notation)
  (fill up vending machine (at any time after power on), insert C50 coin (at any time), expect water button is enabled (some time later))
- $T_2 = \{(\sigma_0^i \xrightarrow{\alpha_1^i} \sigma_1^i; \sigma_0 \xrightarrow{\alpha_1} \sigma_1) \mid \sigma_0^i(x) = 7 \wedge \sigma_1(y) = 49\}$
  (input 7, expect output 49, don't care for other variables' values; shorthand notation: $(7; 49)$)
- $T_3 = \{(\sigma_0^i \xrightarrow{\epsilon} \sigma_1^i; \sigma_0 \xrightarrow{\epsilon} \sigma_1)\}$ $\sigma_0^i = \sigma_0^i = 0[x := 7]$, $\sigma_0 = 0$, $\sigma_1 = 0[y := 49]$
  (each and every variable value at start and at end fixed)

Test Case Execution, Test Suite

Test Case Execution, Test Suite

- An **execution** of test case T for software S is a computation path of S

$$\pi = \begin{pmatrix} \sigma_0^i \\ \sigma_0^o \end{pmatrix} \xrightarrow[\alpha_1^o]{\alpha_1^i} \begin{pmatrix} \sigma_1^i \\ \sigma_1^o \end{pmatrix} \xrightarrow[\alpha_2^o]{\alpha_2^i} \cdots \text{ where } \sigma_0^i \xrightarrow{\alpha_1^i} \sigma_1^i \xrightarrow{\alpha_2^i} \sigma_2^i \cdots = In_i \text{ for some } i \text{ in } T.$$

- The **test case execution** is called
  - **succesful** (or **positive**) if it discovered an error, i.e. if $\pi \notin Soll_i$.
    (Alternative: test item failed to pass test; confusing: "test failed".)
  - **unsuccesful** (or **negative**) if it did not discover an error, i.e. if $\pi \in Soll_i$.
    (Alternative: test item passed test; okay: "test passed".)

  Note: if input sequence not adhered to, or power outage, etc., it is not a test execution.

- A **test suite** is a set of test cases.
  Execution, **positive**, and **negative** are lifted canonically.

The Outcome of Systematic Tests Depends on...

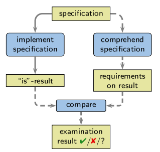
- **inputs**:
  - the input vector of the test case (of course), possibly with timing constraints,
  - other interaction, e.g., from network,
  - initial memory content,
  - etc.
- **(environmental) conditions**:
  any aspects which could have an effect on the outcome of the test such as
  - which program (version) is tested? built with which compiler, linker, etc.?
  - test host (OS, architecture, memory size, connected devices (configuration?), etc.)
  - which other software (in which version, configuration) is involved?
  - who tested when?
  - etc.

... so strictly speaking **all of them** need to be specified within (or as an extension to) In.

- **In practice**, this is hardly possible — but one wants to specify as much as possible in order to achieve **reproducibility**.
- **One approach**:
  have a fixed build environment, a fixed test host which does not do any other jobs, etc.

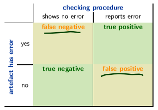
Software Examination *(in Particular Testing)*

- In each check, there are **two paths** from specification to result:
  - the **production path** (using model, source code, executable, etc.), and
  - the **examination path** (using requirements specification).
- A check can only discover errors on **exactly one** of the paths.
- What is not on the paths, is not checked; crucial: **specification** and **comparison**.
- Difference detected: examination result is **positive**.

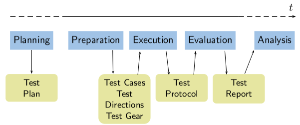


(Ludewig and Lichter, 2013)

Recall:



Test Conduction



- **Test Gear**:

test driver— A software module used to invoke a module under test and, often, provide test inputs, control and monitor execution, and report test results.
Synonym: test harness. **IEEE 610.12** (1990)

stub(1) A skeletal or special-purpose implementation of a software module, used to develop or test a module that calls or is otherwise dependent on it.
(2) A computer program statement substituting for the body of a software module that is or will be defined elsewhere. **IEEE 610.12** (1990)

hardware-in-the-loop, **software-in-the-loop**: the final implementation is running on (prototype) hardware, other system component are simulated by a separate computer.

Specific Testing Notions

- How are the test cases **chosen**?
  - Considering the structure of the test item (**glass-box** or **structure** test).
  - Considering only the specification (**black-box** or **function** test).
- How much **effort** is put into testing?

  execution trial — does the program run at all?
  throw-away-test — invent input and judge output on-the-fly,
  systematic test — somebody (not author!) derives test cases, defines input/soll, documents test execution.

  In the long run, **systematic tests** are more **economic**.
- **Complexity** of the test item:

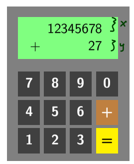
  unit test — a single program unit is tested (function, sub-routine, method, class, etc.)
  module test — a component is tested,
  integration test — the interplay between components is tested.
  system test — tests whole system.

Specific Testing Notions Cont'd

- Which **property** is tested?

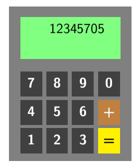
  function test — functionality as specified by the requirements documents,
  installation test — is it possible to install the software with the provided documentation and tools?
  recomminsioning test — is it possible to bring the system back to operation after operation was stopped?
  availability test — does the system run for the required amount of time without issues,
  load and stress test — does the system behave as required under high or highest load? . . . under overload?
  "Hey, let's try how many game objects can be handled!" — that's an experiment, not a test.
  regression test — does the new version of the software behave like the old one on inputs where no behaviour change is expected?
  response time , **minimal hardware (software) requirements**, etc.
- Which roles are **involved** in testing?
  - only the developer, or selected (potential) customers (**alpha** and **beta** test),
  - **acceptance test** — the customer tests whether the system (or parts of it, at milestones) test whether the system is acceptable.

The Crux of Software Testing



- **Requirement**:
  If the display shows x, $+$, and y, then after pressing =,
  - the sum of x and y is displayed if $x + y$ has at most 8 digits,
  - otherwise "-E-" is displayed.

The Crux of Software Testing



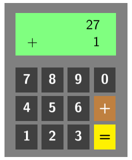
- **Requirement**:
  If the display shows x, $+$, and y, then after pressing =,
  - the sum of x and y is displayed if $x + y$ has at most 8 digits,
  - otherwise "-E-" is displayed.

Testing the Pocket Calculator

Test some representatives of "equivalence classes":

- $n+1$, n small, e.g. $27+1$
- $n+m$, n small, m small (for non error), e.g. $13+27$
- $n+m$, n big, m big (for non error), e.g. $12345+678$
- $n+m$, n huge, m small (for error), e.g. $99999999+1$
- ...

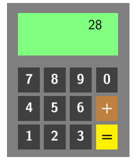
Testing the Pocket Calculator



Test some representatives of "equivalence classes":

- $n+1$, n small, e.g. $27+1$
- $n+m$, n small, m small (for non error), e.g. $13+27$
- $n+m$, n big, m big (for non error), e.g. $12345+678$
- $n+m$, n huge, m small (for error), e.g. $99999999+1$
- ...

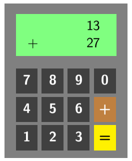
Testing the Pocket Calculator



Test some representatives of "equivalence classes":

- $n+1$, n small, e.g. $27+1$
- $n+m$, n small, m small (for non error), e.g. $13+27$
- $n+m$, n big, m big (for non error), e.g. $12345+678$
- $n+m$, n huge, m small (for error), e.g. $99999999+1$
- ...

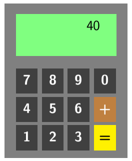
Testing the Pocket Calculator



Test some representatives of "equivalence classes":

- $n+1$, n small, e.g. $27+1$
- $n+m$, n small, m small (for non error), e.g. $13+27$
- $n+m$, n big, m big (for non error), e.g. $12345+678$
- $n+m$, n huge, m small (for error), e.g. $99999999+1$
- ...

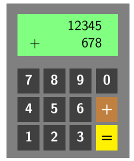
Testing the Pocket Calculator



Test some representatives of "equivalence classes":

- $n+1$, n small, e.g. $27+1$
- $n+m$, n small, m small (for non error), e.g. $13+27$
- $n+m$, n big, m big (for non error), e.g. $12345+678$
- $n+m$, n huge, m small (for error), e.g. $99999999+1$
- ...

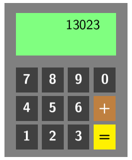
Testing the Pocket Calculator



Test some representatives of "equivalence classes":

- $n+1$, n small, e.g. $27+1$
- $n+m$, n small, m small (for non error), e.g. $13+27$
- $n+m$, n big, m big (for non error), e.g. $12345+678$
- $n+m$, n huge, m small (for error), e.g. $99999999+1$
- ...

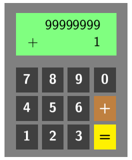
Testing the Pocket Calculator



Test some representatives of "equivalence classes":

- $n+1$, n small, e.g. $27+1$
- $n+m$, n small, m small (for non error), e.g. $13+27$
- $n+m$, n big, m big (for non error), e.g. $12345+678$
- $n+m$, n huge, m small (for error), e.g. $99999999+1$
- ...

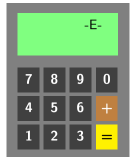
Testing the Pocket Calculator



Test some representatives of "equivalence classes":

- $n+1$, n small, e.g. $27+1$
- $n+m$, n small, m small (for non error), e.g. $13+27$
- $n+m$, n big, m big (for non error), e.g. $12345+678$
- $n+m$, n huge, m small (for error), e.g. $99999999+1$
- ...

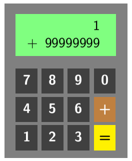
Testing the Pocket Calculator



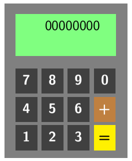
Test some representatives of "equivalence classes":

- $n+1$, n small, e.g. $27+1$
- $n+m$, n small, m small (for non error), e.g. $13+27$
- $n+m$, n big, m big (for non error), e.g. $12345+678$
- $n+m$, n huge, m small (for error), e.g. $99999999+1$
- ...

Testing the Pocket Calculator: One More Try



Testing the Pocket Calculator: One More Try



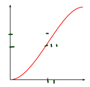
- Oops...

Behind the Scenes: Test "$99999999+1$" Failed Because...

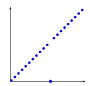
```
int add( int x, int y )
{
  if (y == 1) // be fast
    return ++x;

  int r = x + y;

  if (r > 99999999)
    r = -1;

  return r;
}
```

increment by 1

Software is Not Continous



A continous function: we can conclude from a point to its environment.



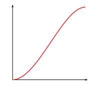
Software is (in general) not continous. . .

```
int f( int x ) {
  int r = 0;
  if (0 <= x && x < 128)
    r = fast_f(x);          // only for [0,127]
  else if (128 < x && x < 1024)
    r = slow_f(x);          // only for [128,1023]
  else
    r = really_slow_f(x); // only for [1024,..]
  return r;
}
```

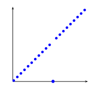
– fast_f, slow_f, really_slow_f correct

– f(x) ≠ 0 for all x is required

Software is Not Continous



A continous function: we can conclude from a point to its environment.



Software is (in general) not continous. . .

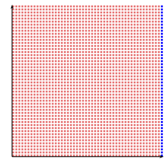
```
int f( int x ) {
  int r = 0;
  if (0 <= x && x < 128)
    r = fast_f(x);          // only for [0,127]
  else if (128 < x && x < 1024)
    r = slow_f(x);          // only for [128,1023]
  else
    r = really_slow_f(x); // only for [1024,..]
  return r;
}
```

- **Range error**: multiple "neighbouring" inputs trigger the error.
- **Point error**: an isolated input value triggers the error.

And Software Usually Has Many Inputs

- **Example**: Simple Pocket Calculator.

  With **one million** different test cases,
  9,999,999,999,000,000 of the 10^{16} possible inputs remain **uncovered**.
  IOW: only 0.00000001% of the possible inputs convered, 99.99999999% not touched.



And if we restart the pocket calculator for each test,
we **do not know anything** about problems with **sequences** of inputs. . .

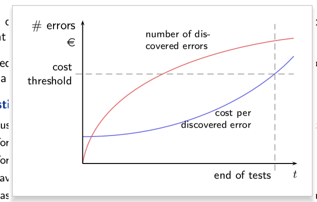
When To Stop Testing?

When To Stop Testing?

- The natural criterion "**when everything has been done**" does not apply for testing — at least not for testing pocket calculators.
- So there need to be defined **criteria** to stop testing; project planning considers these criteria and experience with them.
- Possible **testing is done** criteria:
  - all (previously) specified test cases have been executed with negative result,
  - testing effort sums up to x hours (days, weeks),
  - testing effort sums up to y (any other useful unit),
  - n errors have been discovered,
  - no error has been discovered during the last z hours (days, weeks) of testing,
  - the average cost per error discovery exceeds a defined threshold c,

When To Stop Testing?

- The natural c… …ly for testing — at
- So there neec… …nsiders these criteria
- Possible **testi**…
  - all (previous… …,
  - testing effor
  - testing effor
  - n errors hav
  - no error has… …g,
  - the average cost per error discovery exceeds a defined threshold c,



When To Stop Testing?

- The natural criterion "**when everything has been done**" does not apply for testing — at least not for testing pocket calculators.
- So there need to be defined **criteria** to stop testing; project planning considers these criteria and experience with them.
- Possible **testing is done** criteria:
  - all (previously) specified test cases have been executed with negative result,
  - testing effort sums up to x hours (days, weeks),
  - testing effort sums up to y (any other useful unit),
  - n errors have been discovered,
  - no error has been discovered during the last z hours (days, weeks) of testing,
  - the average cost per error discovery exceeds a defined threshold c,

  Values for x, y, n, z, c are fixed based on experience, estimation, budget, etc..
- **Of course**: not all equally reasonable or compatible with each testing approach.

Choosing Test Cases

Choosing Test Cases

A test case is a **good test case** if discovers with high probability an unknown error.
An ideal test case should be

- **representative**, i.e. represent a whole class of inputs,
- **error sensitive**, i.e. has high probability to detect an error,
- **of low redundancy**, i.e. it does not test what other test cases also test.

The wish for representative test cases is **particularly problematic**:

- Recall **point errors** (pocket calculator, fast/slow f, . . .).

In general, we do not know which inputs lie in an equivalence class wrt. errors.

Yet there is a large body on literature on how to construct representative test cases, **assuming** we know the equivalence classes.

"Acceptable" equivalence classes: Based on requirement specification, e.g.

- valid and invalid inputs (to check whether input validation works),
- different classes of inputs considered in the requirements, e.g. "buy water", "buy soft-drink", "buy tea" vs. "buy beverage".

Lion and Error Hunting

> "He/she who is hunting lions, should know how a lion looks like. He/she should also know where the lion likes to stay, which traces the lion leaves behind, and which sounds the lion makes." (Ludewig and Lichter, 2013)

Hunting errors in software is (basically) the same.

Some traditional popular belief on software error habitat:

- Software errors — in contrast to lions — (seem to) enjoy
  - range boundaries, e.g.
    - 0, 1, 27 if software works on inputs from $[0, 27]$,
    - -1, 28 for error handling,
    - $-2^{31} - 1$, 2^{31} on 32-bit architectures,
    - boundaries of arrays (first, last element),
    - boundaries of loops (first, last iteration),
  - special cases of the problem (empty list, use-case without actor, . . .),
  - special cases of the programming language semantics,
  - complex implementations.

Where Do We Get The "Soll"-Values From?

- In an **ideal world**, all test cases are pairs $(In, Soll)$ with proper "soll"-values.
  As, for example, defined by the formal requirements specification.
  Advantage: we can mechanically, objectively check for positive/negative.
- In the **this world**,
  - the formal requirements specification may only **reflectively** describe acceptable results without giving a **procedure** to compute the results.
  - there may not be a formal requirements specification, e.g.
    - "the game objects should be rendered properly",
    - "the compiler must translate the program correctly",
    - "the notification message should appear on a proper screen position",
    - "the data must be available for at least 10 days".
    - etc.

    Then: need another instance to decide whether the observation is acceptable.
- The testing community prefers to call **any instance** which decides whether results are acceptable an **oracle**.
- I prefer not to call decisions based on **formally defined** test cases "oracle" . . . ;-)

Glass-Box Testing: Coverage

Glass-Box Testing: Coverage

- **Coverage** is a property of **test cases** and **test suite**.
- **Recall**: An **execution** of test case $T = (In, Soll)$ for software S is a computation path

$$\begin{pmatrix} \sigma_0^i \\ \sigma_0^o \end{pmatrix} \xrightarrow[\alpha_1^o]{\alpha_1^i} \begin{pmatrix} \sigma_1^i \\ \sigma_1^o \end{pmatrix} \xrightarrow[\alpha_2^o]{\alpha_2^i} \cdots \text{ where } \sigma_0^i \xrightarrow{\alpha_1^i} \sigma_1^i \xrightarrow{\alpha_2^i} \sigma_2^i \cdots = In.$$

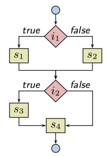
- Let S be a **program** (or model) consisting of **statements** S_{Stm}, **conditions** S_{Cnd}, and a **control flow graph** (V, E) (as defined by the programming language).
- **Assume** that each state σ gives information on statements, conditions, and control flow graph edges **which were executed** right before obtaining σ:

$$stm : \Sigma \to 2^{S_{Stm}}, \qquad cnd : \Sigma \to 2^{S_{Cnd}}, \qquad edg : \Sigma \to 2^{E}$$

- T achieves $p\,\%$ **statement coverage** if and only if $p = \frac{|\bigcup_{i \in \mathbb{N}_0} stm(\sigma_i)|}{|S_{Stm}|}$, $|S_{Stm}| \neq 0$.
- T achieves $p\,\%$ **branch coverage** if and only if $p = \frac{|\bigcup_{i \in \mathbb{N}_0} edg(\sigma_i)|}{|E|}$, $|E| \neq 0$.
- **Define**: $p = 100$ for empty program.
- Statement/branch coverage canonically extends to test suite $\mathcal{T}$.

Coverage Example

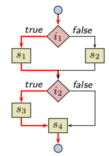
```
int f( int x, int y, int z )
{
i1:  if (x > 100 ∧ y > 10)
s1:     z = z * 2;
     else
s2:     z = z/2;
i2:  if (x > 500 ∨ y > 50)
s3:     z = z * 5;
s4:  return z;
}
```



- Requirement: $\{true\}\ f\ \{true\}$ (no abnormal termination)

Coverage Example

```
int f( int x, int y, int z )
{
i1:  if (x > 100 ∧ y > 10)
s1:     z = z * 2;
     else
s2:     z = z/2;
i2:  if (x > 500 ∨ y > 50)
s3:     z = z * 5;
s4:  return z;
}
```

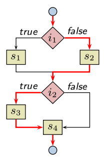


- Requirement: $\{true\}\ f\ \{true\}$ (no abnormal termination)

x, y, z	i_1/t	i_1/f	s_1	s_2	i_2/t	i_2/f	c_1	c_2	s_3	s_4	% stm	% cfg	i_2/% term
501, 11, 0													

Coverage Example

```
int f( int x, int y, int z )
{
i1:  if (x > 100 ∧ y > 10)
s1:     z = z * 2;
     else
s2:     z = z/2;
i2:  if (x > 500 ∨ y > 50)
s3:     z = z * 5;
s4:  return z;
}
```

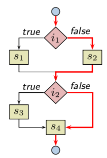


- Requirement: $\{true\}\ f\ \{true\}$ (no abnormal termination)

x, y, z	i_1/t	i_1/f	s_1	s_2	i_2/t	i_2/f	c_1	c_2	s_3	s_4	% stm	% cfg	i_2/% term
501, 11, 0	✔		✔		✔		✔		✔	✔	75	50	25
501, 0, 0													

Coverage Example

```
int f( int x, int y, int z )
{
i1:  if (x > 100 ∧ y > 10)
s1:     z = z * 2;
     else
s2:     z = z/2;
i2:  if (x > 500 ∨ y > 50)
s3:     z = z * 5;
s4:  return z;
}
```

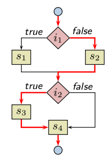


- Requirement: $\{true\}\ f\ \{true\}$ (no abnormal termination)

x, y, z	i_1/t	i_1/f	s_1	s_2	i_2/t	i_2/f	c_1	c_2	s_3	s_4	% stm	% cfg	i_2/% term
501, 11, 0	✔		✔		✔		✔		✔	✔	75	50	25
501, 0, 0		✔		✔	✔		✔		✔	✔	100	75	25
0, 0, 0													

Coverage Example

```
int f( int x, int y, int z )
{
i1:  if (x > 100 ∧ y > 10)
s1:     z = z * 2;
     else
s2:     z = z/2;
i2:  if (x > 500 ∨ y > 50)
s3:     z = z * 5;
s4:  return z;
}
```

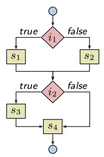


- Requirement: $\{true\}\ f\ \{true\}$ (no abnormal termination)

x, y, z	i_1/t	i_1/f	s_1	s_2	i_2/t	i_2/f	c_1	c_2	s_3	s_4	% stm	% cfg	i_2/% term
501, 11, 0	✔		✔		✔		✔		✔	✔	75	50	25
501, 0, 0		✔		✔	✔		✔		✔	✔	100	75	25
0, 0, 0		✔		✔		✔				✔	100	100	75
0, 51, 0													

Coverage Example

```
int f( int x, int y, int z )
{
 i1: if (x > 100 ∧ y > 10)
 s1:     z = z * 2;
     else
 s2:     z = z/2;
 i2: if (x > 500 ∨ y > 50)
 s3:     z = z * 5;
 s4: return z;
}
```



- Requirement: $\{true\}\ f\ \{true\}$ (no abnormal termination)

x, y, z	i_1/t	i_1/f	s_1	s_2	i_2/t	i_2/f	c_1	c_2	s_3	s_4	% stm	% cfg	i_2/% term
$501, 11, 0$	✔		✔		✔		✔		✔	✔	75	50	25
$501, 0, 0$		✔		✔	✔		✔		✔	✔	100	75	25
$0, 0, 0$		✔		✔		✔				✔	100	100	75
$0, 51, 0$		✔		✔	✔			✔		✔	100	100	100

Term Coverage

- Consider the statement

$$\texttt{if}\ (\overbrace{A \wedge (B \vee (C \wedge D)) \vee E}^{expr})\ \texttt{then} \ldots;$$

  $A, \ldots, E$ are **minimal** boolean terms, e.g. $x > 0$, but not $a \vee b$.

- **Branch coverage** is easy: use $(A = 0, \ldots, E = 0)$ and $(A = 0, \ldots, E = 1)$.
- **Additional goal**: check whether there are useless terms, or terms causing abnormal program termination.

A	B	C	D	E	%
1	**1**	0	0	0	20
1	**0**	**0**	1	**0**	50
1	0	**1**	**1**	0	70
0	0	1	0	**1**	80

- **Term Coverage** (for an expression $expr$):
  - Let $\beta : \{A_1, \ldots, A_n\} \to \mathbb{B}$ be a valuation of the terms.
  - Term A_i is b-**effective** in β for $expr$ if and only if

$$\beta(A_i) = b \text{ and } [\![expr]\!](\beta[A_i/\mathit{true}]) \neq [\![expr]\!](\beta[A_i/\mathit{false}]).$$

  - $\Xi \subseteq (\{A_1, \ldots, A_n\} \to \mathbb{B})$ achieves $p\,\%$ **term coverage** if and only if

$$p = \frac{|\{A_i^b \mid \exists \beta \in \Xi \bullet A_i \text{ is } b\text{-effective in } \beta\}|}{2n}.$$

Unreachable Code

```
             int f( int x, int y, int z )
             {
              i1: if (x ≠ x)
never  ▷      s1:     z = y/0;
              i2: if (x = x ∨ z/0 = 27)
              s2:     z = z * 2;        never
              s3: return z;
             }
```

- Statement s_1 is **never executed** ($x \neq x \iff \mathit{false}$), thus 100 % coverage **not achievable**.
- Is statement s_1 an **error** anyway. . . ?
- Term $y/0$ is never evaluated either (short-circuit evaluation)

Conclusions from Coverage Measures

- Assume, we are testing property $\varphi = \{p\}\ f\ \{q\}$ (maybe just $q = \mathit{true}$ with ↯),
- assume our test suite $\mathcal{T}$ achieved $100\,\%$ statement / branch / term coverage.

What does this tell us about f? Or: what can we conclude from coverage measures?

- $100\,\%$ **statement** coverage:
  - "there is no statement, which **necessarily** violates φ"
    (Still, there may be many, many computation paths which violate φ,
    and which just have not been touched by $\mathcal{T}$, e.g. differing in variables' valuation.)
  - "there is no unreachable statement"
- $100\,\%$ **branch** (**term**) coverage:
  - "there is no single branch (term) which **necessarily causes** violations of φ"
    IOW: "for each condition (term), there is one computation path satisfying φ where the condition (term) evaluates to *true*/*false*"
  - "there is no unused condition (term)"

Not more (→ exercises)!
That's **something**, but not as much as "100 %" may sound. . .

Coverage Measures in Certification

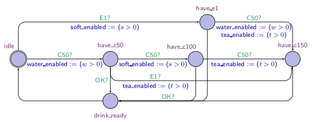
- (Seems that) DO-178B,

  Software Considerations in Airborne Systems and Equipment Certification,

  which deals with the safety of software used in certain airborne systems,
- requires certain **coverage results**.
  (Next to development process requirements, reviews, unit testing, etc.)
- Currently, the standard moves towards accepting certain verification or static analysis tools to support (or even replace?) some testing obligations.

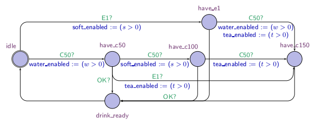
Model-Based Testing

Model-based Testing



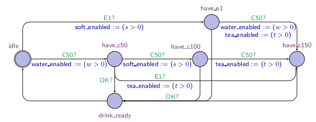
- Does some software **implement** the given CFA model of the CoinValidator?

Model-based Testing



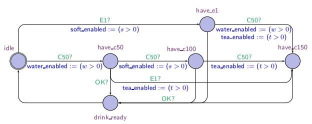
- Does some software **implement** the given CFA model of the CoinValidator?
- **One approach**: check whether **each state** of the model has some reachable **corresponding configuration** in the software.
  - $T_1 = (\mathsf{C50}, \mathsf{C50}, \mathsf{C50}; \{\pi \mid \exists\, i < j < k < \ell \bullet \pi^i \sim \mathsf{idle}, \pi^j \sim \mathsf{h\_c50}, \pi^k \sim \mathsf{h\_c100}, \pi^\ell \sim \mathsf{h\_c150}\})$
    checks: can we reach 'idle', 'have_c50', 'have_c100', 'have_c150'?

Model-based Testing



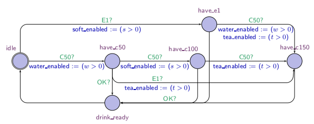
- Does some software **implement** the given CFA model of the CoinValidator?
- **One approach**: check whether **each state** of the model has some reachable **corresponding configuration** in the software.
  - $T_1 = (\mathsf{C50}, \mathsf{C50}, \mathsf{C50}; \{\pi \mid \exists\, i < j < k < \ell \bullet \pi^i \sim \mathsf{idle}, \pi^j \sim \mathsf{h\_c50}, \pi^k \sim \mathsf{h\_c100}, \pi^\ell \sim \mathsf{h\_c150}\})$
    checks: can we reach 'idle', 'have_c50', 'have_c100', 'have_c150'?
  - $T_2 = (\mathsf{C50}, \mathsf{C50}, \mathsf{C50}; \dots)$ checks for 'have_e1'.

Model-based Testing



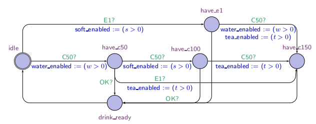
- Does some software **implement** the given CFA model of the CoinValidator?
- **One approach**: check whether **each state** of the model has some reachable **corresponding configuration** in the software.
  - $T_1 = (\mathsf{C50}, \mathsf{C50}, \mathsf{C50}; \{\pi \mid \exists\, i < j < k < \ell \bullet \pi^i \sim \mathsf{idle}, \pi^j \sim \mathsf{h\_c50}, \pi^k \sim \mathsf{h\_c100}, \pi^\ell \sim \mathsf{h\_c150}\})$
    checks: can we reach 'idle', 'have_c50', 'have_c100', 'have_c150'?
  - $T_2 = (\mathsf{C50}, \mathsf{C50}, \mathsf{C50}; \dots)$ checks for 'have_e1'.
  - To check for 'drink_ready', more interaction is necessary.

Model-based Testing



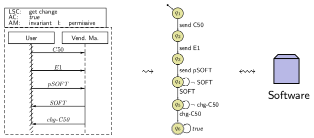
- Does some software **implement** the given CFA model of the CoinValidator?
- **One approach**: check whether **each state** of the model has some reachable **corresponding configuration** in the software.
  - $T_1 = (\mathsf{C50}, \mathsf{C50}, \mathsf{C50}; \{\pi \mid \exists\, i < j < k < \ell \bullet \pi^i \sim \mathsf{idle}, \pi^j \sim \mathsf{h\_c50}, \pi^k \sim \mathsf{h\_c100}, \pi^\ell \sim \mathsf{h\_c150}\})$
    checks: can we reach 'idle', 'have_c50', 'have_c100', 'have_c150'?
  - $T_2 = (\mathsf{C50}, \mathsf{C50}, \mathsf{C50}; \dots)$ checks for 'have_e1'.
  - To check for 'drink_ready', more interaction is necessary.
- **Or**: Check whether **each edge** of the model has **corresponding** behaviour in the software.

Model-based Testing



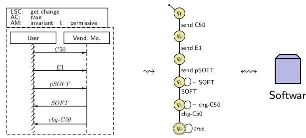
- Does some software **implement** the given CFA model of the CoinValidator?
- **One approach**: check whether **each state** of the model has some reachable **corresponding configuration** in the software.
  - $T_1 = (\mathsf{C50}, \mathsf{C50}, \mathsf{C50}; \{\pi \mid \exists\, i < j < k < \ell \bullet \pi^i \sim \mathsf{idle}, \pi^j \sim \mathsf{h\_c50}, \pi^k \sim \mathsf{h\_c100}, \pi^\ell \sim \mathsf{h\_c150}\})$
    checks: can we reach 'idle', 'have_c50', 'have_c100', 'have_c150'?
  - $T_2 = (\mathsf{C50}, \mathsf{C50}, \mathsf{C50}; \dots)$ checks for 'have_e1'.
  - To check for 'drink_ready', more interaction is necessary.
- **Or**: Check whether **each edge** of the model has **corresponding** behaviour in the software.
- **Advantage**: input sequences can automatically be generated from the model.

Existential LSCs as Test Driver & Monitor (Lettrari and Klose, 2001)



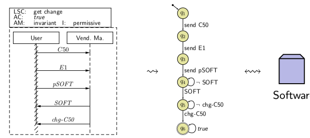
- If the LSC has designated **environment instance** lines, we can distinguish:
  - messages expected to originate **from** the environemnt (driver role),
  - messages expected adressed **to** the environemnt (monitor role).

Existential LSCs as Test Driver & Monitor (Lettrari and Klose, 2001)



- If the LSC has designated **environment instance** lines, we can distinguish:
  - messages expected to originate **from** the environemnt (driver role),
  - messages expected adressed **to** the environemnt (monitor role).
- Adjust the TBA-construction algorithm to construct a **test driver & monitor** and have it (possibly with some **glue logic** in the middle) interact with the software (or a model of it).
- **Test passed** (i.e., test unsuccessful) if and only if TBA state q_6 is reached.

Existential LSCs as Test Driver & Monitor (Lettrari and Klose, 2001)



- If the LSC has designated **environment instance** lines, we can distinguish:
  - messages expected to originate **from** the environemnt (driver role),
  - messages expected adressed **to** the environemnt (monitor role).
- Adjust the TBA-construction algorithm to construct a **test driver & monitor** and have it (possibly with some **glue logic** in the middle) interact with the software (or a model of it).
- **Test passed** (i.e., test unsuccessful) if and only if TBA state q_6 is reached.
- We may need to **refine** the LSC by adding an activation condition, or communication which drives the system under test into the desired start state.

Statistical Testing

Another Approach: Statistical Tests

One proposal to deal with the **uncertainty of tests**, and to **avoid bias** (people tend to choose expected inputs): classical **statistical testing**.

Another Approach: Statistical Tests

One proposal to deal with the **uncertainty of tests**, and to **avoid bias** (people tend to choose expected inputs): classical **statistical testing**.

- Randomly choose and apply test cases $T_1, \dots, T_n$,
  - **if an error is found**: good, we certainly know there is an error,
  - **if no error is found**:
    refuse hypothesis "program is not correct" with a certain confidence interval.

  Needs stochastical assumptions on error distribution and truly random test cases.

  (Confidence interval may get large — reflecting the low information tests give.)

Another Approach: Statistical Tests

One proposal to deal with the **uncertainty of tests**, and to **avoid bias** (people tend to choose expected inputs): classical **statistical testing**.

- Randomly choose and apply test cases $T_1, \dots, T_n$,
  - **if an error is found**: good, we certainly know there is an error,
  - **if no error is found**:
    refuse hypothesis "program is not correct" with a certain confidence interval.

  Needs stochastical assumptions on error distribution and truly random test cases.

  (Confidence interval may get large — reflecting the low information tests give.)

(Ludewig and Lichter, 2013) name the following objections against statistical testing:

Another Approach: Statistical Tests

One proposal to deal with the **uncertainty of tests**, and to **avoid bias** (people tend to choose expected inputs): classical **statistical testing**.

- Randomly choose and apply test cases $T_1, \dots, T_n$,
  - **if an error is found**: good, we certainly know there is an error,
  - **if no error is found**:
    refuse hypothesis "program is not correct" with a certain confidence interval.

  Needs stochastical assumptions on error distribution and truly random test cases.

  (Confidence interval may get large — reflecting the low information tests give.)

(Ludewig and Lichter, 2013) name the following objections against statistical testing:

- In particular for interactive software, the primary goal is often that the "typical user" does not experience failures. Statistical testing (in general) may also cover a lot of "**untypical user behaviour**", unless **user-models** are used.

Another Approach: Statistical Tests

One proposal to deal with the **uncertainty of tests**, and to **avoid bias** (people tend to choose expected inputs): classical **statistical testing**.

- Randomly choose and apply test cases $T_1, \dots, T_n$,
  - **if an error is found**: good, we certainly know there is an error,
  - **if no error is found**:
    refuse hypothesis "program is not correct" with a certain confidence interval.

  Needs stochastical assumptions on error distribution and truly random test cases.

  (Confidence interval may get large — reflecting the low information tests give.)

(Ludewig and Lichter, 2013) name the following objections against statistical testing:

- In particular for interactive software, the primary goal is often that the "typical user" does not experience failures. Statistical testing (in general) may also cover a lot of "**untypical user behaviour**", unless **user-models** are used.
- Statistical testing needs a method to **compute "soll"-values** for the randomly chosen inputs; that is easy for "does not crash" but can be difficult in general.

Another Approach: Statistical Tests

One proposal to deal with the **uncertainty of tests**, and to **avoid bias** (people tend to choose expected inputs): classical **statistical testing**.

- Randomly choose and apply test cases $T_1, \dots, T_n$,
  - **if an error is found**: good, we certainly know there is an error,
  - **if no error is found**:
    refuse hypothesis "program is not correct" with a certain confidence interval.

  Needs stochastical assumptions on error distribution and truly random test cases.

  (Confidence interval may get large — reflecting the low information tests give.)

(Ludewig and Lichter, 2013) name the following objections against statistical testing:

- In particular for interactive software, the primary goal is often that the "typical user" does not experience failures. Statistical testing (in general) may also cover a lot of "**untypical user behaviour**", unless **user-models** are used.
- Statistical testing needs a method to **compute "soll"-values** for the randomly chosen inputs; that is easy for "does not crash" but can be difficult in general.
- There is a high risk for **not finding point** or **small-range** errors which do live **in their "natural habitat"** as expected by testers.

Findings in the literature can at best be called **inconclusive**.

One Approach: Black-Box-Testing of Filter-like Software

- A low profile approach† when a formal (requirements) specification is not available, not even "agile-style" in form of test cases
- whenever* a feature** is considered finished,
  (i) make up **inputs** for (at least one) test case,
  (ii) create **script** which **runs** the program on these inputs,
  (iii) carefully **examine** the outputs for whether they are acceptable,
  (iv) **if no**: repair,
  (v) **if yes**: define the observed output as "soll",
  (vi) extend **script** to compare ist/soll and add to test suite.

†: best for pipe/filter style software, where comparing output with "soll" is trivial.

*: if test case creation is postponed too long, chances are high that there will not be any test cases at all. **Experience**: "too long" is very short.

**: error handling is also a feature.

Discussion

Advantages of testing (in particular over inspection):

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).
- Invested effort can be **re-used**: properly prepared and documented tests can be re-executed with low effort, in particular fully automatic tests; important in maintenance.

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).
- Invested effort can be **re-used**: properly prepared and documented tests can be re-executed with low effort, in particular fully automatic tests; important in maintenance.
- The **test environment** is (implicitly) subject of testing;
  errors in additional components and tools may show up.

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).
- Invested effort can be **re-used**: properly prepared and documented tests can be re-executed with low effort, in particular fully automatic tests; important in maintenance.
- The **test environment** is (implicitly) subject of testing;
  errors in additional components and tools may show up.
- System behaviour (efficiency, usability) becomes **visible**, even if not explicitly subject of a test.

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).
- Invested effort can be **re-used**: properly prepared and documented tests can be re-executed with low effort, in particular fully automatic tests; important in maintenance.
- The **test environment** is (implicitly) subject of testing;
  errors in additional components and tools may show up.
- System behaviour (efficiency, usability) becomes **visible**, even if not explicitly subject of a test.

Disadvantages:

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).
- Invested effort can be **re-used**: properly prepared and documented tests can be re-executed with low effort, in particular fully automatic tests; important in maintenance.
- The **test environment** is (implicitly) subject of testing;
  errors in additional components and tools may show up.
- System behaviour (efficiency, usability) becomes **visible**, even if not explicitly subject of a test.

Disadvantages:

- A proof of correctness is practically **impossible**, tests are seldomly **exhaustive**.

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).
- Invested effort can be **re-used**: properly prepared and documented tests can be re-executed with low effort, in particular fully automatic tests; important in maintenance.
- The **test environment** is (implicitly) subject of testing;
  errors in additional components and tools may show up.
- System behaviour (efficiency, usability) becomes **visible**, even if not explicitly subject of a test.

Disadvantages:

- A proof of correctness is practically **impossible**, tests are seldomly **exhaustive**.
- It can be **extremely hard** to provoke environment conditions like interrupts or critical timings ("two buttons pressed at the same time"),

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).
- Invested effort can be **re-used**: properly prepared and documented tests can be re-executed with low effort, in particular fully automatic tests; important in maintenance.
- The **test environment** is (implicitly) subject of testing;
  errors in additional components and tools may show up.
- System behaviour (efficiency, usability) becomes **visible**, even if not explicitly subject of a test.

Disadvantages:

- A proof of correctness is practically **impossible**, tests are seldomly **exhaustive**.
- It can be **extremely hard** to provoke environment conditions like interrupts or critical timings ("two buttons pressed at the same time"),
- Other **properties** of the implementation (like readability, maintainability) are not subject of the tests (but, e.g., of reviews),

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).
- Invested effort can be **re-used**: properly prepared and documented tests can be re-executed with low effort, in particular fully automatic tests; important in maintenance.
- The **test environment** is (implicitly) subject of testing;
  errors in additional components and tools may show up.
- System behaviour (efficiency, usability) becomes **visible**, even if not explicitly subject of a test.

Disadvantages:

- A proof of correctness is practically **impossible**, tests are seldomly **exhaustive**.
- It can be **extremely hard** to provoke environment conditions like interrupts or critical timings ("two buttons pressed at the same time"),
- Other **properties** of the implementation (like readability, maintainability) are not subject of the tests (but, e.g., of reviews),
- Tests tend to focus only on the code, **other artefacts** (documentation, etc.) are hard to test.

  (Some say, developers tend to focus (too much) on coding, anyway.)

  Recall: some agile methods turn this into a feature: there's only requirements, tests, and code.

Discussion

Advantages of testing (in particular over inspection):

- Testing is a "**natural**" checking procedure; "everybody can test".
- The systematic test is reproducible and **objective**
  (if the start configuration is reproducible and the test environment deterministic).
- Invested effort can be **re-used**: properly prepared and documented tests can be re-executed with low effort, in particular fully automatic tests; important in maintenance.
- The **test environment** is (implicitly) subject of testing;
  errors in additional components and tools may show up.
- System behaviour (efficiency, usability) becomes **visible**, even if not explicitly subject of a test.

Disadvantages:

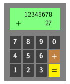
- A proof of correctness is practically **impossible**, tests are seldomly **exhaustive**.
- It can be **extremely hard** to provoke environment conditions like interrupts or critical timings ("two buttons pressed at the same time"),
- Other **properties** of the implementation (like readability, maintainability) are not subject of the tests (but, e.g., of reviews),
- Tests tend to focus only on the code, **other artefacts** (documentation, etc.) are hard to test.

  (Some say, developers tend to focus (too much) on coding, anyway.)

  Recall: some agile methods turn this into a feature: there's only requirements, tests, and code.
- Positive tests show **the presence** of errors, but not their cause;
  the positive result may be false, caused by flawed test gear.

Run-Time Verification

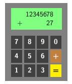
Run-Time Verification




```
int main() {

  while (true) {
    int x = read_number();
    int y = read_number();

    int sum = add( x, y );

    display(sum);
  }
}
```

- If we have **an implementation** for checking whether an output is correct wrt. a given input (according to requirements),
- we can just **embed this implementation** into the actual software, and
- thereby **check satisfaction** of the requirement during **each run**.
- → **run-time verification**.

Run-Time Verification




```
int main() {

  while (true) {
    int x = read_number();
    int y = read_number();

    int sum = add( x, y );

    display(sum);
  }
}
```

```
void verify_sum( int x, int y,
                 int sum )
{
  if (sum != (x+y)
      || (x + y > 99999999
          && !(sum < 0)))
  {
    fprintf( stderr,
      "verify_sum:␣error\n" );
    abort();
  }
}
```

- If we have **an implementation** for checking whether an output is correct wrt. a given input (according to requirements),
- we can just **embed this implementation** into the actual software, and
- thereby **check satisfaction** of the requirement during **each run**.
- → **run-time verification**.

Run-Time Verification


```
int main() {

  while (true) {
    int x = read_number();
    int y = read_number();

    int sum = add( x, y );

    verify_sum( x, y, sum );

    display(sum);
  }
}
```

```
void verify_sum( int x, int y,
                 int sum )
{
  if (sum != (x+y)
      || (x + y > 99999999
          && !(sum < 0)))
  {
    fprintf( stderr,
      "verify_sum:␣error\n" );
    abort();
  }
}
```

- If we have **an implementation** for checking whether an output is correct wrt. a given input (according to requirements),
- we can just **embed this implementation** into the actual software, and
- thereby **check satisfaction** of the requirement during **each run**.
- → **run-time verification**.

Simplest Case: Assertions

- Maybe the simplest instance of runtime verification: **Assertions**.
- Available in standard libraries of many programming languages, e.g. C:

Simplest Case: Assertions

- Maybe the simplest instance of runtime verification: **Assertions**.
- Available in standard libraries of many programming languages, e.g. C:

```
ASSERT(3)              Linux Programmer's Manual              ASSERT(3)

NAME
       assert − abort the program if assertion is false

SYNOPSIS
       #include <assert.h>

       void assert(scalar expression);

DESCRIPTION
                    [...] the macro assert() prints an error message to stan
       dard error and terminates the program by calling abort(3) if expression
       is false (i.e., compares equal to zero).

       The purpose of this macro is to help the programmer find bugs in his
       program. The message "assertion failed in file foo.c, function
       do_bar(), line 1287" is of no help at all to a user.
```


Simplest Case: Assertions

- Maybe the simplest instance of runtime verification: **Assertions**.
- Available in standard libraries of many programming languages, e.g. C:

```
ASSERT(3)              Linux Programmer's Manual              ASSERT(3)

NAME
       assert − abort the program if assertion is false

SYNOPSIS
       #include <assert.h>

       void assert(scalar expression);

DESCRIPTION
                    [...] the macro assert() prints an error message to stan
       dard error and terminates the program by calling abort(3) if expression
       is false (i.e., compares equal to zero).

       The purpose of this macro is to help the programmer find bugs in his
       program. The message "assertion failed in file foo.c, function
       do_bar(), line 1287" is of no help at all to a user.
```

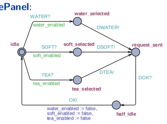
- Assertions at work:

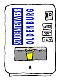
```
int square( int x )
{
  assert( x < sqrt(x) );

  return x * x;
}
```

```
void f( ... ) {
  assert( p );
  ...
  assert( q );
}
```

More Complex Case: LSC Observer

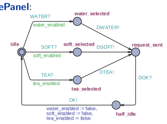
ChoicePanel:

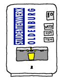




More Complex Case: LSC Observer

ChoicePanel:

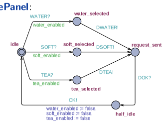


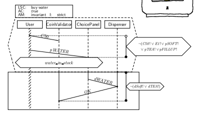


```
st :  { idle, wsel, ssel, tsel, reqs, half };

take_event( E : { TAU, WATER, SOFT, TEA, ...  } ) {
  bool stable = 1;
  switch (st) {
    case idle :
      switch (E) {
        case WATER :
          if (water_enabled) { st := wsel; stable := 0; }
          ;;
        case SOFT :
          ...
      }
    case wsel:
      switch (E) {
        case TAU :
          send_DWATER(); st := reqs;

          ;;
} }
```


More Complex Case: LSC Observer

ChoicePanel:

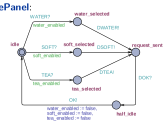


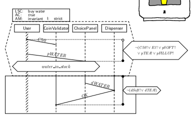


```
st :  { idle, wsel, ssel, tsel, reqs, half };

take_event( E : { TAU, WATER, SOFT, TEA, ...  } ) {
  bool stable = 1;
  switch (st) {
    case idle :
      switch (E) {
        case WATER :
          if (water_enabled) { st := wsel; stable := 0; }
          ;;
        case SOFT :
          ...
      }
    case wsel:
      switch (E) {
        case TAU :
          send_DWATER(); st := reqs;

          ;;
} }
```

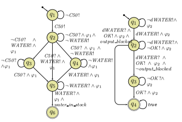

More Complex Case: LSC Observer

ChoicePanel:



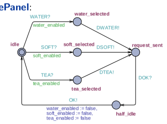


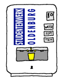
```
st :  { idle, wsel, ssel, tsel, reqs, half };

take_event( E : { TAU, WATER, SOFT, TEA, ...  } ) {
  bool stable = 1;
  switch (st) {
    case idle :
      switch (E) {
        case WATER :
          if (water_enabled) { st := wsel; stable := 0; }
          ;;
        case SOFT :
          ...
      }
    case wsel:
      switch (E) {
        case TAU :
          send_DWATER(); st := reqs;

          ;;
} }
```

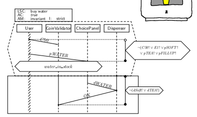


More Complex Case: LSC Observer

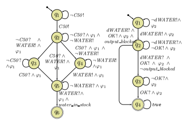
ChoicePanel:





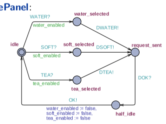


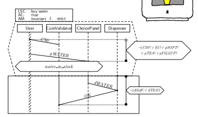
```
st :  { idle, wsel, ssel, tsel, reqs, half };

take_event( E : { TAU, WATER, SOFT, TEA, ...  } ) {
  bool stable = 1;
  switch (st) {
    case idle :
      switch (E) {
        case WATER :
          if (water_enabled) { st := wsel; stable := 0; }
          ;;
        case SOFT :
          ...
      }
    case wsel:
      switch (E) {
        case TAU :
          send_DWATER(); st := reqs;

          ;;
} }
```



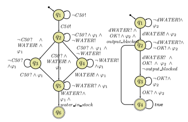
More Complex Case: LSC Observer

ChoicePanel:





```
st :  { idle, wsel, ssel, tsel, reqs, half };

take_event( E : { TAU, WATER, SOFT, TEA, ...  } ) {
  bool stable = 1;
  switch (st) {
    case idle :
      switch (E) {
        case WATER :
          if (water_enabled) { st := wsel; stable := 0; }
          ;;
        case SOFT :
          ...
      }
    case wsel:
      switch (E) {
        case TAU :
          send_DWATER(); st := reqs;
          hey_observer_I_just_sent_DWATER();
          ;;
} }
```



Run-Time Verification: Discussion

- **Experience**:
  During development, **assertions** for pre/post conditions and intermediate invariants are an extremely powerful tool with **very good gain/effort ratio** (low effort, high gain).
  - Effectively work as safe-guard against unexpected use of functions and regression, e.g. during later maintenance or efficiency improvement.
  - Can serve as **formal** (support of) documentation: "Dear reader, at this point in the program, I expect this condition to hold, because. . . ".

Run-Time Verification: Discussion

- **Experience**:
  During development, **assertions** for pre/post conditions and intermediate invariants are an extremely powerful tool with **very good gain/effort ratio** (low effort, high gain).
  - Effectively work as safe-guard against unexpected use of functions and regression, e.g. during later maintenance or efficiency improvement.
  - Can serve as **formal** (support of) documentation: "Dear reader, at this point in the program, I expect this condition to hold, because. . . ".

- **Usually**:
  Development version **with** (cf. `assert(3)`) / release version **without** run-time verification.
  If run-time verification enabled in release version,
  - software should terminate as gracefully as possible (e.g. try to save data),
  - save information from assertion failure if possible.

Run-Time Verification: Discussion

- **Experience**:
  During development, **assertions** for pre/post conditions and intermediate invariants are an extremely powerful tool with **very good gain/effort ratio** (low effort, high gain).
  - Effectively work as safe-guard against unexpected use of functions and regression, e.g. during later maintenance or efficiency improvement.
  - Can serve as **formal** (support of) documentation: "Dear reader, at this point in the program, I expect this condition to hold, because. . . ".
- **Usually**:
  Development version **with** (cf. `assert(3)`) / release version **without** run-time verification.
  If run-time verification enabled in release version,
  - software should terminate as gracefully as possible (e.g. try to save data),
  - save information from assertion failure if possible.

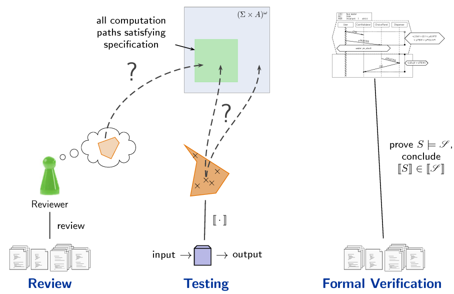
- Run-time verification can be arbitrarily complicated and complex, e.g., construction of observers for LSCs or temporal logic, e.g., expensive checking of data, etc.

Run-Time Verification: Discussion

- **Experience**:
  During development, **assertions** for pre/post conditions and intermediate invariants are an extremely powerful tool with **very good gain/effort ratio** (low effort, high gain).
  - Effectively work as safe-guard against unexpected use of functions and regression, e.g. during later maintenance or efficiency improvement.
  - Can serve as **formal** (support of) documentation: "Dear reader, at this point in the program, I expect this condition to hold, because. . . ".
- **Usually**:
  Development version **with** (cf. `assert(3)`) / release version **without** run-time verification.
  If run-time verification enabled in release version,
  - software should terminate as gracefully as possible (e.g. try to save data),
  - save information from assertion failure if possible.
- Run-time verification can be arbitrarily complicated and complex, e.g., construction of observers for LSCs or temporal logic, e.g., expensive checking of data, etc.

- **Drawback**: development and release software have different computation paths — with bad luck, the software only behaves well **because of** the run-time verification code. . .

Recall: Three Basic Directions



Review

Reviews

- **Review item**: can be every closed, human-readable part of software (document, module, test data, installation manual, etc.)

  Social aspect: it is an **artefact** which is examined, not the **human** (who created it).

Reviews

- **Review item**: can be every closed, human-readable part of software (document, module, test data, installation manual, etc.)

  Social aspect: it is an **artefact** which is examined, not the **human** (who created it).

- **Input to Review Session**:
  - the **review item**, and **reference documents** which enable an assessment (requirements specification, guidelines (e.g. coding conventions), catalogue of questions ("all variables initialised?"), etc.)

Reviews

- **Review item**: can be every closed, human-readable part of software (document, module, test data, installation manual, etc.)

  Social aspect: it is an **artefact** which is examined, not the **human** (who created it).

- **Input to Review Session**:
  - the **review item**, and **reference documents** which enable an assessment (requirements specification, guidelines (e.g. coding conventions), catalogue of questions ("all variables initialised?"), etc.)

- **Roles**:

  Moderator: leads session, responsible for properly conducted procedure.

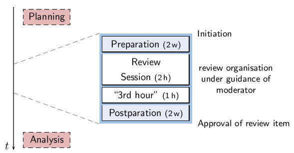
  Author: (representative of the) creator(s) of the artefact under review; is present to listen to the discussions, can answer questions; does not speak up if not asked.

  Reviewer(s): person who is able to judge the artefact under review; maybe different reviewers for different aspects (programming, tool usage, etc.), at best experienced in detecting inconsistencies or incompleteness.

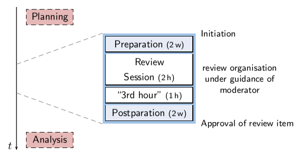
  Transcript Writer: keeps minutes of review session, can be assumed by author.

  The **review team** consists of everybody but the author(s).

Review Procedure



Review Procedure



- review triggered, e.g., by submission to revision control system: moderator invites (include review item in invitation), state review missions,
- **preparation**: reviewers investigate review item,
- **review session**: reviewers report, evaluate and document issues; solve open questions,
- **"3rd hour"**: time for informal chat, reviewers may state proposals for solutions or improvements,
- **postparation**, rework: responsibility of author(s),
- reviewers re-assess reworked review item (until approval).
- **planning**: reviews need time in project plan; **analysis**: improve development and review process.

Review Rules *(Ludewig and Lichter, 2013)*

(i) **moderator** organises, invites to, conducts review,

(ii) the review session is **limited to 2 hours** — if needed: more sessions

(iii) **moderator** may terminate review if conduction not possible (inputs, preparation, or people missing),

(iv) the **review item** is under review, not the author(s), **reviewers** choose their wording accordingly, **authors** neither defend themselves nor the review item,

(v) roles are **not mixed up**, the moderator does not act as reviewer,

(vi) **style** issues (outside fixed conventions) are not discussed,

(vii) the review team is **not** supposed to **develop solutions**, issues are **not** noted in form of tasks for the author(s),

(viii) each **reviewer** gets the opportunity to present her/his findings appropriately,

(ix) reviewers need to reach **consensus** on issues, consensus is noted down,

(x) **issues** are classified as: **critical** (review unusable for purpose), **major** (usability severely affected), **minor** (usability hardly affected), **good** (no problem).

(xi) **review team** declares: accept **without changes**, accept **with changes**, do not accept.

(xii) **protocol** is signed by all participants.

Weaker and Stronger Variants

- **Review**

Weaker and Stronger Variants

- **Review**
- **Design and Code Inspection** (Fagan, 1976, 1986)
  - deluxe variant of review,
  - approx. 50% more time, approx. 50% more faults found.

Weaker and Stronger Variants

- **Structured Walkthrough**
  - simple variant of review: **developer** moderates walkthrough-session, presents artefact, reviewer pose (prepared or spontaneous) questions, issues are noted down,
  - variants: with or without preparation (do reviewers see the artefact before the session?)
  - less effort, less effective.

  disadvantages: unclear reponsibilities; "salesman"-author may trick reviewers.
- **Review**
- **Design and Code Inspection** (Fagan, 1976, 1986)
  - deluxe variant of review,
  - approx. 50% more time, approx. 50% more faults found.

Weaker and Stronger Variants

- **Comment** ('Stellungnahme')
  - colleague(s) of developer read artefacts,
  - developer considers feedback,

  advantage: low organisational effort; **disadvantages**: choice of colleagues may be biased; no protocol; consideration of comments at discretion of developer.
- **Structured Walkthrough**
  - simple variant of review: **developer** moderates walkthrough-session, presents artefact, reviewer pose (prepared or spontaneous) questions, issues are noted down,
  - variants: with or without preparation (do reviewers see the artefact before the session?)
  - less effort, less effective.

  disadvantages: unclear reponsibilities; "salesman"-author may trick reviewers.
- **Review**
- **Design and Code Inspection** (Fagan, 1976, 1986)
  - deluxe variant of review,
  - approx. 50% more time, approx. 50% more faults found.

Weaker and Stronger Variants

- **Careful Reading** ('Durchsicht')
  - done by developer,
  - recommendation: "away from screen" (use print-out or different device and situation)
- **Comment** ('Stellungnahme')
  - colleague(s) of developer read artefacts,
  - developer considers feedback,

  advantage: low organisational effort; **disadvantages**: choice of colleagues may be biased; no protocol; consideration of comments at discretion of developer.
- **Structured Walkthrough**
  - simple variant of review: **developer** moderates walkthrough-session, presents artefact, reviewer pose (prepared or spontaneous) questions, issues are noted down,
  - variants: with or without preparation (do reviewers see the artefact before the session?)
  - less effort, less effective.

  disadvantages: unclear reponsibilities; "salesman"-author may trick reviewers.
- **Review**
- **Design and Code Inspection** (Fagan, 1976, 1986)
  - deluxe variant of review,
  - approx. 50% more time, approx. 50% more faults found.

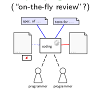
Weaker and Stronger Variants

- **Careful Reading** ('Durchsicht')
  - done by developer,
  - recommendation: "away from screen" (use print-out or different device and situation)
- **Comment** ('Stellungnahme')
  - colleague(s) of developer read artefacts,
  - developer considers feedback,

  advantage: low organisational effort; **disadvantages**: choice of colleagues may be biased; no protocol; consideration of comments at discretion of developer.
- **Structured Walkthrough**
  - simple variant of review: **developer** moderates walkthrough-session, presents artefact, reviewer pose (prepared or spontaneous) questions, issues are noted down,
  - variants: with or without preparation (do reviewers see the artefact before the session?)
  - less effort, less effective.

  disadvantages: unclear reponsibilities; "salesman"-author may trick reviewers.
- **Review**
- **Design and Code Inspection** (Fagan, 1976, 1986)
  - deluxe variant of review,
  - approx. 50% more time, approx. 50% more faults found.

XP's pair programming
("on-the-fly review"?)



Concluding Discussion

Techniques Revisited

	auto-matic	prove "can run"	toolchain considered	exhaus-tive	prove correct	partial results	entry cost
Test	(✔)	✔	✔	✘	✘	✔	✔
Runtime-Verification							
Review							
Static Checking							
Verification							

Strengths:
- can be fully automatic (yet not easy for GUI programs);
- negative test proves "program not completely broken", "can run" (or positive scenarios);
- final product is examined, thus toolchain and platform considered;
- one can stop at any time and take partial results;
- few, simple test cases are usually easy to obtain;
- provides reproducible counter-examples (good starting point for repair).

Weaknesses:
- (in most cases) vastly incomplete, thus no proofs of correctness;
- creating test cases for complex functions (or complex conditions) can be difficult;
- maintaining many, complex test cases be challenging.
- executing many tests may need substantial time (but: can be run in parallel);

Techniques Revisited

	auto-matic	prove "can run"	toolchain considered	exhaus-tive	prove correct	partial results	entry cost
Test	(✔)	✔	✔	✘	✘	✔	✔
Runtime-Verification	✔	(✔)	✔	(✘)	✘	✔	(✔)
Review							
Static Checking							
Verification							

Strengths:
- fully automatic (once observers are in place);
- provides counter-example, not necessarily reproducible;
- (nearly) final product is examined, thus toolchain and platform considered;
- one can stop at any time and take partial results;
- `assert`-statements have a very good effort/effect ratio.

Weaknesses:
- may negatively affect performance;
- code is changed, program may only run because of the observers;
- completeness depends on usage, may also be vastly incomplete, so no correctness proofs;
- constructing observers for complex properties may be difficult, one needs to learn how to construct observers.

Techniques Revisited

	auto-matic	prove "can run"	toolchain considered	exhaus-tive	prove correct	partial results	entry cost
Test	(✔)	✔	✔	✘	✘	✔	✔
Runtime-Verification	✔	(✔)	✔	(✘)	✘	✔	(✔)
Review	✘	✘	✘	(✔)	(✔)	✔	(✔)
Static Checking							
Verification							

Strengths:
- human readers can understand the code, may spot point errors;
- reported to be highly effective;
- one can stop at any time and take partial results;
- intermediate entry costs; good effort/effect ratio achievable.

Weaknesses:
- no tool support;
- no results on actual execution, toolchain not reviewed;
- human readers may overlook errors; usually not aiming at proofs.
- does (in general) not provide counter-examples, developers may deny existence of error.

Techniques Revisited

	auto-matic	prove "can run"	toolchain considered	exhaus-tive	prove correct	partial results	entry cost
Test	(✔)	✔	✔	✘	✘	✔	✔
Runtime-Verification	✔	(✔)	✔	(✘)	✘	✔	(✔)
Review	✘	✘	✘	(✔)	(✔)	✔	(✔)
Static Checking	✔	(✘)	✘	✔	(✔)	✔	(✘)
Verification							

Strengths:
- there are (commercial), fully automatic tools (lint, Coverity, Polyspace, etc.);
- some tools are complete (relative to assumptions on language semantics, platform, etc.);
- can be faster than testing (at the price of many false positives);
- one can stop at any time and take partial results.

Weaknesses:
- no results on actual execution, toolchain not reviewed;
- can be very resource consuming (if few false positives wanted);
- many false positives can be very annoying to developers (if fast checks wanted);
- distinguish false from true positives can be challenging;
- configuring the tools (to limit false positives) can be challenging.

Techniques Revisited

	auto-matic	prove "can run"	toolchain considered	exhaus-tive	prove correct	partial results	entry cost
Test	(✔)	✔	✔	✘	✘	✔	✔
Runtime-Verification	✔	(✔)	✔	(✘)	✘	✔	(✔)
Review	✘	✘	✘	(✔)	(✔)	✔	(✔)
Static Checking	✔	(✘)	✘	✔	(✔)	✔	(✘)
Verification	(✔)	✘	✘	✔	✔	(✘)	✘

Strengths:
- some tool support available (few commercial tools);
- complete (relative to assumptions on language semantics, platform, etc.);
- thus can provide correctness proofs;
- can prove correctness for multiple language semantics and platforms at a time;
- can be more efficient than other techniques.

Weaknesses:
- no results on actual execution, toolchain not reviewed;
- not many intermediate results: "half of a proof" may not allow any useful conclusions;
- entry cost high: significant training is useful to know how to deal with tool limitations;
- proving things is difficult: failing to find a proof does not allow any useful conclusion;
- false negatives (broken program "proved" correct) hard to detect.

Concluding Recommendations

- Not having at least one (systematic) test for each feature is (**grossly**?) **negligent**.

  IOW: without at least one test for each feature, **it is not software engineering**.

General Guidelines: Do's and Don'ts

- Do not use special **examination versions** for examination.
  (Test-harness, stubs, etc. can be used; yet may have errors which may undermine results.)

General Guidelines: Do's and Don'ts

- Do not use special **examination versions** for examination.
  (Test-harness, stubs, etc. can be used; yet may have errors which may undermine results.)
- Do not **stop examination** when first error is detected.
  Clear: Examination can (and should) be aborted if the examined program is not executable at all.

General Guidelines: Do's and Don'ts

- Do not use special **examination versions** for examination.
  (Test-harness, stubs, etc. can be used; yet may have errors which may undermine results.)
- Do not **stop examination** when first error is detected.
  Clear: Examination can (and should) be aborted if the examined program is not executable at all.
- Do not **modify** the artefact under examination during examinatin.
  - changes/corrections during examination:
    in the end unclear **what exactly** has been examined ("moving target"),
    (results need to be uniquely traceable to one artefact version.)
  - fundamental flaws sometimes easier to detect
    with a **complete picture** of unsuccessful/successful tests,
  - **changes are particularly error-prone**, should not happen "en passant" in examination,
  - fixing flaws during examination may cause them to go uncounted in the **statistics**
    (which we need for all kinds of estimation),
  - roles **developer** and **examinor** are different anyway:
    an **examinor** fixing flaws would violate the role assignment.

General Guidelines: Do's and Don'ts

- Do not use special **examination versions** for examination.
  (Test-harness, stubs, etc. can be used; yet may have errors which may undermine results.)
- Do not **stop examination** when first error is detected.
  Clear: Examination can (and should) be aborted if the examined program is not executable at all.
- Do not **modify** the artefact under examination during examinatin.
  - changes/corrections during examination:
    in the end unclear **what exactly** has been examined ("moving target"),
    (results need to be uniquely traceable to one artefact version.)
  - fundamental flaws sometimes easier to detect
    with a **complete picture** of unsuccessful/successful tests,
  - **changes are particularly error-prone**, should not happen "en passant" in examination,
  - fixing flaws during examination may cause them to go uncounted in the **statistics**
    (which we need for all kinds of estimation),
  - roles **developer** and **examinor** are different anyway:
    an **examinor** fixing flaws would violate the role assignment.
- In particular: Do not switch (fine grained) between **examination and debugging**.

So All Hope is Lost. . . ?

- Seems like computer systems more or less inevitably have errors.

So All Hope is Lost. . . ?

- Seems like computer systems more or less inevitably have errors.
- So **why** does my (heavily computerised) Airbus **fly at all**?

So All Hope is Lost. . . ?

- Seems like computer systems more or less inevitably have errors.
- So **why** does my (heavily computerised) Airbus **fly at all**?
  - Firstly, aerospace software maybe has the lowest error rate of all softwares due to **very careful development**, **very thorough analysis** (e.g. fault tree analysis), and **strong regulatory obligations** ("no proof of correctness, no take-off").

So All Hope is Lost. . . ?

- Seems like computer systems more or less inevitably have errors.
- So **why** does my (heavily computerised) Airbus **fly at all**?
  - Firstly, aerospace software maybe has the lowest error rate of all softwares due to **very careful development**, **very thorough analysis** (e.g. fault tree analysis), and **strong regulatory obligations** ("no proof of correctness, no take-off").
  - **Plus**: classical engineering wisdom for high reliability: **Redundancy**.

    Highly-critical components may be present 3-times redundant, developed by 3 different teams, compiled by 3 different compilers, running on 3 different platforms, . . .

So All Hope is Lost. . . ?

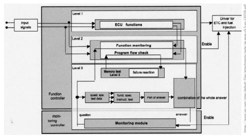
- Seems like computer systems more or less inevitably have errors.
- So **why** does my (heavily computerised) Airbus **fly at all**?
  - Firstly, aerospace software maybe has the lowest error rate of all softwares due to **very careful development**, **very thorough analysis** (e.g. fault tree analysis), and **strong regulatory obligations** ("no proof of correctness, no take-off").
  - **Plus**: classical engineering wisdom for high reliability: **Redundancy**.

    Highly-critical components may be present 3-times redundant, developed by 3 different teams, compiled by 3 different compilers, running on 3 different platforms, . . .
- And **why** does my (heavily computerised) car, infusion pump, etc. **not do harm**?

So All Hope is Lost. . . ?

- Seems like computer systems more or less inevitably have errors.
- So **why** does my (heavily computerised) Airbus **fly at all**?
  - Firstly, aerospace software maybe has the lowest error rate of all softwares due to **very careful development**, **very thorough analysis** (e.g. fault tree analysis), and **strong regulatory obligations** ("no proof of correctness, no take-off").
  - **Plus**: classical engineering wisdom for high reliability: **Redundancy**.

    Highly-critical components may be present 3-times redundant, developed by 3 different teams, compiled by 3 different compilers, running on 3 different platforms, . . .
- And **why** does my (heavily computerised) car, infusion pump, etc. **not do harm**?
  - Again, classical engineering wisdom for high reliability: **Run-time monitoring**.



Proposal: Dependability Cases (Jackson, 2009)

- A **dependable** system is one you can **depend** on — that is, you can place your trust in it.

Proposal: Dependability Cases (Jackson, 2009)

- A **dependable** system is one you can **depend** on — that is, you can place your trust in it.
- **Proposed Approach**:

Proposal: Dependability Cases (Jackson, 2009)

- A **dependable** system is one you can **depend** on — that is, you can place your trust in it.
- **Proposed Approach**:
  - identify the **critical requirements**, and determine what **level of confidence** is needed.
    Most systems do also have **non-critical** requirements.

Proposal: Dependability Cases (Jackson, 2009)

- A **dependable** system is one you can **depend** on — that is, you can place your trust in it.
- **Proposed Approach**:
  - identify the **critical requirements**, and determine what **level of confidence** is needed.
    Most systems do also have **non-critical** requirements.
  - Construct a **dependability case**:
    - an argument, that the software, in concert with other components, establishes the critical properties.

Proposal: Dependability Cases (Jackson, 2009)

- A **dependable** system is one you can **depend** on — that is, you can place your trust in it.
- **Proposed Approach**:
  - identify the **critical requirements**, and determine what **level of confidence** is needed.
    Most systems do also have **non-critical** requirements.
  - Construct a **dependability case**:
    - an argument, that the software, in concert with other components, establishes the critical properties.
  - The case should be
    - **auditable**: can (easily) be evaluated by third-party certifier.
    - **complete**: no holes in the argument, any assumptions that are not justified should be noted (e.g. assumptions on compiler, on protocol obeyed by users, etc.)
    - **sound**: e.g. should not claim full correctness [...] based on nonexhaustive testing; should not make unwarranted assumptions on independence of component failures; etc.

Proposal: Dependability Cases (Jackson, 2009)

- A **dependable** system is one you can **depend** on — that is, you can place your trust in it.
- **Proposed Approach**:
  - identify the **critical requirements**, and determine what **level of confidence** is needed.
    Most systems do also have **non-critical** requirements.
  - Construct a **dependability case**:
    - an argument, that the software, in concert with other components, establishes the critical properties.
  - The case should be
    - **auditable**: can (easily) be evaluated by third-party certifier.
    - **complete**: no holes in the argument, any assumptions that are not justified should be noted (e.g. assumptions on compiler, on protocol obeyed by users, etc.)
    - **sound**: e.g. should not claim full correctness [...] based on nonexhaustive testing; should not make unwarranted assumptions on independence of component failures; etc.
- IOW: "Developers [should] **express the critical properties** and **make an explicit argument** that the system satisfies them."
  (As opposed to, e.g. requiring **term coverage** (which is usually not exhaustive), or requiring **only** coding conventions and procedure models, which may support, but do not **prove** dependability.)

References

References

Fagan, M. (1976). Design and code inspections to reduce errors in program development. *IBM Systems Journal*, 15(3):182–211.

Fagan, M. (1986). Advances in software inspections. *IEEE Transactions On Software Engineering*, 12(7):744–751.

IEEE (1990). *IEEE Standard Glossary of Software Engineering Terminology*. Std 610.12-1990.

Jackson, D. (2009). A direct path to dependable software. *Comm. ACM*, 52(4).

Lettrari, M. and Klose, J. (2001). Scenario-based monitoring and testing of real-time UML models. In Gogolla, M. and Kobryn, C., editors, *UML*, number 2185 in Lecture Notes in Computer Science, pages 317–328. Springer-Verlag.

Ludewig, J. and Lichter, H. (2013). *Software Engineering*. dpunkt.verlag, 3. edition.