Softwaretechnik / Software-Engineering

Lecture 15: Testing

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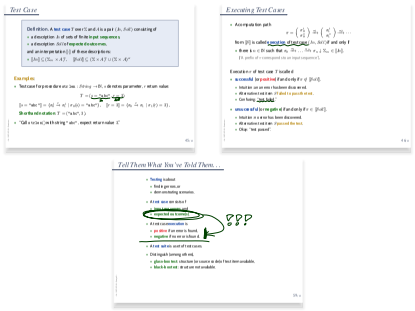
Topic Area Code Quality Assurance: Content

VL 14 – VL 15 – VL 16 – VL 17

- **Introduction and Vocabulary**
  - Test case, test suite, test execution.
  - Positive and negative outcomes.
- **Limits of Software Testing**
- **Glass-Box Testing**
  - Statement-, branch-, term-**coverage**.
- **Other Approaches**
  - **Model-based testing**.
  - **Runtime verification**.
- **Software quality assurance** in a **larger scope**.
- **Program Verification**
  - partial and total **correctness**,
  - **Proof System PD**.
- **Review**

Content

Recall: Test Case, Test Execution



Not Executing Test Cases

- Consider the test case

  $T = (\text{""}, 0)$

  for procedure `strlen`.
  (“Empty string has length 0.”)
- A tester observes the following software behaviour:

  $$\pi = \underbrace{\{s \mapsto \text{NULL}, r \mapsto 0\}}_{=\sigma_0} \xrightarrow{T} \underbrace{\textit{program-abortion}}_{\sigma_1} \neq$$

- Test execution **positive** or **negative**?
  N/A *N/A*

Note:

- If a tester does not adhere to an allowed input sequence of T, π **is not** a test execution.
  Thus π is neither positive nor negative (only defined for test executions).
- Same case: power outage (if continuous power supply is considered in input sequence).

By The Way... (Good Design)

- **High quality software** should be aware of its specification.
  and “**complain**” if operated outside of specification, e.g.
  - throw an exception,
  - abort program execution,
  - (at least) print an error message,
  - etc.

  Not: “garbage in, garbage out”
- **Example**: `strlen(3)` (C standard)
  - Allowed inputs are C-strings, return value is an integer,
  - `NULL` is not a C-string!
  - Thus, on input `NULL`, “complain” instead of just return an arbitrary number or “crash”.

Test Suite

- A **test suite** is a finite set of test cases $\{T_1, \ldots, T_n\}$.
- An **execution** of a **test suite** is a set of computation paths, such that there is at least one execution for each test case.
- An **execution** of a **test suite** is called **positive** if and only if at least one test case execution is **positive**.

  Otherwise, it is called **negative**.

Tests vs. Systematic Tests

Systematic Test – a test such that
- (environment) conditions are defined or precisely documented.
- inputs have been chosen systematically.
- results are documented and assessed according to criteria that have been fixed before. (Ludewig and Lichter, 2013)

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

Not (even) a test (in the sense of this weak definition):
- any **inspection** of the program (no execution),
- **demo** of the program (other goal),
- analysis by software-tools for, e.g., values of **metrics** (other goal),
- **investigation** of the program with a debugger (other goal).

(Our) Synonyms for **non-systematic tests**: Experiment, 'Rumprobieren'.

In the following: test means systematic test; if not systematic, call it **experiment**.

Content

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 (→ "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

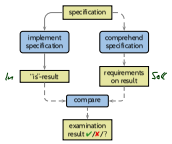
- Which roles are **involved** in testing?
  - **inhouse test** –
    only developers (meaning: quality assurance roles),
  - **alpha** and **beta** test –
    selected (potential) customers,
  - **acceptance test** –
    the customer tests whether the system (or parts of it, at milestones) test whether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

Content

The Limits of Software Testing

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:

Recall: Quotes On Testing

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

Why Can't We Show The Absence of Errors (in General)?

Consider a **simple pocket calculator** for adding 8-digit decimals:

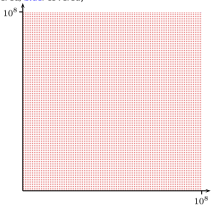
- **Requirement**: If the display shows x, $+$, and y, then after pressing $=$,
  - the sum of x and y is displayed if $x + y$ has at most 8 digits,
  - otherwise "-E-" is displayed.
- With 8 digits, both x and y range over $[0, 10^8 - 1]$.
- Thus there are $10^{16} = 10,000,000,000,000,000$ possible input pairs (x, y) to be considered
  for **exhaustive testing**, i.e. testing every possible case!
- And if we restart the pocket calculator for each test,
  we **do not know anything** about problems with **sequences** of inputs…
  (Local variables may not be re-initialised properly, for example.)

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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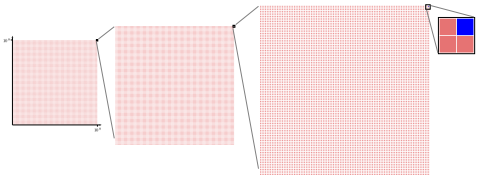


Content

Choosing Test Cases

Generic Requirements on Good Test Cases: Reproducibility

- Test executions should be (as) **reproducible** and **objective** (as possible).
- So, **strictly speaking**, a test case is a triple $(In, Soll, Env)$
  comprising a description Env of **(environmental) conditions**.

  Env describes any aspects which **could have an effect**
  on the outcome of a test execution and cannot be specified as part of In, 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** is supposed to test **when**?
  - etc. etc.

Full reproducibility is hardly possible **in practice** – obviously (err, why…?).

- **Steps** towards **reproducibility** and **objectivity**:
  - have a fixed build environment,
  - use a fixed test host which does not do any other jobs,
  - execute test cases **automatically** (test scripts).

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

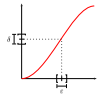
- **of low redundancy**, i.e. it does not test what other test cases also test.
- **error sensitive**, i.e. has high probability to detect an error,
  (Probability should at least be greater than 0.)
- **representative**, i.e. represent a whole class of inputs,
  (i.e., software S passes $(In, Soll)$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

Point vs. Range Errors

- Software is (in general) **not continous**.
  - Consider a continuous function, e.g. the one to the right:
    For sufficiently small ε-environments of an input, the outputs **differ only by a small amount** δ.
  - 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.



  - 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.

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

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 → 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 $T_1, \ldots, T_n$ 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.)

(And: 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).

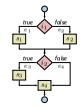
- In the following, we assume that
  - S has a control flow graph $(V, E)_S$, and statements $Stm_S \subseteq V$ and branches $Cnd_S \subseteq E$,
  - each computation path prefix $\sigma_0 \xrightarrow{\alpha_1} \sigma_1 \xrightarrow{\alpha_2} \sigma_2 \cdots \xrightarrow{\alpha_n} \sigma_n$ gives information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

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

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



Statements and Branches by Example

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

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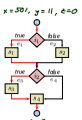


	σ_0	$\xrightarrow{\alpha_1}$	σ_1	$\xrightarrow{\alpha_2}$	σ_2	$\xrightarrow{\alpha_3}$	σ_3	$\xrightarrow{\alpha_4}$	σ_4	$\xrightarrow{\alpha_5}$	σ_5	$\xrightarrow{\alpha_6}$	σ_6
	pc: 1 x: 501 y: 11 z: 0		pc: 3 x: 501 y: 11 z: 0		pc: 4 x: 501 y: 11 z: 0		pc: 7 x: 501 y: 11 z: 0		pc: 8 x: 501 y: 11 z: 0		pc: 9 x: 501 y: 11 z: 0		pc: 10 x: 501 y: 11 z: 0
stm:	{}		{}		$\{s_1\}$		{}		$\{s_3\}$		$\{s_4\}$		{}
cnd:	{}		{}		{}		$\{e_3\}$		{}		{}		{}

i1/true, i2/true

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 π of T achieves $p\,\%$ branch coverage if and only if

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

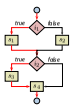
  Test case T achieves $p\,\%$ branch coverage if and only if $p = \min_{\pi \text{ execution of } T} cov_{cnd}(\pi)$.

- Define: $p = 100$ for empty program. (More precisely: $Stm_S = \emptyset$ and $Cnd_S = \emptyset$, respectively.)
- Statement/branch coverage canonically extends to test suite $\mathcal{T} = \{T_1, \ldots, T_n\}$.
  For example, given $\pi_1 = \sigma_0^1 \cdots, \ldots, \pi_n = \sigma_0^n \cdots$, 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											%	%	c_2/%
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	term
501, 11, 0	✓		✓		✓		✓			✓	75	50	25
12, 11, 0		✓		✓		✓				✓	100	100	

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```
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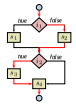

- **Requirement**: {*true*} f {*true*} (no abnormal termination), i.e. $Sol = \Sigma^* \cup \Sigma^\omega$.

											test suite coverage		
In x, y, z	i_1/t	i_1/f	s_1	s_2	i_2/t	i_2/f	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 $A, \ldots, E$ 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.

	A	B	C	D	E	b	%
β_1	1	1	0	0	0	1	20
β_2	1	0	0	1	0	0	50
β_3	1	0	1	1	0	1	70
β_4	0	0	1	0	1	1	80

red: b-effective, black: otherwise

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

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

  - $\Xi \subseteq (\{A_1, \ldots, A_n\} \to \mathrm{B})$ 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)
  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 $x \neq x \iff \mathit{false}$),
  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 φ:
  - **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 φ"
    (Still, there may be many, many computation paths which violate φ,
    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 φ"
    In other words: "for each condition (term), there is one computation path
    satisfying φ where the condition (term) evaluates to *true*, and one for *false*."
  - "there is no unused condition (term)"

Not more (→ 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.

Tell Them What You've Told Them…

- A check can **only discover** errors on **exactly one** path.
- Software testing is **challenging** because
  - typically **huge input space**,
  - software is **non-continous**,
- 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.

References

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