Todo list

PUTTING SOFTWARE TESTING TERMINOLOGY TO THE TEST

PUTTING SOFTWARE TESTING TERMINOLOGY TO THE TEST

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Lay Abstract

Important: Lay abstract.

Abstract

Testing is a pervasive software development activity that is often complicated and expensive (if not simply overlooked), partly due to the lack of a standardized and consistent taxonomy for software testing. This hinders precise communication, leading to discrepancies across the literature and even within individual documents! In this paper, we systematically examine the current state of software testing terminology. We 1) identify established standards and prominent testing resources, 2) capture relevant testing terms from these sources, along with their definitions and relationships—both explicit and implicit—and 3) construct graphs to visualize and analyze this data. Our research uncovered 532 test approaches and four in-scope methods for describing "implied" test approaches. We also build a tool for generating graphs that illustrate relations between test approaches and track discrepancies captured by this tool and manually through the research process. Our results reveal 215 discrepancies, including ten terms used as synonyms to two (or more) disjoint test approaches and 14 pairs of test approaches may either be synonyms or have a parent-child relationship. They also reveal notable confusion surrounding functional, operational acceptance, recovery, and scalability testing. These findings make clear the urgent need for improved testing terminology so that the discussion, analysis and implementation of various test approaches can be more coherent. We provide some preliminary advice on how to achieve this standardization.

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List of Source Codes

List of Abbreviations and Symbols

c-use/C-use	Computation data Use
DAC	Differential Assertion Checking
DblPend	Double Pendulum
DOM	Document Object Model
du-path/DU-path	Definition-Use path
EMSEC	EManations SECurity
GlassBR	Glass BReaking
HREF	Hypertext REFerence
ISTQB	International Software Testing Qualifications Board
ML	Machine Learning
MR	Metamorphic Relation
OAT	Operational (Acceptance)/Orthogonal Array Testing
p-use/P-use	Predicate data Use
PDF	Portable Document Format
QAI	Quality Assurance Institute
RAC	Runtime Assertion Checking
SglPend	Single Pendulum
SSP	Slope Stability analysis Program
SUT	System Under Test
SV	Software Verification
SWEBOK Guide	Guide to the SoftWare Engineering Body Of Knowledge
SWHS	Solar Water Heating System
TOAT	Taguchi's Orthogonal Array Testing
V&V	Verification and Validation

Reading Notes

Before reading this thesis, I encourage you to read through these notes, keeping them in mind while reading.

- The source code of this thesis is publicly available.
- This thesis template is primarily intended for usage by the computer science community[1]. However, anyone is free to use it.
- I've tried my best to make this template conform to the thesis requirements as per those set forth in 2021 by McMaster University. However, you should double-check that your usage of this template is compliant with whatever the "current" rules are.

Important: Replace reading notes.

[1] Hence why there are some LaTeX macros for "code" snippets.

Declaration of Academic Achievement

This research and analysis was performed by Samuel Crawford under the guidance, supervision, and recommendations of Drs. Spencer Smith and Jacques Carette. The resulting contributions are three glossaries—one for each of test approaches, software qualities (see Section 2.4.2), and supplementary terms—as well as the tools for data visualization and automated analysis outlined in Chapter 4. These are all available on an open-source repo for independent analysis and, ideally, extension as more test approaches are discovered and documented.

Chapter 1

Introduction

Testing software is complicated, expensive, and often overlooked. The productivity of testing and testing research would benefit from a standard language for communication. For example, Kaner et al. (2011, p. 7) give the example of complete testing, which could require the tester to discover "every bug in the product", exhaust the time allocated to the testing phase, or simply implement every test previously agreed upon. Having a clear definition of "complete testing" reduces the chance for miscommunication and, ultimately, the tester getting "blamed for not doing … [their] job" (p. 7). These benefits permeate software testing terminology. If software engineering holds code to high standards of clarity, consistency, and robustness, the same should apply to its supporting literature! This is even more important when seeking to generate test cases automatically. Our own project Drasil (Carette et al., 2021) has the goal of "generating all of the software artifacts for (well understood) research software". Before we can include test cases as a generated artifact, the domain of testing, including known testing approaches, needs to be "well understood", which requires a "stable knowledge base" (Hunt et al., 2021). Unfortunately, a search for a systematic, rigorous, and complete taxonomy for software testing revealed that the existing ones are inadequate and mostly focus on the high-level testing process rather than the testing approaches themselves:

ProWritingAid suggests that including "and incomplete" is redundant

- Tebes et al. (2020) focus on *parts* of the testing process (e.g., test goal, test plan, testing role, testable entity) and how they relate to one another,
- Souza et al. (2017) prioritize organizing testing approaches over defining them, and
- Unterkalmsteiner et al. (2014) focus on the "information linkage or transfer" (p. A:6) between requirements engineering and software testing and "do[] not aim at providing a systematic and exhaustive state-of-the-art survey of [either domain]" (p. A:2).

Some existing collections of software testing terminology were found, but in addition to being incomplete, they also contained many oversights. For example, ISO/IEC and IEEE (2017) provide the following term-definition pairs:

- **Event Sequence Analysis:** "per" (p. 170)
- **Operable:** "state of" (p. 301)

These definitions are nonsensical and do not define the terms they claim to! To be sure, they *cannot* correspond to the terms given since the parts of speech are mismatched: the first defines a noun phrase as a preposition, and the second an adjective as a noun phrase fragment. ISO/IEC and IEEE (2017) also define "device" as a "mechanism or piece of equipment designed to serve a purpose or perform a function" (p. 136), but do not define "equipment" and only define "mechanism" in the software sense as "the means used by a function to transform input into output" (p. 270). This is an example of an incomplete definition; while the definition of "device" seems logical at first glance, it actually leaves much undefined.

OG IEEE 1998

This problem also extends to test approaches, and discrepancies between the definitions of test approaches can lead to the miscommunication mentioned by Kaner et al. (2011, p. 7). ISO/IEC and IEEE categorize experience-based testing as both a test design technique and a test practice on the same page—twice (2022, Fig. 2, p. 34)! The structure of tours can be defined as either quite general (ISO/IEC and IEEE, 2022, p. 34) or "organized around a special focus" (Hamburg and Mogyorodi, 2024). Load testing is performed with loads "between anticipated conditions of low, typical, and peak usage" (ISO/IEC and IEEE, 2022, p. 5) or loads that are as large as possible (Patton, 2006, p. 86). Alpha testing is performed by "users within the organization developing the software" (ISO/IEC and IEEE, 2017, p. 17), "a small, selected group of potential users" (Washizaki, 2024, p. 5-8), or "roles outside the development organization" conducted "in the developer's test environment" (Hamburg and Mogyorodi, 2024). With inconsistencies such as these, it is clear that there is a notable gap in the literature, one which we attempt to describe and fill. While the creation of a complete taxonomy is unreasonable, especially considering the pace at which the field of software changes, we can make progress towards this goal that others can extend and update as new test approaches emerge.

The following three research questions guide this process:

1. What testing approaches do the literature describe?
2. Are these descriptions consistent?
3. Can we systematically resolve any of these inconsistencies?

We start by recording the 532 test approaches mentioned by 61 sources (described in Section 3.1), recording their name, category (see Section 3.2.1), definition, parent(s) (see Section 3.2.2) and synonym(s), if any. We also keep a record of any other notes, such as uncertainties, prerequisites, and other resources to investigate. An excerpt of some of these approaches, along with their recorded information (excluding other notes for brevity), is given in Table 1.1.

This document describes this process, as well as its results, in more detail. We first define the scope of what kinds of software testing are of interest (Chapter 2) and examine the existing literature (Chapter 3), partially through the use of tools

created for analysis (Chapter 4). Despite the amount of well understood and organized knowledge, there are still many discrepancies in the literature, either within the same source or between various sources (Chapter 5). This reinforces the need for a proper taxonomy! We provide some potential solutions covering some of these discrepancies (Chapter 6).

Table 1.1: Selected entries from glossary of test approaches with "Notes" column excluded for brevity.

Name	Approach Category	Definition	Parent(s)	Synonym(s)
A/B Testing	Practice (ISO/IEC and IEEE, 2022, p. 22), Type (implied by Firesmith, 2015, p. 58)	Testing "that allows testers to determine which of two systems or components performs better" (ISO/IEC and IEEE, 2022, p. 1)	Statistical Testing (ISO/IEC and IEEE, 2022, pp. 1, 35), Usability Testing (Firesmith, 2015, p. 58)	Split-Run Testing (ISO/IEC and IEEE, 2022, pp. 1, 35)
All Combinations Testing	Technique (ISO/IEC and IEEE, 2022, p. 22; 2021, pp. 2, 16; Washizaki, 2024, p. 5-11)	Testing that covers "all unique combinations of P-V pairs" (ISO/IEC and IEEE, 2021, p. 16)	Combinatorial Testing (ISO/IEC and IEEE, 2022, p. 22; 2021, pp. 2, 16, Fig. 2; Washizaki, 2024, p. 5-11)	—
Big-Bang Testing	Level (inferred from integration testing)	"Testing in which … [components of a system] are combined all at once into an overall system, rather than in stages" (ISO/IEC and IEEE, 2017, p. 45)	Integration Testing (ISO/IEC and IEEE, 2017, p. 45; Washizaki, 2024, p. 5-7; Sharma et al., 2021, p. 603; Kam, 2008, p. 42)	—
Classification Tree Method	Technique (ISO/IEC and IEEE, 2022, p. 22; 2021, pp. 2, 12, Fig. 2; Hamburg and Mogyorodi, 2024)	Testing "based on exercising classes in a classification tree" (ISO/IEC and IEEE, 2021, p. 22)	Specification-based Testing (ISO/IEC and IEEE, 2022, p. 22; 2021, pp. 2, 12, Fig. 2; Hamburg and Mogyorodi, 2024; Firesmith, 2015, p. 47), Model-based Testing (ISO/IEC and IEEE, 2022, p. 13; 2021, pp. 6, 12)	Classification Tree Technique (Hamburg and Mogyorodi, 2024)
Data Flow Testing	Technique (ISO/IEC and IEEE, 2022, p. 22; 2021, pp. 3, 27; Washizaki, 2024, p. 5-13; Kam, 2008, p. 43)	A "class of … techniques based on exercising definition-use pairs" (ISO/IEC and IEEE, 2021, p. 3; similar on p. 27)	Structure-based Testing (ISO/IEC and IEEE, 2022, p. 22; 2021, pp. 3, 27, Fig. 2; Kam, 2008, p. 43), Control Flow Testing (2021, p. 27; implied by Washizaki, 2024, p. 5-13; ISO/IEC and IEEE, 2017, p. 101), Model-based Testing (2021, p. 27; implied by Doğan et al., 2014, p. 179), Web Application Testing (p. 179; can be in Kam, 2008, pp. 16-17)	—

Chapter 2

Scope

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Since our motivation is restricted to testing code, only this component of Verification and Validation (V&V) is considered. However, some test approaches are used for testing things other than code, and some approaches can be used for both! In these cases, only the subsections of these approaches focused on code are considered. For example, reliability testing and maintainability testing can start *without* code by "measur[ing] structural attributes of representations of the software" (Fenton and Pfleeger, 1997, p. 18), but only reliability and maintainability testing performed on code *itself* is in scope of this research. Therefore, some practices are excluded from consideration either in part or in full; hardware testing (Section 2.1) and the V&V of other artifacts (Section 2.2) are completely out of scope, as well as relevant areas of other testing approaches that are otherwise in scope. Static testing can be performed on code, so while it isn't relevant to the original motivation of this work, it is a useful component of software testing and is therefore included at this level of analysis (Section 2.3). Finally, some test approaches can be derived from other categories of testing-related terminology (Section 2.4); of these, approaches derived from programming languages (Section 2.4.5) or other orthogonal test approaches (Section 2.4.6) are out of scope.

2.1 Hardware Testing

While testing the software run *on* or in control *of* hardware is in scope, testing performed on the hardware itself is out of scope. The following are some examples of hardware testing approaches:

- Ergonomics testing and proximity-based testing (see Hamburg and Mogyorodi, 2024) are out of scope, since they are used for testing hardware.
- Similarly, EManations SECurity (EMSEC) testing (ISO, 2021; Zhou et al., 2012, p. 95), which deals with the "security risk" of "information leakage via electromagnetic emanation" (Zhou et al., 2012, p. 95), is also out of scope.
- All the examples of domain-specific testing given by Firesmith (2015, p. 26) are focused on hardware, so these examples are out of scope. However, this might not be representative of all types (e.g., Machine Learning (ML) model testing seems domain-specific), so some subset of domain-specific testing may be in scope.

- Conversely, the examples of environmental tolerance testing given by Firesmith (2015, p. 56) do *not* seem to apply to software. For example, radiation tolerance testing seems to focus on hardware, such as motors (Mukhin et al., 2022), robots (Zhang et al., 2020), or "nanolayered carbide and nitride materials" (Tunes et al., 2022, p. 1). Acceleration tolerance testing seems to focus on astronauts (Morgun et al., 1999, p. 11), aviators (Howe and Johnson, 1995, pp. 27, 42), or catalysts (Liu et al., 2023, p. 1463) and acoustic tolerance testing on rats (Holley et al., 1996), which are even less related! Since these all focus on environment-specific factors that would not impact the code, this category of testing is also out of scope.

- Similarly, Knüvener Mackert GmbH (2022) uses the terms "software qualification testing" and "system qualification testing" in the context of the automotive industry. While these may be in scope, the more general idea of "qualification testing" seems to refer to the process of making a hardware component, such as an electronic component (Ahsan et al., 2020), gas generator (Parate et al., 2021) or photovoltaic device, "into a reliable and marketable product" (Suhir et al., 2013, p. 1). Therefore, it is currently unclear if this is in scope.

Investigate further

- Orthogonal Array Testing (OAT) can be used when testing software (Mandl, 1985) (in scope) but can also be used for hardware (Valcheva, 2013, pp. 471-472), such as "processors … made from pre-built and pre-tested hardware components" (p. 471) (out of scope). A subset of OAT called "Taguchi's Orthogonal Array Testing (TOAT)" is used for "experimental design problems in manufacturing" (Yu et al., 2011, p. 1573) or "product and manufacturing process design" (Tsui, 2007, p. 44) and is thus also out of scope.

- Since control systems often have a software *and* hardware component (ISO, 2015; Preuße et al., 2012; Forsyth et al., 2004), only the software component is in scope. In some cases, it is unclear whether the "loops"[1] being tested are implemented by software or hardware, such as those in wide-area damping controllers (Pierre et al., 2017; Trudnowski et al., 2017).

  - A related note: "path coverage" or "path testing" seems to be able to refer to either paths through code (as a subset of control-flow testing) (Washizaki, 2024, p. 5-13) or through a model, such as a finite-state machine (as a subset of model-based testing) (Doğan et al., 2014, p. 184).

2.2 V&V of Other Artifacts

The only testing of a software artifact produced by the software life cycle that is in scope is testing of the software itself, as demonstrated by the following examples:

[1] Humorously, the testing of loops in chemical systems (Dominguez-Pumar et al., 2020) and copper loops (Goralski, 1999) are out of scope.

- Design reviews and documentation reviews are out of scope, as they focus on the V&V of design (ISO/IEC and IEEE, 2017, pp. 132) and documentation (p. 144), respectively.
- Security audits can focus on "an organization's … processes and infrastructure" (Hamburg and Mogyorodi, 2024) (out of scope) or "aim to ensure that all of the products installed on a site are secure when checked against the known vulnerabilities for those products" (Gerrard, 2000b, p. 28) (in scope).
- Error seeding is the "process of intentionally adding known faults[2] to those already in a computer program", done to both "monitor[] the rate of detection and removal", which is a part of V&V of the V&V itself (out of scope), "and estimat[e] the number of faults remaining" (ISO/IEC and IEEE, 2017, p. 165), which helps verify the actual code (in scope).
- Fault injection testing, where "faults are artificially introduced[2] into the SUT [System Under Test]", can be used to evaluate the effectiveness of a test suite (Washizaki, 2024, p. 5-18), which is a part of V&V of the V&V itself (out of scope), or "to test the robustness of the system in the event of internal and external failures" (ISO/IEC and IEEE, 2022, p. 42), which helps verify the actual code (in scope).
- "Mutation [t]esting was originally conceived as a technique to evaluate test suites in which a mutant is a slightly modified version of the SUT" (Washizaki, 2024, p. 5-15), which is in the realm of V&V of the V&V itself (out of scope). However, it "can also be categorized as a structure-based technique" and can be used to assist fuzz and metamorphic testing (Washizaki, 2024, p. 5-15) (in scope).

2.3 Static Testing

Sometimes, static testing is excluded from software testing (Ammann and Offutt, 2017, p. 222; Firesmith, 2015, p. 13), restricting "testing" to mean dynamic validation (Washizaki, 2024, p. 5-1) or verification "in which a system or component is executed" (ISO/IEC and IEEE, 2017, p. 427). However, "terminology is not uniform among different communities, and some use the term 'testing' to refer to static techniques[3] as well" (Washizaki, 2024, p. 5-2). This is done by Gerrard (2000a, pp. 8-9) and ISO/IEC and IEEE (2022, p. 17); the latter even explicitly exclude static testing in another document (2017, p. 440)!

Could this be added as a scope discrepancy?

Static testing generally seems more ad hoc and less relevant for our original goal (the automatic generation of tests). In particular, many techniques require

[2] While error seeding and fault injection testing both introduce faults as part of testing, they do so with different goals: to "estimat[e] the number of faults remaining" (ISO/IEC and IEEE, 2017, p. 165) and "test the robustness of the system" (2022, p. 42), respectively. Therefore, these approaches are not considered synonyms, and the lack of this relation in the literature is not included in Section 5.2.1 as a synonym discrepancy.

[3] Not formally defined, but distinct from the notion of "test technique" described in Table 3.1.

human intervention, either by design (such as code inspections) or to identify and resolve false positives (such as intentional exceptions to linting rules). Nevertheless, understanding the breadth of testing approaches requires a "complete" picture of how software can be tested and how the various approaches relate to one another. Parts of these static approaches may even be generated in the future! For these reasons, we keep static testing in scope for this stage of our work, even though static testing will likely be removed at a later step of analysis based on our original motivation.

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2.4 Derived Test Approaches

Since the field of software is ever-evolving, being able to adapt to, talk about, and understand new developments in software testing is crucial. In addition to methods of categorizing test approaches, the literature also suggests that other categories of testing-related terminology can be used to define new test approaches. These include coverage metrics (Section 2.4.1), software qualities (Section 2.4.2), requirements (Section 2.4.3), and attacks (Section 2.4.4), which are meaningful enough to merit analysis and are therefore in scope. Some approaches given in the literature are derived from programming languages (Section 2.4.5) or other orthogonal test approaches (Section 2.4.6), but these are out of scope as the information they provide is captured by other approaches.

2.4.1 Coverage-driven Techniques

Test techniques are able to "identify test coverage items … and derive corresponding test cases" (ISO/IEC and IEEE, 2022, p. 11; similar in 2017, p. 467) in a "systematic" way (2017, p. 464). This allows for "the coverage achieved by a specific test design technique" to be calculated as a percentage of "the number of test coverage items covered by executed test cases" (2021, p. 30). Therefore, a given coverage metric implies a test approach aimed to maximize it. For example, path testing "aims to execute all entry-to-exit control flow paths in a SUT's control flow graph" (Washizaki, 2024, p. 5-13), thus maximizing the path coverage (see Sharma et al., 2021, Fig. 1).

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2.4.2 Quality-driven Types

Since test types are "focused on specific quality characteristics" (ISO/IEC and IEEE, 2022, p. 15; 2021, p. 7; 2017, p. 473), they can be derived from software qualities: "capabilit[ies] of software product[s] to satisfy stated and implied needs when used under specified conditions" (ISO/IEC and IEEE, 2017, p. 424). This is supported by reliability and performance testing, which are both examples of test types (ISO/IEC and IEEE, 2022; 2021) that are based on their underlying qualities (Fenton and Pfleeger, 1997, p. 18). Given the importance of software qualities to defining test types, the definitions of 76 software qualities are also tracked in this current work. This was done by capturing their definitions, any

OG IEEE 2013

OG ISO/IEC 2014

See #21, #23, and #27

precedent for the existence of an associated test type, and any additional notes in a glossary. Over time, software qualities were "upgraded" to test types when mentioned (or implied) by a source. Examples of this include conformance testing (Washizaki, 2024, p. 5-7; Jard et al., 1999, p. 25; implied by ISO/IEC and IEEE, 2017, p. 93) and efficiency testing (Kam, 2008, p. 44).

2.4.3 Requirements-driven Approaches

While not as universally applicable, some types of requirements have associated types of testing (e.g., functional, non-functional, security). This may mean that categories of requirements *also* imply related testing approaches (such as "technical testing"). Even assuming this is the case, some types of requirements do not apply to the code itself, and as such are out of scope, such as:

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- **Nontechnical Requirement:** a "requirement affecting product and service acquisition or development that is not a property of the product or service" (ISO/IEC and IEEE, 2017, p. 293)
- **Physical Requirement:** a "requirement that specifies a physical characteristic that a system or system component must possess" (ISO/IEC and IEEE, 2017, p. 322)

2.4.4 Attacks

While attacks can be "malicious" (ISO/IEC and IEEE, 2017, p. 7), they are also given as a test practice (2022, p. 34; see Table 5.4). This means that software attacks, such as code injection and password cracking (Hamburg and Mogyorodi, 2024), can also be used for testing software, and only this kind of software attack is in scope. This is supported by the fact that penetration testing is also called "ethical hacking testing" (Washizaki, 2024, p. 13-4) or just "ethical hacking" (Gerrard, 2000b, p. 28); while hacking in general is not a test approach, doing so systematically to test and improve the software is.

2.4.5 Language-specific Approaches

Specific programming languages are sometimes used to define test approaches. If the reliance on a specific programming language is intentional, then this really implies an underlying test approach that may be generalized to other languages. These are therefore considered out-of-scope, including the following examples:

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- "They implemented an approach … for JavaScript testing (referred to as Randomized)" (Doğan et al., 2014, p. 192); this really refers to random testing used within JavaScript
- "SQL statement coverage" is really just statement coverage used specifically for SQL statements (Doğan et al., 2014, Tab. 13)

OG Alalfi et al., 2010

- "Faults specific to PHP" is just a subcategory of fault-based testing, since "execution failures … caused by missing an included file, wrong MySQL quer[ies] and uncaught exceptions" are not exclusive to PHP (Doğan et al., 2014, Tab. 27)

OG Artzi et al., 2008

- While "HTML testing" is listed or implied by Gerrard (2000a, Tab. 2; 2000b, Tab. 1, p. 3) and Patton (2006, p. 220), it seems to be a combination of syntax testing, functionality testing, hyperlink testing/link checking, cross-browser compatibility testing, performance testing, and content checking (Gerrard, 2000b, p. 3)

2.4.6 Orthogonally Derived Approaches

Some test approaches appear to be combinations of other (seemingly orthogonal) approaches. While the use of a combination term can sometimes make sense, such as when writing a paper or performing testing that focuses on the intersection between two test approaches, they are sometimes given the same "weight" as their atomic counterparts. For example, Hamburg and Mogyorodi (2024) include "formal reviews" and "informal reviews" in their glossary as separate terms, despite their definitions essentially boiling down to "reviews that follow (or do not follow) a formal process", which do not provide any new information. Regardless, these are considered out of scope since their details are captured as the in-scope test approaches that comprise them. For the following examples, we indicate the combination for the first item but omit the rest for brevity as the name makes it clear what the combination is:

1. Black box conformance testing (Jard et al., 1999, p. 25) (combining black box and conformance testing)
2. Black-box integration testing (Sakamoto et al., 2013, p. 345-346)
3. Checklist-based reviews (Hamburg and Mogyorodi, 2024)
4. Closed-loop HiL verification (Preuße et al., 2012, p. 6)
5. Closed-loop protection system testing (Forsyth et al., 2004, p. 331)
6. Endurance stability testing (Firesmith, 2015, p. 55)
7. End-to-end functionality testing (ISO/IEC and IEEE, 2021, p. 20; Gerrard, 2000a, Tab. 2)
8. Formal reviews (Hamburg and Mogyorodi, 2024)
9. Gray-box integration testing (Sakamoto et al., 2013, p. 344)
10. Incremental integration testing (Sharma et al., 2021, p. 601)

OG [19]

11. Informal reviews (Hamburg and Mogyorodi, 2024)

12. Infrastructure compatibility testing (Firesmith, 2015, p. 53)
13. Invariant-based automatic testing (Doğan et al., 2014, pp. 184-185, Tab. 21), including for "AJAX user interfaces" (p. 191)
14. Legacy system integration (testing) (Gerrard, 2000a, Tab. 2)
15. Manual procedure testing (Firesmith, 2015, p. 47)
16. Manual security audits (Gerrard, 2000b, p. 28)
17. Model-based GUI testing (Doğan et al., 2014, Tab. 1; implied by Sakamoto et al., 2013, p. 356)
18. Model-based web application testing (implied by Sakamoto et al., 2013, p. 356)
19. Non-functional search-based testing (Doğan et al., 2014, Tab. 1)
20. Offline MBT (Hamburg and Mogyorodi, 2024)
21. Online MBT (Hamburg and Mogyorodi, 2024)
22. Role-based reviews (Hamburg and Mogyorodi, 2024)
23. Scenario walkthroughs (Gerrard, 2000a, Fig. 4)
24. Scenario-based reviews (Hamburg and Mogyorodi, 2024)
25. Security attacks (Hamburg and Mogyorodi, 2024)
26. Statistical web testing (Doğan et al., 2014, p. 185)
27. Usability test script(ing) (Hamburg and Mogyorodi, 2024)
28. Web application regression testing (Doğan et al., 2014, Tab. 21)
29. White-box unit testing (Sakamoto et al., 2013, pp. 345-346)

The existence of orthogonal combinations could allow for other test approaches to be extrapolated from them. For example, Moghadam (2019) uses the phrase "machine learning-assisted performance testing"; since performance testing is a known test approach, this may imply the existence of the test approach "machine learning-assisted testing". Likewise, Jard et al. (1999) use the phrases "local synchronous testing" and "remote asynchronous testing". While these can be decomposed, for example, into local testing and synchronous testing, the two resulting approaches may not be orthogonal, potentially even having a parent-child relation (defined in Section 3.2.2).

Chapter 3

Methodology

3.1 Sources

As there is no single authoritative source on software testing terminology, we need to look at many to see how various terms are used in practice. Starting from some set of sources, we then use "snowball sampling", a "method of … sample selection … used to locate hidden populations" (Johnson, 2014), to gather further sources (see Section 3.4). Sources with a similar degree of "trustworthiness" are grouped into categories; sources that are more "trustworthy":

1. have gone through a peer-review process,
2. are written by numerous, well-respected authors,
3. are informed by many sources, and
4. are accepted and used in the field of software.

We therefore create the following categories, given in order of descending trustworthiness: established standards (Section 3.1.1), "meta-level" collections (Section 3.1.2), textbooks (Section 3.1.3), and papers and other documents (Section 3.1.4). Additionally, some information is inferred; although these data do not come from the literature, they are given in Section 3.1.5 for completeness. Each category is given a unique colour in Figures 6.1 to 6.5 to better visualize the source of information in these graphs. A summary of how many sources comprise each category is given in Figure 3.1.

3.1.1 Established Standards

(ISO/IEC and IEEE, 2022; 2021; 2019; 2017; 2016; 2013; IEEE, 2012; ISO, 2022; 2015; ISO/IEC, 2023a;b; 2018; 2015; 2011)

- Colored green
- Information on software development and testing from standards bodies

- Written by reputable organizations for use in software engineering; for example, "the purpose of the ISO/IEC/IEEE 29119 series is to define an internationally agreed set of standards for software testing that can be used by any organization when performing any form of software testing" (ISO/IEC and IEEE, 2022, p. vii; similar in 2016, p. ix)

3.1.2 "Meta-level" Collections

(Hamburg and Mogyorodi, 2024; Washizaki, 2024; Firesmith, 2015; Doğan et al., 2014; Bourque and Fairley, 2014)

- Colored blue
- Collections of relevant terminology, such as ISTQB's glossary (Hamburg and Mogyorodi, 2024), the SWEBOK Guide (Washizaki, 2024; Bourque and Fairley, 2014), and Doğan et al.'s literature review (2014)
- Built up from various sources, including established standards (see Section 3.1.1), and often written by a large organization (such as ISTQB); the SWEBOK Guide is "proposed as a suitable foundation for government licensing, for the regulation of software engineers, and for the development of university curricula in software engineering" (Kaner et al., 2011, p. xix)

3.1.3 Textbooks

(Dennis et al., 2012; Kaner et al., 2011; Patton, 2006; Perry, 2006; Gerrard and Thompson, 2002; Peters and Pedrycz, 2000; van Vliet, 2000)

- Colored maroon
- Textbooks trusted at McMaster (Patton, 2006; Peters and Pedrycz, 2000; van Vliet, 2000) were the original (albeit ad hoc and arbitrary) starting point
- Written by smaller sets of authors, but with a formal review process before publication
- Used as resources for teaching software engineering and may be used as guides in industry

3.1.4 Papers and Other Documents

(Bas, 2024; ChatGPT (GPT-4o), 2024; LambdaTest, 2024; Pandey, 2023; Knüvener Mackert GmbH, 2022; Sharma et al., 2021; Kanewala and Yueh Chen, 2019; Moghadam, 2019; Bajammal and Mesbah, 2018; Souza et al., 2017; Dhok and Ramanathan, 2016; Barr et al., 2015; Kuļešovs et al., 2013; Lahiri et al., 2013; Sakamoto et al., 2013; Valcheva, 2013; Preuße et al., 2012; Godefroid and Luchaup, 2011; Yu et al., 2011; Choudhary et al., 2010; Kam, 2008; Rus et al., 2008; Tsui,

2007; Barbosa et al., 2006; Baresi and Pezzè, 2006; Berdine et al., 2006; Chalin et al., 2006; Sangwan and LaPlante, 2006; Forsyth et al., 2004; Sneed and Göschl, 2000; Gerrard, 2000a;b; Jard et al., 1999; Bocchino and Hamilton, 1996; Mandl, 1985)

- Colored black
- Mainly consists of academic papers: journal articles, conference papers, reports (Kam, 2008; Gerrard, 2000a;b), and a thesis (Bas, 2024)
- Written by much smaller sets of authors with unknown peer review processes
- Much less widespread than other categories of sources
- Many of these sources were investigated to "fill in" missing definitions (see Section 3.4)
- Also included (for brevity) are some less-than-academic sources to investigate how terms are used in practice, such as websites (LambdaTest, 2024; Pandey, 2023), a booklet (Knüvener Mackert GmbH, 2022), and ChatGPT (GPT-4o) (2024) (with claims supported by Rus et al. (2008))

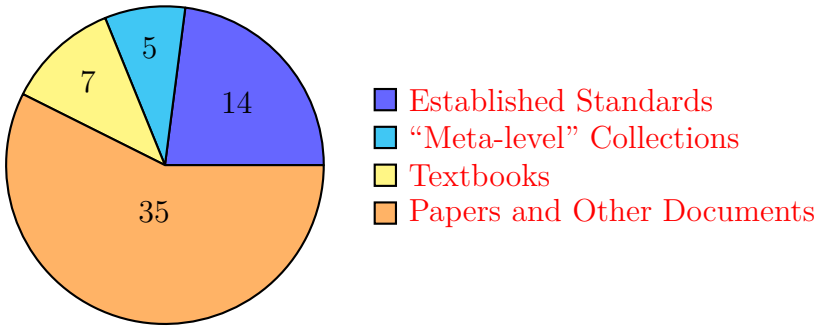


Figure 3.1: Summary of how many sources comprise each source category.

3.1.5 Inferences

While not as clear-cut as the other source categories, some information is inferred from the content of other sources. This includes "surface-level" analysis that follows straightforwardly but isn't explicitly stated. Examples of this are large scale integration testing and legacy system integration testing, described by Gerrard in (2000b, p. 30) and (2000a, Tab. 2; 2000b, Tab. 1), respectively. While he never explicitly says so, it can be inferred that these approaches are children of integration testing and system integration testing, respectively. Inferred relations such as these are colored gray and inferred discrepancies are given in Section 5.8.

3.2 Terminology

This research was intended to describe the current state of testing terminology instead of prematurely applying any classifications to reduce bias. Therefore, the notions of test approach categories (Section 3.2.1) and parent-child relations (Section 3.2.2) arose naturally from the literature. Even though these are "results" of this research, they are defined here for clarity since they are used throughout this thesis. We also define the notion of "rigidity" in Section 3.2.3.

3.2.1 Categories of Testing Approaches

Different sources categorize software testing approaches differently; while it is useful to record and think about these categorizations, following one (or more) during the research stage could lead to bias and a prescriptive categorization instead of letting one emerge descriptively during the analysis stage. Since these categorizations are not mutually exclusive, it also means that more than one could be useful (both in general and for this research).

ISO/IEC and IEEE (2022) provide the classification of test approaches in Table 3.1, while other sources (Barbosa et al., 2006; Souza et al., 2017) use alternative categories (see Table 3.2). These will provide other perspectives when determining if the categorization in Table 3.1 is sufficient. Nevertheless, these categories ("test level" and "test type" in particular) seem to be widely used. For example, in addition to the IEEE sources (given in Table 3.1), six additional sources give unit testing, integration testing, system testing, and acceptance testing as examples of test levels (Washizaki, 2024, pp. 5-6 to 5-7; Hamburg and Mogyorodi, 2024; Kulešovs et al., 2013, p. 218; Perry, 2006, p. 807-808; Peters and Pedrycz, 2000, pp. 443-445; Gerrard, 2000a, pp. 9, 13), although they may use a different term for "test level" (see Table 3.1). Because of their widespread use and their usefulness when focusing on a particular subset of testing, these categories are used for now. A "metric" category was considered in addition to this categorization, but was decided to be out of the scope of this project, instead being captured by coverage-driven testing (see Section 2.4.1).

OG Black, 2009

See #21 and #22

Related testing approaches may be grouped into a "class" or "family" to group those with "commonalities and well-identified variabilities that can be instantiated", where "the commonalities are large and the variabilities smaller" (Carette, 2024). Examples of these are the classes of combinatorial (ISO/IEC and IEEE, 2021, p. 15) and data flow testing (p. 3) and the family of performance-related testing (Moghadam, 2019, p. 1187)[1], and may also be implied for security testing, a test type that consists of "a number of techniques[2]" (ISO/IEC and IEEE, 2021, p. 40).

It also seems that the categories given in Table 3.1 are orthogonal. For example, "a test type can be performed at a single test level or across several test levels"

[1]The original source describes "performance testing … as a family of performance-related testing techniques", but it makes more sense to consider "performance-related testing" as the "family" with "performance testing" being one of the variabilities (see Section 6.3).

[2]This may or may not be distinct from the notion of "test technique" described in Table 3.1.

(ISO/IEC and IEEE, 2022, p. 15; 2021, p. 7), and "Keyword-Driven Testing [sic] can be applied at all testing levels (e.g. [sic] component testing, system testing) and for various types of testing (e.g. [sic] functional testing[3], reliability testing)" (2016, p. 4). Due to this, a specific test approach can be derived by combining test approaches from different categories; see Section 2.4.6 for some examples of this.

[3]See Section 5.3.2.

Table 3.1: IEEE Testing Terminology

Term	Definition	Examples
Approach	A "high-level test implementation choice, typically made as part of the test strategy design activity" that includes "test level, test type, test technique, test practice and the form of static testing to be used" (ISO/IEC and IEEE, 2022, p. 10); described by a *test strategy* (2017, p. 472) and is also used to "pick the particular test case values" (2017, p. 465)	black or white box, minimum and maximum boundary value testing (ISO/IEC and IEEE, 2017, p. 465)
(Design)[a] Technique	A "defined" and "systematic" (ISO/IEC and IEEE, 2017, p. 464) "procedure used to create or select a test model, identify test coverage items, and derive corresponding test cases" (2022, p. 11; similar in 2017, p. 467) "that … generate evidence that test item requirements have been met or that defects are present in a test item" (2021, p. vii); "a variety … is typically required to suitably cover any system" (2022, p. 33) and is "often selected based on team skills and familiarity, on the format of the test basis", and on expectations (2022, p. 23)	equivalence partitioning, boundary value analysis, branch testing (ISO/IEC and IEEE, 2022, p. 11)
Level[b] (sometimes "Phase"[c] or "Stage"[d])	A stage of testing "typically associated with the achievement of particular objectives and used to treat particular risks", each performed in sequence (ISO/IEC and IEEE, 2022, p. 12; 2021, p. 6) with their "own documentation and resources" (2017, p. 469); more generally, "designat[es] … the coverage and detail" (2017, p. 249)	unit/component testing, integration testing, system testing, acceptance testing (ISO/IEC and IEEE, 2022, p. 12; 2021, p. 6; 2017, p. 467)
Practice	A "conceptual framework that can be applied to … [a] test process to facilitate testing" (ISO/IEC and IEEE, 2022, p. 14; 2017, p. 471; OG IEEE 2013); more generally, a "specific type of activity that contributes to the execution of a process" (2017, p. 331)	scripted testing, exploratory testing, automated testing (ISO/IEC and IEEE, 2022, p. 20)
Type	"Testing that is focused on specific quality characteristics" (ISO/IEC and IEEE, 2022, p. 15; 2021, p. 7; 2017, p. 473; OG IEEE 2013)	security testing, usability testing, performance testing (ISO/IEC and IEEE, 2022, p. 15; 2017, p. 473)

[a] "Design technique" is sometimes abbreviated to "technique" (ISO/IEC and IEEE, 2022, p. 11; Hamburg and Mogyorodi, 2024).

[b] "Test level" can also refer to the scope of a test process; for example, "across the whole organization" or only "to specific projects" (ISO/IEC and IEEE, 2022, p. 24).

[c] "Test phase" can be a synonym for "test level" (ISO/IEC and IEEE, 2017, p. 469; 2013, p. 9) but can also refer to the "period of time in the software life cycle" when testing occurs (2017, p. 470), usually after the implementation phase (2017, pp. 420, 509; Perry, 2006, p. 56).

[d] Used by (Washizaki, 2024, pp. 5-6 to 5-7; Hamburg and Mogyorodi, 2024; van Vliet, 2000, pp. 438-440; Gerrard, 2000a, pp. 9, 13).

Table 3.2: Other Testing Terminology

Term	Definition	Examples	IEEE Equivalent
Guidance	none given (Barbosa et al., 2006, p. 3)	none given	Technique?
Level	"Distinguished based on the object of testing, the *target*, or on the purpose or *objective*" (Washizaki, 2024, p. 5-6); these are "orthogonal" and "determine how the test suite is identified … regarding its consistency … and its composition" (p. 5-2)	Target: unit, integration, system (Washizaki, 2024, pp. 5-6 to 5-7; Souza et al., 2017, p. 3), acceptance testing (Washizaki, 2024, p. 5-7) Objective: conformance, installation, regression, performance, reliability, security (Washizaki, 2024, pp. 5-7 to 5-9)	Target: Level Obj.: Type?
Method	none given (Barbosa et al., 2006, p. 3)	none given	Practice?
Phase	none given	unit, integration, system, regression testing (Perry, 2006, p. 221; Barbosa et al., 2006, p. 3)	Level
Procedure	The basis for how testing is performed that guides the process; "categorized in[to] testing methods, testing guidances and testing techniques" (Barbosa et al., 2006, p. 3)	none given generally; see examples of "Technique"	Approach
Process	"A sequence of testing steps" (Barbosa et al., 2006, p. 2) "based on a development technology and … paradigm, as well as on a testing procedure" (p. 3)	none given	Practice
Stage	An alternative to the "traditional … test stages" that is based on "clear technical groupings" (Gerrard, 2000a, p. 13); see "Level" in Table 3.1	desktop development testing, infrastructure testing, system testing, large scale integration, and post-deployment monitoring (Gerrard, 2000a, p. 13)	Level
Technique	"Systematic procedures and approaches for generating or selecting the most suitable test suites" (Washizaki, 2024, p. 5-10) "on a sound theoretical basis" (Barbosa et al., 2006, p. 3)	specification-, structure-, experience-, fault-, usage-based testing (Washizaki, 2024, pp. 5-10, 5-13 to 5-15); black-box, white-box, defect/fault-based, model-based testing (Souza et al., 2017, p. 3; OG Mathur, 2012); functional, structural, error-based, state-based testing (Barbosa et al., 2006, p. 3)	Technique

The literature provides many other ways to categorize test approaches. While these are less-defined and as such are not used, they are given here for completeness. Note that "there is a lot of overlap between different classes of testing" (Firesmith, 2015, p. 8), meaning that "one category [of test techniques] might deal with combining two or more techniques" (Washizaki, 2024, p. 5-10). For example, "performance, load and stress testing might considerably overlap in many areas" (Moghadam, 2019, p. 1187). A side effect of this is that it is difficult to "untangle" these classes; for example, take the following sentence: "whitebox fuzzing extends dynamic test generation based on symbolic execution and constraint solving from unit testing to whole-application security testing" (Godefroid and Luchaup, 2011, p. 23)!

Despite these challenges, it is useful to understand the differences between testing classes because tests from multiple subsets within the same category, such as functional and structural, "use different sources of information and have been shown to highlight different problems" (Washizaki, 2024, p. 5-16). However, some subsets, such as deterministic and random, may have "conditions that make one approach more effective than the other" (Washizaki, 2024, p. 5-16). The following categories may also be more relevant in specific situations or to specific teams than the ones given by ISO/IEC and IEEE in Table 3.1.

- Visibility of code: black-, white-, or grey-box (specificational/functional, structural, or a mix of the two) (ISO/IEC and IEEE, 2021, p. 8; Washizaki, 2024, pp. 5-10, 5-16; Sharma et al., 2021, p. 601, called "testing approaches" and (stepwise) code reading replaced "grey-box testing"; Ammann and Offutt, 2017, pp. 57-58; Kuļešovs et al., 2013, p. 213; Patton, 2006, pp. 53, 218; Perry, 2006, p. 69; Kam, 2008, pp. 4-5, called "testing methods")

OG [3, 4, 5, 8]

- Source of information for design: specification, structure, or experience (ISO/IEC and IEEE, 2021, p. 8)
  - Source of test data: specification-, implementation-, or error-oriented (Peters and Pedrycz, 2000, p. 440)
- Test case selection process: deterministic or random (Washizaki, 2024, p. 5-16)
- Coverage criteria: input space partitioning, graph coverage, logic coverage, or syntax-based testing (Ammann and Offutt, 2017, pp. 18-19)
- Question: what-, when-, where-, who-, why-, how-, and how-well-based testing; these are then divided into a total of "16 categories of testing types"[4] (Firesmith, 2015, p. 17)
- Execution of code: static or dynamic (Kuļešovs et al., 2013, p. 214; Gerrard, 2000a, p. 12; Patton, 2006, p. 53); we also consider this categorization meaningful (see Section 2.3)
- Goal of testing: verification or validation (Kuļešovs et al., 2013, p. 214; Perry, 2006, pp. 69-70)

[4]Not formally defined, but distinct from the notion of "test type" described in Table 3.1.

- Property of code (Kuļešovs et al., 2013, p. 213) or test target (Kam, 2008, pp. 4-5): functional or non-functional
- Human involvement: manual or automated (Kuļešovs et al., 2013, p. 214)
- Structuredness: scripted or exploratory (Kuļešovs et al., 2013, p. 214)
- Coverage requirement: data or control flow (Kam, 2008, pp. 4-5)
- Test factor: ("attributes of the software that, if they are wanted, pose a risk to the success of the software"; also called "quality factor" or "quality attribute" (Perry, 2006, p. 40)): correctness, file integrity, authorization, audit trail, continuity of processing, service levels (e.g., response time), access control, compliance, reliability, ease of use, maintainability, portability, coupling (e.g., with other applications in a given environment), performance, and ease of operation (e.g., documentation, training) (Perry, 2006, pp. 40-41)
- Adequacy criterion: coverage-, fault-, or error-based ("based on knowledge of the typical errors that people make") (van Vliet, 2000, pp. 398-399)
- Priority[5]: smoke, usability, performance, or functionality testing (Gerrard, 2000a, p. 12)
- Category of test "type"[6]: static testing, test browsing, functional testing, non-functional testing, or large scale integration (testing) (Gerrard, 2000a, p. 12)
- Purpose: correctness, performance, reliability, or security (Pan, 1999)

Additionally, Engström "investigated classifications of research" (Engström and Petersen, 2015, p. 1) on the following four testing techniques. "They are neither orthogonal nor necessarily useful for the purpose of identifying relevant evaluation points from a problem perspective" (p. 1), so it is unclear why they were included at all:

- **Combinatorial testing:** how the system under test is modelled, "which combination strategies are used to generate test suites and how test cases are prioritized" (pp. 1-2)
- **Model-based testing:** the information represented and described by the test model (p. 2)
- **Search-based testing:** "how techniques[7] had been empirically evaluated (i.e. objective and context)" (p. 2)
- **Unit testing:** "source of information (e.g. code, specifications or testers intuition)" (p. 2)

[5] In the context of testing e-business projects.

[6] "Each type of test addresses a different risk area" (Gerrard, 2000a, p. 12), which is distinct from the notion of "test type" described in Table 3.1.

[7] Not formally defined, but distinct from the notion of "test technique" described in Table 3.1.

3.2.2 Parent-Child Relations

Many test approaches are multi-faceted and can be "specialized" into others, such as performance-related testing (see Section 6.3). These "specializations" will be referred to as "children" or "sub-approaches" of the multi-faceted "parent". This nomenclature also extends to other categories given in Section 3.2.1 and Table 3.1, such as "sub-type". One example of these specializations is the "stronger than" relation (also called the "subsumes" relation) described by van Vliet (2000, p. 432): when comparing adequacy criteria (which "specif[y] requirements for testing" (p. 402)), "criterion X is stronger than criterion Y if, for all programs P and all test sets T, X-adequacy implies Y-adequacy". While this relation only "compares the thoroughness of test techniques, not their ability to detect faults" (p. 434), it is sufficient to consider one a child of the other.

3.2.3 Rigidity

Since there is a considerable degree of nuance introduced by the use of natural language, not all discrepancies are equal! To capture this nuance and provide a more complete picture, we make a distinction between explicit and implicit discrepancies, such as in Tables 5.1 and 5.2. A piece of information is "implicit" if:

- it is not directly given by a source but seems to be implied, and/or
- it is only true some of the time (e.g., under certain conditions).

Discrepancies based on implicit information are themselves implicit. These are automatically detected when generating graphs and analyzing discrepancies (see Sections 4.1 and 4.2, respectively) by looking for indicators of uncertainty, such as question marks, " (Testing)" (which indicates that a test approach isn't explicitly denoted as such; note the inclusion of the space), and the keywords "implied", "inferred", "can be", "should be", "ideally", "usually", "most", "likely", "often", "if", and "although" (see the relevant source code). These words were used when creating the glossaries to capture varying degrees of nuance, such as when a test approach "can be" a child of another or is a synonym of another "most of the time", but isn't always. As an example, Table 5.3 contains relations that are explicit, implicit, and both; implicit relations are marked by the phrase "implied by".

3.3 Procedure

To track terminology used in the literature, we build a glossary of test approaches, including the term itself, its definition, and any synonyms or parents (see Section 3.2.2). Any other notes, such as uncertainties, prerequisites, and other resources to investigate, are also recorded. If an approach is assigned a category, such as those found in Table 3.1 and some outliers (e.g., "artifact"), this is also tracked for future investigation.

See #39 and #44

Most sources are analyzed in their entirety to systematically extract terminology, especially established standards (see Section 3.1.1). Sources that were only partially investigated include those chosen for a specific area of interest or based on a test approach that was determined to be out-of-scope, such as some sources given in Section 3.4. Heuristics are used to guide this process, by investigating:

- glossaries and lists of terms,
- testing-related terms (e.g., terms containing "test(ing)", "review(s)", "audit(s)", "validation", or "verification"),
- terms that had emerged as part of already-discovered testing approaches, *especially* those that were ambiguous or prompted further discussion (e.g., terms containing "performance", "recovery", "component", "bottom-up", "boundary", or "configuration"), and
- terms that implied testing approaches[8] (see Section 2.4).

When terms are given similar definitions by multiple sources, the clearest and most concise version is kept. If definitions from different sources overlap, provide different information, or contradict, they are merged to paint a more complete picture. When contradictions or other discrepancies (see Chapter 5) arise, they are investigated and documented. Any test approaches that are mentioned but not defined are added to the glossary to indicate they should be investigated further (see Section 3.4). Similar methodologies are used for tracking software qualities (see Section 2.4.2) and supplementary terminology that is shared by multiple approaches or is too complicated to explain inline; these are tracked in separate documents. The name, definition, and synonym(s) of all terms are tracked, as well as any precedence for a related test type for a given software quality.

During the first pass of data collection, all software-testing-focused terms are included. Some of them are less applicable to test case automation (such as static testing; see Section 2.3) or too broad (such as attacks; see Section 2.4.4), so they will be omitted during future analysis. However, some terms came up that seemed to be relevant to testing but were so vague, they didn't provide any new information. These were decided to be not worth tracking and are listed below:

See #39

See #55

See #39, #44, and #28

- **Evaluation:** the "systematic determination of the extent to which an entity meets its specified criteria" (ISO/IEC and IEEE, 2017, p. 167)
- **Product Analysis:** the "process of evaluating a product by manual or automated means to determine if the product has certain characteristics" (ISO/IEC and IEEE, 2017, p. 343)
- **Quality Audit:** "a structured, independent process to determine if project activities comply with organizational and project policies, processes, and procedures" (ISO/IEC and IEEE, 2017, p. 361)

OG PMBOK

[8] Since these methods for deriving test approaches only arose as research progressed, some examples would have been missed during the first pass(es) of resources investigated earlier in the process. While reiterating over them would be ideal, this may not be possible due to time constraints.

- **Software Product Evaluation:** a "technical operation that consists of producing an assessment of one or more characteristics of a software product according to a specified procedure" (ISO/IEC and IEEE, 2017, p. 424)

3.4 Undefined Terms

The search process led to some testing approaches being mentioned without definition; (ISO/IEC and IEEE, 2022) and (Firesmith, 2015) in particular introduced many. Once the standards in Section 3.1.1 had been exhausted, we devised a strategy to look for sources that explicitly define these terms, consistent with our snowballing approach. This uncovers new approaches, both in and out of scope (such as EManations SECurity (EMSEC) testing, HTML testing, and aspects of orthogonal array testing and loop testing; see Chapter 2).

The following terms (and their respective related terms) were explored in the following sources, bringing the number of testing approaches from 448 to 532 and the number of *undefined* terms from 156 to 172 (the assumption can be made that about 81% of added terms also included a definition):

- **Assertion Checking:** Lahiri et al. (2013); Chalin et al. (2006); Berdine et al. (2006)
- **Loop Testing**[9]**:** Dhok and Ramanathan (2016); Godefroid and Luchaup (2011); Preuße et al. (2012); Forsyth et al. (2004)
- **EMSEC Testing:** Zhou et al. (2012); ISO (2021)
- **Asynchronous Testing:** Jard et al. (1999)
- **Performance(-related) Testing:** Moghadam (2019)
- **Web Application Testing:** Doğan et al. (2014); Kam (2008)
  - **HTML Testing:** Choudhary et al. (2010); Sneed and Göschl (2000); Gerrard (2000b)
  - **Document Object Model (DOM) Testing:** Bajammal and Mesbah (2018)
- **Sandwich Testing:** Sharma et al. (2021); Sangwan and LaPlante (2006)
- **Orthogonal Array Testing**[10]**:** Mandl (1985); Valcheva (2013)
- **Backup Testing**[11]**:** Bas (2024)

[9] (ISO, 2015) and (ISO, 2022) were used as reference for terms but not fully investigated, (Trudnowski et al., 2017) and (Pierre et al., 2017) were added as potentially in scope, and (Goralski, 1999) and (Dominguez-Pumar et al., 2020) were added as out-of-scope examples.

[10] (Yu et al., 2011) and (Tsui, 2007) were added as out-of-scope examples.

[11] See Section 5.5.

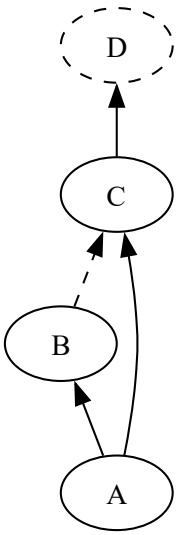
Chapter 4

Tools

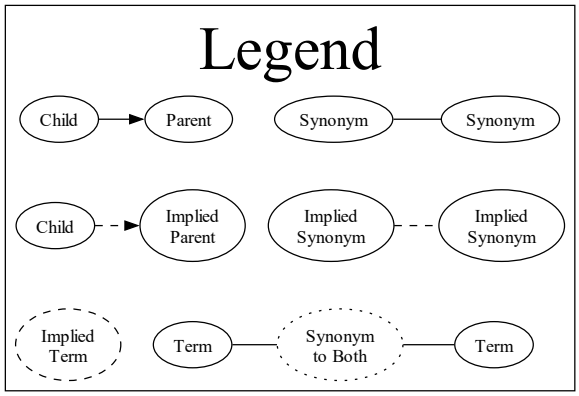
To better understand our findings, we build tools to visualize the relations between test approaches more intuitively (Section 4.1) and track discrepancies surrounding them automatically (Section 4.2). While this *could* be done manually, it would be prone to error due to the amount of data involved (for example, 532 test approaches were identified). Additionally, there are many situations where the underlying data would change, such as performing more detailed analysis, correcting errors, and adding data from new or updated documents; these would all require the corresponding graphs to be updated, which would be tedious. Automating these processes also allows the impacts of smaller changes to be observed. This both provides more context when analyzing data, such as revealing an unexpected discrepancy that arises from a new relation between two approaches, and helps verify the tools themselves, such as ensuring that an added discrepancy affects counts as expected.

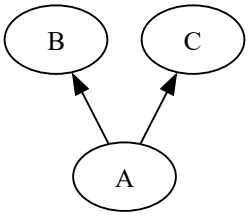
4.1 Approach Graph Generation

To better visualize how test approaches relate to each other, we developed a tool to automatically generate graphs of these relations. Since parent-child and synonym relations between approaches are tracked in our approach glossary in a consistent format, they can be parsed systematically. For example, if the entries in Table 4.1 appear in the glossary, then their parent relations are displayed as Figure 4.1a in the generated graph. Relevant citation information is also captured in our glossary following the author-year citation format, including "reusing" information from previous citations. For example, the first row of Table 4.1 contains the citation "(Author, 0000; 0001)", which means that this information was present in two documents by "Author": one written in the year 0000, and one in 0001. The following citation, "(0000)", contains no author, which means it was written by the same one as the previous citation. These citations are processed according to this logic (see the relevant source code) so they can be consistently tracked throughout the analysis.

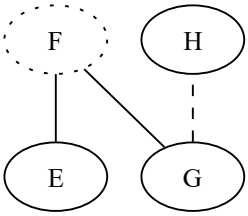


(a) Graph from Table 4.1.

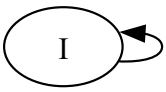




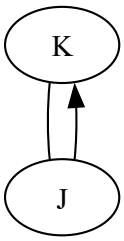
(b) Rigid graph from Table 4.1.



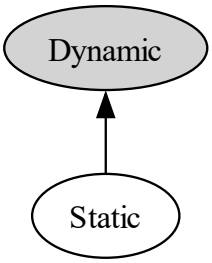
(c) Graph from Table 4.2.



(d) Self-loop graph.



(e) Graph of a pair of terms with a parent-child *and* synonym relation.



(f) Static graph.

Figure 4.1: Example generated graphs.

Name	Parent(s)
A	B (Author, 0000; 0001), C (0000)
B	C (implied by Author, 0000)
C	D (Author, 0002)
D (implied by Author, 0002)	

Table 4.1: Example glossary entries demonstrating how parent relations are tracked.

All parent-child relations are graphed, as well as synonym relations where either:

1. both synonyms have their own rows in the glossary, or
2. a term is a synonym to more than one term with its own row in the glossary.

These conditions are also deduced from the information parsed from the glossary. For example, if the entries in Table 4.2 appear in the glossary, then they are displayed as Figure 4.1c in the generated graph (note that X does not appear since it does not meet the criteria given above).

Name	Synonym(s)
E	F (Author, 0000; implied by 0001)
G	F (Author, 0002), H (implied by 0000)
H	X

Table 4.2: Example glossary entries demonstrating how synonym relations are tracked.

This allows for automatic detection of some classes of discrepancies. The most trivial to automate is "multi-synonym" relations, which are already found to generate the graph as desired. The list found in Section 5.2.1 is automatically generated based on glossary entries such as those found in Table 4.2. The self-referential definitions in Section 5.2.2 were also trivial, found by simply looking for lines in the generated .tex files starting with `I -> I` which would result in the graph in Figure 4.1d. A similar process is used to detect instances where two approaches have a synonym *and* a parent-child relation. A dictionary of each term's synonyms is built to evaluate which synonym relations are notable enough to include in the graph, and these mappings are then checked to see if one appears as a parent of the other. For example, if J and K are synonyms, a generated .tex file with a parent line starting with `J -> K` would result in these approaches being graphed as shown in Figure 4.1e.

The visual nature of these graphs makes it possible to represent both explicit and implicit relations without double counting them during the analysis in Section 4.2. If a relation is both explicit *and* implicit, the implicit relation is only

shown in the graph if it is from a more "trusted" source category (see Section 3.1); note that only the explicit synonym relation between E and F from Table 4.1 is shown in Figure 4.1c. Implicit approaches and relations are denoted by dashed lines, as shown in Figures 4.1a and 4.1c; explicit approaches are *always* denoted by solid lines, even if they are also implicit. "Rigid" versions of these graphs that exclude implicit approaches and relations can also be generated; the rigid version of Figure 4.1a is given in Figure 4.1b.

Since these graphs tend to be large, it is useful to focus on specific subsets of them. Graphs limited to approaches from a given approach category (see Section 3.2.1) are generated, as well as a graph of static approaches. This is done both because ISO/IEC and IEEE (2022, Fig. 2) consider static testing a separate approach category and since it is quite different from dynamic testing (see Section 2.3). Generated graphs of static testing approaches include any relations with dynamic approaches (since they are our primary focus) which are colored gray, as shown in Figure 4.1f. Additionally, more specific subsets of these graphs can be generated based on a given subset of approaches to include, such as those pertaining to recovery or scability (see Sections 5.5 and 5.6, respectively), as shown in Figures 6.1 and 6.3, respectively (albeit with manually created legends). By specifying sets of approaches and relations to add or remove, these generated graphs can be updated in accordance with our recommendations in Chapter 6, as shown in Figures 6.2 and 6.4, respectively. These modifications can also be inherited, as in Figure 6.5, which was generated based on the modifications from Figures 6.2 and 6.4 and then manually tweaked.

Ensure these tweaks are on an up-to-date version!

4.2 Discrepancy Analysis

In addition to analyzing specific discrepancies, an overview of their amounts, sources, rigidities (see Section 3.2.3), classes, and categories is also useful. Subsets of this task can be automated (Section 4.2.1) and the remaining manual portion can be augmented with automated tools (Section 4.2.2).

To understand where discrepancies exist in the literature, they are grouped based on the source categories (as described in Section 3.1) responsible for them. Each discrepancy is then counted *once* per source category if it appears within it *and/or* between it and a more "trusted" category. This avoids counting the same discrepancy twice for a given category, which would result in the number of *occurrences* of all discrepancies, instead of the number of discrepancies *themselves*, which is more useful. An exception to this is Figure 5.1, which counts the following sources of discrepancies separately:

See #83

1. those within a single document,
2. those between documents by the same author(s) or standards organization(s), and
3. those within a source category.

As before, these are not double counted, meaning that the maximum number of counted discrepancies possible within a *single* source category in Figure 5.1 is three (one for each type). This only occurs if there is an example of each discrepancy source that is *not* ignored to avoid double counting; for example, while a single discrepancy within a single document would technically fulfill all three criteria, it would only be counted once.

As an example of this process, consider a discrepancy *within* an IEEE document (e.g., two different definitions are given for a term within the same IEEE document) *and* between another IEEE document, the ISTQB glossary *and* two papers. This would add one to the following rows of Tables 5.1 and 5.2 in the relevant column:

- **Established Standards**: this discrepancy occurs:

  1. within one standard and
  2. between two standards.

  This increments the count by just one to avoid double counting and would do so even if only one of the above conditions was true. A more nuanced breakdown of discrepancies that identifies those within a singular document and those between documents by the same author is given in Figure 5.1 and explained in more detail in Section 4.2.2.

- **"Meta-level" Collections**: this discrepancy occurs between a source in this category and a "more trusted" one (the IEEE standards).

- **Papers and Other Documents**: this discrepancy occurs between a source in this category and a "more trusted" one. Even though there are two sources in this category *and* two "more trusted" categories involved, this increments the count by just one to avoid double counting.

4.2.1 Automated Discrepancy Analysis

As outlined in Section 4.1, some types of discrepancies can be detected automatically. While just counting the total number of these types of discrepancies is trivial, tracking the source(s) of these discrepancies is more involved. Since the appropriate citations for each piece of information is tracked (see Tables 4.1 and 4.2 for examples of how these citations are formatted in the glossaries), they can be used to find the offending source categories. This comes with the added benefit of these citations being available to be formatted for use with LaTeX's citation commands for inclusion in this document.

Comparing the authors and years of each source related to a given discrepancy can determine if it manifests within a single document and/or between documents by the same author(s) when creating Figure 5.1. Then, the relevant sources can be sorted into their categories based on their citations (see the relevant source code). This determines the appropriate row of Tables 5.1 and 5.2 and the appropriate graph and slice in Figure 5.1. These lists of sources can then be distilled down to sets of categories which are compared against each other to determine how many

times a given discrepancy manifests between source categories. Examples of this process are described in more detail in Section 4.2.2.

Alongside this citation information are the keywords relevant for assessing a piece of information's rigidity (see Section 3.2.3). This is useful when counting discrepancies, since a discrepancy can be both explicit and implicit, but should not be double counted as both! When counting discrepancies in Tables 5.1 and 5.2, a given discrepancy is counted only for its most "rigid" manifestation (i.e., it will only increment a value in the "Implicit" column if it is *not* also explicit).

See #83

4.2.2 Augmented Discrepancy Analysis

While some subsets of discrepancies can be deduced automatically from analyzing the testing approach glossary, other types of discrepancies need to be tracked manually. This is done by adding comments to the relevant LaTeX files (generated or not) of the form

```
% Discrep count (CAT, CLS): {A1} {A2} … | {B1} … | {C1} …
```

which can then be parsed to detemine where discrepancies occur. `CAT` is a placeholder for the discrepancy's category (see Section 5.2) identifier and `CLS` is a placeholder for its class (see Section 5.1) identifier. These designations are ommitted from the following examples of these comments. Each group of sources is separated with a pipe symbol to be compared with the others, so any number of groups are permitted. If only one group is present, it is compared with itself. For example, the first line below means that source X has a discrepancy with itself, while the second line adds a discrepancy between X and Y.

```
% Discrep count: {X}
% Discrep count: {X} | {X} {Y}
```

Discrepancies between groups are not double counted; this means the following line adds discrepancies between X and Z *and* between Y and Z, without counting the discrepancy between X and Z twice.

```
% Discrep count: {X} | {X} {Y} | {Z}
```

Each source is given using its BibTeX key wrapped in curly braces to mimic LaTeX's citation commands for ease of parsing, with the exception of the ISTQB glossary, due to its use of custom commands via `\citealias`. For example, the line

```
% Discrep count: {IEEE2022} | {IEEE2022} {IEEE2017}
↪  ISTQB {Kam2008} {Bas2024}
```

would be parsed as the example given in Section 4.2. Since the IEEE documents are written by the same standards organizations (ISO/IEC and IEEE), they are counted as a discrepancy between documents by the same author(s) in Figure 5.1.

The rigidity (see Section 3.2.3) of discrepancies can also be manually specified by inserting the phrase "implied by" after the sources of explicit information and before those of implicit information. Parsing this information follows the same rules as the automatic discrepancy analysis (see Section 4.2.1). For example, the line

```
% Discrep count: {IEEE2022} implied by {Kam2008} |
↪  {IEEE2017} implied by {IEEE2022}
```

indicates that the following discrepancies are present. The second discrepancy only affects Figure 5.1 since it is less "rigid" than the first discrepancy within standards (see Section 3.1.1). The rest increment their corresponding count in Figure 5.1 and Tables 5.1 and 5.2 by only one:

- an explicit discrepancy between documents by ISO/IEC and IEEE,
- an implicit discrepancy within a single document, and
- an implicit discrepancy between a paper and a standard.

Chapter 5

Discrepancies

After gathering all these data[1], we found many discrepancies. To better understand and analyze these discrepancies, each one is given a "class" and a "category". Discrepancy Classes describe *how* a discrepancy manifests syntactically; examples include Mistakes and Omissions. On the other hand, Discrepancy Categories describe the knowledge domain in which a discrepancy manifests semantically; examples include Synonym Relation Discrepancies and Parent-Child Relation Discrepancies. As an example, the structure of tours can be defined as either quite general (ISO/IEC and IEEE, 2022, p. 34) or "organized around a special focus" (Hamburg and Mogyorodi, 2024), which is a case of contradictory definitions; therefore, it is included with the Contradictions (its class) *and* with the Definition Discrepancies (its category). Within these sections, "more significant" discrepancies are listed first, followed by "less significant" ones omitted from the paper version of this thesis. They are then sorted based on their source category (see Section 3.1).

A summary of how many discrepancies there are by class and by category is shown in Tables 5.1 and 5.2, respectively, where a given row corresponds to the number of discrepancies either within that source category (see Section 3.1) and/or with a "more trusted" one (i.e., a previous row in the table). The numbers of (Exp)licit and (Imp)licit (see Section 3.2.3) discrepancies are also presented in these tables. Since each discrepancy is given a class *and* a category, the totals per source and grand totals in these tables are equal. However, the numbers of discrepancies listed in Sections 5.1 and 5.2 are not equal, as those automatically uncovered based on semantics (see Section 4.2.1) are only listed in the corresponding category section for clarity; they still contribute to the counts in Table 5.1!

Moreover, certain "subsets" of testing revealed many interconnected discrepancies. These are given in their respective sections as a "third view" to keep related information together, but still count towards the classes and categories of discrepancies listed above (Section 4.2.2 outlines how this is done), causing a further mismatch between the counts in Tables 5.1 and 5.2 and the counts in Sections 5.1 and 5.2. The "problem" subsets of testing include Functional Testing, Operational (Acceptance) Testing (OAT), Recovery Testing, Scalability Testing, and Compatibility Testing. Finally, Inferred Discrepancies are also given for completeness,

[1] Available in `ApproachGlossary.csv`, `QualityGlossary.csv`, and `SuppGlossary.csv` at https://github.com/samm82/TestGen-Thesis.

despite being less certain and thus not contributing to any counts.

Table 5.1: Breakdown of identified Discrepancy Classes by Source Category.

Source Category	Mistakes		Omissions		Contradictions		Ambiguities		Overlaps		Redunancies		Total
	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp	
Established Standards	4	1	2	0	17	5	3	0	5	0	0	0	37
"Meta-level" Collections	10	0	1	0	27	17	8	3	5	1	1	0	73
Textbooks	6	0	1	0	33	5	5	0	1	0	0	0	51
Papers and Other Documents	7	1	4	0	19	6	9	3	2	1	2	0	54
Total	27	2	8	0	96	33	25	6	13	2	3	0	215

Table 5.2: Breakdown of identified Discrepancy Categories by Source Category.

Source Category	Synonyms		Parents		Categories		Definitions		Terminology		Citations		Total
	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp	Exp	Imp	
Established Standards	3	2	6	0	10	2	9	2	3	0	0	0	37
"Meta-level" Collections	8	4	7	3	7	12	16	0	10	2	4	0	73
Textbooks	12	1	8	3	2	0	17	1	7	0	0	0	51
Papers and Other Documents	14	7	8	0	9	2	5	0	7	2	0	0	54
Total	37	14	29	6	28	16	47	3	27	4	4	0	215

5.1 Discrepancy Classes

The following sections list observed discrepancies grouped by *how* the discrepancy manifests. These include Mistakes, Omissions, Contradictions, Ambiguities, Overlaps, and Redunancies.

5.1.1 Mistakes

The following are cases where information is incorrect; this includes cases Terminology included that should *not* have been, untrue claims about Citations, and simple typos:

1. Since keyword-driven testing can be used for automated *or* manual testing (ISO/IEC and IEEE, 2016, pp. 4, 6), the claim that "test cases can be either manual test cases or keyword test cases" (p. 6) is incorrect.

2. The terms "acceleration tolerance testing" and "acoustic tolerance testing" seem to only refer to software testing in (Firesmith, 2015, p. 56); elsewhere, they seem to refer to testing the acoustic tolerance of rats (Holley et al., 1996) or the acceleration tolerance of astronauts (Morgun et al., 1999, p. 11), aviators (Howe and Johnson, 1995, pp. 27, 42), or catalysts (Liu et al., 2023, p. 1463), which don't exactly seem relevant…

Is this a scope discrep?

3. Patton (2006, p. 119) says that branch testing is "the simplest form of path testing" which seems incorrect.

4. Peters and Pedrycz claim that "structural testing subsumes white box testing" but they seem to describe the same thing: they say "structure tests are aimed at exercising the internal logic of a software system" and "in white box testing …, using detailed knowledge of code, one creates a battery of tests in such a way that they exercise all components of the code (say, statements, branches, paths)" on the same page (2000, p. 447)!

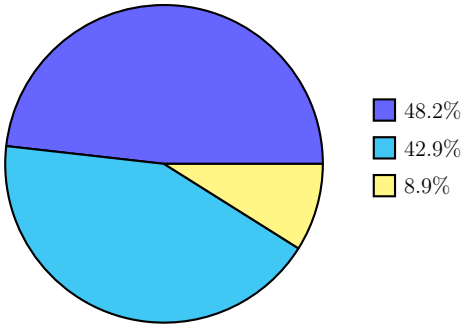
OG Beizer

5. Kam (2008, p. 46) says that the goal of negative testing is "showing that a component or system does not work" which is not true; if robustness is an important quality for the system, then testing the system "in a way for which it was not intended to be used" (Hamburg and Mogyorodi, 2024) (i.e., negative testing) is one way to help test this!

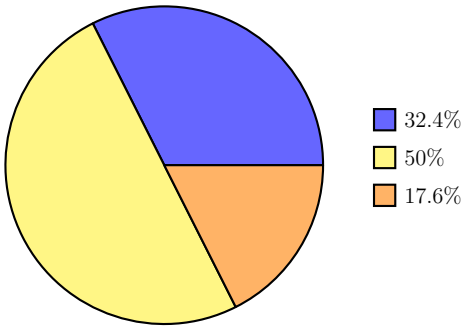
6. A typo in (ISO/IEC and IEEE, 2021, Fig. 2) means that "specification-based techniques" is listed twice, when the latter should be "structure-based techniques".

7. ISO/IEC and IEEE use the same definition for "partial correctness" (2017, p. 314) and "total correctness" (p. 480).

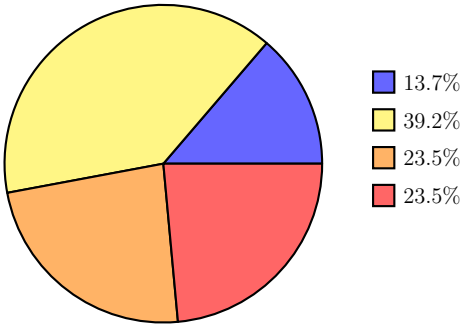
8. The definition of "math testing" given by Hamburg and Mogyorodi (2024) is too specific to be useful, likely taken from an example instead of a general definition: "testing to determine the correctness of the pay table implementation, the random number generator results, and the return to player computations".



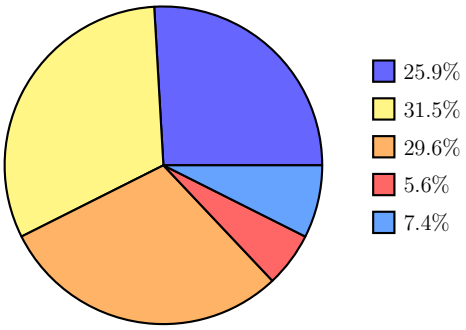
(a) Discrepancies found in Established Standards.



(b) Discrepancies found in "Meta-level" Collections.



(c) Discrepancies found in Textbooks.



(d) Discrepancies found in Papers and Other Documents.

Legend

- Within a single document
- Between documents by the same author(s) or standards organization(s)
- Between a document from this category and a standard
- Between a document from this category and a "meta-level" document
- Between a document from this category and a textbook
- Between a document from this category and a paper

Figure 5.1: Sources of discrepancies based on source category.

9. A similar issue exists with multiplayer testing, where its definition specifies "the casino game world" (Hamburg and Mogyorodi, 2024).

10. "Par sheet testing" from (Hamburg and Mogyorodi, 2024) seems to refer to the specific example brought up in this definition discrepancy and does not seem more widely applicable, since a "PAR sheet" is "a list of all the symbols on each reel of a slot machine" (Bluejay, 2024).

Does this belong here?

11. The source that Hamburg and Mogyorodi (2024) cite for the definition of "test type" does not seem to actually provide a definition.

12. The same is true for "visual testing" (Hamburg and Mogyorodi, 2024).

13. The same is true for "security attack" (Hamburg and Mogyorodi, 2024).

14. Doğan et al. (2014, p. 184) claim that Sakamoto et al. (2013) define "prime path coverage", but they do not.

15. Peters and Pedrycz imply that decision coverage is a child of both c-use coverage *and* p-use coverage (2000, Fig. 12.31); this seems incorrect, since decisions are the result of p-uses, *not* c-uses, and only the p-use relation is implied by (ISO/IEC and IEEE, 2021, Fig. F.1).

OG Reid 1996

16. Kam (2008) misspells "state-based" as "state-base" (pp. 13, 15) and "stated-base" (Tab. 1).

17. Sneed and Göschl (2000, p. 18) give "white-box testing", "grey-box testing", and "black-box testing" as synonyms for "module testing", "integration testing", and "system testing", respectively, but this mapping is incorrect; black-box testing can be performed on a module, for example.

OG Hetzel88

find source

18. The previous discrepancy makes the claim that "red-box testing" is a synonym for "acceptance testing" (Sneed and Göschl, 2000, p. 18) lose credibility.

19. Kam (2008, p. 46) seems to imply that "mutation testing" is a synonym of "back-to-back testing" but these are two quite distinct techniques.

5.1.2 Omissions

The following are cases where information (usually Definitions) *should have* been included but was not:

1. Integration testing, system testing, and system integration testing are all listed as "common test levels" (ISO/IEC and IEEE, 2022, p. 12; 2021, p. 6), but no definitions are given for the latter two, making it unclear what "system integration testing" is; it is a combination of the two? somewhere on the spectrum between them? It is listed as a child of integration testing by Hamburg and Mogyorodi (2024) and of system testing by Firesmith (2015, p. 23).

2. Similarly, component testing, integration testing, and component integration testing are all listed in (ISO/IEC and IEEE, 2017), but "component integration testing" is only defined as "testing of groups of related components" (ISO/IEC and IEEE, 2017, p. 82); it is a combination of the two? somewhere on the spectrum between them? As above, it is listed as a child of integration testing by Hamburg and Mogyorodi (2024).

3. Kam (2008, p. 42) says "See *boundary value analysis*," for the glossary entry of "boundary value testing" but does not provide this definition.

4. The acronym "SoS" is used but not defined by Firesmith (2015, p. 23).

5. Van Vliet defines many types of data flow coverage, including all-p-uses, all-p-uses/some-c-uses, and all-c-uses/some-p-uses (2000, p. 425), but excludes all-c-uses, which is implied by these definitions and defined elsewhere (ISO/IEC and IEEE, 2021, p. 27; 2017, p. 83; Peters and Pedrycz, 2000, p. 479).

6. Bas (2024, p. 16) lists "three [backup] location categories: local, offsite and cloud based [sic]" but does not define or discuss "offsite backups" (pp. 16-17).

7. Gerrard (2000a, Tab. 2) makes a distinction between "transaction verification" and "transaction testing" and uses the phrase "transaction flows" (Fig. 5) but doesn't explain them.

8. Availability testing isn't assigned to a test priority (Gerrard, 2000a, Tab. 2), despite the claim that "the test types[2] have been allocated a slot against the four test priorities" (p. 13); I think usability and/or performance would have made sense.

5.1.3 Contradictions

The following are cases where multiple sources of information (sometimes within the same document!) disagree; note that cases where all sources of information are incorrect are considered contradictions and not Mistakes, since this would require analysis that has not been performed yet:

1. While ISO/IEC and IEEE (2022, p. 8) say regression testing and retesting are two distinct approaches (as does Firesmith (2015, p. 34)), they define regression testing as a form of "selective retesting" in (2017, p. 372) (as does Washizaki (2024, pp. 5-8, 6-5, 7-5 to 7-6)). Moreover, the two possible variations of regression testing given by (van Vliet, 2000, p. 411) are "retest-all" and "selective retest", which is possibly the source of the above misconception; these two in tandem create a cyclic relation between regression testing and selective retesting.

Are these separate approaches?

[2] "Each type of test addresses a different risk area" (Gerrard, 2000a, p. 12), which is distinct from the notion of "test type" described in Table 3.1.

2. A component is an "entity with discrete structure … within a system considered at a particular level of analysis" (ISO/IEC, 2023b) and "the terms module, component, and unit [sic] are often used interchangeably or defined to be subelements of one another in different ways depending upon the context" with no standardized relationship (ISO/IEC and IEEE, 2017, p. 82). For example, Hamburg and Mogyorodi (2024) define them as synonyms while Baresi and Pezzè (2006, p. 107) say "components differ from classical modules for being re-used in different contexts independently of their development". Additionally, since components are structurally, functionally, or logically discrete (ISO/IEC and IEEE, 2017, p. 419) and "can be tested in isolation" (Hamburg and Mogyorodi, 2024), "unit/component/module testing" could refer to the testing of both a module *and* a specific function in a module, introducing a further level of ambiguity.

See #14

3. Performance testing and security testing are given as subtypes of reliability testing by (ISO/IEC, 2023a), but these are all listed separately by (Firesmith, 2015, p. 53).

4. Path testing can "aim[] to execute all entry-to-exit control flow paths in a SUT's control flow graph" (Washizaki, 2024, p. 5-13) or "all or selected paths through a computer program" (ISO/IEC and IEEE, 2017, p. 316; similar in Patton, 2006, p. 119).

5. The structure of tours can be defined as either quite general (ISO/IEC and IEEE, 2022, p. 34) or "organized around a special focus" (Hamburg and Mogyorodi, 2024).

6. Alpha testing is performed by "users within the organization developing the software" (ISO/IEC and IEEE, 2017, p. 17), "a small, selected group of potential users" (Washizaki, 2024, p. 5-8), or "roles outside the development organization" conducted "in the developer's test environment" (Hamburg and Mogyorodi, 2024).

7. While Patton (2006, p. 120) implies that condition testing is a sub-technique of path testing, van Vliet (2000, Fig. 13.17) says that multiple condition coverage (which seems to be a synonym of condition coverage (p. 422)) does not subsume and is not subsumed by path coverage.

8. Load testing is performed with loads "between anticipated conditions of low, typical, and peak usage" (ISO/IEC and IEEE, 2022, p. 5) or loads that are as large as possible (Patton, 2006, p. 86).

9. State testing requires that "all states in the state model … [are] 'visited' " in (ISO/IEC and IEEE, 2021, p. 19) which is only one of its possible criteria in (Patton, 2006, pp. 82-83).

10. ISO/IEC and IEEE (2017, p. 456) say system testing is "conducted on a complete, integrated system" (which Peters and Pedrycz (2000, Tab. 12.3)

and van Vliet (2000, p. 439) agree with), while Patton (2006, p. 109) says it can also be done on "at least a major portion" of the product.

11. "Walkthroughs" and "structured walkthroughs" are given as synonyms by Hamburg and Mogyorodi (2024) but Peters and Pedrycz (2000, p. 484) imply that they are different, saying a more structured walkthrough may have specific roles.

12. Patton (2006, p. 92, emphasis added) says that reviews are "*the* process[es] under which static white-box testing is performed" but correctness proofs are given as another example by van Vliet (2000, pp. 418-419).

13. While a computation data use is defined as the "use of the value of a variable in *any* type of statement" (ISO/IEC and IEEE, 2021, p. 2; 2017, p. 83, emphasis added), it is often qualified to *not* be a predicate data use (van Vliet, 2000, p. 424; implied by ISO/IEC and IEEE, 2021, p. 27).

OG 2015

14. ISO/IEC and IEEE define an "extended entry (decision) table" both as a decision table where the "conditions consist of multiple values rather than simple Booleans" (2021, p. 18) and one where "the conditions and actions are generally described but are incomplete" (2017, p. 175).

OG ISO1984

15. ISO/IEC and IEEE's definition of "all-c-uses testing"—testing that aims to execute all data "use[s] of the value of a variable in any type of statement" (2017, p. 83)—is *much* more vague than the definition given in (2021, p. 27): testing that exercises "control flow sub-paths from each variable definition to each c-use of that definition (with no intervening definitions)" (similar in van Vliet, 2000, p. 425; Peters and Pedrycz, 2000, p. 479).

OG 2015

16. The claim that "test cases can be either manual test cases or keyword test cases" (ISO/IEC and IEEE, 2016, p. 6) implies that "keyword-driven testing" could be a synonym of "automated testing" instead of its child, which seems more reasonable (2016, p. 4; 2022, p. 35).

17. Different capitalizations of the abbreviations of "computation data use" and "predicate data use" are used: the lowercase "c-use" and "p-use" (ISO/IEC and IEEE, 2021, pp. 3, 27-29, 35-36, 114-155, 117-118, 129; 2017, p. 124; Peters and Pedrycz, 2000, p. 477, Tab. 12.6) and the uppercase "C-use" and "P-use" (van Vliet, 2000, pp. 424-425).

18. Similarly for "definition-use" (such as in "definition-use path"), both the lowercase "du" (ISO/IEC and IEEE, 2021, pp. 3, 27, 29, 35, 119-121, 129; Peters and Pedrycz, 2000, pp. 478-479) and the uppercase "DU" (van Vliet, 2000, p. 425) are used.

19. Van Vliet specifies that every successor of a data definition use needs to be executed as part of all-uses testing (2000, pp. 424-425), but this condition is not included elsewhere (ISO/IEC and IEEE, 2021, pp. 28-29; 2017, p. 120; Peters and Pedrycz, 2000, pp. 478-479).

20. All-du-paths testing is usually defined as exercising all "loop-free control flow sub-paths from each variable definition to every use (both p-use and c-use) of that definition (with no intervening definitions)" (ISO/IEC and IEEE, 2021, p. 29; similar in 2017, p. 125; Washizaki, 2024, p. 5-13; Peters and Pedrycz, 2000, p. 479); however, paths containing simple cycles may also be required (van Vliet, 2000, p. 425).

21. Van Vliet says that all-p-uses testing is only stronger than all-edges (branch) testing if there are infeasible paths (2000, pp. 432-433), but ISO/IEC and IEEE do not specify this caveat (2021, Fig. F.1).

OG Reid, 1996

22. Similarly, van Vliet says that all-du-paths testing is only stronger than all-uses testing if there are infeasible paths (2000, pp. 432-433), but Washizaki does not specify this caveat (2024, p. 5-13).

23. Acceptance testing is "usually performed by the purchaser … with the … vendor" (ISO/IEC and IEEE, 2017, p. 5), "may or may not involve the developers of the system" (Bourque and Fairley, 2014, p. 4-6), and/or "is often performed under supervision of the user organization" (van Vliet, 2000, p. 439); these descriptions of who the testers are contradict each other *and* all introduce some uncertainty ("usually", "may or may not", and "often", respectively).

Does this merit counting this as an Ambiguity as well as a Contradiction?

24. Although ad hoc testing is classified as a "technique" (Washizaki, 2024, p. 5-14), it is one in which "no recognized test design technique is used" (Kam, 2008, p. 42).

5.1.4 Ambiguities

The following are cases where information (usually Definitions or distinctions between Terminology) is unclear:

1. The distinctions between development testing (ISO/IEC and IEEE, 2017, p. 136), developmental testing (Firesmith, 2015, p. 30), and developer testing (Firesmith, 2015, p. 39; Gerrard, 2000a, p. 11) are unclear and seem miniscule.

Is this a def discrep?

2. Hamburg and Mogyorodi (2024) define "Machine Learning (ML) model testing" and "ML functional performance" in terms of "ML functional performance criteria", which is defined in terms of "ML functional performance metrics", which is defined as "a set of measures that relate to the functional correctness of an ML system". The use of "performance" (or "correctness") in these definitions is at best ambiguous and at worst incorrect.

3. "Installability testing" is given as a test type (ISO/IEC and IEEE, 2022, p. 22; 2021, p. 38; 2017, p. 228), while "installation testing" is given as a test level (van Vliet, 2000, p. 439; implied by Washizaki, 2024, p. 5-8). Since "installation testing" is not given as an example of a test level throughout

the sources that describe them (see Section 3.2.1), it is likely that the term "installability testing" with all its related information should be used instead.

4. Hamburg and Mogyorodi (2024) claim that code inspections are related to peer reviews but Patton (2006, pp. 94-95) makes them quite distinct.

5. "Data definition" is defined as a "statement where a variable is assigned a value" (ISO/IEC and IEEE, 2021, p. 3; 2017, p. 115; similar in 2012, p. 27; van Vliet, 2000, p. 424), but for functional programming languages such as Haskell with immutable variables (Wikibooks Contributors, 2023), this could cause confusion and/or be imprecise.

OG 2015

6. While ergonomics testing is out of scope (as it tests hardware, not software), its definition of "testing to determine whether a component or system and its input devices are being used properly with correct posture" (Hamburg and Mogyorodi, 2024) seems to focus on how the system is *used* as opposed to the system *itself*.

7. Hamburg and Mogyorodi (2024) describe the term "software in the loop" as a kind of testing, while the source they reference seems to describe "Software-in-the-Loop-Simulation" as a "simulation environment" that may support software integration testing (Knüvener Mackert GmbH, 2022, p. 153); is this a testing approach or a tool that supports testing?

8. While model testing is said to test the object under test, it seems to describe testing the models themselves (Firesmith, 2015, p. 20); using the models to test the object under test seems to be called "driver-based testing" (p. 33).

9. Similarly, it is ambiguous whether "tool/environment testing" refers to testing the tools/environment *themselves* or *using* them to test the object under test; the latter is implied, but the wording of its subtypes (Firesmith, 2015, p. 25) seems to imply the former.

10. Retesting and regression testing seem to be separated from the rest of the testing approaches (ISO/IEC and IEEE, 2022, p. 23), but it is not clearly detailed why; Barbosa et al. (2006, p. 3) consider regression testing to be a test level, but since it is not given as an example of a test level throughout the sources that describe them (see Section 3.2.1), it is likely that it is at best not universal and at worst incorrect.

11. "Conformance testing" is implied to be a synonym of "compliance testing" by Kam (2008, p. 43) which only makes sense because of the vague definition of the latter: "testing to determine the compliance of the component or system".

5.1.5 Overlaps

The following are cases where information overlaps, such as nonatomic Definitions and Terminology:

1. The SWEBOK Guide V4 defines "privacy testing" as testing that "assess[es] the security and privacy of users' personal data to prevent local attacks" (Washizaki, 2024, p. 5-10); this seems to overlap (both in scope and name) with the definition of "security testing" in (ISO/IEC and IEEE, 2022, p. 7): testing "conducted to evaluate the degree to which a test item, and associated data and information, [sic] are protected so that" only "authorized persons or systems" can use them as intended.

2. "Orthogonal array testing" (Washizaki, 2024, pp. 5-1, 5-11; implied by Valcheva, 2013, pp. 467, 473; Yu et al., 2011, pp. 1573-1577, 1580) and "operational acceptance testing" (Firesmith, 2015, p. 30) have the same acronym ("OAT").

3. ISO/IEC and IEEE say that "test level" and "test phase" are synonyms, both meaning a "specific instantiation of [a] test sub-process" (2017, pp. 469, 470; 2013, p. 9), but there are also alternative definitions for them. "Test level" can also refer to the scope of a test process; for example, "across the whole organization" or only "to specific projects" (2022, p. 24), while "test phase" can also refer to the "period of time in the software life cycle" when testing occurs (2017, p. 470), usually after the implementation phase (2017, pp. 420, 509; Perry, 2006, p. 56).

4. ISO/IEC and IEEE provide a definition for "inspections and audits" (2017, p. 228), despite also giving definitions for "inspection" (p. 227) and "audit" (p. 36); while the first term *could* be considered a superset of the latter two, this distinction doesn't seem useful.

5. "Customer acceptance testing" and "contract(ual) acceptance testing" have the same acronym ("CAT") (Firesmith, 2015, p. 30).

6. The same is true for "hardware-in-the-loop testing" and "human-in-the-loop testing" ("HIL") (Firesmith, 2015, p. 23), although Preuße et al. (2012, p. 2) use "HiL" for the former.

7. "Visual browser validation" is described as both static *and* dynamic in the same table (Gerrard, 2000a, Tab. 2), even though they are implied to be orthogonal classifications: "test types can be static *or* dynamic" (p. 12, emphasis added).

5.1.6 Redunancies

The following are cases of redundant information:

1. While correct, ISTQB's definition of "specification-based testing" is not helpful: "testing based on an analysis of the specification of the component or system" (Hamburg and Mogyorodi, 2024).

2. The phrase "continuous automated testing" (Gerrard, 2000a, p. 11) is redundant since continuous testing is a sub-category of automated testing (ISO/IEC and IEEE, 2022, p. 35; Hamburg and Mogyorodi, 2024).

5.2 Discrepancy Categories

The following sections list observed discrepancies grouped by *what area* the discrepancy manifests in. These include Synonym Relation Discrepancies, Parent-Child Relation Discrepancies, Test Approach Category Discrepancies, Definition Discrepancies, Terminology Discrepancies, and Citation Discrepancies.

5.2.1 Synonym Relation Discrepancies

more in Umar2000

The same approach often has many names. For example, *specification-based testing* is also called:

1. Black-Box Testing (ISO/IEC and IEEE, 2022, p. 9; 2021, p. 8; 2017, p. 431; Washizaki, 2024, p. 5-10; Hamburg and Mogyorodi, 2024; Firesmith, 2015, p. 46 (without hyphen); Sakamoto et al., 2013, p. 344; van Vliet, 2000, p. 399)
2. Closed-Box Testing (ISO/IEC and IEEE, 2022, p. 9; 2017, p. 431)
3. Functional Testing[3] (ISO/IEC and IEEE, 2017, p. 196; Kam, 2008, p. 44; van Vliet, 2000, p. 399; implied by ISO/IEC and IEEE, 2021, p. 129; 2017, p. 431)
4. Domain Testing (Washizaki, 2024, p. 5-10)
5. Input Domain-Based Testing (implied by Bourque and Fairley, 2014, p. 4-8)

While some of these synonyms may express mild variations, their core meaning is nevertheless the same. Here we use the terms "specification-based" and "structure-based testing" as they articulate the source of the information for designing test cases, but a team or project also using gray-box testing may prefer the terms "black-box" and "white-box testing" for consistency. Thus, synonyms do not inherently signify a discrepancy. Unfortunately, there are many instances of incorrect or ambiguous synonyms, such as the following:

1. A component is an "entity with discrete structure … within a system considered at a particular level of analysis" (ISO/IEC, 2023b) and "the terms module, component, and unit [sic] are often used interchangeably or defined to be subelements of one another in different ways depending upon the context" with no standardized relationship (ISO/IEC and IEEE, 2017, p. 82). For example, Hamburg and Mogyorodi (2024) define them as synonyms while Baresi and Pezzè (2006, p. 107) say "components differ from classical modules for being re-used in different contexts independently of their development". Additionally, since components are structurally, functionally, or logically discrete (ISO/IEC and IEEE, 2017, p. 419) and "can be tested in isolation" (Hamburg and Mogyorodi, 2024), "unit/component/module testing" could refer to the testing of both a module *and* a specific function in a module, introducing a further level of ambiguity.

See #14

[3] This may be an outlier; see Section 5.3.1.

2. Hamburg and Mogyorodi (2024) claim that code inspections are related to peer reviews but Patton (2006, pp. 94-95) makes them quite distinct.

3. "Walkthroughs" and "structured walkthroughs" are given as synonyms by Hamburg and Mogyorodi (2024) but Peters and Pedrycz (2000, p. 484) imply that they are different, saying a more structured walkthrough may have specific roles.

4. Peters and Pedrycz claim that "structural testing subsumes white box testing" but they seem to describe the same thing: they say "structure tests are aimed at exercising the internal logic of a software system" and "in white box testing …, using detailed knowledge of code, one creates a battery of tests in such a way that they exercise all components of the code (say, statements, branches, paths)" on the same page (2000, p. 447)!

5. ISO/IEC and IEEE say that "test level" and "test phase" are synonyms, both meaning a "specific instantiation of [a] test sub-process" (2017, pp. 469, 470; 2013, p. 9), but there are also alternative definitions for them. "Test level" can also refer to the scope of a test process; for example, "across the whole organization" or only "to specific projects" (2022, p. 24), while "test phase" can also refer to the "period of time in the software life cycle" when testing occurs (2017, p. 470), usually after the implementation phase (2017, pp. 420, 509; Perry, 2006, p. 56).

6. The claim that "test cases can be either manual test cases or keyword test cases" (ISO/IEC and IEEE, 2016, p. 6) implies that "keyword-driven testing" could be a synonym of "automated testing" instead of its child, which seems more reasonable (2016, p. 4; 2022, p. 35).

OG Hetzel88

7. Sneed and Göschl (2000, p. 18) give "white-box testing", "grey-box testing", and "black-box testing" as synonyms for "module testing", "integration testing", and "system testing", respectively, but this mapping is incorrect; black-box testing can be performed on a module, for example.

find source

8. The previous discrepancy makes the claim that "red-box testing" is a synonym for "acceptance testing" (Sneed and Göschl, 2000, p. 18) lose credibility.

9. Kam (2008, p. 46) seems to imply that "mutation testing" is a synonym of "back-to-back testing" but these are two quite distinct techniques.

10. "Conformance testing" is implied to be a synonym of "compliance testing" by Kam (2008, p. 43) which only makes sense because of the vague definition of the latter: "testing to determine the compliance of the component or system".

There are also cases in which a term is given as a synonym to two (or more) disjoint, unrelated terms, making the relation between the given synonyms ambiguous. Ten of these cases were identified through automatic analysis of the generated graphs, listed below:

1. **Condition Testing:**
    - Branch Condition Combination Testing (Patton, 2006, p. 120; Sharma et al., 2021, Fig. 1)
    - Branch Condition Testing (Hamburg and Mogyorodi, 2024)
    - Decision Testing (Washizaki, 2024, p. 5-13)
2. **Invalid Testing:**
    - Error Tolerance Testing (Kam, 2008, p. 45)
    - Negative Testing (Hamburg and Mogyorodi, 2024; implied by ISO/IEC and IEEE, 2021, p. 10)
3. **Soak Testing:**
    - Endurance Testing (ISO/IEC and IEEE, 2021, p. 39)
    - Reliability Testing[4] (Gerrard, 2000a, Tab. 2; 2000b, Tab. 1, p. 26)
4. **User Scenario Testing:**
    - Scenario Testing (Hamburg and Mogyorodi, 2024)
    - Use Case Testing[5] (Kam, 2008, p. 48; although "an actor can be a user or another system" (ISO/IEC and IEEE, 2021, p. 20))
5. **Functional Testing:**
    - Behavioural Testing (van Vliet, 2000, p. 399)
    - Correctness Testing (Washizaki, 2024, p. 5-7)
    - Specification-based Testing (ISO/IEC and IEEE, 2017, p. 196; Kam, 2008, p. 44; van Vliet, 2000, p. 399; implied by ISO/IEC and IEEE, 2021, p. 129; 2017, p. 431)
6. **Link Testing:**
    - Branch Testing (implied by ISO/IEC and IEEE, 2021, p. 24)
    - Component Integration Testing (Kam, 2008, p. 45)
    - Integration Testing (implied by Gerrard, 2000a, p. 13)
7. **Exhaustive Testing:**
    - Branch Condition Combination Testing (if "each subcondition is viewed as a single input" in Peters and Pedrycz, 2000, p. 464)

[4]Endurance testing is given as a kind of reliability testing by Firesmith (2015, p. 55), although the terms are not synonyms.

[5]"Scenario testing" and "use case testing" are given as synonyms by Hamburg and Mogyorodi (2024) and Kam (2008, pp. 47-49) but listed separately by ISO/IEC and IEEE (2022, p. 22), who also give "use case testing" as a "common form of scenario testing" (2021, p. 20). This implies that "use case testing" may instead be a child of "user scenario testing" (see Table 5.3).

- Path Testing (van Vliet, 2000, p. 421)

8. **State-based Testing:**
   - State Transition Testing (Firesmith, 2015, p. 47)
   - State-based Web Browser Testing (Doğan et al., 2014, p. 193)
9. **Static Verification:**
   - Static Assertion Checking[6] (Chalin et al., 2006, p. 343)
   - Static Testing (implied by Chalin et al., 2006, p. 343)
10. **Testing-to-Fail:**
    - Forcing Exception Testing (Patton, 2006, pp. 66-67, 78)
    - Negative Testing (Patton, 2006, pp. 67, 78, 84-87)

5.2.2 Parent-Child Relation Discrepancies

Parent-Child Relations are also not immune to difficulties, as shown by the following discrepancies:

1. While ISO/IEC and IEEE (2022, p. 8) say regression testing and retesting are two distinct approaches (as does Firesmith (2015, p. 34)), they define regression testing as a form of "selective retesting" in (2017, p. 372) (as does Washizaki (2024, pp. 5-8, 6-5, 7-5 to 7-6)). Moreover, the two possible variations of regression testing given by (van Vliet, 2000, p. 411) are "retest-all" and "selective retest", which is possibly the source of the above misconception; these two in tandem create a cyclic relation between regression testing and selective retesting.

   Are these separate approaches?

2. Performance testing and security testing are given as subtypes of reliability testing by (ISO/IEC, 2023a), but these are all listed separately by (Firesmith, 2015, p. 53).
3. Patton (2006, p. 119) says that branch testing is "the simplest form of path testing" which seems incorrect.
4. While Patton (2006, p. 120) implies that condition testing is a sub-technique of path testing, van Vliet (2000, Fig. 13.17) says that multiple condition coverage (which seems to be a synonym of condition coverage (p. 422)) does not subsume and is not subsumed by path coverage.

[6] Chalin et al. (2006, p. 343) list Runtime Assertion Checking (RAC) and Software Verification (SV) as "two complementary forms of assertion checking"; based on how the term "static assertion checking" is used by Lahiri et al. (2013, p. 345), it seems like this should be the complement to RAC instead.

5. ISO/IEC and IEEE provide a definition for "inspections and audits" (2017, p. 228), despite also giving definitions for "inspection" (p. 227) and "audit" (p. 36); while the first term *could* be considered a superset of the latter two, this distinction doesn't seem useful.

6. Peters and Pedrycz imply that decision coverage is a child of both c-use coverage *and* p-use coverage (2000, Fig. 12.31); this seems incorrect, since decisions are the result of p-uses, *not* c-uses, and only the p-use relation is implied by (ISO/IEC and IEEE, 2021, Fig. F.1).

OG Reid 1996

testing and security testing are given as subtypes of reliability testing by (ISO/IEC, 2023a), but these are all listed separately by (Firesmith, 2015, p. 53).

Additionally, some self-referential definitions imply that a test approach is a parent of itself. Since these are by nature self-contained within a given source, these are counted *once* as explicit discrepancies within their sources in Tables 5.1 and 5.2. The following examples were identified through automatic analysis of the generated graphs:

1. Performance Testing (Gerrard, 2000a, Tab. 2; 2000b, Tab. 1)

2. System Testing (Firesmith, 2015, p. 23)

3. Usability Testing (Gerrard, 2000a, Tab. 2; 2000b, Tab. 1)

Interestingly, performance testing is *not* described as a sub-approach of usability testing by (Gerrard, 2000a;b), which would have been more meaningful information to capture.

There are also pairs of synonyms where one is described as a sub-approach of the other, abusing the meaning of "synonym" and causing confusion. We identified 14 of these pairs through automatic analysis of the generated graphs, which are given in Table 5.3. Of particular note is the relation between path testing and exhaustive testing. While van Vliet (2000, p. 421) claims that path testing done completely "is equivalent to exhaustively testing the program"[7], this overlooks the effect of implementation issues (Peters and Pedrycz, 2000, p. 476) and input data (2000, p. 467; Patton, 2006, p. 121) on the code's behaviour. Exhaustive testing requires "all combinations of input values *and* preconditions … [to be] tested" (ISO/IEC and IEEE, 2022, p. 4, emphasis added; similar in Hamburg and Mogyorodi, 2024; Patton, 2006, p. 121). Finally, it is worth pointing out that fault tolerance testing may also be a sub-approach of reliability testing (ISO/IEC and IEEE, 2017, p. 375; Washizaki, 2024, p. 7-10), which is distinct from robustness testing (Firesmith, 2015, p. 53).

[7]The contradictory definitions of path testing given in Definitions Discrepancy 4 add another layer of complexity to this claim.

Table 5.3: Pairs of test approaches with a parent-child *and* synonym relation.

"Child" → "Parent"	**Parent-Child Source(s)**	**Synonym Source(s)**
All Transitions Testing → State Transition Testing	(ISO/IEC and IEEE, 2021, p. 19)	(Kam, 2008, p. 15)
Co-existence Testing → Compatibility Testing	(ISO/IEC, 2023a; ISO/IEC and IEEE, 2022, p. 3; 2021, Tab. A.1)	(ISO/IEC and IEEE, 2021, p. 37)
Fault Tolerance Testing → Robustness Testing	(Firesmith, 2015, p. 56)	(Hamburg and Mogyorodi, 2024)
Functional Testing → Specification-based Testing	(ISO/IEC and IEEE, 2021, p. 38)	(ISO/IEC and IEEE, 2017, p. 196; Kam, 2008, p. 44; van Vliet, 2000, p. 399; implied by ISO/IEC and IEEE, 2021, p. 129; 2017, p. 431)
Orthogonal Array Testing → Pairwise Testing	(Mandl, 1985, p. 1055)	(Washizaki, 2024, p. 5-11; Valcheva, 2013, p. 473)
Path Testing → Exhaustive Testing	(Peters and Pedrycz, 2000, pp. 466-467, 476; implied by Patton, 2006, pp. 120-121)	(van Vliet, 2000, p. 421)
Performance Testing → Performance-related Testing	(ISO/IEC and IEEE, 2022, p. 22; 2021, p. 38)	(Moghadam, 2019, p. 1187)
Structural Testing → Structure-based Testing	(Patton, 2006, pp. 105-121)	(ISO/IEC and IEEE, 2022, p. 9; 2017, pp. 443-444; Hamburg and Mogyorodi, 2024)
Use Case Testing → Scenario Testing	(ISO/IEC and IEEE, 2021, p. 20; OG Hass, 2008)	(Hamburg and Mogyorodi, 2024; Kam, 2008, pp. 47-49)
Branch Condition Combination Testing → Decision Testing	(implied by the caveat of "atomic conditions" in Hamburg and Mogyorodi, 2024)	(Washizaki, 2024, p. 5-13)
Dynamic Analysis → Dynamic Testing	(inferred from its static counterpart in ISO/IEC and IEEE, 2022, pp. 9, 17, 25, 28; Hamburg and Mogyorodi, 2024)	(ISO/IEC and IEEE, 2017, p. 149)
Reviews → Structural Analysis	(Patton, 2006, p. 92)	(implied by Patton, 2006, p. 92)

Continued on next page

Table 5.3: Pairs of test approaches with a parent-child *and* synonym relation. (Continued)

"Child" → "Parent"	**Parent-Child Source(s)**	**Synonym Source(s)**
Beta Testing → User Testing	(implied by Firesmith, 2015, p. 39)	(implied by Firesmith, 2015, p. 39)
Branch Condition Combination Testing → Exhaustive Testing	(implied by Patton, 2006, p. 121)	(if "each subcondition is viewed as a single input" in Peters and Pedrycz, 2000, p. 464)

5.2.3 Test Approach Category Discrepancies

While the IEEE categorization of testing approaches described in Table 3.1 is useful, it is not without its faults. One issue, which is not inherent to the categorization itself, is the fact that it is not used consistently (see Table 3.2). The most blatant example of this is that ISO/IEC and IEEE (2017, p. 286) describe mutation testing as a methodology, even though this is not one of the categories *they* created! Additionally, the boundaries between approaches within a category may be unclear: "although each technique is defined independently of all others, in practice [sic] some can be used in combination with other techniques" (ISO/IEC and IEEE, 2021, p. 8). For example, "the test coverage items derived by applying equivalence partitioning can be used to identify the input parameters of test cases derived for scenario testing" (p. 8). Even the categories themselves are not consistently defined, and some approaches are categorized differently by different sources; these differences are tracked so they can be analyzed more systematically.

See #21

1. Since keyword-driven testing can be used for automated *or* manual testing (ISO/IEC and IEEE, 2016, pp. 4, 6), the claim that "test cases can be either manual test cases or keyword test cases" (p. 6) is incorrect.

2. Retesting and regression testing seem to be separated from the rest of the testing approaches (ISO/IEC and IEEE, 2022, p. 23), but it is not clearly detailed why; Barbosa et al. (2006, p. 3) consider regression testing to be a test level, but since it is not given as an example of a test level throughout the sources that describe them (see Section 3.2.1), it is likely that it is at best not universal and at worst incorrect.

3. Although ad hoc testing is classified as a "technique" (Washizaki, 2024, p. 5-14), it is one in which "no recognized test design technique is used" (Kam, 2008, p. 42).

4. "Visual browser validation" is described as both static *and* dynamic in the same table (Gerrard, 2000a, Tab. 2), even though they are implied to be orthogonal classifications: "test types can be static *or* dynamic" (p. 12, emphasis added).

Some category discrepancies can be detected automatically, given in Table 5.4; of these, experience-based testing is of particular note. ISO/IEC and IEEE categorize experience-based testing as both a test design technique and a test practice on the same page—twice (2022, Fig. 2, p. 34)! These authors previously say "experience-based testing practices like exploratory testing … are not … techniques for designing test cases", although they "can use … test techniques" (2021, p. viii). In addition to contradicting other authors (including themselves in (2022, p. 34)!), it also implies that "experience-based test design techniques" are techniques used by the *practice* of experience-based testing, not that experience-based testing is *itself* a test technique. If this is the case, it makes the distinction between "practice" and "technique" less useful, which may explain why experience-based testing is categorized inconsistently in the literature.

See #64

Subapproaches of experience-based tesing, such as error guessing and exploratory testing, are also categorized ambiguously, causing confusion on how categories and

parent-child relations (see Section 3.2.2) interact. ISO/IEC and IEEE (2022, p. 34, emphasis added) say "[another standard (ISO/IEC and IEEE, 2021)] describes the experience-based test *design technique* of error guessing. Other experience-based test *practices* include (but are not limited to) exploratory testing …, tours, attacks, and checklist-based testing"; this seems to imply that error guessing is both a technique *and* a practice, which does not make sense if these categories are orthogonal. Similarly, the conflicting categorizations of beta testing in Table 5.4 may also propagate to closed beta testing and open beta testing; since this is an inferrence, it is omitted from that table and instead included in Table 5.5. These kinds of inconsistencies between parent and child test approach categorizations may indicate that categories are not transitive or that more thought must be given to them.

Table 5.4: Test approaches with more than one category.

Test Approach	Category 1	Category 2
Capacity Testing	Technique (ISO/IEC and IEEE, 2021, p. 38)	Type (ISO/IEC and IEEE, 2022, p. 22; 2013, p. 2; Firesmith, 2015, p. 53; implied by its quality (ISO/IEC, 2023a; ISO/IEC and IEEE, 2021, Tab. A.1))
Data-driven Testing	Practice (ISO/IEC and IEEE, 2022, p. 22)	Technique (Kam, 2008, p. 43; OG Fewster and Graham)
Endurance Testing	Technique (ISO/IEC and IEEE, 2021, p. 38)	Type (ISO/IEC and IEEE, 2013, p. 2; implied by Firesmith, 2015, p. 55)
Experience-based Testing	Practice (ISO/IEC and IEEE, 2022, pp. 22, 34; 2021, p. viii)	Technique (ISO/IEC and IEEE, 2022, pp. 4, 22; 2021, p. 4; Washizaki, 2024, p. 5-13; Hamburg and Mogyorodi, 2024; Firesmith, 2015, p. 46)
Exploratory Testing	Practice (ISO/IEC and IEEE, 2022, pp. 20, 22, 34; 2021, p. viii)	Technique (ISO/IEC and IEEE, 2022, p. 34; Washizaki, 2024, p. 5-14; inferred from experience-based testing)
Load Testing	Technique (ISO/IEC and IEEE, 2021, p. 38)	Type (ISO/IEC and IEEE, 2022, pp. 5, 20, 22; 2017, p. 253; OG IEEE 2013; Hamburg and Mogyorodi, 2024; implied by Firesmith, 2015, p. 54)
Model-based Testing	Practice (ISO/IEC and IEEE, 2022, p. 22; 2021, p. viii)	Technique (Kam, 2008, p. 4; implied by ISO/IEC and IEEE, 2021, p. 7; 2017, p. 469)
Mutation Testing	Methodology (ISO/IEC and IEEE, 2017, p. 286)	Technique (Washizaki, 2024, p. 5-15; van Vliet, 2000, pp. 428-429)
Performance Testing	Technique (ISO/IEC and IEEE, 2021, p. 38)	Type (ISO/IEC and IEEE, 2022, pp. 7, 22, 26-27; 2021, p. 7; implied by Firesmith, 2015, p. 53)
Proofs of Correctness	Artifact (ISO/IEC and IEEE, 2017, p. 355)	Technique (ISO/IEC and IEEE, 2017, p. 355; van Vliet, 2000, p. 418)
Proofs of Partial Correctness	Artifact (ISO/IEC and IEEE, 2017, p. 355)	Technique (ISO/IEC and IEEE, 2017, p. 355)
Proofs of Total Correctness	Artifact (ISO/IEC and IEEE, 2017, p. 355)	Technique (ISO/IEC and IEEE, 2017, p. 355)
Stress Testing	Technique (ISO/IEC and IEEE, 2021, p. 38)	Type (ISO/IEC and IEEE, 2022, pp. 9, 22; 2017, p. 442; implied by Firesmith, 2015, p. 54)

Continued on next page

Table 5.4: Test approaches with more than one category. (Continued)

Test Approach	Category 1	Category 2
A/B Testing	Practice (ISO/IEC and IEEE, 2022, p. 22)	Type (implied by Firesmith, 2015, p. 58)
Alpha Testing	Level (ISO/IEC and IEEE, 2022, p. 22; inferred from acceptance testing)	Type (implied by Firesmith, 2015, p. 58)
Attacks	Practice (ISO/IEC and IEEE, 2022, p. 34)	Technique (implied by Hamburg and Mogyorodi, 2024)
Beta Testing	Level (ISO/IEC and IEEE, 2022, p. 22; inferred from acceptance testing)	Type (implied by Firesmith, 2015, p. 58)
Error Guessing	Practice (implied by ISO/IEC and IEEE, 2022, p. 34)	Technique (ISO/IEC and IEEE, 2022, pp. 4, 22, 34; 2021, pp. 4, 11, 29, Fig. 2; 2013, p. 3; Washizaki, 2024, p. 5-13)
Penetration Testing	Technique (ISO/IEC and IEEE, 2021, p. 40; Hamburg and Mogyorodi, 2024)	Type (implied by Firesmith, 2015, p. 57; inferred from security testing)
Volume Testing	Technique (ISO/IEC and IEEE, 2021, p. 38)	Type (implied by Firesmith, 2015, p. 54)
End-to-end Testing	Level? (Hamburg and Mogyorodi, 2024)	Type (Hamburg and Mogyorodi, 2024)
Privacy Testing	Technique (ISO/IEC and IEEE, 2021, p. 40)	Type?
Security Audits	Practice? (ISO/IEC and IEEE, 2021, p. 40)	Technique (ISO/IEC and IEEE, 2021, p. 40)
Vulnerability Scanning	Practice?	Technique (ISO/IEC and IEEE, 2021, p. 40)
Infrastructure Testing	Level? (Gerrard, 2000a, p. 13)	Type (implied by Firesmith, 2015, p. 57)
Interface Testing	Level (implied by ISO/IEC and IEEE, 2017, p. 235; Sakamoto et al., 2013, p. 343; inferred from integration testing)	Type? (Kam, 2008, p. 45)

5.2.4 Definition Discrepancies

Perhaps the most interesting category for those seeking to understand how to apply a given test approach, there are many discrepancies between how test approaches, as well as supporting terms, are defined:

1. Integration testing, system testing, and system integration testing are all listed as "common test levels" (ISO/IEC and IEEE, 2022, p. 12; 2021, p. 6), but no definitions are given for the latter two, making it unclear what "system integration testing" is; it is a combination of the two? somewhere on the spectrum between them? It is listed as a child of integration testing by Hamburg and Mogyorodi (2024) and of system testing by Firesmith (2015, p. 23).

2. Similarly, component testing, integration testing, and component integration testing are all listed in (ISO/IEC and IEEE, 2017), but "component integration testing" is only defined as "testing of groups of related components" (ISO/IEC and IEEE, 2017, p. 82); it is a combination of the two? somewhere on the spectrum between them? As above, it is listed as a child of integration testing by Hamburg and Mogyorodi (2024).

3. The SWEBOK Guide V4 defines "privacy testing" as testing that "assess[es] the security and privacy of users' personal data to prevent local attacks" (Washizaki, 2024, p. 5-10); this seems to overlap (both in scope and name) with the definition of "security testing" in (ISO/IEC and IEEE, 2022, p. 7): testing "conducted to evaluate the degree to which a test item, and associated data and information, [sic] are protected so that" only "authorized persons or systems" can use them as intended.

4. Path testing can "aim[] to execute all entry-to-exit control flow paths in a SUT's control flow graph" (Washizaki, 2024, p. 5-13) or "all or selected paths through a computer program" (ISO/IEC and IEEE, 2017, p. 316; similar in Patton, 2006, p. 119).

5. The structure of tours can be defined as either quite general (ISO/IEC and IEEE, 2022, p. 34) or "organized around a special focus" (Hamburg and Mogyorodi, 2024).

6. Alpha testing is performed by "users within the organization developing the software" (ISO/IEC and IEEE, 2017, p. 17), "a small, selected group of potential users" (Washizaki, 2024, p. 5-8), or "roles outside the development organization" conducted "in the developer's test environment" (Hamburg and Mogyorodi, 2024).

7. Hamburg and Mogyorodi (2024) define "Machine Learning (ML) model testing" and "ML functional performance" in terms of "ML functional performance criteria", which is defined in terms of "ML functional performance metrics", which is defined as "a set of measures that relate to the functional correctness of an ML system". The use of "performance" (or "correctness") in these definitions is at best ambiguous and at worst incorrect.

8. Load testing is performed with loads "between anticipated conditions of low, typical, and peak usage" (ISO/IEC and IEEE, 2022, p. 5) or loads that are as large as possible (Patton, 2006, p. 86).

9. State testing requires that "all states in the state model … [are] 'visited' " in (ISO/IEC and IEEE, 2021, p. 19) which is only one of its possible criteria in (Patton, 2006, pp. 82-83).

10. ISO/IEC and IEEE (2017, p. 456) say system testing is "conducted on a complete, integrated system" (which Peters and Pedrycz (2000, Tab. 12.3) and van Vliet (2000, p. 439) agree with), while Patton (2006, p. 109) says it can also be done on "at least a major portion" of the product.

11. Patton (2006, p. 92, emphasis added) says that reviews are "*the* process[es] under which static white-box testing is performed" but correctness proofs are given as another example by van Vliet (2000, pp. 418-419).

OG Beizer

12. Kam (2008, p. 46) says that the goal of negative testing is "showing that a component or system does not work" which is not true; if robustness is an important quality for the system, then testing the system "in a way for which it was not intended to be used" (Hamburg and Mogyorodi, 2024) (i.e., negative testing) is one way to help test this!

13. Kam (2008, p. 42) says "See *boundary value analysis*," for the glossary entry of "boundary value testing" but does not provide this definition.

14. While a computation data use is defined as the "use of the value of a variable in *any* type of statement" (ISO/IEC and IEEE, 2021, p. 2; 2017, p. 83, emphasis added), it is often qualified to *not* be a predicate data use (van Vliet, 2000, p. 424; implied by ISO/IEC and IEEE, 2021, p. 27).

OG 2015

15. ISO/IEC and IEEE define an "extended entry (decision) table" both as a decision table where the "conditions consist of multiple values rather than simple Booleans" (2021, p. 18) and one where "the conditions and actions are generally described but are incomplete" (2017, p. 175).

OG ISO1984

16. ISO/IEC and IEEE use the same definition for "partial correctness" (2017, p. 314) and "total correctness" (p. 480).

17. ISO/IEC and IEEE's definition of "all-c-uses testing"—testing that aims to execute all data "use[s] of the value of a variable in any type of statement" (2017, p. 83)—is *much* more vague than the definition given in (2021, p. 27): testing that exercises "control flow sub-paths from each variable definition to each c-use of that definition (with no intervening definitions)" (similar in van Vliet, 2000, p. 425; Peters and Pedrycz, 2000, p. 479).

OG 2015

18. "Data definition" is defined as a "statement where a variable is assigned a value" (ISO/IEC and IEEE, 2021, p. 3; 2017, p. 115; similar in 2012, p. 27; van Vliet, 2000, p. 424), but for functional programming languages such as

OG 2015

Haskell with immutable variables (Wikibooks Contributors, 2023), this could cause confusion and/or be imprecise.

19. While ergonomics testing is out of scope (as it tests hardware, not software), its definition of "testing to determine whether a component or system and its input devices are being used properly with correct posture" (Hamburg and Mogyorodi, 2024) seems to focus on how the system is *used* as opposed to the system *itself*.

20. Hamburg and Mogyorodi (2024) describe the term "software in the loop" as a kind of testing, while the source they reference seems to describe "Software-in-the-Loop-Simulation" as a "simulation environment" that may support software integration testing (Knüvener Mackert GmbH, 2022, p. 153); is this a testing approach or a tool that supports testing?

21. The definition of "math testing" given by Hamburg and Mogyorodi (2024) is too specific to be useful, likely taken from an example instead of a general definition: "testing to determine the correctness of the pay table implementation, the random number generator results, and the return to player computations".

22. A similar issue exists with multiplayer testing, where its definition specifies "the casino game world" (Hamburg and Mogyorodi, 2024).

23. While correct, ISTQB's definition of "specification-based testing" is not helpful: "testing based on an analysis of the specification of the component or system" (Hamburg and Mogyorodi, 2024).

24. While model testing is said to test the object under test, it seems to describe testing the models themselves (Firesmith, 2015, p. 20); using the models to test the object under test seems to be called "driver-based testing" (p. 33).

25. Similarly, it is ambiguous whether "tool/environment testing" refers to testing the tools/environment *themselves* or *using* them to test the object under test; the latter is implied, but the wording of its subtypes (Firesmith, 2015, p. 25) seems to imply the former.

26. The acronym "SoS" is used but not defined by Firesmith (2015, p. 23).

27. Van Vliet defines many types of data flow coverage, including all-p-uses, all-p-uses/some-c-uses, and all-c-uses/some-p-uses (2000, p. 425), but excludes all-c-uses, which is implied by these definitions and defined elsewhere (ISO/IEC and IEEE, 2021, p. 27; 2017, p. 83; Peters and Pedrycz, 2000, p. 479).

28. Van Vliet specifies that every successor of a data definition use needs to be executed as part of all-uses testing (2000, pp. 424-425), but this condition is not included elsewhere (ISO/IEC and IEEE, 2021, pp. 28-29; 2017, p. 120; Peters and Pedrycz, 2000, pp. 478-479).

29. All-du-paths testing is usually defined as exercising all "loop-free control flow sub-paths from each variable definition to every use (both p-use and c-use) of that definition (with no intervening definitions)" (ISO/IEC and IEEE, 2021, p. 29; similar in 2017, p. 125; Washizaki, 2024, p. 5-13; Peters and Pedrycz, 2000, p. 479); however, paths containing simple cycles may also be required (van Vliet, 2000, p. 425).

30. Van Vliet says that all-p-uses testing is only stronger than all-edges (branch) testing if there are infeasible paths (2000, pp. 432-433), but ISO/IEC and IEEE do not specify this caveat (2021, Fig. F.1).

OG Reid, 1996

31. Similarly, van Vliet says that all-du-paths testing is only stronger than all-uses testing if there are infeasible paths (2000, pp. 432-433), but Washizaki does not specify this caveat (2024, p. 5-13).

32. Acceptance testing is "usually performed by the purchaser … with the … vendor" (ISO/IEC and IEEE, 2017, p. 5), "may or may not involve the developers of the system" (Bourque and Fairley, 2014, p. 4-6), and/or "is often performed under supervision of the user organization" (van Vliet, 2000, p. 439); these descriptions of who the testers are contradict each other *and* all introduce some uncertainty ("usually", "may or may not", and "often", respectively).

Does this merit counting this as an Ambiguity as well as a Contradiction?

33. Bas (2024, p. 16) lists "three [backup] location categories: local, offsite and cloud based [sic]" but does not define or discuss "offsite backups" (pp. 16-17).

34. Gerrard (2000a, Tab. 2) makes a distinction between "transaction verification" and "transaction testing" and uses the phrase "transaction flows" (Fig. 5) but doesn't explain them.

35. Availability testing isn't assigned to a test priority (Gerrard, 2000a, Tab. 2), despite the claim that "the test types[8] have been allocated a slot against the four test priorities" (p. 13); I think usability and/or performance would have made sense.

Also of note: (ISO/IEC and IEEE, 2022; 2021), from the ISO/IEC/IEEE 29119 family of standards, mention the following 23 test approaches without defining them. This means that out of the 114 test approaches they mention, about 20% have no associated definition!

However, the previous version of this standard, (2013), generally explained two, provided references for two, and explicitly defined one of these terms, for a total of five definitions that could (should) have been included in (2022)! These terms have been underlined, *italicized*, and **bolded**, respectively. Additionally, entries marked with an asterisk* were defined (at least partially) in (2017), which would have been available when creating this family of standards. These terms bring the

[8] "Each type of test addresses a different risk area" (Gerrard, 2000a, p. 12), which is distinct from the notion of "test type" described in Table 3.1.

total count of terms that could (should) have been defined to nine; almost 40% of undefined test approaches could have been defined!

- Acceptance Testing*
- Alpha Testing*
- Beta Testing*
- Capture-Replay Driven Testing
- Data-driven Testing
- Error-based Testing
- Factory Acceptance Testing
- Fault Injection Testing
- Functional Suitability Testing (also mentioned but not defined in (ISO/IEC and IEEE, 2017))
- Integration Testing*
- Model Verification
- Operational Acceptance Testing
- Orthogonal Array Testing
- Production Verification Testing
- Recovery Testing* (Failover/Recovery Testing, Back-up/Recovery Testing, **Backup and Recovery Testing***, Recovery*; see Section 5.5)
- Response-Time Testing
- *Reviews* (ISO/IEC 20246) (Code Reviews*)
- Scalability Testing (defined as a synonym of "capacity testing"; see Section 5.6)
- Statistical Testing
- System Integration Testing (System Integration*)
- System Testing* (also mentioned but not defined in (ISO/IEC and IEEE, 2013))
- *Unit Testing** (IEEE Std 1008-1987, IEEE Standard for Software Unit Testing implicitly listed in the bibliography!)
- User Acceptance Testing

5.2.5 Terminology Discrepancies

While some discrepancies exist because the definition of a term is wrong, others exist because term's *name* or *label* is wrong! This could be considered a "sister" category of Definition Discrepancies, but these discrepancies seemed different enough to merit their own category. This most often manifests as terms that are included in reference material that should not have been, terms that share the same acronym, and terms that have typos or are redundant. The following discrepancies are presented in that order:

1. The distinctions between development testing (ISO/IEC and IEEE, 2017, p. 136), developmental testing (Firesmith, 2015, p. 30), and developer testing (Firesmith, 2015, p. 39; Gerrard, 2000a, p. 11) are unclear and seem miniscule.

Is this a def discrep?

2. The terms "acceleration tolerance testing" and "acoustic tolerance testing" seem to only refer to software testing in (Firesmith, 2015, p. 56); elsewhere, they seem to refer to testing the acoustic tolerance of rats (Holley et al., 1996) or the acceleration tolerance of astronauts (Morgun et al., 1999, p. 11), aviators (Howe and Johnson, 1995, pp. 27, 42), or catalysts (Liu et al., 2023, p. 1463), which don't exactly seem relevant…

Is this a scope discrep?

3. "Orthogonal array testing" (Washizaki, 2024, pp. 5-1, 5-11; implied by Valcheva, 2013, pp. 467, 473; Yu et al., 2011, pp. 1573-1577, 1580) and "operational acceptance testing" (Firesmith, 2015, p. 30) have the same acronym ("OAT").

4. "Installability testing" is given as a test type (ISO/IEC and IEEE, 2022, p. 22; 2021, p. 38; 2017, p. 228), while "installation testing" is given as a test level (van Vliet, 2000, p. 439; implied by Washizaki, 2024, p. 5-8). Since "installation testing" is not given as an example of a test level throughout the sources that describe them (see Section 3.2.1), it is likely that the term "installability testing" with all its related information should be used instead.

5. A typo in (ISO/IEC and IEEE, 2021, Fig. 2) means that "specification-based techniques" is listed twice, when the latter should be "structure-based techniques".

6. "Par sheet testing" from (Hamburg and Mogyorodi, 2024) seems to refer to the specific example brought up in this definition discrepancy and does not seem more widely applicable, since a "PAR sheet" is "a list of all the symbols on each reel of a slot machine" (Bluejay, 2024).

Does this belong here?

7. "Customer acceptance testing" and "contract(ual) acceptance testing" have the same acronym ("CAT") (Firesmith, 2015, p. 30).

8. The same is true for "hardware-in-the-loop testing" and "human-in-the-loop testing" ("HIL") (Firesmith, 2015, p. 23), although Preuße et al. (2012, p. 2) use "HiL" for the former.

9. Different capitalizations of the abbreviations of "computation data use" and "predicate data use" are used: the lowercase "c-use" and "p-use" (ISO/IEC and IEEE, 2021, pp. 3, 27-29, 35-36, 114-155, 117-118, 129; 2017, p. 124; Peters and Pedrycz, 2000, p. 477, Tab. 12.6) and the uppercase "C-use" and "P-use" (van Vliet, 2000, pp. 424-425).

10. Similarly for "definition-use" (such as in "definition-use path"), both the lowercase "du" (ISO/IEC and IEEE, 2021, pp. 3, 27, 29, 35, 119-121, 129; Peters and Pedrycz, 2000, pp. 478-479) and the uppercase "DU" (van Vliet, 2000, p. 425) are used.

11. The phrase "continuous automated testing" (Gerrard, 2000a, p. 11) is redundant since continuous testing is a sub-category of automated testing (ISO/IEC and IEEE, 2022, p. 35; Hamburg and Mogyorodi, 2024).

12. Kam (2008) misspells "state-based" as "state-base" (pp. 13, 15) and "stated-base" (Tab. 1).

5.2.6 Citation Discrepancies

Sometimes a document cites another for a piece of information that does not appear! The following discrepancies are examples of this:

1. The source that Hamburg and Mogyorodi (2024) cite for the definition of "test type" does not seem to actually provide a definition.

2. The same is true for "visual testing" (Hamburg and Mogyorodi, 2024).

3. The same is true for "security attack" (Hamburg and Mogyorodi, 2024).

4. Doğan et al. (2014, p. 184) claim that Sakamoto et al. (2013) define "prime path coverage", but they do not.

5.3 Functional Testing

"Functional testing" is described alongside many other, likely related, terms. This leads to confusion about what distinguishes these terms, as shown by the following five:

5.3.1 Specification-based Testing

This is defined as "testing in which the principal test basis is the external inputs and outputs of the test item" (ISO/IEC and IEEE, 2022, p. 9). This agrees with a definition of "functional testing": "testing that … focuses solely on the outputs generated in response to selected inputs and execution conditions" (ISO/IEC and IEEE, 2017, p. 196). Notably, ISO/IEC and IEEE (2017) lists both as synonyms of "black-box testing" (pp. 431, 196, respectively), despite them sometimes being defined separately. For example, the International Software Testing Qualifications

van Vliet (2000, p. 399) may list these as synonyms; investigate

Board (ISTQB) defines "specification-based testing" as "testing based on an analysis of the specification of the component or system" (and gives "black-box testing" as a synonym) and "functional testing" as "testing performed to evaluate if a component or system satisfies functional requirements" (specifying no synonyms) (Hamburg and Mogyorodi, 2024); the latter references ISO/IEC and IEEE (2017, p. 196) ("testing conducted to evaluate the compliance of a system or component with specified functional requirements") which *has* "black-box testing" as a synonym, and mirrors ISO/IEC and IEEE (2022, p. 21) (testing "used to check the implementation of functional requirements"). Overall, specification-based testing (ISO/IEC and IEEE, 2022, pp. 2-4, 6-9, 22) and black-box testing (Washizaki, 2024, p. 5-10; Souza et al., 2017, p. 3) are test design techniques used to "derive corresponding test cases" (ISO/IEC and IEEE, 2022, p. 11) from "selected inputs and execution conditions" (ISO/IEC and IEEE, 2017, p. 196).

5.3.2 Correctness Testing

Washizaki says "test cases can be designed to check that the functional specifications are correctly implemented, which is variously referred to in the literature as conformance testing, correctness testing or functional testing" (2024, p. 5-7); this mirrors previous definitions of "functional testing" (ISO/IEC and IEEE, 2022, p. 21; 2017, p. 196) but groups it with "correctness testing". Since "correctness" is a software quality (ISO/IEC and IEEE, 2017, p. 104; Washizaki, 2024, p. 3-13) which is what defines a "test type" (ISO/IEC and IEEE, 2022, p. 15) (see Section 2.4.2), it seems consistent to label "functional testing" as a "test type" (ISO/IEC and IEEE, 2022, pp. 15, 20, 22; 2021, pp. 7, 38, Tab. A.1; 2016, p. 4). However, this conflicts with its categorization as a "technique" if considered a synonym of Specification-based Testing. Additionally, "correctness testing" is listed separately from "functionality testing" by Firesmith (2015, p. 53).

5.3.3 Conformance Testing

Testing that ensures "that the functional specifications are correctly implemented", and can be called "conformance testing" or "functional testing" (Washizaki, 2024, p. 5-7). "Conformance testing" is later defined as testing used "to verify that the SUT conforms to standards, rules, specifications, requirements, design, processes, or practices" (Washizaki, 2024, p. 5-7). This definition seems to be a superset of testing methods mentioned earlier as the latter includes "standards, rules, requirements, design, processes, … [and]" practices in *addition* to specifications!

A complicating factor is that "compliance testing" is also (plausibly) given as a synonym of "conformance testing" (Kam, 2008, p. 43). However, "conformance testing" can also be defined as testing that evaluates the degree to which "results … fall within the limits that define acceptable variation for a quality requirement" (ISO/IEC and IEEE, 2017, p. 93), which seems to describe something different.

OG PMBOK 5th ed.

5.3.4 Functional Suitability Testing

Procedure testing is called a "type of functional suitability testing" (ISO/IEC and IEEE, 2022, p. 7) but no definition of that term is given. "Functional suitability" is the "capability of a product to provide functions that meet stated and implied needs of intended users when it is used under specified conditions", including meeting "the functional specification" (ISO/IEC, 2023a). This seems to align with the definition of "functional testing" as related to "black-box/specification-based testing". "Functional suitability" has three child terms: "functional completeness" (the "capability of a product to provide a set of functions that covers all the specified tasks and intended users' objectives"), "functional correctness" (the "capability of a product to provide accurate results when used by intended users"), and "functional appropriateness" (the "capability of a product to provide functions that facilitate the accomplishment of specified tasks and objectives") (ISO/IEC, 2023a). Notably, "functional correctness", which includes precision and accuracy (ISO/IEC, 2023a; Hamburg and Mogyorodi, 2024), seems to align with the quality/ies that would be tested by "correctness" testing.

5.3.5 Functionality Testing

"Functionality" is defined as the "capabilities of the various … features provided by a product" (ISO/IEC and IEEE, 2017, p. 196) and is said to be a synonym of "functional suitability" (Hamburg and Mogyorodi, 2024), although it seems like it should really be a synonym of "functional completeness" based on (ISO/IEC, 2023a), which would make "functional suitability" a sub-approach. Its associated test type is implied to be a sub-approach of build verification testing (Hamburg and Mogyorodi, 2024) and made distinct from "functional testing"; interestingly, security is described as a sub-approach of both non-functional and functionality testing (Gerrard, 2000a, Tab. 2). "Functionality testing" is listed separately from "correctness testing" by Firesmith (2015, p. 53).

5.4 Operational (Acceptance) Testing (OAT)

Some sources refer to "operational acceptance testing" (ISO/IEC and IEEE, 2022, p. 22; Hamburg and Mogyorodi, 2024) while some refer to "operational testing" (Washizaki, 2024, p. 6-9, in the context of software engineering operations; ISO/IEC, 2018; ISO/IEC and IEEE, 2017, p. 303; Bourque and Fairley, 2014, pp. 4-6, 4-9). A distinction is sometimes made (Firesmith, 2015, p. 30) but without accompanying definitions, it is hard to evaluate its merit. Since this terminology is not standardized, I propose that the two terms are treated as synonyms (as done by other sources (LambdaTest, 2024; Bocchino and Hamilton, 1996)) as a type of acceptance testing (ISO/IEC and IEEE, 2022, p. 22; Hamburg and Mogyorodi, 2024) that focuses on "non-functional" attributes of the system (LambdaTest, 2024).

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A summary of definitions of "operational (acceptance) testing" is that it is "test[ing] to determine the correct installation, configuration and operation of a module and that it operates securely in the operational environment" (ISO/IEC,

2018) or "evaluate a system or component in its operational environment" (ISO/IEC and IEEE, 2017, p. 303), particularly "to determine if operations and/or systems administration staff can accept [it]" (Hamburg and Mogyorodi, 2024).

5.5 Recovery Testing

"Recovery testing" is "testing … aimed at verifying software restart capabilities after a system crash or other disaster" (Washizaki, 2024, p. 5-9) including "recover[ing] the data directly affected and re-establish[ing] the desired state of the system" (ISO/IEC, 2023a; similar in Washizaki, 2024, p. 7-10) so that the system "can perform required functions" (ISO/IEC and IEEE, 2017, p. 370). It is also called "recoverability testing" (Kam, 2008, p. 47) and potentially "restart & recovery (testing)" (Gerrard, 2000a, Fig. 5). The following terms, along with "recovery testing" itself (ISO/IEC and IEEE, 2022, p. 22) are all classified as test types, and the relations between them can be found in Figure 6.1.

- **Recoverability Testing:** Testing "how well a system or software can recover data during an interruption or failure" (Washizaki, 2024, p. 7-10; similar in ISO/IEC, 2023a) and "re-establish the desired state of the system" (ISO/IEC, 2023a). Synonym for "recovery testing" in Kam (2008, p. 47).
- **Disaster/Recovery Testing** serves to evaluate if a system can "return to normal operation after a hardware or software failure" (ISO/IEC and IEEE, 2017, p. 140) or if "operation of the test item can be transferred to a different operating site and … be transferred back again once the failure has been resolved" (2021, p. 37). These two definitions seem to describe different aspects of the system, where the first is intrinsic to the hardware/software and the second might not be.
- **Backup and Recovery Testing** "measures the degree to which system state can be restored from backup within specified parameters of time, cost, completeness, and accuracy in the event of failure" (ISO/IEC and IEEE, 2013, p. 2). This may be what is meant by "recovery testing" in the context of performance-related testing and seems to correspond to the definition of "disaster/recovery testing" in (2017, p. 140).
- **Backup/Recovery Testing:** Testing that determines the ability "to restor[e] from back-up memory in the event of failure, without transfer[ing] to a different operating site or back-up system" (ISO/IEC and IEEE, 2021, p. 37). This seems to correspond to the definition of "disaster/recovery testing" in (2021, p. 37). It is also given as a sub-type of "disaster/recovery testing", even though that tests if "operation of the test item can be transferred to a different operating site" (p. 37). It also seems to overlap with "backup and recovery testing", which adds confusion.
- **Failover/Recovery Testing:** Testing that determines the ability "to mov[e] to a back-up system in the event of failure, without transfer[ing] to a different operating site" (ISO/IEC and IEEE, 2021, p. 37). This is given as a

sub-type of "disaster/recovery testing", even though that tests if "operation of the test item can be transferred to a different operating site" (p. 37).

- **Failover Testing:** Testing that "validates the SUT's ability to manage heavy loads or unexpected failure to continue typical operations" (Washizaki, 2024, p. 5-9) by entering a "backup operational mode in which [these responsibilities] … are assumed by a secondary system" (Hamburg and Mogyorodi, 2024). While not *explicitly* related to recovery, "failover/recovery testing" also describes the idea of "failover", and Firesmith (2015, p. 56) uses the term "failover and recovery testing", which could be a synonym of both of these terms.

5.6 Scalability Testing

There were three ambiguities around the term "scalability testing", listed below. The relations between these test approaches (and other relevant ones) are shown in Figure 6.3.

1. ISO/IEC and IEEE give "scalability testing" as a synonym of "capacity testing" (2021, p. 39) while other sources differentiate between the two (Firesmith, 2015, p. 53; Bas, 2024, pp. 22-23)

2. ISO/IEC and IEEE give the external modification of the system as part of "scalability" (2021, p. 39), while ISO/IEC (2023a) imply that it is limited to the system itself

3. The SWEBOK Guide V4's definition of "scalability testing" (Washizaki, 2024, p. 5-9) is really a definition of usability testing!

5.7 Compatibility Testing

"Compatibility testing" is defined as "testing that measures the degree to which a test item can function satisfactorily alongside other independent products in a shared environment (co-existence), and where necessary, exchanges information with other systems or components (interoperability)" (ISO/IEC and IEEE, 2022, p. 3). This definition is nonatomic as it combines the ideas of "co-existence" and "interoperability". The term "interoperability testing" is not defined, but is used three times (ISO/IEC and IEEE, 2022, pp. 22, 43) (although the third usage seems like it should be "portability testing"). This implies that "co-existence testing" and "interoperability testing" should be defined as their own terms, which is supported by definitions of "co-existence" and "interoperability" often being separate (Hamburg and Mogyorodi, 2024; ISO/IEC and IEEE, 2017, pp. 73, 237), the definition of "interoperability testing" from ISO/IEC and IEEE (2017, p. 238), and the decomposition of "compatibility" into "co-existence" and "interoperability" by ISO/IEC (2023a)! The "interoperability" element of "compatibility testing" is explicitly excluded by ISO/IEC and IEEE (2021, p. 37), (incorrectly) implying that

"compatibility testing" and "co-existence testing" are synonyms. Furthermore, the definition of "compatibility testing" in (Kam, 2008, p. 43) unhelpfully says "See *interoperability testing*", adding another layer of confusion to the direction of their relationship.

5.8 Inferred Discrepancies

Along the course of this analysis, we inferred many potential discrepancies. Some of these have a conflicting source while others do not. These are excluded from any counts of the numbers of discrepancies, since they are more subjective, but are given below for completeness.

5.8.1 Inferred Synonym Discrepancies

See Section 5.2.1.

1. **Production Acceptance Testing:**
    - Operational Testing (Hamburg and Mogyorodi, 2024)[9]
    - Production Verification Testing[10]
2. **Operational Testing:**
    - Field Testing
    - Qualification Testing

Additionally, Kam (2008, p. 46) gives "program testing" as a synonym of "component testing" but it probably should be a synonym of "system testing" instead.

5.8.2 Inferred Parent Discrepancies

As in Table 5.3, some discrepancies occur when test approaches are classified as both children/parents *and* synonyms. The first two lists below give approaches that are given one of these relations by at least one source when it may make more sense for them to have the other relation. The third list gives approaches that could be inferred to have either relation, so more thought would have to be given before a recommendation can be made.

Pairs labelled as "children/parents"

1. Programmer Testing → Developer Testing (Firesmith, 2015, p. 39)

[9] "Operational" and "production acceptance testing" are treated as synonyms by Hamburg and Mogyorodi (2024) but listed separately by Firesmith (2015, p. 30).

[10] "Production acceptance testing" (Firesmith, 2015, p. 30) seems to be the same as "production verification testing" (ISO/IEC and IEEE, 2022, p. 22) but neither is defined.

Pairs labelled as "synonyms"

1. Structured Walkthroughs → Walkthroughs[11] (Hamburg and Mogyorodi, 2024)
2. Functionality Testing → Functional Suitability Testing (implied by Hamburg and Mogyorodi, 2024; this seems wrong)

Pairs that could be "children/parents" *or* "synonyms"

1. Field Testing → Operational Testing
2. Organization-based Testing → Role-based Testing[12]
3. Scenario-based Evaluations → Scenario-based Testing
4. System Qualification Testing → System Testing

See #59

Additionally, (Gerrard, 2000a, Tab. 2) does *not* give "functionality testing" as a parent of "end-to-end functionality testing".

5.8.3 Inferred Category Discrepancies

See Section 5.2.3.

Table 5.5: Test approaches inferred to have more than one category.

Test Approach	Category 1	Category 2
Fuzz Testing	Practice (inferred from mathematical-based testing)	Technique (ISO/IEC and IEEE, 2022, p. 36; Hamburg and Mogyorodi, 2024)
Closed Beta Testing	Level (inferred from beta testing)	Type (implied by Firesmith, 2015, p. 58)
Open Beta Testing	Level (inferred from beta testing)	Type (implied by Firesmith, 2015, p. 58)

5.8.4 Other Inferred Discrepancies

The following are discrepancies that, if were more concrete, would also be included alongside the other discrepancies:

- "Fuzz testing" is "tagged" (?) as "artificial intelligence" (ISO/IEC and IEEE, 2022, p. 5).
- Gerrard's definition for "security audits" seems too specific, only applying to "the products installed on a site" and "the known vulnerabilities for those products" (2000b, p. 28).

[11] See Item Synonyms Discrepancy 3.

[12] The distinction between organization- and role-based testing in (Firesmith, 2015, pp. 17, 37, 39) seems arbitrary, but further investigation may prove it to be meaningful.

Chapter 6

Recommendations

We provide different recommendations for resolving various discrepancies (see Chapter 5). This was done with the goal of organizing them more logically and making them:

1. Atomic (e.g., disaster/recovery testing seems to have two disjoint definitions)
2. Straightforward (e.g., backup and recovery testing's definition implies the idea of performance, but its name does not ; failover/recovery testing, failover and recovery testing, and failover testing are all given separately)
3. Consistent (e.g., backup/recovery testing and failover/recovery testing explicitly exclude an aspect included in its parent disaster/recovery testing)

The following are our recommendations for the areas of Recovery, Scalability, and Performance(-related) Testing, along with graphs of these subsets.

6.1 Recovery Testing

The following terms should be used in place of the current terminology to more clearly distinguish between different recovery-related test approaches. The result of the proposed terminology, along with their relations, is demonstrated in Figures 6.1 and 6.2.

- **Recoverability Testing:** "Testing … aimed at verifying software restart capabilities after a system crash or other disaster" (Washizaki, 2024, p. 5-9) including "recover[ing] the data directly affected and re-establish[ing] the desired state of the system" (ISO/IEC, 2023a; similar in Washizaki, 2024, p. 7-10) so that the system "can perform required functions" (ISO/IEC and IEEE, 2017, p. 370). "Recovery testing" will be a synonym, as in (Kam, 2008, p. 47), since it is the more prevalent term throughout various sources, although "recoverability testing" is preferred to indicate that this explicitly focuses on the *ability* to recover, not the *performance* of recovering.

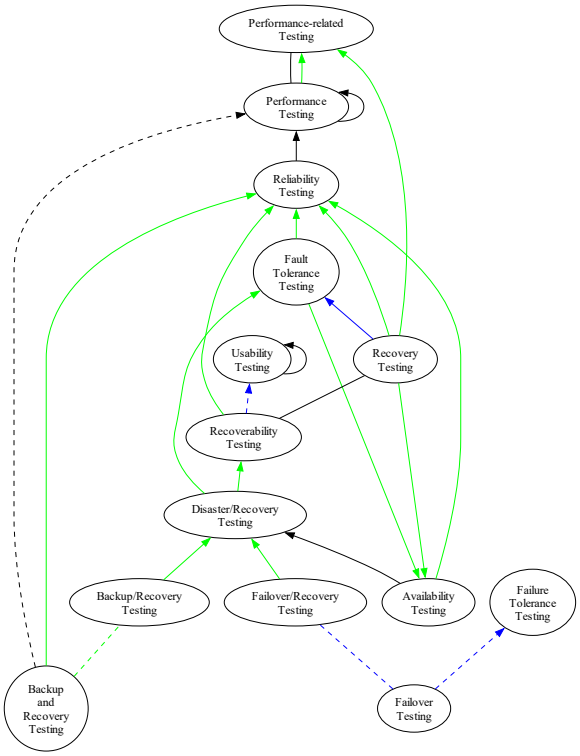

Figure 6.1: Current relations between "recovery testing" terms.

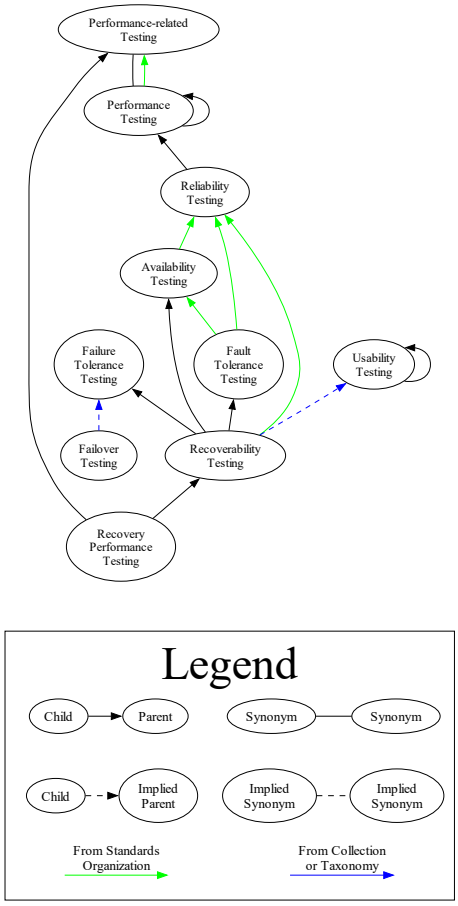

Figure 6.2: Proposed relations between rationalized "recovery testing" terms.

- **Failover Testing:** Testing that "validates the SUT's ability to manage heavy loads or unexpected failure to continue typical operations" (Washizaki, 2024, p. 5-9) by entering a "backup operational mode in which [these responsibilities] … are assumed by a secondary system" (Hamburg and Mogyorodi, 2024). This will replace "failover/recovery testing", since it is more clear, and since this is one way that a system can recover from failure, it will be a subset of "recovery testing".

- **Transfer Recovery Testing:** Testing to evaluate if, in the case of a failure, "operation of the test item can be transferred to a different operating site and … be transferred back again once the failure has been resolved" (2021, p. 37). This replaces the second definition of "disaster/recovery testing", since the first is just a description of "recovery testing", and could potentially be considered as a kind of failover testing. This may not be intrinsic to the hardware/software (e.g., may be the responsibility of humans/processes).

- **Backup Recovery Testing:** Testing that determines the ability "to restor[e] from back-up memory in the event of failure" (ISO/IEC and IEEE, 2021, p. 37). The qualification that this occurs "without transfer[ing] to a different operating site or back-up system" (p. 37) *could* be made explicit, but this is implied since it is separate from transfer recovery testing and failover testing, respectively.

- **Recovery Performance Testing:** Testing "how well a system or software can recover … [from] an interruption or failure" (Washizaki, 2024, p. 7-10; similar in ISO/IEC, 2023a) "within specified parameters of time, cost, completeness, and accuracy" (ISO/IEC and IEEE, 2013, p. 2). The distinction between the performance-related elements of recovery testing seemed to be meaningful, but was not captured consistently by the literature. This will be a subset of "performance-related testing" (see Section 6.3) as "recovery testing" is in (ISO/IEC and IEEE, 2022, p. 22). This could also be extended into testing the performance of specific elements of recovery (e.g., failover performance testing), but this be too fine-grained and may better be captured as an orthogonally derived test approach.

See #40

6.2 Scalability Testing

The ambiguity around scalability testing found in the literature is resolved and/or explained by other sources! ISO/IEC and IEEE give "scalability testing" as a synonym of "capacity testing", defined as the testing of a system's ability to "perform under conditions that may need to be supported in the future", which "may include assessing what level of additional resources (e.g. memory, disk capacity, network bandwidth) will be required to support anticipated future loads" (2021, p. 39). This focus on "the future" is supported by Hamburg and Mogyorodi, who define "scalability" as "the degree to which a component or system can be adjusted for changing capacity" (2024); the original source they reference agrees, defining it as "the measure of a system's ability to be upgraded to accommodate increased loads" (Gerrard and Thompson, 2002, p. 381). In contrast, capacity testing focuses on the system's present state, evaluating the "capability of a product to meet requirements for the maximum limits of a product parameter", such as the number of concurrent users, transaction throughput, or database size (ISO/IEC, 2023a). Because of this nuance, it makes more sense to consider these terms separate and *not* synonyms, as done by Firesmith (2015, p. 53) and Bas (2024, pp. 22-23).

Unfortunately, only focusing on future capacity requirements still leaves room for ambiguity. While the previous definition of "scalability testing" includes the external modification of the system, ISO/IEC describes it as testing the "capability of a product to handle growing or shrinking workloads or to adapt its capacity to handle variability" (2023a), implying that this is done by the system itself. The potential reason for this is implied by the SWEBOK Guide V4's claim that one objective of elasticity testing is "to evaluate scalability" (Washizaki, 2024, p. 5-9): ISO/IEC's notion of "scalability" likely refers more accurately to "elasticity"!

This also makes sense in the context of other definitions provided by the SWEBOK Guide V4:

- **Scalability:** "the software's ability to increase and scale up on its nonfunctional requirements, such as load, number of transactions, and volume of data" (Washizaki, 2024, p. 5-5). Based on this definition, scalability testing is then a subtype of load testing and volume testing, as well as potentially transaction flow testing.
- **Elasticity Testing**[1]**:** testing that "assesses the ability of the SUT … to rapidly expand or shrink compute, memory, and storage resources without compromising the capacity to meet peak utilization" (Washizaki, 2024, p. 5-9). Based on this definition, elasticity testing is then a subtype of memory management testing (with both being a subtype of resource utilization testing) and stress testing.

This distinction is also consistent with how the terms are used in industry: Pandey says that scalability is the ability to "increase … performance or efficiency as demand increases over time", while elasticity allows a system to "tackle changes in the workload [that] occur for a short period" (2023).

See #35

To make things even more confusing, the SWEBOK Guide V4 says "scalability testing evaluates the capability to use and learn the system and the user documentation" and "focuses on the system's effectiveness in supporting user tasks and the ability to recover from user errors" (Washizaki, 2024, p. 5-9). This seems to define "usability testing" with elements of functional and recovery testing, which is completely separate from the definitions of "scalability", "capacity", and "elasticity testing"! This definition should simply be disregarded, since it is inconsistent with the rest of the literature. The removal of the previous two synonym relations is demonstrated in Figures 6.3 and 6.4.

6.3 Performance(-related) Testing

"Performance testing" is defined as testing "conducted to evaluate the degree to which a test item accomplishes its designated functions" (ISO/IEC and IEEE, 2022, p. 7; 2017, p. 320; similar in 2021, pp. 38-39; Moghadam, 2019, p. 1187). It does this by "measuring the performance metrics" (Moghadam, 2019, p. 1187; similar in Hamburg and Mogyorodi, 2024) (such as the "system's capacity for growth" (Gerrard, 2000b, p. 23)), "detecting the functional problems appearing under certain execution conditions" (Moghadam, 2019, p. 1187), and "detecting violations of non-functional requirements under expected and stress conditions" (Moghadam, 2019, p. 1187; similar in Washizaki, 2024, p. 5-9). It is performed either …

1. "within given constraints of time and other resources" (ISO/IEC and IEEE, 2022, p. 7; 2017, p. 320; similar in Moghadam, 2019, p. 1187), or

[1] While this definition seems correct, it only cites a single source **that doesn't contain the words "elasticity" or "elastic"**!

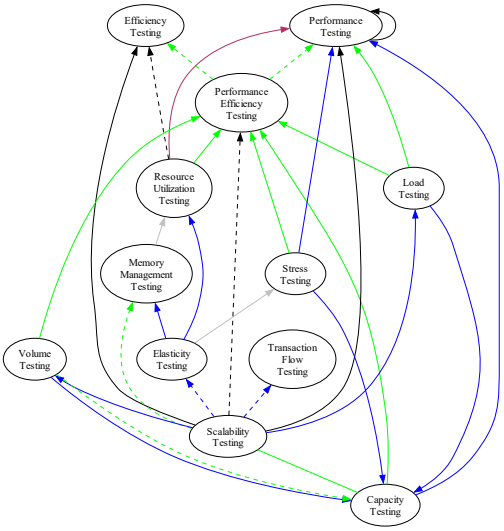

Figure 6.3: Current relations between "scalability testing" terms.

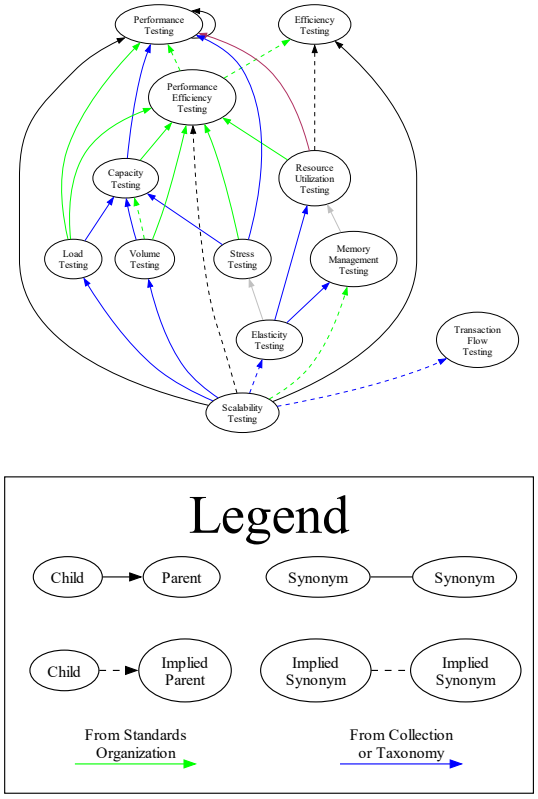

Figure 6.4: Proposed relations between rationalized "scalability testing" terms.

2. "under a 'typical' load" (ISO/IEC and IEEE, 2021, p. 39).

It is listed as a subset of performance-related testing, which is defined as testing "to determine whether a test item performs as required when it is placed under various types and sizes of 'load' " (2021, p. 38), along with other approaches like load and capacity testing (ISO/IEC and IEEE, 2022, p. 22). Note that "performance, load and stress testing might considerably overlap in many areas" (Moghadam, 2019, p. 1187). In contrast, Washizaki (2024, p. 5-9) gives "capacity and response time" as examples of "performance characteristics" that performance testing would seek to "assess", which seems to imply that these are sub-approaches to performance testing instead. This is consistent with how some sources treat "performance testing" and "performance-related testing" as synonyms (Washizaki, 2024, p. 5-9; Moghadam, 2019, p. 1187), as noted in Section 5.2.1. This makes sense because of how general the concept of "performance" is; most definitions of "performance testing" seem to treat it as a category of tests.

However, it seems more consistent to infer that the definition of "performance-related testing" is the more general one often assigned to "performance testing" performed "within given constraints of time and other resources" (ISO/IEC and IEEE, 2022, p. 7; 2017, p. 320; similar in Moghadam, 2019, p. 1187), and "per-

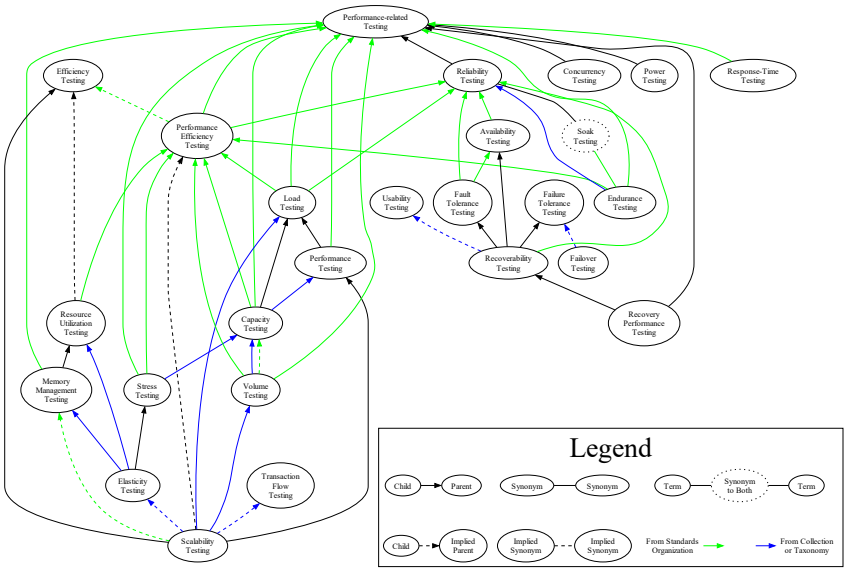

Figure 6.5: Proposed relations between rationalized "performance-related testing" terms.

formance testing" is a sub-approach of this performed "under a 'typical' load" (ISO/IEC and IEEE, 2021, p. 39). This has other implications for relations between these types of testing; for example, "load testing" usually occurs "between anticipated conditions of low, typical, and peak usage" (ISO/IEC and IEEE, 2022, p. 5; 2021, p. 39; 2017, p. 253; Hamburg and Mogyorodi, 2024), so it is a child of "performance-related testing" and a parent of "performance testing".

OG IEEE 2013

Finally, the "self-loops" mentioned in Section 5.2.2 provide no new information and can be removed. These changes (along with those from Sections 6.1 and 6.2 made implicitly) result in the relations shown in Figure 6.5.

Chapter 7

Development Process

The following is a rough outline of the steps I have gone through this far for this project:

- Start developing system tests (this was pushed for later to focus on unit tests)
- Test inputting default values as `floats` and `ints`
- Check constraints for valid input
- Check constraints for invalid input
- Test the calculations of:
  - `t_flight`
  - `p_land`
  - `d_offset`
  - `s`
- Test the writing of valid output
- Test for projectile going long
- Integrate system tests into existing unit tests
- Test for assumption violation of `g`
  - Code generation could be flawed, so we can't assume assumptions are respected
  - Test cases shouldn't necessarily match what is done by the code; for example, g = 0 shouldn't really give a `ZeroDivisionError`; it should be a `ValueError`
  - This inspired the potential for The Use of Assertions in Code
- Test that calculations stop on a constraint violation; this is a requirement should be met by the software (see Section 7.3)

- Test behaviour with empty input file
- Start creation of test summary (for `InputParameters` module)
  - It was difficult to judge test case coverage/quality from the code itself
  - This is not really a test plan, as it doesn't capture the testing philosophy
  - Rationale for each test explains why it supports coverage and how Drasil derived (would derive) it
- Start researching testing
- Implement generation of `__init__.py` files (#3516)
- Start the Generating Requirements subproject

7.1 Improvements to Manual Test Code

Even though this code will eventually be generated by Drasil, it is important that it is still human-readable, for the benefit of those reading the code later. This is one of the goals of Drasil (see #3417 for an example of a similar issue). As such, the following improvements were discovered and implement in the manually created testing code:

- use pytest's parameterization
- reuse functions/data for consistency
- improve import structure
- use `conftest` for running code before all tests of a module

7.1.1 Testing with Mocks

When testing code, it is common to first test lower-level modules, then assume that these modules work when testing higher-level modules. An example would be using an input module to set up test cases for a calculation module after testing the input module. This makes sense when writing test cases manually since it reduces the amount of code that needs to be written and still provides a reasonably high assurance in the software; if there is an issue with the input module that affects the calculation module tests, the issue would be revealed when testing the input module.

However, since these test cases will be generated by Drasil, they can be consistently generated with no additional effort. This means that the testing of each module can be done completely independently, increasing the confidence in the tests.

7.2 The Use of Assertions in Code

While assertions are often only used when testing, they can also be used in the code itself to enforce constraints or preconditions; they act like documentation that determines behaviour! For example, they could be used to ensure that assumptions about values (like the value for gravitational acceleration) are respected by the code, which gives a higher degree of confidence in the code. This process is known as "assertion checking" (Lahiri et al., 2013) .

investigate OG sources

7.3 Generating Requirements

I structured my manually created test cases around Projectile's functional requirements, as these are the most objective aspects of the generated code to test automatically. One of these requirements was "Verify-Input-Values", which said "Check the entered input values to ensure that they do not exceed the data constraints. If any of the input values are out of bounds, an error message is displayed and the calculations stop." This led me to develop a test case to ensure that if an input constraint was violated, the calculations would stop (Source Code A.3).

However, this test case failed, since the actual implementation of the code did *not* stop upon an input constraint violation. This was because the code choice for what to do on a constraint violation (Source Code A.4) was "disconnected" from the manually written requirement (Source Code A.5), as described in #3523.

Should I include the definition of `Constraints`?

This problem has been encountered before (#3259) and presented a good opportunity for generation to encourage reusability and consistency. However, since it makes sense to first verify outputs before actually outputting them and inserting generated requirements among manually created ones seemed challenging, it made sense to first generate an output requirement.

While working on Drasil in the summer of 2019, I implemented the generation of an input requirement across most examples (#1844). I had also attempted to generate an output requirement, but due to time constraints, this was not feasible. The main issue with this change was the desire to capture the source of each output for traceability; this source was attached to the `InstanceModel` (or rarely, `DataDefinition`) and not the underlying `Quantity` that was used for a program's outputs. The way I had attempted to do this was to add the reference as a `Sentence` in a tuple.

Taking another look at this four years later allowed us to see that we should be storing the outputs of a program as their underlying models, allowing us to keep the source information with it . While there is some discussion about how this might change in the future , for now, all outputs of a program should be `InstanceModels`. Since this change required adding the `Referable` constraints to the output field of `SystemInformation`, the outputs of all examples needed to be updated to satisfy this constraint; this meant that generating the output requirement of each example was nearly trivial once the outputs were specified correctly. After modifying `DataDefinitions` in GlassBR that were outputs to be `InstanceModels` (#3569; #3583), reorganizing the requirements of SWHS (#3589; #3607), and clarifying

cite Dr. Smith

add refs to 'underlying Theory' comment and 'not all outputs be IMs' comment

add constraints

the outputs of SWHS (#3589), SglPend (#3533), DblPend (#3533), GamePhysics (#3609), and SSP (#3630), the output requirement was ready to be generated.

Chapter 8

Research

It was realized early on in the process that it would be beneficial to understand the different kinds of testing (including what they test, what artifacts are needed to perform them, etc.). This section provides some results of this research, as well as some information on why and how it was performed.

A justification for why we decided to do this should be added

8.1 Existing Taxonomies, Ontologies, and the State of Practice

One thing we may want to consider when building a taxonomy/ontology is the semantic difference between related terms. For example, one ontology found that the term " 'IntegrationTest' is a kind of Context (with semantic of stage, but not a kind of Activity)" while " 'IntegrationTesting' has semantic of Level-based Testing that is a kind of Testing Activity [or] … of Test strategy" (Tebes et al., 2019, p. 157).

A note on testing artifacts is that they are "produced and used throughout the testing process" and include test plans, test procedures, test cases, and test results (Souza et al., 2017, p. 3). The role of testing artifacts is not specified in (Barbosa et al., 2006); requirements, drivers, and source code are all treated the same with no distinction (Barbosa et al., 2006, p. 3).

add acronym?

In (Souza et al., 2017), the ontology (ROoST) is made to answer a series of questions, including "What is the test level of a testing activity?" and "What are the artifacts used by a testing activity?" (Souza et al., 2017, pp. 8-9).

is this punctuation right?

The question "How do testing artifacts relate to each other?" (Souza et al., 2017, p. 8) is later broken down into multiple questions, such as "What are the test case inputs of a given test case?" and "What are the expected results of a given test case?" (Souza et al., 2017, p. 21). *These questions seem to overlap with the questions we were trying to ask about different testing techniques.* Tebes et al. (2019, pp. 152-153) may provide some sources for software testing terminology and definitions (this seems to include the ones suggested by Dr. Carette) in addition to a list of ontologies (some of which have been investigated).

One software testing model developed by the Quality Assurance Institute (QAI) includes the test environment ("conditions …that both enable and constrain how

testing is performed", including mission, goals, strategy, "management support, resources, work processes, tools, motivation"), test process (testing "standards and procedures"), and tester competency ("skill sets needed to test software in a test environment") (Perry, 2006, pp. 5-6).

Another source introduced the notion of an "intervention": "an act performed (e.g. use of a technique[1] or a process change) to adapt testing to a specific context, to solve a test issue, to diagnose testing or to improve testing" (Engström and Petersen, 2015, p. 1) and noted that "academia tend[s] to focus on characteristics of the intervention [while] industrial standards categorize the area from a process perspective" (Engström and Petersen, 2015, p. 2). It provides a structure to "capture both a problem perspective and a solution perspective with respect to software testing" (Engström and Petersen, 2015, pp. 3-4), but this seems to focus more on test interventions and challenges rather than approaches (Engström and Petersen, 2015, Fig. 5).

8.2 Definitions

- Software testing: "the process of executing a program with the intent of finding errors" (Peters and Pedrycz, 2000, p. 438) . "Testing can reveal failures, but the faults causing them are what can and must be removed" (Washizaki, 2024, p. 5-3); it can also include certification, quality assurance, and quality improvement (Washizaki, 2024, p. 5-4). Involves "specific preconditions [and] … stimuli so that its actual behavior can be compared with its expected or required behavior", including control flows, data flows, and postconditions (Firesmith, 2015, p. 11), and "an evaluation … of some aspect of the system or component" based on "results [that] are observed or recorded" (ISO/IEC and IEEE, 2022, p. 10; 2021, p. 6; 2017, p. 465)

OG Myers 1976

OG ISO/IEC 2014

- Test case: "the specification of all the entities that are essential for the execution, such as input values, execution and timing conditions, testing procedure, and the expected outcomes" (Washizaki, 2024, pp. 5-1 to 5-2)

- Defect: "an observable difference between what the software is intended to do and what it does" (Washizaki, 2024, p. 1-1); "can be used to refer to either a fault or a failure, [sic] when the distinction is not important" (Bourque and Fairley, 2014, p. 4-3)

OG?

- Error: "a human action that produces an incorrect result" (van Vliet, 2000, p. 399)

- Fault: "the manifestation of an error" in the software itself (van Vliet, 2000, p. 400); "the *cause* of a malfunction" (Washizaki, 2024, p. 5-3)

- Failure: incorrect output or behaviour resulting from encountering a fault; can be defined as not meeting specifications or expectations and "is a rela-

[1] Not formally defined, but distinct from the notion of "test technique" described in Table 3.1.

tive notion" (van Vliet, 2000, p. 400); "an undesired effect observed in the system's delivered service" (Washizaki, 2024, p. 5-3)

- Verification: "the process of evaluating a system or component to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase" (van Vliet, 2000, p. 400)
- Validation: "the process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements" (van Vliet, 2000, p. 400)
- Test Suite Reduction: the process of reducing the size of a test suite while maintaining the same coverage (Barr et al., 2015, p. 519); can be accomplished through mutation testing
- Test Case Reduction: the process of "removing side-effect free functions" from an individual test case to "reduc[e] test oracle costs" (Barr et al., 2015, p. 519)
- Probe: "a statement inserted into a program" for the purpose of dynamic testing (Peters and Pedrycz, 2000, p. 438)

8.2.1 Documentation

- Verification and Validation (V&V) Plan: a document for the "planning of test activities" described by IEEE Standard 1012 (van Vliet, 2000, p. 411)
- Test Plan: "a document describing the scope, approach, resources, and schedule of intended test activities" in more detail that the V&V Plan (van Vliet, 2000, pp. 412-413); should also outline entry and exit conditions for the testing activities as well as any risk sources and levels (Peters and Pedrycz, 2000, p. 445)
- Test Design documentation: "specifies … the details of the test approach and identifies the associated tests" (van Vliet, 2000, p. 413)
- Test Case documentation: "specifies inputs, predicted outputs and execution conditions for each test item" (van Vliet, 2000, p. 413)
- Test Procedure documentation: "specifies the sequence of actions for the execution of each test" (van Vliet, 2000, p. 413)
- Test Report documentation: "provides information on the results of testing tasks", addressing software verification and validation reporting (van Vliet, 2000, p. 413)

8.3 General Testing Notes

See #54

OG ISO 26262

- The scope of testing is very dependent on what type of software is being tested, as this informs what information/artifacts are available, which approaches are relevant, and which tacit knowledge is present. For example, a method table is a tool for tracking the "test approaches, testing techniques and test types that are required depending … on the context of the test object" (Hamburg and Mogyorodi, 2024) , although this is more specific to the automotive domain

- If faults exist in programs, they "must be considered faulty, even if we cannot devise test cases that reveal the faults" (van Vliet, 2000, p. 401)

- "There is no established consensus on which techniques … are the most effective. The only consensus is that the selection will vary as it should be dependent on a number of factors" (ISO/IEC and IEEE, 2021, p. 128; similar in van Vliet, 2000, p. 440), and it is advised to use many techniques when testing (p. 440). This supports the principle of *independence of testing*: the "separation of responsibilities, which encourages the accomplishment of objective testing" (Hamburg and Mogyorodi, 2024)

8.3.1 Steps to Testing (Peters and Pedrycz, 2000, p. 443)

1. Identify the goal(s) of the test
2. Decide on an approach
3. Develop the tests
4. Determine the expected results
5. Run the tests
6. Compare the expected results to the actual results

8.3.2 Test Oracles

A test oracle is a "source of information for determining whether a test has passed or failed" (ISO/IEC and IEEE, 2022, p. 13) or that "the SUT behaved correctly … and according to the expected outcomes" and can be "human or mechanical" (Washizaki, 2024, p. 5-5). Oracles provide either "a 'pass' or 'fail' verdict"; otherwise, "the test output is classified as inconclusive" (Washizaki, 2024, p. 5-5). This process can be "deterministic" (returning a Boolean value) or "probabilistic" (returning "a real number in the closed interval $[0, 1]$") (Barr et al., 2015, p. 509). Probabilistic test oracles can be used to reduce the computation cost (since test oracles are "typically computationally expensive") (Barr et al., 2015, p. 509) or in "situations where some degree of imprecision can be tolerated" since they "offer a probability that [a given] test case is acceptable" (Barr et al., 2015, p. 510). The

SWEBOK Guide V4 lists "unambiguous requirements specifications, behavioral models, and code annotations" as examples (Washizaki, 2024, p. 5-5), and Barr et al. provides four categories (2015, p. 510):

- Specified test oracle: "judge[s] all behavioural aspects of a system with respect to a given formal specification" (Barr et al., 2015, p. 510)
- Derived test oracle: any "artefact[] from which a test oracle may be derived—for instance, a previous version of the system" or "program documentation"; this includes regression testing, metamorphic testing (Barr et al., 2015, p. 510), and invariant detection (either known in advance or "learned from the program") (Barr et al., 2015, p. 516)
  - This seems to prove "relative correctness" as opposed to "absolute correctness" (Lahiri et al., 2013, p. 345) since this derived oracle may be wrong!
  - "Two versions can be checked for semantic equivalence to ensure the correctness of [a] transformation" in a process that can be done "incrementally" (Lahiri et al., 2013, p. 345)
  - Note that the term "invariant" may be used in different ways (see (Chalin et al., 2006, p. 348))
- Pseudo-oracle: a type of derived test oracle that is "an alternative version of the program produced independently" (by a different team, in a different language, etc.) (Barr et al., 2015, p. 515) . *We could potentially use the programs generated in other languages as pseudo-oracles!*

see ISO 29119-11

- Implicit test oracles: detect "'obvious' faults such as a program crash" (potentially due to a null pointer, deadlock, memory leak, etc.) (Barr et al., 2015, p. 510)
- "Lack of an automated test oracle": for example; a human oracle generating sample data that is "realistic" and "valid", (Barr et al., 2015, pp. 510-511), crowdsourcing (Barr et al., 2015, p. 520), or a "Wideband Delphi": "an expert-based test estimation technique that … uses the collective wisdom of the team members" (Hamburg and Mogyorodi, 2024)

8.3.3 Generating Test Cases

- "Impl[ies] a reduction in human effort and cost, with the potential to impact the test coverage positively", and a given "policy could be reused in analogous situations which leads to even more efficiency in terms of required efforts" (Moghadam, 2019, p. 1187)
- "A **test adequacy criterion** … specifies requirements for testing … and can be used … as a test case generator. … [For example, i]f a 100% statement coverage has not been achieved yet, an additional test case is selected that covers one or more statements yet untested" (van Vliet, 2000, p. 402)

- "Test data generators" are mentioned on (van Vliet, 2000, p. 410) but not described

Investigate

- "Dynamic test generation consists of running a program while simultaneously executing the program symbolically in order to gather constrains on inputs from conditional statements encountered along the execution (Godefroid and Luchaup, 2011, p. 23)

OG [11, 6]

- "Generating tests to detect [loop inefficiencies]" is difficult due to "virtual call resolution", reachability conditions, and order-sensitivity (Dhok and Ramanathan, 2016, p. 896)
- Can be facilitated by "testing frameworks such as JUnit [that] automate the testing process by writing test code" (Sakamoto et al., 2013, p. 344)
- Assertion checking requires "auxiliary invariants", and while "many … can be synthesized automatically by invariant generation methods, the undecidable nature (or the high practical complexity) of assertion checking precludes complete automation for a general class of user-supplied assertions" (Lahiri et al., 2013, p. 345)
  - Differential Assertion Checking (DAC) can be supported by "automatic invariant generation" (Lahiri et al., 2013, p. 345)
- *Automated interface discovery* can be used "for test-case generation for web applications" (Doğan et al., 2014, p. 184)

OG Halfond and Orso, 2007

- "Concrete and symbolic execution" can be used in "a dynamic test generation technique … for PHP applications" (Doğan et al., 2014, p. 192)

OG Artzi et al., 2008

- COBRA is a tool that "generates test cases automatically and applies them to the simulated industrial control system in a SiL Test" (Preuße et al., 2012, p. 2)
- Test case generation is useful for instances where one kind of testing is difficult, but can be generated from a different, simpler kind (e.g., asynchronous testing from synchronous testing (Jard et al., 1999))
- Since some values may not always be applicable to a given scenario (e.g., a test case for zero doesn't make sense if there is a constraint that the value in question cannot be zero), the user should likely be able to select categories of tests to generate instead of Drasil just generating all possible test cases based on the inputs (Smith and Carette, 2023)
- "Test suite augmentation techniques specialise in identifying and generating" new tests based on changes "that add new features", but they could be extended to also augment "the expected output" and "the existing *oracles*" (Barr et al., 2015, p. 516)

Investigate!

8.4 Examples of Metamorphic Relations (MRs)

- The distance between two points should be the same regardless of which one is the "start" point (ISO/IEC and IEEE, 2021, p. 22)
- "If a person smokes more cigarettes, then their expected age of death will probably decrease (and not increase)" (ISO/IEC and IEEE, 2021, p. 22)
- "For a function that translates speech into text[,] … the same speech at different input volume levels … [should result in] the same text" (ISO/IEC and IEEE, 2021, p. 22)
- The average of a list of numbers should be equal (within floating-point errors) regardless of the list's order (Kanewala and Yueh Chen, 2019, p. 67)
- For matrices, if $B = B_1 + B_2$, then $A \times B = A \times B_1 + A \times B_2$ (Kanewala and Yueh Chen, 2019, pp. 68-69)
- Symmetry of trigonometric functions; for example, $\sin(x) = \sin(-x)$ and $\sin(x) = \sin(x + 360°)$ (Kanewala and Yueh Chen, 2019, p. 70)
- Modifying input parameters to observe expected changes to a model's output (e.g., testing epidemiological models calibrated with "data from the 1918 Influenza outbreak"); by "making changes to various model parameters … authors identified an error in the output method of the agent based epidemiological model" (Kanewala and Yueh Chen, 2019, p. 70)
- Using machine learning to predict likely MRs to identify faults in mutated versions of a program (about 90% in this case) (Kanewala and Yueh Chen, 2019, p. 71)

8.5 Roadblocks to Testing

- Intractability: it is generally impossible to test a program exhaustively (Washizaki, 2024, p. 5-5; ISO/IEC and IEEE, 2022, p. 4; van Vliet, 2000, p. 421; Peters and Pedrycz, 2000, pp. 439, 461)
- Adequacy: to counter the issue of intractability, it is desirable "to reduce the cardinality of the test suites while keeping the same effectiveness in terms of coverage or fault detection rate" (Washizaki, 2024, p. 5-4) which is difficult to do objectively; see also "minimization", the process of "removing redundant test cases" (Washizaki, 2024, p. 5-4)
- Undecidability (Peters and Pedrycz, 2000, p. 439): it is impossible to know certain properties about a program, such as if it will halt (i.e., the Halting Problem (Gurfinkel, 2017, p. 4)), so "automatic testing can't be guaranteed to always work" for all properties (Nelson, 1999)

Add paragraph/section number?

8.5.1 Roadblocks to Testing Scientific Software (Kanewala and Yueh Chen, 2019, p. 67)

- "Correct answers are often unknown": if the results were already known, there would be no need to develop software to model them (Kanewala and Yueh Chen, 2019, p. 67); in other words, complete test oracles don't exist "in all but the most trivial cases" (Barr et al., 2015, p. 510), and even if they are, the "automation of mechanized oracles can be difficult and expensive" (Washizaki, 2024, p. 5.5)
- "Practically difficult to validate the computed output": complex calculations and outputs are difficult to verify (Kanewala and Yueh Chen, 2019, p. 67)
- "Inherent uncertainties": since scientific software models scenarios that occur in a chaotic and imperfect world, not every factor can be accounted for (Kanewala and Yueh Chen, 2019, p. 67)
- "Choosing suitable tolerances": difficult to decide what tolerance(s) to use when dealing with floating-point numbers (Kanewala and Yueh Chen, 2019, p. 67)
- "Incompatible testing tools": while scientific software is often written in languages like FORTRAN, testing tools are often written in languages like Java or C++ (Kanewala and Yueh Chen, 2019, p. 67)

Out of this list, only the first two apply. The scenarios modelled by Drasil are idealized and ignore uncertainties like air resistance, wind direction, and gravitational fluctuations. There are not any instances where special consideration for floating-point arithmetic must be taken; the default tolerance used for relevant testing frameworks has been used and is likely sufficient for future testing. On a related note, the scientific software we are trying to test is already generated in languages with widely-used testing frameworks.

Add example

Add source(s)?

Chapter 9

Extras

Writing Directives

- What macros do I want the reader to know about?

9.1 Writing Directives

I enjoy writing directives (mostly questions) to navigate what I should be writing about in each chapter. You can do this using:

Source Code 9.1: Pseudocode: exWD

```
\begin{writingdirectives}
    \item What macros do I want the reader to know about?
\end{writingdirectives}
```

Personally, I put them at the top of chapter files, just after chapter declarations.

9.2 HREFs

For PDFs, we have (at least) 2 ways of viewing them: on our computers, and printed out on paper. If you choose to view through your computer, reading links (as they are linked in this example, inlined everywhere with "clickable" links) is fine. However, if you choose to read it on printed paper, you will find trouble clicking on those same links. To mitigate this issue, I built the "porthref" macro (see `macros.tex` for the definition) to build links that appear as clickable text when "compiling for computer-focused reading," and adds links to footnotes when "compiling for printing-focused reading." There is an option (`compilingforprinting`) in the `manifest.tex` file that controls whether PDF builds should be done for

computers or for printers. For example, by default, McMaster is made with clickable functionaity, but if you change the `manifest.tex` option as mentioned, then you will see the link in a footnote (try it out!).

Source Code 9.2: Pseudocode: exPHref

```
\porthref{McMaster}{https://www.mcmaster.ca/}
```

9.3 Pseudocode Code Snippets

For pseudocode, you can also use the pseudocode environment, such as that used in Source Code A.7.

9.4 TODOs

While writing, I plastered my thesis with notes for future work because, for whatever reason, I just didn't want to, or wasn't able to, do said work at that time. To help me sort out my notes, I used the `todonotes` package with a few extra macros (defined in `macros.tex`). For example,...

Important notes:

Important: "Important" notes.

Generic inlined notes:

Generic inlined notes.

Later: TODO notes for later! For finishing touches, etc.

Notes for later:

Some "easy" notes:

Easy: Easier notes.

Tedious work:

Needs time: Tedious notes.

Q #1: Questions I might have?

Questions:

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Appendix

Source Code A.3: Tests for main with an invalid input file

```
# from
↪  https://stackoverflow.com/questions/54071312/how-to-pass-command-line-argv
## \brief Tests main with invalid input file
# \par Types of Testing:
# Dynamic Black-Box (Behavioural) Testing
# Boundary Conditions
# Default, Empty, Blank, Null, Zero, and None
# Invalid, Wrong, Incorrect, and Garbage Data
# Logic Flow Testing
@mark.parametrize("filename", invalid_value_input_files)
@mark.xfail
def test_main_invalid(monkeypatch, filename):
    # from
    ↪  https://stackoverflow.com/questions/10840533/most-pythonic-way-to-del
    try:
        remove(output_filename)
    except OSError as e: # this would be "except OSError, e:"
    ↪  before Python 2.6
        if e.errno != ENOENT: # no such file or directory
            raise # re-raise exception if a different error
            ↪  occurred


    assert not path.exists(output_filename)


    with monkeypatch.context() as m:
        m.setattr(sys, 'argv', ['Control.py',
        ↪  str(Path("test/test_input") / f"{filename}.txt")])
        Control.main()

    assert not path.exists(output_filename)
```

Source Code A.4: Projectile's choice for constraint violation behaviour in code

```
    srsConstraints = makeConstraints Warning Warning,
```

Source Code A.5: Projectile's manually created input verification requirement

```
verifyParamsDesc = foldlSent [S "Check the entered", plural
↪  inValue,
    S "to ensure that they do not exceed the" +:+. namedRef (datCon
    ↪  [] []) (plural datumConstraint),
    S "If any of the", plural inValue, S "are out of bounds" `sC`
    S "an", phrase errMsg, S "is displayed" `S.andThe` plural
    ↪  calculation, S "stop"]
```

Source Code A.6: "MultiDefinitions" (MultiDefn) Definition

```
-- | 'MultiDefn's are QDefinition factories, used for showing one
↪  or more ways
--   we can define a QDefinition.
data MultiDefn e = MultiDefn{
  -- | UID
  _rUid :: UID,
  -- | Underlying quantity it defines.
  _qd :: QuantityDict,
  -- | Explanation of the different ways we can define a quantity.
  _rDesc :: Sentence,
  -- | All possible ways we can define the related quantity.
  _rvs :: NE.NonEmpty (DefiningExpr e)
}
```

Source Code A.7: Pseudocode: Broken QuantityDict Chunk Retriever

```
retrieveQD :: UID -> ChunkDB -> Maybe QuantityDict
retrieveQD u cdb = do
    (Chunk expectedQd) <- lookup u cdb
    pure expectedQd
```