# *Softwaretechnik / Software-Engineering*

# *Lecture 15: Testing*

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# Topic Area Code Quality Assurance: Content

| | |
|---|---|
| VL 15 | • **Introduction and Vocabulary** |
| ⋮ | • Test case, test suite, test execution. |
| | • Positive and negative outcomes. |
| | • **Limits of Software Testing** |
| VL 16 | • **Glass-Box Testing** |
| | • Statement-, branch-, term-**coverage**. |
| ⋮ | • **Other Approaches** |
| | • **Model-based testing**, |
| | • **Runtime verification**. |
| | • **Program Verification** |
| VL 17 | • partial and total **correctness**, |
| ⋮ | • **Proof System PD**. |
| VL 18 | • **Review** |
| ⋮ | |

# Recall: Test Case, Test Execution

## Test Case

**Definition.** A **test case** $T$ over $\Sigma$ and $A$ is a pair $(In, Soll)$ consisting of

- a description $In$ of sets of finite **input sequences**,
- a description $Soll$ of **expected outcomes**,

and an interpretation $[\![\cdot]\!]$ of these descriptions:

- $[\![In]\!] \subseteq (\Sigma_{in} \times A)^*$, $\quad [\![Soll]\!] \subseteq (\Sigma \times A)^* \cup (\Sigma \times A)^\omega$

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## Executing Test Cases

- A computation path

$$\pi = \begin{pmatrix} \sigma_0^i \\ \sigma_0^o \end{pmatrix} \xrightarrow{\alpha_1} \begin{pmatrix} \sigma_1^i \\ \sigma_1^o \end{pmatrix} \xrightarrow{\alpha_2} \cdots$$

  from $[\![S]\!]$ is called **execution** of test case $(In, Soll)$ if and only if
  - there is $n \in \mathbb{N}$ such that $\sigma_0 \xrightarrow{\alpha_1} \ldots \xrightarrow{\alpha_n} \sigma_n \downarrow \Sigma_{in} \in [\![In]\!]$.
    ("A prefix of $\pi$ corresponds to an input sequence").

Execution $\pi$ of test case $T$ is called

- **successful** (or **positive**) if and only if $\pi \notin [\![Soll]\!]$.
  - Intuition: an an error has been discovered.
  - Alternative: test item $S$ failed to pass the test.
  - Confusing: "test failed".
- **unsuccessful** (or **negative**) if and only if $\pi \in [\![Soll]\!]$.
  - Intuition: no error has been discovered.
  - Alternative: test item $S$ passed the test.
  - Okay: "test passed".

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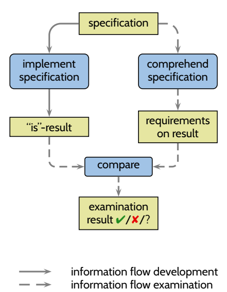
## Software Examination *(in Particular Testing)*

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




(Ludewig and Lichter, 2013)

**Recall**:

| | | checking procedure: shows no error | checking procedure: reports error |
|---|---|---|---|
| artefact has error | yes | false negative | true positive |
| artefact has error | no | true negative | false positive |

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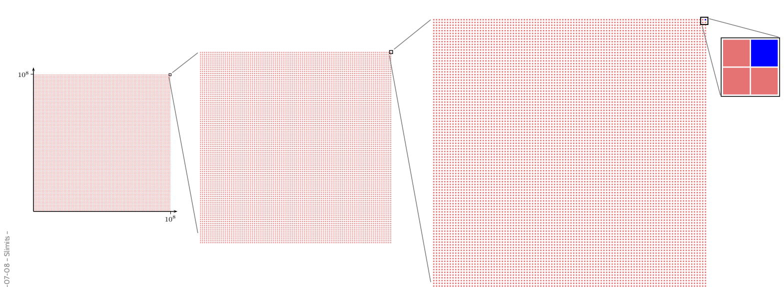
## Observation: Software Usually Has Many Inputs

- **Example**: Simple Pocket Calculator.

  With **ten thousand** (10,000) **different** test cases (that's a lot!), 9,999,999,999,990,000 of the $10^{16}$ possible inputs remain **uncovered**.

  **In other words**:
  Only $0.0000000001\%$ of the possible inputs are covered, $99.9999999999\%$ not touched.
- **In diagrams**: (red: uncovered, blue: covered)



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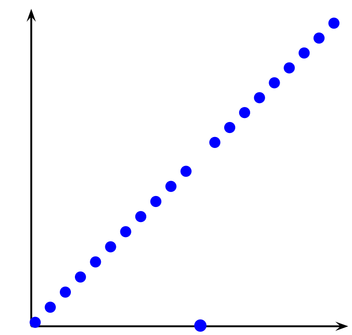
# Point vs. Range Errors

- For software, (in general, without extra information) we **can not conclude** from some values to others.

- Software behaviour is (in general) **not continous**.

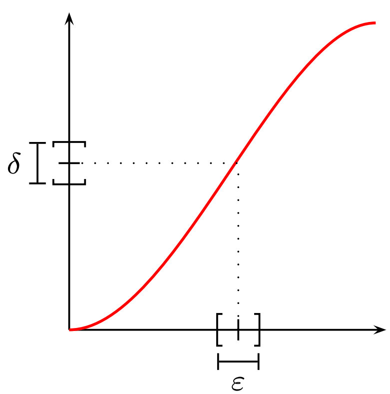
  - For software, adjacent inputs **may yield arbitrarily distant** output values.

    **Vocabulary**:

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

  - Consider a continuous function, e.g. the one to the right:

    For sufficiently small $\varepsilon$-environments of an input, the outputs **differ only by a small amount** $\delta$.

  - Physical systems are (to a certain extent) continous:
    - For example, if a bridge endures a single car of 1000 kg, we strongly expect the bridge to endure cars of 990 kg or 1010 kg.
    - And anything of weight smaller than 1000 kg can be expected to be endured.

# Content

- **Some more vocabulary**
- **Choosing Test Cases**
  - Generic **requirements** on good test cases
  - Approaches:
    - **Statistical** testing
    - Expected outcomes: Test **Oracle** :-/
    - **Habitat**-based
    - **Glass-Box Testing**
      - **Statement** / **Branch** / **term coverage**
      - **Conclusions** from coverage measures
- **When To Stop Testing?**
- **Model-Based Testing**
- **Testing in the Development Process**

- **Formal Program Verification**
  - **Deterministic Programs**
    - **Syntax**, **Semantics**, Termination, Divergence

## *Testing Vocabulary*

# *Specific Testing Notions*

- How are the test cases **chosen**?
  - Considering only the specification (**black-box** or **function** test).
  - Considering the structure of the test item (**glass-box** or **structure** 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 ($\rightarrow$ "**rumprobieren**"),

  **systematic test** — somebody (not author!) derives test cases, defines input/soll, documents test execution.

  Experience: 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 a 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?

  **recommissioning 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.

  **resource tests** —
  response time, minimal hardware (software) requirements, etc.

  **regression test** —
  does the new version of the software behave like the old one
  on inputs where no behaviour change is expected?

# Specific Testing Notions Cont'd

- Which roles are **involved** in testing?
  - **inhouse test** —
    only developers (meaning: quality assurance roles),
  - **alpha** and **beta** test —
    selected (potential) customers,
  - **acceptance test** —
    the customer tests whether the system (or parts of it, at milestones) test whether the system is acceptable.

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# *Choosing Test Cases*

# How to Choose Test Cases?

- **A first rule-of-thumb**:

> "Everything, which is required, **must** be examined/checked. Otherwise it is **uncertain** whether the requirements have been **understood** and **realised**."
>
> (Ludewig and Lichter, 2013)

**In other words**:

- Not having
  - at least one (systematic) test case
    - for each (required) feature
      - is (**grossly**?) **negligent**. (Dt.: (grob?) fahrlässig).

- **In even other words:**
  Without at least one test case for each feature, we can **hardly speak of** software **engineering**.

- **Good project management**: document for each test case which feature(s) it tests.

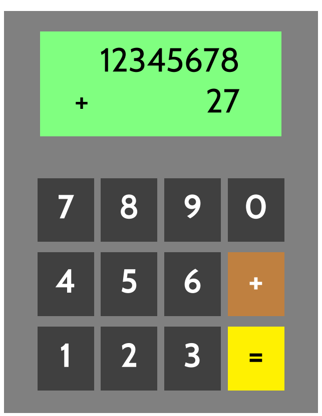
# *What Else Makes a Test Case a Good Test Case?*

A test case is a **good test case** if it discovers — with high probability — an **unknown error**.

An **ideal test case** $(In, Soll)$ would be

- **of low redundancy**, i.e. it does not test what other test cases also test.
- **error sensitive**, i.e. has high probability to detect an error,
  (Probability should at least be greater than 0.)
- **representative**, i.e. represent a whole class of inputs,
  (i.e., software $S$ passes $(In, Soll)$ if and only $S$ behaves well for all $In'$ from the class)

The idea of **representative**:




- If $(12345678, 27; 12345705)$ **was** representative for $(0, 27; 27)$, $(1, 27; 28)$, etc.
- then from a **negative** execution of test case $(12345678, 27; 12345705)$
- we **could** conclude that $(0, 27; 27)$, etc. will be negative as well.
- Is it / can we?

# *What Else Makes a Test Case a Good Test Case?*

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

- In general, we **do not know** which inputs lie in an equivalence class **wrt. a certain error**.
- Yet there is a large body on literature on how to construct representative test cases, **assuming** we know the equivalence classes.

**Of course**: ***If*** we ***know*** equivalence classes,
we should exploit that knowledge to optimise the number of test cases.

But it is **perfectly reasonable** to test representatives
of **equivalence classes induced by the specification**, e.g.

- valid and invalid inputs (to check whether input validation works at all),
- different classes of inputs considered in the requirements,
  like “C50”, “E1” coins in the vending machine $\rightarrow$ have at least one test case with each.

**Recall**: one should have at least one test case per feature.

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# *Statistical Testing*

# *One Approach: Statistical Tests*

Classical **statistical testing** is one approach to deal with

- in practice not exhaustively testable **huge input space**,
- **tester bias**.

  (People tend to choose "good-will" inputs and disregard (tacit?) corner-cases; recall: the developer is not a good tester.)

**Procedure**:

- Randomly (!) choose test cases $T_1, \dots, T_n$ for test suite $\mathcal{T}$.
- Execute test suite $\mathcal{T}$.
- **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 significance niveau.

    (Significance niveau may be unsatisfactory with small test suites.)
- **Note**: Approach needs stochastical assumptions on error distribution and truly random test cases.

# *Statistical Testing: Discussion*

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

- In particular for interactive software, the **primary requirement** is often **no failures are experienced by the "typical user"**.

  Statistical testing (in general) may also cover a lot of "**untypical user behaviours**" unless (sophisticated) **user-models** are used.

- Statistical testing needs a method to **compute "soll"-values** for the randomly chosen inputs.

  That is easy for requirement "does not crash", but can be difficult in general.

- There is a high risk for **not finding** **point** or **small-range** errors.

  If they live in their **"natural habitat"**, carefully crafted test cases would probably uncover them.

Findings in the literature can at best be called inconclusive.

*Getting Soll-Values*

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

**Recall**: A test case is a pair $(In, Soll)$ with proper expected (or "soll") values.

- In an **ideal world**, all "soll"-values are **defined** by the (formal) requirements specification and effectively **pre-computable**.

- In **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 a **(test) oracle**.

  I'd prefer **not to call** automatic derivation of "soll"-values from a **formal specification** an "oracle"... ; - ) ("person or agency considered to provide wise and insightful [...] prophetic predictions or precognition of the future, inspired by the gods." says Wikipedia)

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# *Habitat-based Testing*

# *Choosing Test Cases Habitat-based*

Some traditional popular belief on software error habitat:

- Software errors **(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),
    - etc.
  - **special cases** of the problem (empty list, use-case without actor, ...),
  - special cases of the programming language semantics,
  - **complex implementations**.

→ **Good idea**: for each test case, note down why it has been chosen.
For example, "demonstrate that corner-case handling is not completely broken".

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# *Glass-Box Testing: Coverage*

# Statements and Branches by Example

**Definition.** Software is a finite description $S$ of a (possibly infinite) set $[\![S]\!]$ of (finite or infinite) computation paths of the form $\sigma_0 \xrightarrow{\alpha_1} \sigma_1 \xrightarrow{\alpha_2} \sigma_2 \cdots$ where

- $\sigma_i \in \Sigma$, $i \in \mathbb{N}_0$, is called state (or configuration), and
- $\alpha_i \in A$, $i \in \mathbb{N}_0$, is called action (or event).

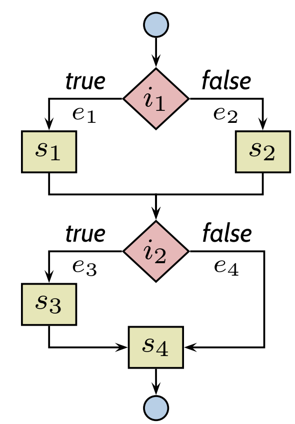
- In the following, we assume that
  - $S$ has a **control flow graph** $(V, E)_S$, and **statements** $Stm_S \subseteq V$ and **branches** $Cnd_S \subseteq E$,
  - each computation path prefix $\sigma_0 \xrightarrow{\alpha_1} \sigma_1 \xrightarrow{\alpha_2} \sigma_2 \cdots \xrightarrow{\alpha_n} \sigma_n$ gives information on statements and control flow graph branch edges **which were executed** right before obtaining $\sigma_n$:

$$stm : (\Sigma \times A)^* \to 2^{Stm_S}, \qquad cnd : (\Sigma \times A)^* \to 2^{Cnd_S},$$

```
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;
}
```

$$Stm_f = \{s_1, s_2, s_3, s_4\}$$

$$Cnd_f = \{e_1, e_2, e_3, e_4\}$$



# Statements and Branches by Example

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$$stm : (\Sigma \times A)^* \to 2^{Stm_S}, \qquad cnd : (\Sigma \times A)^* \to 2^{Cnd_S},$$

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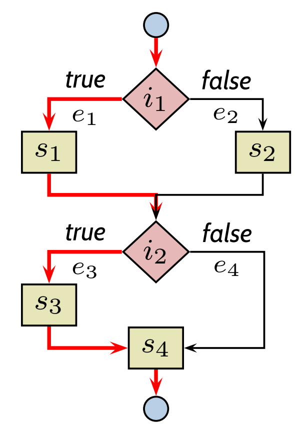
  s1:     z = z * 2;
          else
  s2:     z = z/2;
  i2: if (x > 500 ∨ y > 50)
  s3:     z = z * 5;
  s4: return z;
}
```

$$Stm_f = \{s_1, s_2, s_3, s_4\}$$

$$Cnd_f = \{e_1, e_2, e_3, e_4\}$$




| | $\sigma_0$ | $\xrightarrow{\alpha_1}$ | $\sigma_1$ | $\xrightarrow{\alpha_2}$ | $\sigma_2$ | $\xrightarrow{\alpha_2}$ | $\sigma_3$ | $\xrightarrow{\alpha_3}$ | $\sigma_4$ | $\xrightarrow{\alpha_4}$ | $\sigma_5$ | $\xrightarrow{\alpha_5}$ | $\sigma_6$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $pc$ : | 1 | | 3 | | 4 | | 7 | | 8 | | 9 | | 10 |
| $x$ : | 501 | | 501 | | 501 | | 501 | | 501 | | 501 | | 501 |
| $y$ : | 11 | | 11 | | 11 | | 11 | | 11 | | 11 | | 11 |
| $z$ : | 0 | | 0 | | 0 | | 0 | | 0 | | 0 | | 0 |

# Statements and Branches by Example

- In the following, we assume that
  - $S$ has a **control flow graph** $(V, E)_S$, and **statements** $Stm_S \subseteq V$ and **branches** $Cnd_S \subseteq E$,
  - each computation path prefix $\sigma_0 \xrightarrow{\alpha_1} \sigma_1 \xrightarrow{\alpha_2} \sigma_2 \cdots \xrightarrow{\alpha_n} \sigma_n$ gives information on statements and control flow graph branch edges **which were executed** right before obtaining $\sigma_n$:

$$stm : (\Sigma \times A)^* \to 2^{Stm_S}, \qquad cnd : (\Sigma \times A)^* \to 2^{Cnd_S},$$

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

$$Stm_f = \{s_1, s_2, s_3, s_4\}$$

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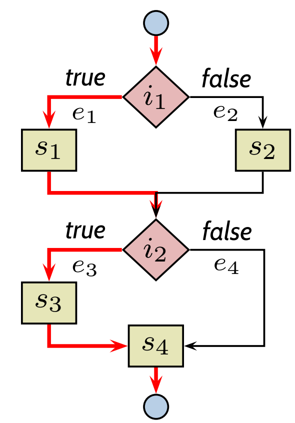



| | $\sigma_0$ | $\xrightarrow{\alpha_1}$ | $\sigma_1$ | $\xrightarrow{\alpha_2}$ | $\sigma_2$ | $\xrightarrow{\alpha_2}$ | $\sigma_3$ | $\xrightarrow{\alpha_3}$ | $\sigma_4$ | $\xrightarrow{\alpha_4}$ | $\sigma_5$ | $\xrightarrow{\alpha_5}$ | $\sigma_6$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $pc: 1$ <br> $x: 501$ <br> $y: 11$ <br> $z: 0$ | | $pc: 3$ <br> $x: 501$ <br> $y: 11$ <br> $z: 0$ | | $pc: 4$ <br> $x: 501$ <br> $y: 11$ <br> $z: 0$ | | $pc: 7$ <br> $x: 501$ <br> $y: 11$ <br> $z: 0$ | | $pc: 8$ <br> $x: 501$ <br> $y: 11$ <br> $z: 0$ | | $pc: 9$ <br> $x: 501$ <br> $y: 11$ <br> $z: 0$ | | $pc: 10$ <br> $x: 501$ <br> $y: 11$ <br> $z: 0$ |
| $stm$: | $\{\}$ | | $\{\}$ | | $\{\}$ | | $\{s_1\}$ | | $\{\}$ | | $\{s_3\}$ | | $\{s_4\}$ |
| $cnd$: | $\{\}$ | | $\{\}$ | | $\{e_1\}$ | | $\{\}$ | | $\{e_3\}$ | | $\{\}$ | | $\{\}$ |

# *Glass-Box Testing: Coverage*

- **Coverage** is a property of **test cases** and **test suites**.

- Execution $\pi = \sigma_0 \xrightarrow{\alpha_1} \cdots$ of test case $T$ achieves $p\,\%$ **statement coverage** if and only if

$$p = cov_{stm}(\pi) := \frac{|\bigcup_{i \in \mathbb{N}_0} stm(\sigma_0 \cdots \sigma_i)|}{|Stm_S|}, |Stm_S| \neq 0.$$

  Test case $T$ achieves $p\,\%$ **statement coverage** if and only if $p = \min_{\pi \text{ execution of } T} cov_{stm}(\pi)$.

- Execution $\pi$ of $T$ achieves $p\,\%$ **branch coverage** if and only if

$$p = cov_{cnd}(\pi) := \frac{|\bigcup_{i \in \mathbb{N}_0} cnd(\sigma_0 \cdots \sigma_i)|}{|Cnd_S|}, |Cnd_S| \neq 0.$$

  Test case $T$ achieves $p\,\%$ **branch coverage** if and only if $p = \min_{\pi \text{ execution of } T} cov_{cnd}(\pi)$.

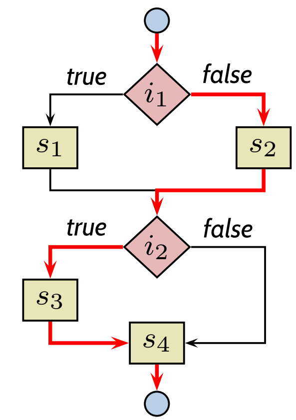
- **Define**: $p = 100$ for empty program. (More precisely: $Stm_S = \emptyset$ and $Cnd_S = \emptyset$, respectively.)

- Statement/branch coverage canonically extends to test suite $\mathcal{T} = \{T_1, \dots, T_n\}$.
  For example, given $\pi_1 = \sigma_0^1 \cdots, \dots, \pi_n = \sigma_0^n \cdots$, then $\mathcal{T}$ achieves

$$p = \frac{|\bigcup_{1 \leq j \leq n} \bigcup_{i \in \mathbb{N}_0} stm(\sigma_0^j \cdots \sigma_i^j)|}{|Stm_S|}, |Stm_S| \neq 0, \text{ **statement coverage**}.$$

# *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;
}
```



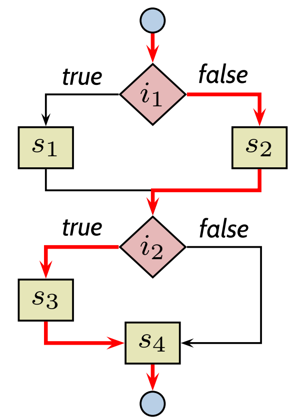

- **Requirement**: $\{true\}\ f\ \{true\}$ (no abnormal termination), i.e. $Soll = \Sigma^* \cup \Sigma^\omega$.

test suite coverage

| *In* $x, y, z$ | $i_1/t$ | $i_1/f$ | $s_1$ | $s_2$ | $i_2/t$ | $i_2/f$ | $c_1$ | $c_2$ | $s_3$ | $s_4$ | % stm | % cnd | $i_2$/% term |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $501, 11, 0$ | ✔ | | ✔ | | ✔ | | ✔ | | ✔ | ✔ | 75 | 50 | 25 |
| $501, 0, 0$ | ✓ | | | ✓ | ✓ | | ✓ | | ✓ | ✓ | 100 | 75 | – |

# 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), i.e. $Soll = \Sigma^* \cup \Sigma^\omega$.

test suite coverage

| *In* $x, y, z$ | $i_1/t$ | $i_1/f$ | $s_1$ | $s_2$ | $i_2/t$ | $i_2/f$ | $c_1$ | $c_2$ | $s_3$ | $s_4$ | % stm | % cnd | $i_2$/% 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

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

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

**Branch coverage** is easy in this case:

Use $In_1$ such that $(A = 0, \ldots, E = 0)$, and $In_2$ such that $(A = 0, \ldots, E = 1)$.

- **Additional goal**:
check whether there are useless terms,
or terms causing abnormal program termination.

- **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 $\beta$ for $expr$ if and only if

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

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

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

| | A | B | C | D | E | b | % |
|---|---|---|---|---|---|---|---|
| $\beta_1$ | 1 | 1 | 0 | 0 | 0 | 1 | 20 |
| $\beta_2$ | 1 | 0 | 0 | 1 | 0 | 0 | 50 |
| $\beta_3$ | 1 | 0 | 1 | 1 | 0 | 1 | 70 |
| $\beta_4$ | 0 | 0 | 1 | 0 | 1 | 1 | 80 |

red: $b$-effective, black: otherwise

# *Unreachable Code*

```
int f( int x, int y, int z )
{
  i1: if (x ≠ x)
  s1:     z = y/0;
  i2: if (x = x ∨ z/0 = 27)
  s2:     z = z * 2;
  s3: return z;
}
```

- Statement $s_1$ is **never executed** (because $x \neq x \iff$ *false*), thus 100 % statement-/branch-/term-coverage is **not achievable**.
- Assume, evaluating $n/0$ causes (undesired) **abnormal program termination**.

  Is statement $s_1$ an **error** in the program…?
- Term $z/0$ in $i_2$ also looks critical…

  (In programming languages with short-circuit evaluation, it is never evaluated.)

# *Conclusions from Coverage Measures*

- Assume, test suite $\mathcal{T}$ tests software $S$ for the following property $\varphi$:
  - pre-condition: $p$,   post-condition: $q$,

  and $S$ passes (!) $\mathcal{T}$, and the execution achieves $100\,\%$ statement / branch / term coverage.

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

- 100 % **statement** coverage:
  - "there is no statement, which **necessarily** violates $\varphi$"

    (Still, there may be many, many computation paths which violate $\varphi$, and which just have not been touched by $\mathcal{T}$.)
  - "there is no unreachable statement"

- 100 % **branch** (**term**) coverage:
  - "there is no single branch (term) which **necessarily causes** violations of $\varphi$"

    In other words: "for each condition (term), there is one computation path satisfying $\varphi$ where the condition (term) evaluates to *true*, and one for *false*."
  - "there is no unused condition (term)"

**Not more** ($\rightarrow$ exercises)!

That's definitely **something**, but not as much as "100 %" may sound like...

# 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 that certain **coverage measures** are reached,
  in particular something similar to **term coverage** (MC/DC coverage).

  (Next to development process requirements, reviews, unit testing, etc.)

- If not required, ask: what is the effort / gain ratio?
  (Average effort to detect an error; term coverage needs high effort.)

- Currently, the standard moves towards accepting certain verification or static analysis tools to support (or even replace?) some testing obligations.

# Content

- **Some more vocabulary**
- **Choosing Test Cases**
  - Generic **requirements** on good test cases
  - Approaches:
    - **Statistical** testing
    - Expected outcomes: Test **Oracle** :-/
    - **Habitat**-based
    - **Glass-Box Testing**
      - **Statement** / **Branch** / **term coverage**
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*When To Stop Testing?*

# *When To Stop Testing?*

- There need to be defined **criteria** for when to stop testing;
  project planning should consider these criteria (and previous experience).

- Possible "**testing completed**" criteria:
  - all (previously) **specified test cases** have been executed with negative result,

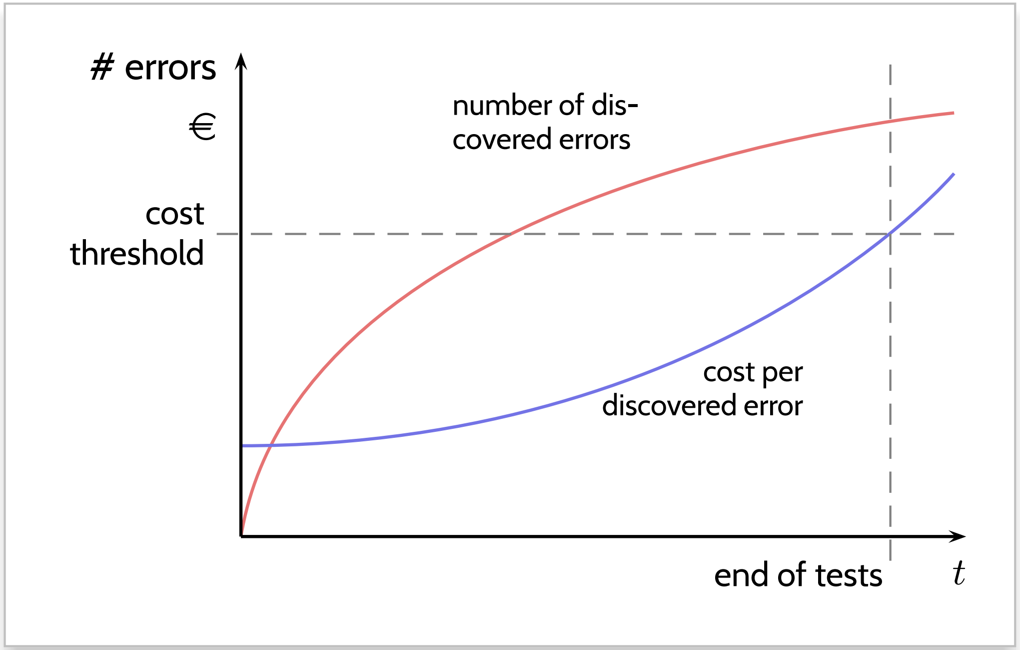
    (**Special case**: All test cases resulting from a certain strategy, like maximal statement coverage have been executed.)
  - **testing effort time** sums up to $x$ (hours, days, weeks),
  - **testing effort** sums up to $y$ (any other useful unit),
  - $n$ **errors** have been discovered,
  - **no error** has been discovered **during** the last $z$ hours (days, weeks) of testing,

  Values for $x$, $y$, $n$, $z$ are fixed based on experience, estimation, budget, etc.

- **Of course**: not all criteria are equally reasonable or compatible with each testing approach.

# Another Criterion

- Another possible "**testing completed**" criterion:
  - The **average cost per error discovery** exceeds a defined threshold $c$.




Value for $c$ is again fixed based on experience, estimation, budget, etc..

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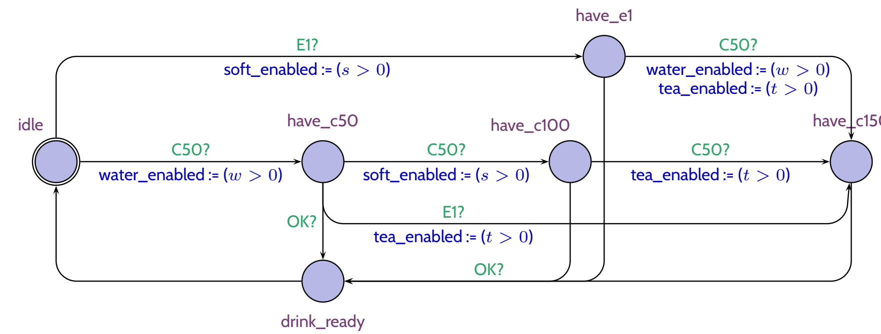
# *Model-Based Testing*

# *Model-based Testing*




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

- **One approach**: **Location Coverage**.

  Check whether for **each location** of the model there is
  a **corresponding configuration** reachable in the software (needs to be observable somehow).

- Input sequences can **automatically be generated** from the model,
  e.g., using Uppaal's "drive-to" feature.
  - Check "can we reach 'idle', 'have_c50', 'have_c100', 'have_c150'?" by

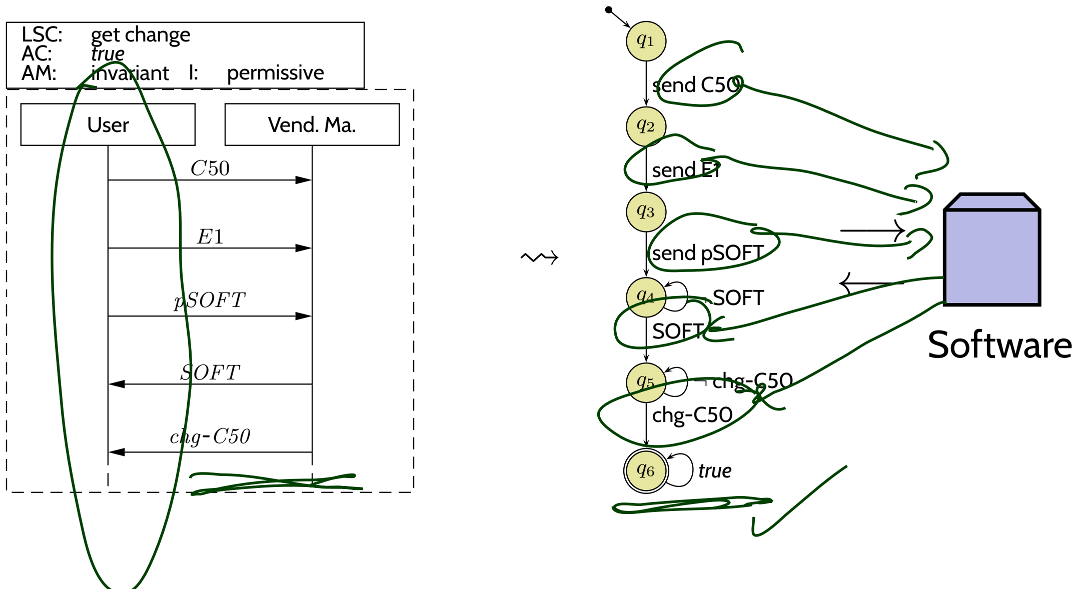
    $$T_1 = (\text{C50}, \text{C50}, \text{C50}; \{\pi \mid \exists\, i < j < k < \ell \bullet \pi^i \sim \text{idle}, \pi^j \sim \text{h\_c50}, \pi^k \sim \text{h\_c100}, \pi^\ell \sim \text{h\_c150}\})$$

  - Check for 'have_e1' by $T_2 = (\text{C50}, \text{C50}, \text{C50}; \dots)$.
  - To check for 'drink_ready', more interaction is necessary.

- **Analogously**: **Edge Coverage**.

  Check whether **each edge** of the model has **corresponding** behaviour in the software.

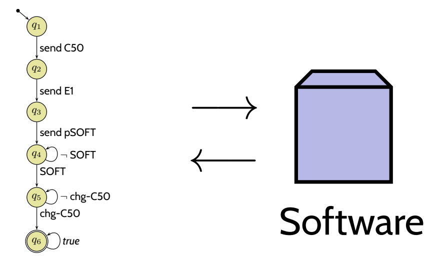
# *Existential LSCs as Test Driver & Monitor* (*Lettrari and Klose, 2001*)



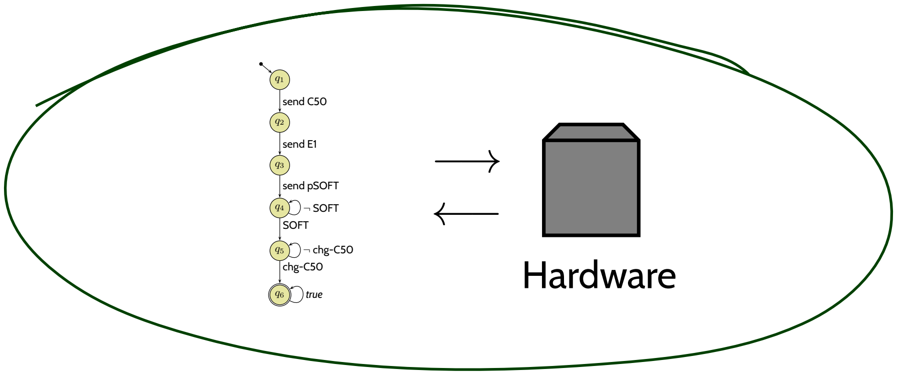

- If the LSC has designated **environment instance** lines, we can distinguish:
  - messages expected to **originate from** the environemnt (**driver role**),
  - messages expected **adressed to** the environemnt (**monitor role**).
- Adjust the TBA-construction algorithm to construct a **test driver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

  **Note**: 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.
- For example the **Rhapsody** tool directly supports this approach.

# *Vocabulary*




- **Software-in-the-loop**:
  The final implementation is examined
  using a separate computer to simulate other system components.




- **Hardware-in-the-loop**:
  The final implementation is running on (prototype) hardware
  which is connected by its standard input/output interface (e.g. CAN-bus)
  to a separate computer which simulates other system components.

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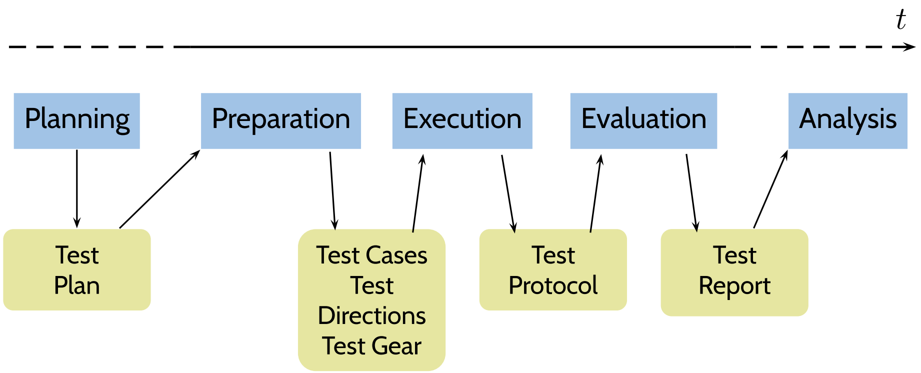
# *Testing in The Software Development Process*

# *Test Conduction: Activities & Artefacts*




(Ludewig and Lichter, 2013)

- **Test Gear**: (may need to be developed in the project!)

> **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)**

- **Roles**: **tester** and **developer** should be different persons!

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# *Tell Them What You've Told Them...*

- There is a **vast amount of literature** on how to choose test cases.

  A good starting point:
  - **at least one test case per feature**,
  - **corner-cases**, extremal values,
  - **error handling**, etc.
- **Glass-box testing**
  - considers the **control flow graph**,
  - defines **coverage measures**.
- **Other approaches**:
  - **statistical** testing, **model-based** testing,
- Define criteria for **"testing done"** (like coverage, or cost per error).
- **Process**: tester and developer should be different persons.

- There are **more approaches** to code quality assurance than (just) **testing**.
- For example, **program verification**.

# *References*

# References

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

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.