Using Machine Learning to Refine Black-box Test Specifications and Test Suites

By

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Abstract

In the context of open source development or software evolution, developers are often faced with potentially large test suites which have been developed with no apparent rationale and which may need to be augmented or refined to ensure sufficient dependability, or even possibly reduced to meet tight deadlines. We will refer to this process as the re-engineering of test suites. It is important to provide both a method and tool support to help people understand the limitations of test suites and their possible redundancies, so as to be able to re-engineer them in a cost effective manner. To address this problem in the case of black-box testing, we propose a method based on machine learning that has shown promising results on two case studies.

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CHAPTER 1 INTRODUCTION

Software Testing is probably the most complex task in the software development cycle. The purpose of software testing is to increase the software engineers' confidence in the proper functioning of the software [1]. A test is the act of exercising software with test cases. Each choice of input data is called a test case. To identify test cases, functional and structural testing techniques are used [2].

In the context of open source development, it is often the case that one is confronted with existing test suites that are based on no explicit rationale or specifications, other than general guidelines for exercising the main user functionalities for example (e.g., based on check lists [3]). For instance, open source software development projects have been shown to lack “attention to basic, accepted, and mature testing techniques [4].” In practice, software developers who intend to reuse open source code are commonly confronted with such ad hoc test suites. It is therefore important to evaluate them and possibly reduce or augment them, depending on whether they are deemed redundant or too weak to achieve a sufficient level of confidence. For instance, Zhao and Elbaum report that in a large proportion of open source software development projects, test suites achieve low source code coverage (e.g., 30%) [4]. Developers hence have an alternative: either build new test suites or reuse existing ones; and they often go for the latter as it (hopefully) reduces effort and therefore costs. This will inevitably lead them to understanding, evaluating and possibly improving these test suites.

Similarly, in an evolution context, because of personnel turnover, the originator of a test suite may not be available and whoever is in charge of modifying and re-testing the software is confronted with understanding and evaluating existing test cases. Even in the context of regression testing, where one needs to select a subset and prioritize existing test cases, it is important to ensure that the original test suite is sufficiently complete and not redundant to minimize the cost.

We propose a partially automated method, based on the application of a machine learning technique, to help software engineers analyze the weaknesses of test suites so as to be able to iteratively improve them. We refer to this process as the re-engineering of test suites as it is similar to what can be seen in re-engineering source code where code information is extracted, abstracted from a design standpoint, and then used to decide about design changes [5].

Our method takes as inputs the test suite, and test specification following the Category-Partition (CP) strategy [6] to be re-engineered. Based on the CP specification, test cases in the test suite are transformed into abstract test cases which are tuples of pairs (category, choice) associated with an output equivalence class (instead of raw inputs/outputs). A machine learning algorithm (C4.5 decision tree algorithm [7]) is used to learn rules that relate pairs (category, choice), modeling input properties, to output equivalence classes. These rules are then analyzed to determine potential improvements to the test suite (e.g., redundant test cases, need for additional test cases) as well as improvements to the CP specification (e.g., need to add a category). The method is applied to a small size but logically complex program (the PackHexChar program), and its effectiveness is evaluated on test suites and CP

specifications created by fully trained 4th year students. The study shows that the iterative process can indeed improve both the test suite and the CP specification to a level that is equivalent to what an expert would likely produce. The method is then applied to an industrial size program, thereby illustrating that it can scale up. Results are also encouraging.

1.1 Contribution

The contributions of this thesis are:

- An iterative, incremental re-engineering process to evaluate and improve a test suite and test specification;
- The identification/definition of clear evaluation criteria;
- The definition of clear test suite improvement mechanisms;
- The evaluation of the proposed method on two case studies;
- Tool support for the case studies.

1.2 Thesis Organization

The rest of the thesis is structured as follows. Related work is described in CHAPTER 2. CHAPTER 3 provides some background on Category-Partition, the black-box testing technique we use, and machine learning. Our iterative approach is described in Figure 4. The results of two case studies are discussed in CHAPTER 5. Conclusions are drawn in CHAPTER 6.

CHAPTER 2 RELATED WORK

In [8], the authors introduce a technique to learn a specification from execution traces. The generated specification is a non-deterministic finite automaton and the authors focus on mining uses of APIs or ADTs (i.e., their specification): nodes of the automaton are calls to the API (or ADT). The automaton is non-deterministic since not all behaviors are necessarily reverse-engineered (this depends on the test cases being used). The authors use a specific machine learning algorithm that generates a probabilistic finite state automaton (PFSA): probabilities are attached to transitions, specifying how often the transitions have been taken. The approach can be the starting point of a testing procedure: The (automaton) specification of an API can be learnt from its use in program P_1 , and its use in program P_2 can be checked against the learnt specification. As opposed to our work, their approach does not guide the definition (or refinement) of test cases.

Execution traces are also used in [9] to learn program behavior: the authors record the execution of branches in the program (inter-procedural) control flow graph. The classifier being learnt is a map between execution traces (i.e., branch execution profiles) and behavior classes (e.g., fail/pass), and can be used to guide the construction (or extension) of a test suite. Assuming a test suite TS for program P exists and has to be augmented, P is first instrumented (to capture branch executions). The instrumented P is executed on TS and branch execution profiles are used to create a classifier. When a new test case is created, it is classified by the classifier. If the classifier cannot classify it, i.e., it cannot decide to which behavior class (e.g.,

fail/pass) the test case corresponds, the test case is associated with a class (i.e., the tester provides a behavior class, typically by building an oracle) and used to refine the classifier. This means that the test case triggers a behavior that was not recognized by the classifier. If the test case is recognized by the classifier, i.e., the behavior was already exercised by TS, it is discarded. Although the classifier helps the tester identify (somewhat) redundant test cases, thus avoiding the cost of building an oracle for them (an oracle is only built for unclassified test cases), the technique requires that the test case be defined by other means and executed before determining whether it is a useful addition or not. The strategy can only be practical if the tester can ensure that the new test data have high chances of triggering new behavior (otherwise, building test cases and more so executing them may be expensive), e.g., if an automatic test data generator is used, as suggested by the authors, there is a risk that many executed test cases be redundant and recognized by the classifier, therefore providing little help. Though the approach is very effective at determining whether a new test case is a useful addition, it provides little help for the definition of new, interesting test cases (the authors assume an automated test input and test case generation procedure is available).

Another execution trace based approach to test suite evaluation and extension is proposed in [10]. As long as the reverse-engineered specification, in the form of so-called ‘likely invariants’ [11], does not change when adding a test case to a test suite, the test case is deemed redundant. This approach does not require the construction of oracles, as opposed to the previous ones. The quality of the result however depends on the program invariant patterns that are used. The program invariants being

discovered from execution information must be instances of a set of pre-defined invariant patterns. An invariant that does not fall into this category cannot be recognized. Furthermore, the approach does not provide guidance regarding the definition of new test cases.

This approach is expanded upon in [12] where the authors use a specification (invariants), reverse-engineered from passing test cases, to determine whether new automatically-generated (mainly randomly) test inputs are illegal, legal, and fault revealing based on the run-time monitoring of invariants. Illegal test cases violate the reverse-engineered pre and post conditions of a method, whereas fault revealing test cases only violate post conditions. However, such a test case may not necessarily represent a failure since the pre and post conditions may not be complete (they have been learnt from a set of test cases that may not have exercised every possible behavior). This is further expanded in [13] where reverse-engineered likely invariants [11] are analyzed by a constraint solver to automatically produce test inputs and test cases. Constraint solving is however limited (e.g., integer variables are supported but not floating point variables). In both [13] and [12], only likely invariants matching pre-defined patterns are considered (recall the discussion above).

In [14] the authors investigate how profiling deployed software, i.e., collecting execution information in the field, can help improve a test suite. No learning mechanism is employed though: additions to the initial in-house test suite entail repeating scenarios observed in the field and new test cases derived from trace data. The use of learning algorithms to understand program executions is applied to the problem of profiling deployed software in [15]. The objective is to be able to

accurately classify program executions as fail or pass executions based on low-cost, limited instrumentation of deployed programs, rather than to improve a test suite.

Baudry *et al.* [16] discuss a white box technique to improve a test suite with a different aim: obtaining a test suite that will facilitate diagnosability by pinpointing faulty statements with a high accuracy. The proposed approach relies on a new testing criterion, that evaluates the “fault locating power” of a test case (measured using Tarantula¹ [17]), to evaluate the test suite to improve, and on a bacterial algorithm (an adaptation of a genetic algorithm [18]) to actually find improved test cases.

In [19] the authors present an adaptive sampling mechanism to identify feasible paths in a control flow graph with high traversing probability. Instead of uniformly sampling the set of paths in the control flow graph of a program (which usually contains a very large number of unfeasible paths), the authors devise an adaptive (learning) approach to ease the identification of feasible paths. The adaptive aspect of the approach is to learn, from the structure of known feasible paths, which branches to traverse in order to obtain a new feasible path.

In [20] the authors present a technique to improve a test suite based on a Z specification of the program/function under test and the Classification Tree method

¹ Tarantula is a visualization tool that gives the user a number of options for visualizing the testing results and the program itself. Tarantula uses the proportion of test cases that fail when executing a specific statement to determine the ranking of statements in terms of their likelihood to contain a fault. One important issue is that this assumes that test cases fail due to the same fault(s), a situation which nearly never occurs in the presence of multiple faults.

[21]². They show how a classification tree of the program input parameters can be created semi-automatically from its Z specification. The classification can be enriched with any category/choice if this is deemed necessary by the tester. The Classification Tree method [21] can then be applied on the classification tree to build test cases. These test cases are predicates on the program input parameters, i.e., conjunctions of the categories/choices in the tree. These predicates are then combined with the predicates of the Z specification (see [20] for details on the combination procedure) to: (1) determine the expected output of a test case, (2) refine the user defined test cases, completing their definitions with categories/choices that have been omitted when applying the Classification Tree method, and (3) identify problems in the Z specification, such as incompleteness (though no guidance is provided to solve this issue).

Many other applications of machine learning techniques to software engineering exist in literature (e.g., [22, 23]) but are less related to our focus on test suite and test specification improvement.

To summarize, our approach differs from the above with respect to one or several of the following aspects: (1) It addresses black-box, functional testing, (2) It provides guidance in terms of new functional test cases to consider (and not only the

² The Classification Tree method [22] is a black-box partition testing technique, supported by a tool, similar to Category-Partition [6]. It allows a tester to define categories and choices (using the Category-Partition terminology) under the form of a tree and define test cases as combinations of classes (there is no notion of constraints like in Category-Partition though).

improvement of existing ones), (3) It helps refine the test specifications from which test cases can be derived following a clear rationale.

CHAPTER 3 BACKGROUND

Our approach, detailed in CHAPTER 4, relies on a well-known black box testing technique, namely Category Partition [6] (Section 3.1), as well as machine learning (Section 3.2).

3.1 Using Category Partition

Category Partition [6] is a well-known black-box testing technique. Compared to equivalence class partitioning that only partitions the input value domain and other black box testing techniques, the Category-Partition method is more general and encompassing. In Equivalence Class Partitioning, classes of input conditions called equivalence classes are identified such that each member of the class causes the same kind of processing and output to occur. In this method, the tester identifies various equivalence classes for partitioning. A class is a set of input conditions that are likely to be handled the same way by the system. If the system were to handle one case in the class erroneously, it would handle all cases erroneously. The Category-Partition method generates test cases that cover functions. To apply the Category-Partition method, one identifies the parameters of each function, as well as external (environment) conditions that affect the function's execution behavior. Then one identifies the characteristics (referred to as categories) of each parameter (and environment conditions) and the choices of each category. Categories are properties of parameters (and environment conditions) that can have an influence on the behavior of the function under test (e.g., comparing the lengths of two sides in the

Triangle program example [2]). Choices (e.g., whether two sides of the triangle are equal or not) are the potential values of a category which stands for a certain character of the category. Choices for a category are mutually exclusive, i.e. for each category only one choice is feasible. Test frames (abstract test data) and test data are generated according to the identified categories and choices: different criteria exist for combining choices in test frames [6].

To illustrate how the Category Partition (CP) [6] black-box testing method works, let us take the well-known and simple Triangle program example [2], which we will also use as a working example to illustrate our method: The complete application of CP to the Triangle program is available in Figure 1. The test input values of the triangle program characterize the length of triangle sides (a , b , c) and its output determines whether these sides correspond to an equilateral, isosceles, or irregular triangle. In addition, the program may determine that the sides cannot correspond to a triangle (based on checking certain inequalities, i.e., choices C6, C12, and C18 in Figure 1) or the side values are illegal (choices C2, C8, and C14 in Figure 1).

In addition to categories and choices describing input parameters of the program, CP requires the identification of categories and choices for environment conditions, i.e., conditions of the environment of the program that may affect its behavior (e.g., contents of a database, state of external systems, load of the processor or network). CP can therefore help characterize functional as well as non-functional behavior, targeting functional testing, performance testing, and robustness testing.

In our context, once categories and choices are defined, we use them to automatically transform each test case into an “abstract” test case. (There are as many abstract test cases as test cases.) In our Triangle example, these properties may correspond to Boolean expressions stating relationships between sides, e.g., how a compares to b and c (category 3 in Figure 1). Taking the “ a compared to b and c ” category as an example, choices could correspond to the two mutually exclusive situations where $a \leq b+c$ (choice C5) and $a > b+c$ (choice C6). Choices C2 ($a \leq 0$), C8 ($b \leq 0$), and C14 ($c \leq 0$) are error conditions, i.e. the length of triangle side cannot be less than or equal to zero. In addition, though we do not make use of them in our approach, Category-Partition requires that “properties” and “selectors” be defined to model interdependencies between choices and thus be used to automatically identify unfeasible combinations of choices across categories [6].

Parameter a Category 1—values for a Choice C1: $a > 0$ Choice C2: $a \leq 0$ Category 2— a versus b Choice C3: $a = b$ Choice C4: $a \neq b$ Category 3— a versus b and c Choice C5: $a \leq b + c$ Choice C6: $a > b + c$	Parameter c Category 7—values for c Choice C13: $c > 0$ Choice C14: $c \leq 0$ Category 8— c versus a Choice C15: $c = a$ Choice C16: $c \neq a$ Category 9— c versus a and b Choice C17: $c \leq a + b$ Choice C18: $c > a + b$
Parameter b Category 4—values for b Choice C7: $b > 0$ Choice C8: $b \leq 0$ Category 5— b versus c Choice C9: $b = c$ Choice C10: $b \neq c$ Category 6— b versus a and c Choice C11: $b \leq a + c$ Choice C12: $b > a + c$	

Figure 1 Triangle Program CP Specification

3.2 C4.5 Decision Trees (DT)

There is a large number of machine learning and data mining techniques [24]. They differ widely in terms of their basic principles, their working assumptions, and their weaknesses and strengths. None of the techniques is inherently better than the other and which one is most appropriate tends to be context dependent. Some of these techniques focus on classification, which is the problem at hand in this thesis as we want to learn about the relationship between inputs and environmental properties (categories and choices) and output equivalent classes.

A specific category of machine learning techniques focuses on generating classification rules [24] which are easily amenable to interpretation. Examples of such techniques include the C4.5 decision tree algorithm [7] (where the paths from the root node of the tree to any leaf can be considered a rule) or the Ripper rule induction algorithm [25]. In our context, the rules would look like properties on test inputs that are being associated with outputs. The main advantage of these techniques is the interpretability of their models: certain conditions imply a certain output equivalence class.

Some techniques, like C4.5, partition the data set (e.g., the set of test cases) in a stepwise manner using complex algorithms and heuristics to avoid over-fitting the data (i.e., determining how deeply to grow a decision tree), with the goal of generating models that are as simple as possible. Others, like Ripper, are so-called covering algorithms that generate rules in a stepwise manner, removing observations that are “covered” by the rule at each step so that the next step works on a reduced set

of observations. With coverage algorithms, rules are interdependent in the sense that they form a “decision list” where rules are supposed to be applicable in the order they were generated. Because this makes their interpretation more difficult, we will use a classification tree algorithm, namely C4.5, and use the WEKA tool [24] to build and assess the trees.

To illustrate the notion of C4.5 decision tree and the output generated by Weka, we take the weather problem [24] as an example. The weather problem is a tiny dataset that relates the weather conditions that are suitable for playing some outdoor game. Instances in the dataset are characterized by the values of four attributes that measure different aspects of weather conditions: Outlook, temperature, humidity, and windy; and the outcome is whether to play or not to play. Table 1 shows the dataset of 14 instances that is used in the weather problem with four attributes and their values; the last column indicates the output. Outlook can be sunny, overcast, or rainy; Temperature can be hot, mild, or cool; humidity can be high or normal; and windy can be true or false.

Outlook	Temperature	Humidity	Windy	Play
Sunny	Hot	High	False	No
Sunny	Hot	High	True	No
Overcast	Hot	High	false	Yes
Rainy	Mild	High	False	yes
Rainy	Cool	Normal	False	Yes
Rainy	Cool	Normal	True	No
Overcast	Cool	Normal	True	Yes
Sunny	Mild	High	False	No
Sunny	Cool	Normal	False	Yes
Rainy	Mild	Normal	False	Yes
Sunny	Mild	Normal	True	Yes
Overcast	Mild	High	True	Yes
Overcast	Hot	Normal	False	Yes
Rainy	Mild	High	True	No

Table 1 The Weather Data [24]

Based on the data in Table 1, WEKA returns³ the result of Figure 2, applying the C4.5 algorithm. Figure 2 shows a decision tree (lines numbered 1 to 7), reports on the number of leaves in the tree (line 8), and shows a confusion matrix (bottom of Figure).

```

1.    Outlook = Sunny
2.    | Humidity = High: No (3.0)
3.    | Humidity = Normal: Yes (2.0)
4.    Outlook = Overcast: Yes (4.0)
5.    Outlook = Rainy
6.    | Windy = True: No (2.0)
7.    | Windy = False: Yes (3.0)

8.    Number of Leaves : 5

9.    Correctly Classified Instances      14      100%
10.   Incorrectly Classified Instances    0        0%

=== Confusion Matrix ===
(a)      (b)    <-- classified as
  9         0 | (a) = Yes
  0         5 | (b) = No

```

Figure 2 C4.5 decision tree for the weather data

It is easy to read a set of rules directly off a decision tree. Traversing a decision tree from the root to each leaf gives a rule, with the path conditions as the antecedent and the leaf as the class or output. This produces rules that are unambiguous, i.e. the order of the conditions does not matter. In this example, the root is the attribute Outlook that has three possible values: Sunny, Overcast, and Rainy. There are two sub-trees: a Humidity sub-tree below Sunny (lines 1 to 3), and a Windy sub-tree below Rainy (lines 5 to 7). There is a total of 5 rules, i.e., 5 leaves, that classify all the instances in Table 1.

³ Using the default verbosity level of WEKA.

It is now easy to read the rules, as illustrated in Figure 3. For instance, rule 1 (lines 1 and 2 in Figure 2) can be read as: If Outlook is Sunny and Humidity is High then the output is don't play. The number in brackets following each leaf indicates the number of instances in the input set that are classified by each rule. This number may be followed by a second number (which is not the case in Figure 2), e.g., 3.0/1.0, in which case the second value (1.0) indicates the number of classification errors (or the number of instances misclassified by that rule) encountered out of the total number of classifications made from the training data in that particular path of the decision tree (3.0). C4.5 builds decision trees from a set of training data using the concept of information entropy [24]. At each node of the tree, C4.5 chooses one attribute of the data that most effectively splits its set of samples into subsets enriched in one class or the other. Its criterion is the normalized information gain (difference in entropy) that results from choosing an attribute for splitting the data. The C4.5 algorithm then recurses on the smaller sublists. Lack of the training data may result in a tree where some leaves (rules) may have no instances covered.

Lines 9 and 10 in Figure 2 show the number (and percentage) of correctly and incorrectly classified instances respectively.

<p>Rule 1: Outlook = Sunny and Humidity = High implies No (3.0)</p> <p>Rule 2: Outlook = Sunny and Humidity = Normal implies Yes (2.0)</p> <p>Rule 3: Outlook = Overcast implies Yes (4.0)</p>	<p>Rule 4: Outlook = Rainy and Windy = True implies No (2.0)</p> <p>Rule 5: Outlook = Rainy and Windy = False implies Yes (3.0)</p>
--	---

Figure 3 Rules explained (from Figure 2)

A confusion matrix [26] contains information about actual and predicted classifications done by a classification system. The performance of such systems is commonly evaluated using the data in the matrix. From the confusion matrix in Figure 2 we see that, nine instances of the class `Yes` are correctly classified using the generated rules. Five instances of the class `No` are correctly classified using the generated rules. Zero instances were incorrectly classified.

Let us suppose that in the weather problem two instances of class `Yes` are misclassified as `No`. The confusion matrix would look like:

(a)	(b)	<-- classified as
7	2	(a) = Yes
0	5	(b) = No

This matrix shows that 7 instances of the known class `Yes` (Play) were correctly classified using the generated rules as members of class `Yes`. 5 instances of the known class `No` (Don't Play) were correctly classified using the generated rules as members of class `No`. 2 instances were incorrectly classified.

CHAPTER 4 METHOD

An overview of the steps involved in the MELBA (Machine Learning based refinement of Black-box test specification) method is briefly described in Section 4.1. Section 4.1 also illustrates how an abstract test suite is obtained and why it is important to have the abstract test suite as opposed to the raw test data. Our method takes as inputs the test suite, and test specification following the Category-Partition (CP) strategy, to be re-engineered. Based on the Category-Partition specification, test cases are transformed into abstract test cases which are tuples of pairs (category, choice) associated with an output equivalence class (instead of raw inputs/outputs). A machine learning algorithm (C4.5 decision tree algorithm) is used to learn rules that relate pairs (category, choice), modeling input properties, to output equivalence classes. These rules are then analyzed to determine potential improvements to the test suite (e.g., redundant test cases, need for additional test cases) as well as improvements to the Category-Partition specification (e.g., need to add a category or choices). Our approach is to identify problems in results produced by C4.5 (Section 4.2) and to relate them to potential causes in terms of test suite or test specification deficiencies (Section 4.3). We illustrate these two steps on our Triangle working example (Figure 1). We discuss strategies to improve a test suite in Section 4.4.

4.1 Overview

Figure 4 provides an overview (as a UML activity diagram) of the steps involved in the MELBA (Machine Learning based refinement of Black-box test specification)

method we will describe in detail in the next sections. The inputs of the method are the test suite to be re-engineered and a test specification (left side of Figure 4).

Figure 4 The MELBA Method

4.1.1 An Iterative Process

We do not make any specific assumption regarding the contents of a test case and the software unit under test (SUT), other than the feasibility of transforming test cases into abstract test cases given pre-defined categories and choices. In particular, we do not assume that the test suite has been *originally* derived according to the Category-Partition method. Though the test specification is assumed in this thesis to follow the category-partition [6] (CP) strategy, future work will investigate how our method could be tailored to other black-box strategies. In the context of CP, the SUT is typically decomposed into user functionalities (e.g., use case) which are then independently tested. However, CP can be applied to the test of sub-systems or even methods, and as other black-box test techniques, the complexity of testing depends on the behavioral specification of the SUT, not necessarily its source code size.

In practice, this test specification may or may not exist to start with, especially if no black-box strategy was used to identify the test cases. In the latter case, which is

likely to be the most common situation, the test specification has to be reverse-engineered, to some extent or created from high level (likely plain language) specification. Furthermore, the output domain has to be divided into equivalence classes. In the context of Category-Partition, the Triangle program [2] is so simple that its output is already under the form of equivalence classes: equilateral, isosceles, irregular triangles, and not a triangle. However, even this could be simplified, for example, into two equivalence classes: Triangle, not Triangle. The level of granularity of this partition of the output domain is a decision of the tester. Increased granularity will result into increased testing effort but will characterize the SUT behavior in a more precise way

As the input domain is modeled using CP categories and choices (Section 3.1), the test suite is then transformed into an abstract test suite (Activity 1 in Figure 4). Recall that each test case in the test suite is transformed into one abstract test case, and that therefore the abstract test suite has the same number of elements (size) as the test suite. An abstract test case shows an output equivalence class and pairs (category, choice) that characterize its inputs, instead of raw inputs. Once the Category-Partition specification is defined, this abstraction activity is easy to automate, as it was done in our case studies. The definition of categories and choices, on the other hand, requires much thinking as one must identify categories and define choices so that they determine output equivalence classes. This represents an up-front investment, and is an issue further discussed in section 4.1.2. Note that the initial categories and choices defined by the tester do not have to be perfect as our method will help identify

problems in their definitions. Additionally, the categories and choices can be defined at varying levels of granularity, which is a decision resting with the tester.

Once an abstract test suite is available, a machine learning algorithm (C4.5 [7]) is used to learn rules that relate pairs (category, choice), modeling input properties, to output equivalence classes (Activity 2 in Figure 4). An example of such rule was discussed in Section 3.2.

These rules are in turn analyzed by a tester (Activity 3 in Figure 4) to determine potential problems that may indicate redundancy among test cases or the need for additional test cases (Activity 4 in Figure 4). Those rules may also indicate that the Category-Partition specification needs to be improved: e.g., an important category is missing or certain choices are ill-defined (Activity 5 in Figure 4). In the next sections, we will detail a number of heuristics that can be used to automatically analyze the C4.5 rules and investigate ways to improve test suites and CP specifications.

The improvement process in Figure 4 is iterative as improvements to either the test suite or test specification can lead to the identification of new problems to be addressed. The learning algorithm will therefore be repeatedly executed (edges from Activities 4 and 5 to Activity 1, followed by Activity 2), which is not an issue as obtaining C4.5 decision trees for a few thousands of (abstract) test cases and a few dozen categories is quick (see Section 4.1.2). The improvement process stops when no more problems can be found in the rules learnt by the machine learning algorithm (Activity 3).

One issue is the presence of faults in the software under test and its impact on MELBA and the C4.5 learning algorithm. MELBA assumes that the initial test suite has been run, failures have been detected and the corresponding faults corrected. In short, the starting point of the iterative improvement process is a possibly incomplete but passing set of test cases. However, as the test suite is augmented with new test cases, failures can arise and new faults can be detected. These faults must then be corrected and the new test cases must pass before re-running C4.5 and obtain a new decision tree. Otherwise, since some of the outputs might be incorrect, this might lead to misclassifications in the tree which, though they would not necessarily prevent the use of MELBA, could make the decision tree analysis more complex.

In the case of forward development, when test cases are defined, possibly even before any source code is written, the approach can still be applied: test inputs and corresponding (expected) outputs are used during the whole refinement process and this does not require any test case execution. When test case implementation is available and identifying the expected output is deemed too difficult (Oracle Problem [27]), test cases can be assembled and the actual output collected to be used in the refinement process.

4.1.2 Manual Effort and Automation

Once the CP specification is defined, the transformation of test cases into abstract test cases is easy to automate. For instance, in our first case study, using a Category-Partition specification of 11 categories and 33 choices and a test suite of 221 test cases, it took a couple of seconds to create 221 abstract test cases. Using the more

complex, second case study, namely the Space program, for which 83 categories and 582 choices are defined, 13,585 test cases are abstracted in less than a minute. In short, Activity 1 in Figure 4 is automated and fast.

The definition of categories and choices, on the other hand, requires much thinking as one must identify categories and define choices so that they determine output equivalence classes. This requires an understanding of the system domain but is, on the other hand, what a tester would typically do when trying to reengineer a test suite, for instance using CP or any other black-box test technique. Though this represents an up-front investment, there is no way one can reuse a test suite or modify a system with confidence without making an effort to understand the relationships between the inputs and outputs of the system.

Activity 2 is another automated step, for which we use the WEKA tool, which implements C4.5. For our first case study, it took less than a second for WEKA to generate a decision tree. In the case of the larger Space problem (second case study), it took eight seconds to generate a tree based on 13,585 abstract test cases.

Activity 3 is partially automated. On the one hand, much information is automatically provided in the WEKA output: misclassifications, categories and choices used in learnt rules, number of instances (i.e., abstract test cases) involved in rules. This information is the source of our heuristics for problem identification described in Section 4.2. The tester then has to identify the causes of those problems, a process that we support with a set of guidelines (Section 4.3).

Activities 4 and 5 are not automated at this point, as this relies on the know-how and expertise of the tester. However, as discussed in the next section, we provide guidance to help identify which categories/choices need to be refined, which abstract test cases need to be defined. Test suite amendment (Activity 4) requires some effort but this is an effort that is anyway incurred if one is trying to improve a test suite.

4.1.3 From raw test data to abstract test cases

The rules produced by C4.5 can be seen as tuples of choices associated with an output equivalence class (or output equivalence class value). Using the triangle CP in Figure 1, the test case $(a=2, b=3, c=3)$ could be abstracted into a tuple such as $(a \leq b+c, b=c, \text{Isosceles})$, where: $a \leq b+c$ is a choice for category Category 3— a versus b and c in Figure 1; $b=c$ is a choice for category Category 5— b versus c in Figure 1. Note that the tuple would contain pairs of the form (category, choice) but we only show choices here to simplify the discussion. Notice that tuples typically involve many more choices as every existing choice condition that applies to a test case is used when creating the corresponding abstract test case. The test case above could then be abstracted into $(a \geq 0, a \neq b, a \leq b+c, b > 0, b=c, b < a+c, c > 0, c \neq a, c \leq a+b, \text{Isosceles})$. Last, it may happen that none of the choices defined for a specific category can be used when creating an abstract test case⁴. In such a situation, we add a “not applicable” (or N/A) choice to the category and use this pseudo choice

⁴ This is typically the case when choices cannot be combined across categories, or when categories cannot be combined. Such a situation would be specified with “properties” and “selectors” if we were applying CP for the purpose of defining test cases, instead of using CP to characterize existing test cases.

in the tuple. For example, assume a program manipulates a string of characters and its behavior depends on whether the string contains only numbers or only letters (the behavior would furthermore depend on whether the string contains capital letters or not). Then one would define (at least) a category `Cat1` with two choices (`c1` and `c2`, respectively) for the two different types of strings, and a category `Cat2` for strings containing letters with two choices (`c3` and `c4`, respectively) specifying whether the string contains capital letters or not. Suppose now that we want to create the abstract test case for a test case where the input parameter contains only numbers. Choice `c1` would be used in the tuple but none of the choices of `Cat2` can be used. We then define a `N/A` choice for `Cat2` and use it in the tuple.

We need to create abstract test cases from concrete (raw) test cases since using raw data will generate meaningless and possibly incorrect decision trees. Rules generated from raw data are meaningless and possibly incorrect because the machine learning algorithm cannot learn which properties are of interest: since the raw data do not contain any information on those properties, the rules can only relate values of the parameters instead of properties of those parameters. Eventhough, in C4.5 continuous-valued attributes are incorporated into the learned tree by dynamically defining new discrete-valued attributes that partition the continuous attribute value into a discrete set of intervals, the only question is how to select the best interval. There are other methods for dealing with numeric attributes (see [40]), but mainly algorithms that can deal with them look to discretise them in some way. This means that they can then be treated just as categorical attributes. But instead of using the dynamically categorized values, we generate such intervals by using CP which can then be improved through

the Melba method. If raw data were to be used, they are to be well distributed in the domain space; the generated tree would then be meaningful and easy to understand. This is however unlikely to happen in practice. To facilitate the learning process, further guidance needs to be provided to the learning algorithm to generate a meaningful tree. Let us use the Triangle program as an example to illustrate this. Executing C4.5 on the raw data for the Triangle program, i.e., the nine test cases in Appendix A.1.4 (Table 4), we obtain the decision tree of Figure 5.

(c) <= 1	
(a) <= -1: null (1.0)	Rule 1
(a) > -1: Equilateral (1.0)	Rule 2
(c) > 1	
(b) <= 1	
(c) <= 2: Isosceles (1.0)	Rule 3
(c) > 2: Not_Triangle (2.0)	Rule 4
(b) > 1	
(a) <= 3: Irregular (2.0)	Rule 5
(a) > 3: Isosceles (2.0)	Rule 6

Figure 5 Triangle Tree generated with raw data

Rule 2 in Figure 5 for instance indicates that if $c \leq 1$ and $a > -1$ then the output class is Equilateral. This is not correct since $c=0$ and $a=0$, which satisfy the condition, should not correspond to a valid triangle. As a second example, consider Rule 6. It indicates that if $c > 1$ and $a > 3$ then the triangle is isosceles. Again, this is not correct as other conditions should hold to have an isosceles triangle. Therefore, we need to transform the (raw) test cases into abstract test cases to guide the learning algorithm. We use the Category-Partition (CP) method to define the test specification and then use the categories and choices to do the mapping between the raw test case data and the categories and choices of the CP to obtain an abstract test suite (as described earlier).

Let us consider the Triangle program with the same 9 test cases. However, this time, instead of using the raw data, we use the abstract test cases obtained using the CP specification in Appendix A.1.2: Table 5 in Appendix A.1.4. We obtain the decision tree of Figure 6. The tree clearly shows the conditions under which each type of triangle is obtained. The rules are accurate and meaningful.

Figure 6 Triangle Tree generated with abstract test data

4.2 Identifying problems in C4.5 decision trees

When analyzing a C4.5 decision tree in the context of our method, we can identify a number of potential problems:

Case 1—Instances (abstract test cases) can be misclassified: the wrong output equivalence class is associated to a test case. In other words, a test case belongs to a tree leaf where the majority of instances belong to another output equivalence class.

Case 2—Certain categories or choices are not used in the tree (i.e., they are not selected as attribute to split a (sub) set of instances in the tree).

Case 3—Certain combinations of choices, across categories, are not present on any path, from the root node to any leaf of the tree.

Case 4—A leaf of a tree contains a large number of instances (test cases).

As mentioned previously, all of the above cases can be automatically detected by a dedicated tool. However, as discussed next (Section 4.3), determining the exact cause of the problem can only be facilitated but not entirely automated.

Note that cases 2 and 3 above have been shown to be the main issues when practitioners apply Category-Partition [6]. In [6] the authors report on three empirical studies during which they studied the ease with which subjects apply the Category-Partition method. Their observation (conclusion) is that practitioners need guidance since missing categories, missing choices, and ill-defined choices (e.g., non disjoint choices) often occur when applying Category-Partition. The authors suggest that practitioners follow a checklist to systematically identify these problems. In some way, we provide automated support and a set of heuristics to help address these problems. Our work also goes beyond this as we also address the improvement of the test suite.

4.3 Linking problems to causes

The problems discussed above all have one or more potential causes, as summarized in Figure 7. Misclassifications in the decision tree (**Case 1**) can have two potential causes: missing category or choice (case 1.1, Section 4.3.1), ill-defined choices (case 1.2, Section 4.3.2). Some categories (or choices) can be defined in the CP specification but not end up being used in the decision tree (**Case 2**). This can also be explained by several potential causes: useless category or choice (case 2.1, Section 4.3.3), missing test cases (case 2.2, Section 4.3.4), and ill-defined choices (case 1.2,

Section 4.3.2). Even if all expected categories show up in the tree, certain combinations of choices across categories may not be exercised by any branch in the tree (**Case 3**). This may be the result of several potential causes: unfeasible combination (case 3.1, Section 4.3.5), missing test cases (case 2.2, Section 4.3.4). The last problem we cover is related to too many test cases in a rule (**Case 4**). It is in general important to minimize functional test suites and ad hoc test suites often turn out to contain such redundancy. In our context, when many test cases end up in a decision tree leaf then the question arises whether they are all necessary. Indeed, this means that a number of test cases exercise the same choice combination for a subset of categories and then, as a result, fall in the same output equivalence class. The tester may then consider whether all these test cases in the same tree leaf are necessary as they have similar properties, lead to similar outputs, and probably exercise the software in a similar fashion. Though this remains a subjective decision that only the tester can make, the decision tree points out potential redundancy. There may be, however, two reasons for redundancy: redundant test cases (case 4.1, Section 4.3.6), ill-defined choices (case 1.2, Section 4.3.2).

Figure 7 Problems and potential causes

Improvements to CP depend on cause(s) and on context. This is therefore up to the tester. Improvements to the test suite (TS) can be made following our heuristic discussed in section 4.4. As illustrated in Figure 7 both cases 1.2 and 2.1 (sections 4.3.2 and 4.3.3) will lead to the refinement of the CP specification, either by adding/deleting categories/choices or redefining choices for existing categories. Section 4.3.2 would require the modification of choice definitions, possibly leading to an increased number of test cases. Section 4.3.3 may lead to removing a category from the CP specification, thus leading to a smaller number of test frames and therefore fewer test cases. As illustrated in Figure 7, cases 1.1, 4.1, and 2.2 (sections 4.3.1, 4.3.6, and 4.3.4) will lead to the refinement of the test suite (TS). Case 2.2 (Section 4.3.4) requires the addition of test cases. It should be fairly easy to differentiate case 4.1 (section 4.3.6) from case 1.2 (section 4.3.2): The presence of misclassifications suggests that 4.3.2 is more plausible; No misclassification probably indicates the presence of redundant test cases. Case 3.1 (section 4.3.5) clearly does not result in any modification of CP or TS (Figure 7).

4.3.1 Case 1.1 - Missing category/choice

A category or choice is missing although it is necessary to determine the appropriate output equivalence class.

Example 1 in Figure 8 is produced by C4.5 if one omits category 7 when using CP for the Triangle program (Figure 1): category 7 tests whether c is strictly positive or not (it has two choices). This omission results in the rule of Example 1 to show the misclassification of 2 instances (abstract test cases) among 26 instances (24+2),

classified as Isosceles triangles by the rule. Recall section 3.2 that decision trees splits on attributes (i.e category/choices) to generate the DT. If the C4.5 algorithm does not find an attribute that correctly classifies instances, it will use the next best attribute to split on, even though it may result in misclassification. The confusion matrix in Figure 9 tells us that those two instances belong to the Not_Triangle class: 2 instances (in bold face) of the class Not_Triangle are misclassified as Isosceles.

<p>Example 1:</p> <pre> (a vs. b) = a=b (b vs. c) = b!=c (c) = c>0: Isosceles (24.0/2.0) </pre>
<p>Example 2:</p> <pre> (a vs. b) = a=b (b vs. c) = b!=c (c) = c>0: Isosceles (24.0/2.0) </pre>

Figure 8 Examples using the Triangle Program

=== Confusion Matrix ===									
a	b	c	d	e	<--	classified as			
54	0	0	0	0		a	=	Equilateral	
0	66	0	0	0		b	=	Isosceles	
0	0	60	0	0		c	=	Irregular	
0	2	18	40	0		d	=	Not_Triangle	
0	0	0	0	12		e	=	null	

Figure 9 Confusion matrix for the Triangle Program with Category 9 removed

4.3.2 Case 1.2 - Ill-defined choices

Even though a category may be necessary and present in the characterization of test cases, the choices may be ill-defined, making the category a poor attribute to explain the output equivalence classes.

Assuming choices (c17 and c18) of category 9 (Figure 1), which is to compare length c to lengths a and b, are incorrectly specified as follows:

C17: $c < a + b$	(should be $\leq$)
C18: $c \geq a + b$	(should be $>$)

C4.5 returns the rule in Example 2 of Figure 8, showing two misclassified instances. Because the relational operators were changed (by moving the “=” operator from c17 to c18), these misclassifications are due to abstract test cases where $c=a+b$. Similarly, ill-defined choices may make a category irrelevant as it does not accurately determine the output classes anymore. Additionally, ill-defined choices can lead to misclassifications but also to the impossibility for C4.5 to further generate accurate rules for a large number of instances.

4.3.3 Case 2.1 - Useless category or choice

A category may be irrelevant if it turns out not to play a role in determining output equivalence classes. This may be due to the fact that the defined output classes are too rough for the category to play a role or simply that it is redundant (correlated) with other categories.

For example, the following category, if added, obviously will not play a role in determining the type of a triangle formed by sides a, b, and c, since its choices are redundant with the choices of categories 2, 5 and 8 in the triangle CP specification (Figure 1). When applying CP, this category would not be selected by C4.5, and would therefore not appear in the decision tree.

CATEGORY 10 - c compared to a
 C19: $c > a$
 C20: $c \leq a$

4.3.4 Case 2.2 - Missing test cases

Missing test cases can also lead to a category or choice not being selected. For example, there may not be test cases that exercise some or all of the choices of a category, thus resulting in that category being partly used (not all its choices are used) or not used at all in the decision tree. Recall section 3.2 that if there is not enough training data (i.e. test cases) that exercises all the variations of the program, the DT will have rules that are not covered by any test cases, and even combinations of choices that are not existent in the decision tree.

For example, to select an extreme case, if all test cases where $a \leq 0$ are removed from the test suite of the Triangle program (i.e., in all the test cases, $a > 0$) then category 1 (Figure 1), which tests whether a is strictly positive or not, will not be selected as this category does not differentiate test cases (instances). Similarly, if test cases that exercise certain combinations of choices are missing from the test suite, then it is impossible for the tree to identify such combinations as relevant to determine output classes.

4.3.5 Case 3.1 - Unfeasible combinations

As it is often the case in the context of CP, some combinations of choices may not be feasible (recall section 3.1).

For example, combination of choices C_6 (i.e., $a > b + c$) and C_{18} (i.e., $c > a + b$) (Figure 1) is not feasible. Recall (Section 4.1.3) that when building an abstract test case from a

concrete test case, we add a N/A choice when a category does not apply to a test case, therefore also suggesting an unfeasible combination of choices.

4.3.6 Case 4.1 - Redundant Test Cases

The most straightforward reason is of course the presence of redundant test cases, as described previously. The second reason for redundant test cases is the presence of ill-defined choices (case 1.2, Section 4.3.2). Ill-defined choices lead to misclassification and thus to a rule that covers many test cases (too many test cases that should be covered by a larger number of rules if choices were correctly defined).

For example the following rule covers 60 test cases (instances); the tester may consider whether all these test cases are necessary as they have similar properties and lead to similar output.

(a vs. b)	=	a!=b
(c vs. a+b)	=	c<=a+b
(a vs. b+c)	=	a<=b+c
(b vs. a+c)	=	b<=a+c
(b vs. c)	=	b!=c
(c vs. a)	=	c!=a: Irregular (60.0)

4.4 Heuristics for Refining Test Suite

As illustrated in Figure 7, a number of causes lead to updating the test suite, either by adding test cases to the test suite (section 4.4.1), or by removing test cases from the test suite (section 4.4.2).

4.4.1 Adding Test Cases

As discussed previously, different reasons can lead to the addition of test cases: a choice may be missing in the tree; a category may be missing in the tree; certain choices are used in the tree but some of their combinations may be missing.

If a category (or choice) is not selected, and the category is deemed useful, then the tester has to create test cases involving each choice of the category⁵. However, the question is which combinations with other choices to include in the test suite? The first solution is to follow the CP method and build all the feasible (according to properties and selectors) combinations of choices and select the ones that are missing in the abstract test suite. We have however discussed that those properties and selectors were not required for applying our method (Section 3.1). Furthermore, this is an expensive option that does not make use of the information provided by the decision tree.

An alternative is to identify which combinations of choices may be relevant to determine the output class and could be missing from the test suite by using the decision tree. Assume that part of the tree obtained from C4.5 shows categories Cat1, Cat2, and Cat3 with choices c1 and c2, c3 and c4, and c5 and c6, respectively, as illustrated in Figure 10 (a). Such a tree excerpt indicates that combining c2 of category Cat1 with c5 or c6 of category Cat3 plays a role in determining output

⁵ As a special case, we consider the situation where the tree shows a possible rule (i.e., possible choice combination) with no instance. The tester can then simply add a test case for that rule satisfying the corresponding choice combination (if that combination is feasible).

equivalence classes (the pairs of choices belong to different paths in the tree). Since Cat1 has another choice than C2, namely C1, we may reasonably expect that Cat3 will also be relevant to determine the output in the context of C1 and that the tester should therefore combine choice C1 with Cat3's choices. Similarly, the tree suggests that the combinations of C2 with Cat2's choices may be missing in the test suite, thus resulting in four test cases being added⁶.

This heuristic can be generalized to cases where category Cat1 is not a *parent* of Cat2 and Cat3 in the tree but rather an *ancestor* of Cat2 and Cat3 (i.e., there are intermediate categories): Figure 10 (b).

Figure 10 Adding Test Cases from the Tree

One advantage of this heuristic is that by using the information provided by the tree, when the tester intends to cover new choices, she does not have only the expensive option to exercise all the feasible combinations of choices, but can focus on combinations that are likely to affect the output.

⁶ There is one exception though: if C1 is an error condition (e.g., an out of range input value), then C1 is not combined with C5 and C6. This is consistent with the CP strategy.

4.4.2 Removing Test Cases

As discussed earlier, it is in general important to minimize functional test suites as ad hoc test suites often turn out to contain such redundancy. In our context, when a rule covers many test cases in a decision tree then the question arises whether they are all necessary. This means that a number of test cases exercise the same choice combinations for a subset of categories and then, as a result, fall in the same output equivalence class. The tester may then consider whether all these test cases in the same rule are necessary as they have similar properties, lead to similar outputs, and probably exercise the software in a similar fashion. Though this remains a subjective decision that only the tester can make; the decision tree points out potential redundancy. There may be, however, two reasons for redundancy: too many test cases for a rule (Section 4.3.6), ill-defined choices (Section 4.3.2).

The heuristic we follow when removing test cases is the following: we randomly remove test cases per leaf (rule) unless the percentage of code coverage drops. Obviously, different code coverage criteria can be used, and the impact of the possible criteria will have to be investigated.

CHAPTER 5 CASE STUDY ONE: PACKHEXCHAR

In this section, we first describe the system used for the case study and the application of CP on this program (Sections 5.1 and 5.2). We then present the design of the case study (Section 5.3) which includes the comparison of CP specifications obtained with MELBA and CP specifications created by experts (Section 5.4). Sections 5.5 and 5.6 describe the results of applying C4.5 decision trees to drive the improvement of the test specifications and test suites. Lastly, we assess the fault detection effectiveness of the improved test suites in section 5.7.

5.1 The PackHexChar Program

PackHexChar is a Java adaptation of the sreadhex procedure, used in the GhostScript program and described in [28], to manipulate hexadecimal characters. The program contains 54 NBNC Java code lines. PackHexChar takes a string of characters representing hexadecimal digits (parameter S) and compacts the representation of the string in binary format (output), specifically as an array of Bytes: e.g., string “34AB”, corresponding to binary values 0011, 0100, 1010, and 1011, is compacted into an array of two Byte values 00110100 and 10101011 (the binary representation of hexadecimal characters ‘3’ and ‘4’ are combined into the first byte value 00110100). In the input string, characters other than hexadecimal ones are ignored. In addition to the array of Bytes, the program returns an integer value. If the input string contains an even number of hexadecimal characters, pairs of hexadecimal characters are compacted, the program returns the array of Bytes and the returned integer value

equals to -1. If the input string contains an odd number of hexadecimal characters, an even number of characters is compacted, and the program returns the remaining hexadecimal character. The user can decide to look at only a sub-string of the input string S, using the input parameter RLEN: the RLEN first characters of S are then analyzed. If RLEN is not a legal value (negative or greater than S's length), the program returns value -2. The user can ask the program to append an hexadecimal character at the beginning of S. This is useful when a string is split and analyzed in pieces with repeated calls to PackHexChar: a call can return a trailing hexadecimal character, which has to be appended at the beginning of the string during the next call. This is done with input parameter ODD_DIGIT. An ODD_DIGIT value of -1 indicates that no character is to be appended. If ODD_DIGIT has an illegal value (strictly below -1 or not an hexadecimal value), the program returns -3.

5.2 Application of Category-Partitioning

We used Category-Partition on the PackHexChar program thereby identifying eleven categories and 35 choices (Appendix A.2). (Note that we did not identify constraints and selectors, as required when applying category-partition [6], since we did not use the technique to devise test cases, but to characterize test cases.). In Appendix A.2, parameter RLEN has two categories and four choices, parameter ODD_DIGIT has two categories and six choices, and parameter S has seven categories and 25 choices.

The output parameter is divided into the following equivalence classes: -1, -2, -3, S[rlen-1], and Odd_digit. Output equivalence classes -1, -2, and -3 are self-explanatory as they are errors. Output equivalence class S[rlen-1] corresponds to

the case where an odd number of hexadecimal characters are packed: the function returns the last character to consider in the string, i.e., the character at position `rlen-1` in string `s`. Output class `Odd_digit` is for the case where no hexadecimal character is packed but input parameter `ODD_DIGIT` contains one, in which case this character is returned.

5.3 Design of the Case Study

Our case study took place in the context of a specialized 4th year course on software testing. The students were properly trained regarding white and black-box testing techniques, including Category-Partition. Recall from the introduction that the MELBA method we propose can be applied in two broad contexts: The reuse, validation, and integration of open source software, and software evolution. We can however further distinguish two situations that require we perform two slightly different types of case studies.

The first situation is when the CP specification is used to generate the test suite and the test suite must evolve to account for changes in the system under test (Evolution context). To emulate this situation, we asked a group of students to devise a CP specification and derive a test suite from it. We then generated the abstract test suites using each student's CP specification and test suite and followed the MELBA process. The results are reported in Section 5.5.

In the second situation we assume we have the test suite but no CP specification (e.g., a typical situation for Open Source Software—OSS). Tester must then reverse-engineer the CP specification based on their understanding of the software functional

behavior and then iteratively refine it. To emulate this situation (referred to as OSS context) we developed our own CP (referred to as *expert CP*). We applied this CP specification to students' test suites and followed the MELBA process. The results are reported in Section 5.6.

Please note that in our case studies we are applying the Melba method. We have not asked the students to do that because of time constraints. By doing so we ensure the Melba process is applied correctly and evaluate its advantages and drawbacks when applied correctly. Future work will evaluate how easy the Melba process can be applied by students.

In both contexts, we selected a subset of the student's work to apply our method. In each context we selected three students' work, making sure to have one poor application of CP (and poor TS), one average application of CP (and average TS), and one good application of CP (and average TS). The criteria used to identify a poor, average and good CP is based on the quality of the categories and choices compared to those of the Expert CP. Test suites are categorized by the number of test cases they contain. In the OSS context we also made sure to select three students other than the one selected for the Evolution context. Students are referred to as students A, B, and C, and X, Y, and Z, in those two contexts, respectively.

In both contexts, we then tried to identify occurrences of problems using the heuristics described in Figure 7. For both contexts, we actually went through the iterative improvement process illustrated in Figure 4: Both test suites and CP specifications were iteratively improved using the patterns we specified in Section

4.3 for analyzing decision trees and their potential relationships to problems in the test suite or CP specification. Due to time constraints, we did not ask the students to go through the iterative process themselves. Instead we, ourselves, went through the process. At the end of the application of the MELBA process, we compare the (improved) CP specification against the expert CP: section 5.4 specifies how we compare CP specifications.

Since we also require code coverage information when removing test cases, Emma [29], an open source toolkit for measuring and reporting java code coverage, is used for our purpose. Emma supports class, method, line (statement) and basic block coverage, aggregated at package, source file, class, and method level. In this case study we use line (statement) coverage to analyze the results.

Last, since the purpose of our approach is to improve a test suite, e.g., to gain more confidence into an open source component, we are interested into whether the test suites we obtain at the end of the iterative process are able to find more faults than the initial test suite. To do so, we generated mutant versions of the PackHexChar program, i.e., faulty versions of the program, and evaluated how many of those mutants (faults) are actually caught by the test suites. This is discussed in section 5.7.

5.4 Comparing Iteration results with Experts'

One important analysis in our case studies is to compare the CP specifications obtained by the expert with the ones obtained after refining the students' CP specifications. We first specify how we intend to compare CP specifications (section 5.4.1), and then illustrate the comparison on an example (section 5.4.2).

5.4.1 Comparing CPs

Recall that a category is a major property or characteristic of a parameter or environment condition of the program that describes how the program behaves with respect to some characteristic of the parameter or environment condition. Each category is decomposed into distinct choices that include all the different kinds of values that are possible for the category. Each choice within a category is therefore “a set of similar values that can be assumed by the type of information in the category.” [6]

When C4.5 builds a decision tree, not all the categories and choices initially defined by the tester in the Category-Partition specification are necessarily used to classify the instances. Some categories and choices will not appear in the tree if they do not determine the program output equivalence classes. This may simply be due to the granularity of the output equivalence classes and may not therefore denote a problem in the Category-Partition specification⁷. When comparing Category-Partition specifications, since our goal is to verify the behavior of the program under test to the level of granularity determined by these output equivalence classes, we only consider

⁷ For instance, in the expert CP (Appendix A.2) Category 10 is about the position of the first non-hexadecimal character in the first `r1en` characters of `S`: the (expert) tester considered that the program may not be able to adequately omit non-hexadecimal characters if they are at the beginning of string `S`. This category does not appear in any tree since it does not determine the program output equivalence classes we have selected. Similarly, Category 11 is about the number of consecutive non-hexadecimal characters in the first `r1en` characters of `S`: the tester considered that omitting one non-hexadecimal character and omitting several consecutive ones would be two situations worth testing. This category does not appear in any tree.

categories and choices that appear in decision trees, that is the categories and choices which seem to have an influence on the identified output equivalence classes.

To compare two Category-Partition specifications, let us first introduce some formalism. We refer to one application of Category-Partition as CP. CP then refers to the categories and choices that are defined by the tester. Let DT be a decision tree generated by CP and test suite TS. CP_{DT} then denotes the subset of the categories and choices of CP that appear in DT. Label *cat* refers to a category, *ch* refers to a choice and we consider CP as a set of categories and choices: e.g., if category *cat* belongs to Category-Partition specification CP, then we write $cat \in CP$. Similarly, we consider that a category is a set of choices: e.g., if choice *ch* is a choice of category *cat*, then we write $ch \in cat$. Given that a choice is “a set of similar values that can be assumed by the type of information in the category” [6] we use set theory to compare choices: e.g., if choice *c* represents a set of values (assumed by the type of information of a category) that is included in the set of values of choice *c'*, then we write $c \subseteq c'$. When the domain of values of a choice *ch* in category *cat* is covered by the domains of values of one or more choices in category *cat'*, we say that choice *ch* in *cat* is covered by one or more choices ch_i' in *cat'* (denoted $ch \subseteq \bigcup_i ch_i'$). We

denote the determination of output equivalence classes O based on choice *ch* as function $DT_o(ch)$: $DT_o(ch)$ is the set of output equivalence classes in O of all the rules in which choice *ch* appears. For a given decision tree DT, keeping choices in other categories constant, $DT_o(choice1) = DT_o(choice2)$ implies that whether one choice

or the other is selected does not matter as far as the defined equivalence classes are concerned.

Definition: Category-Partition specification equivalence

Given two category-partition specifications CP and CP' , we say that CP and CP' are equivalent with respect to a given set of output equivalence classes O (denoted $CP \equiv_O CP'$) if and only if, given the two decision trees DT_1 and DT_2 generated from CP and CP' respectively (i.e., from different test suites), for each category cat in CP_{DT_1} there is a category cat' in CP'_{DT_2} such that each choice ch in cat is covered by one or more choices ch_i' in cat' such that differences in the definitions of choices do not affect the determination of the output equivalence classes in O .

$$CP \equiv_O CP' \Leftrightarrow \begin{cases} \left(\forall cat \in CP_{DT_1} \exists cat' \in CP'_{DT_2} \mid \right. \\ \left. \left(\forall ch \in cat \exists ch_1', \dots, ch_n' \in cat' \mid ch \subseteq \bigcup_i ch_i' \right) \right) & (1) \\ or \\ \left(\forall ch' \in cat' \exists ch_1, \dots, ch_m \in cat \mid ch' \subseteq \bigcup_i ch_i \text{ and } DT_O(ch_i') = DT_O(ch) \right) & (2) \end{cases}$$

In the formal definition above, CP_{DT_1} are the categories and choices selected by C4.5 to construct DT_1 and CP_{DT_2} are the categories and choices selected by C4.5 to construct DT_2 . Choices of categories in CP_{DT_1} may be covered by one or more choices of categories in CP_{DT_2} (case 1), or choices of categories in CP_{DT_2} may be covered by one or more choices of categories in CP_{DT_1} with the same output equivalence class (case 2).

Note that the CP specification equivalence definition assumes that the two decision trees being compared have comparable sets of choices: i.e., a choice of a tree is

always included in a choice of the other tree, or the other way round. This means that we assume the improvement process discussed in Figure 4 leads to such comparable situation. These assumptions will be confirmed by experiments.

5.4.2 CP specification comparison: an example

As an example, we compare the categories and choices of the expert and one student's Category-Partition specifications (student C). Figure 11 shows CP_{DT} of both the expert and student C's specifications. First note that Figure 11 does not show all the categories and choices of the expert and student CP specifications. This is to be expected since, as discussed previously, we only consider categories and choices that appear in decision trees.

Choice C1 ($r_{len} = 0$) in the expert CP_{DT} represents a set of values assumed by the type of information in Category 1. It is the same set as choice C1 ($\{0\}$) in student C's CP_{DT} (case 1). Choice C2 ($r_{len} = [1...sLength]$) in the expert CP_{DT} represents a set of values assumed by the type of information in category 1. It is the same set as choice C2 ($[1 - s.length]$) in student C's CP_{DT} (case 1). Choices C3 and C4 of category 2 in the expert CP_{DT} represents a set of values ($r_{len} < 0$ or $r_{len} > sLength$) that is included in the set of values represented by choice C3 of category 1 (anything else than $\{0\}$ and $[1 - s.length]$) in student C's CP_{DT} (case 1). Choice C5 in the expert CP_{DT} is the same set as choice C4 in student C's CP_{DT} (case 1). The set of values represented by choices C6, C7, and C8 of category 3 in the expert CP_{DT} is included in the set of values represented by choice C5 of category 2 in student C's CP_{DT} (case 1). The set of values represented by choices C9 and C10 of category 4 in the expert CP_{DT} is

included in the set of values represented by choice C6 of category 2 in student C's CP_{DT} (case 1). Choice C28, C29, and C30 in the expert CP_{DT} represents a set of values assumed by the type of information in category 9 which is the same set as the one of choices C12, C13, and C14 in student C's CP_{DT} (case 1).

Expert CP	Student C's CP
Parameter RLEN CATEGORY 1-Valid values for rlen C1: rlen = 0 C2: rlen = [1...sLength] CATEGORY 2-Invalid values for rlen C3: rlen < 0 C4: rlen > sLength Parameter ODD_DIGIT CATEGORY 3-Valid values for odd_digit C5: odd_digit = -1 C6: odd_digit= [0...9] C7: odd_digit= [A...F] C8: odd_digit= [a...f] CATEGORY 4-Invalid values for odd_digit C9: odd_digit < -1 C10: odd_digit > 15 Parameter S CATEGORY 9-Number of hexadecimal characters in the first rlen characters of S C28: Odd C29: Even C30: Zero	Parameter: RLEN Category 1: number of characters to read C1: {0} C2: [1 - s.length] C3: anything else Parameter: ODD_DIGIT Category 2: Extra digit to parse C4: {-1} C5: [0 - 15] C6: anything else Parameter: S Category 5: Number of valid hex characters from 0 to rlen C12: Odd C13: Even C14: Zero

Figure 11 CP for the Expert CP and Student C's CP

Conversely, we can compare the categories and choices of student C's Category-Partition specification with the Expert Category-Partition specification. Choice C1 ({0}) in the student CP_{DT} represents a set of values assumed by the type of information in Category 1. It is the same set as choice C1 (rlen = 0) in the expert CP_{DT} (case 1). Choice C2 ([1 - s.length]) in the student CP_{DT} represents a set of values assumed by the type of information in category 1. It is the same set as choice C2 (rlen = [1...sLength]) in the expert CP_{DT} (case 1). Choice C3 of category 1 in the student CP_{DT}

(anything else than {0} and [1 - s.length]) includes the set of values represented by choice C3 and C4 ($r_{len} < 0$ or $r_{len} > sLength$) of category 2 in the expert CP_{DT} . And the set of output equivalence classes of C3 and C4 in the expert CP equals the set of output equivalence classes of C3 in the student CP (case 2). Choice C4 ({-1}) in the student CP_{DT} represents a set of values assumed by the type of information in Category 1. It is the same set as choice C5 ($odd_digit = -1$) in the expert CP_{DT} (case 1). Choice C5 ([0 - 15]) of category 2 in student C's CP_{DT} includes in the set of values represented by choices C6, C7, and C8 of category 3 in the expert CP_{DT} , and the output equivalence classes are the same (case 2). Choice C6 of category 2 in student C's CP_{DT} includes the set of values represented by choices C9 and C10 of category 4 in the expert CP_{DT} (case 1). Choices C12, C13, and C14 in student C's CP_{DT} represent sets of values assumed by the type of information in category 9 which are the same sets as the ones of choices C28, C29, and C30 in the expert CP_{DT} (case 1).

Therefore expert CP is equivalent to student C's CP. Appendix B gives a mapping between categories and choices of the Expert CP and other students' CPs.

5.5 Results with Student's CP–Evolution Context

5.5.1 Student A's CP and TS

Student A's test suite contains 20 test cases. We created 20 abstract test cases using A's Category-Partition specifications (Appendix A.3). Executing C4.5 on these abstract test cases, we obtain the decision tree (and confusion matrix) of Figure 12 made of 12 rules (following the WEKA format for displaying trees). This tree shows a number of issues (bold face). First, there is one misclassification (a test case with

output equivalence class `S[rLen-1]` is misclassified as having output equivalence class `-1.0`): Case 1 in Section 4.2. An analysis of the program specification and test suite shows that a category is missing (Section 4.3.1): The student failed to realize that only the `RLEN` first characters are compacted (Section 5.1). The tree also shows missing combinations of choices (Case 3), e.g., `allValid` (in category `SCHARTYPE`) is combined with `odd_digit=-1` (Rule1) but not with `odd_digit=[0...15]` (rules 7, 8, 9). Some missing combinations are even explicit as they correspond to rules with no instance (three examples identified by `(0.0)` in bold face: rules 3, 5, and 9), these are, however, unfeasible choice combinations (Section 4.3.5). For instance, rule 3 is unfeasible because if “`SLENGTH = EvenLength`” i.e. the length of the string is even, then the type of characters in the string (i.e. `SCHARTYPE`) either has to be `allValid` or `Mixed` (`Mixed` represents a mix of valid and invalid characters or all invalid characters), and never “N/A”. Hence rule 3 is an unfeasible combination of choices. Rule 5 and 9 are unfeasible because choices “`rLen=[1..Slength]`” and “`SLENGTH = Empty`” contradict each other, hence leading to unfeasible combinations.

```

RLEN = rlen=[1..Slength]
| ODD_DIGIT = odd_digit=-1
| | SLENGTH = EvenLength
| | | SCHARTYPE = allValid: -1.0 (4.0/1.0)      Rule 1
| | | SCHARTYPE = Mixed: S[rlen-1] (3.0)      Rule 2
| | | SCHARTYPE = N/A: S[rlen-1] (0.0)        Rule 3
| | SLENGTH = OddLength: S[rlen-1] (3.0)      Rule 4
| | SLENGTH = Empty: S[rlen-1] (0.0)          Rule 5
| ODD_DIGIT = odd_digit>=16: -3.0 (1.0)      Rule 6
| ODD_DIGIT = odd_digit=[0..15]
| | SLENGTH = EvenLength: S[rlen-1] (1.0)      Rule 7
| | SLENGTH = OddLength: -1.0 (2.0)          Rule 8
| | SLENGTH = Empty: -1.0 (0.0)              Rule 9
RLEN = rlen=0: -1.0 (4.0)                    Rule 10
RLEN = rlen>Slength: -2.0 (1.0)              Rule 11
RLEN = rlen<0: -2.0 (1.0)                    Rule 12

=== Confusion Matrix ===

a  b  c  d  <-- Classified as
9  0  0  0  | a = -1.0
1  7  0  0  | b = S[rlen-1]
0  0  2  0  | c = -2.0
0  0  0  1  | d = -3.0

```

Figure 12 Student A's TS + A's CP – Iteration 1

We first add the following missing category (Activity 5, Figure 4) (Recall section 5.3 that it is the expert who applies the Melba method):

Category: Number of hexadecimal characters in the first rlen characters of input string s
 Choice 1: Odd
 Choice 2: Even
 Choice 3: Zero

Once the abstract test cases are (automatically) re-created from the updated CP, the execution of C4.5 produces the decision tree of Figure 13 made of 10 rules. As expected, the tree no longer shows misclassification. However, it shows that some choice combinations are missing (Case 3), two of them being explicitly identified in rules with no instance (rules 3 and 7). Rule 7 is an unfeasible combination of choices (Section 4.3.5) because choices “rlen=[1...Slength]” and “SLENGTH = Empty”

contradict each other, whereas rule 3 is a feasible (missing) combination indicating of a missing test case (Case 2.2).

RLEN = rlen=[1..Slength]	
ODD_DIGIT = odd_digit=-1	
#RLENCCHARS = Even: -1.0 (3.0)	Rule 1
#RLENCCHARS = Odd: S[rlen-1] (7.0)	Rule 2
#RLENCCHARS = Zero: S[rlen-1] (0.0)	Rule 3
ODD_DIGIT = odd_digit>=16: -3.0 (1.0)	Rule 4
ODD_DIGIT = odd_digit=[0...15]	
SLENGTH = EvenLength: S[rlen-1] (1.0)	Rule 5
SLENGTH = OddLength: -1.0 (2.0)	Rule 6
SLENGTH = Empty: -1.0 (0.0)	Rule 7
RLEN = rlen=0: -1.0 (4.0)	Rule 8
RLEN = rlen>Slength: -2.0 (1.0)	Rule 9
RLEN = rlen<0: -2.0 (1.0)	Rule 10

Figure 13 Student A's TS + A's CP – Iteration 2

Following the heuristic described in Section 4.4, one can identify the following 15 missing combinations of choices in the decision tree, nine of which are already exercised by the 20 original test cases. The six missing combinations of choices for which there is no test case in the test suite are identified with a '*'.

RLEN = rlen=[1...Slength]	RLEN = rlen=[1...Slength]
ODD_DIGIT = odd_digit=-1	ODD_DIGIT = odd_digit=-1
#RLENCCHARS = Zero: *	SLENGTH = EvenLength:
ODD_DIGIT = odd_digit=[0...15]	SLENGTH = OddLength:
#RLENCCHARS = Even:	
#RLENCCHARS = Odd:	RLEN = rlen=0:
#RLENCCHARS = Zero: *	ODD_DIGIT = odd_digit=-1
ODD_DIGIT = odd_digit<=-2 *	SLENGTH = EvenLength:
	SLENGTH = OddLength:
	SLENGTH = Empty:
RLEN = rlen=0:	ODD_DIGIT = odd_digit=[0...15]
ODD_DIGIT = odd_digit=-1	SLENGTH = EvenLength: *
#RLENCCHARS = Zero:	SLENGTH = OddLength: *
ODD_DIGIT = odd_digit=[0...15]	SLENGTH = Empty: *
#RLENCCHARS = Zero:	

Test cases are added for the above six missing combinations of choices. Abstract test cases are created and C4.5 is re-run, producing the decision tree of Figure 14 made of 14 rules. There is no misclassification, but a number of rules have zero instances (rules 2, 4, and 8), or the number of instances is large which could therefore indicate

redundant test cases (Case 4). Rules 2 and 4 with no instance are unfeasible choice combinations (Case 3.1), because it is not possible for the number of the first `rLen` characters in string `s` to be even “`RLENCHARS = Even`” and `rLen` to be zero or less than zero. Rule 8 with zero instances is feasible, suggesting a missing test case (Case 2.2). Since this choice combination involves an error condition (illegal input value `rLen>SLength`) which is already used in a test case (Rule 3 in the tree), we do not consider this a missing combination of choices (Case 2.2 and footnote 6 on page 46), but since it is still a feasible combination it appears in the tree. The tree also suggests that the following five combinations of choices are missing:

<pre> ODD_DIGIT = odd_digit=-1 #RLENCHARS = Odd RLEN = rlen=[1...SLength]: 1 </pre>	<pre> ODD_DIGIT = odd_digit=[0...15] #RLENCHARS = Even RLEN = rlen=[1...SLength]: 2 #RLENCHARS = Odd RLEN = rlen=[1...SLength]: 3 #RLENCHARS = Zero: RLEN = rlen=[1...SLength]: 4 RLEN = rlen=0: 5 </pre>
---	---

These combinations are however already exercised in the 26 test cases⁸, and Figure 14 is therefore the final decision tree.

⁸ For instance, all the seven test cases in rule 5 satisfy `rlen=[1..SLength]`. The other choices of `RLEN` are not combined with this choice of `RLENCHARS (Odd)` as they either involve an error choice that is already exercised once in the test suite (i.e., `rlen<0` and `rlen>SLength`) or it does not make sense to combine them (combining `#RLENCHARS=Odd` and `rlen=0` does not make sense: we compact 0 characters in the string and therefore the number of hexadecimal characters in the string does not matter).

ODD_DIGIT = odd_digit=-1	
#RLENCHARS = Even	
RLEN = rlen=[1...Slength]: -1.0 (3.0)	Rule 1
RLEN = rlen=0: -1.0 (0.0)	Rule 2
RLEN = rlen>Slength: -2.0 (1.0)	Rule 3
RLEN = rlen<0: -1.0 (0.0)	Rule 4
#RLENCHARS = Odd: S[rLEN-1] (7.0)	Rule 5
#RLENCHARS = Zero	
RLEN = rlen=[1...Slength]: -1.0 (1.0)	Rule 6
RLEN = rlen=0: -1.0 (4.0)	Rule 7
RLEN = rlen>Slength: -1.0 (0.0)	Rule 8
RLEN = rlen<0: -2.0 (1.0)	Rule 9
ODD_DIGIT = odd_digit>=16: -3.0 (1.0)	Rule 10
ODD_DIGIT = odd_digit=[0...15]	
#RLENCHARS = Even: S[rLEN-1] (1.0)	Rule 11
#RLENCHARS = Odd: -1.0 (2.0)	Rule 12
#RLENCHARS = Zero: odd_digit (4.0)	Rule 13
ODD_DIGIT = odd_digit<=-2: -3.0 (1.0)	Rule 14

Figure 14 Student A's TS + A's CP – Iteration 3

The final student CP, which contains eight categories and 16 choices, of which categories 1, 2, 3, 4, and 7 (i.e. five categories and eleven choices) are used in the tree, is equivalent to the expert CP (section 5.4.1).

Depending on time and resource constraints, as a final step to improve the test suite, one may want to reduce the number of test cases (instances) because some rules cover more than one instance (Section 4.3.6).

We removed some of the test cases in those rules (randomly selected), keeping one test case for each one of those rules while still maintaining the same code coverage. The final decision tree is shown in Figure 15 with 14 rules.

```

ODD_DIGIT = odd_digit=-1
| #RLENCHARS = Even
| | RLEN = rlen=[1...Slength]: -1.0 (1.0)
| | RLEN = rlen=0: -1.0 (0.0)
| | RLEN = rlen>Slength: -2.0 (1.0)
| | RLEN = rlen<0: -1.0 (0.0)
| #RLENCHARS = Odd: S[rlen-1] (1.0)
| #RLENCHARS = Zero
| | RLEN = rlen=[1...Slength]: -1.0 (1.0)
| | RLEN = rlen=0: -1.0 (1.0)
| | RLEN = rlen>Slength: -1.0 (0.0)
| | RLEN = rlen<0: -2.0 (1.0)
ODD_DIGIT = odd_digit>=16: -3.0 (1.0)
ODD_DIGIT = odd_digit=[0...15]
| #RLENCHARS = Even: S[rlen-1] (1.0)
| #RLENCHARS = Odd: -1.0 (1.0)
| #RLENCHARS = Zero: odd_digit (1.0)
ODD_DIGIT = odd_digit<=-2: -3.0 (1.0)

```

Figure 15 Student A's TS + A's CP – Final Tree

5.5.2 Student B's CP and TS

Student B's test suite contains 31 test cases. We created 31 abstract test cases using B's Category-Partition specifications (Appendix A.4). Executing C4.5 on these abstract test cases, we obtain the decision tree (and confusion matrix) of Figure 16 with 14 rules. The decision tree shows eight misclassified test cases (Case 1, rules 2, 5 and 11); six instances of $S[rlen-1]$ are misclassified as -1 and two instances of -1 are classified as $S[rlen-1]$. This again is due to the student failing to recognize that the program compacts the first RLEN hexadecimal characters in the input string, resulting in a missing category in student B's CP (Case 1.1). Following the heuristic described in Section 4.4, the following combinations of choices are also missing in the decision tree (Case 3):

<pre> ODD_DIGIT = odd_digit=-1 SLENGTH = OddLength: SLENGTH = EvenLength: SLENGTH = Empty: ODD_DIGIT = odd_digit=-1 RLEN = rlen=0: RLEN = 0<rlen<sLength SLENGTH VS. RLEN = sLength>rlen SCHARTYPE = allValid: SCHARTYPE = N/A: SCHARTYPE = allInvalid: SCHARTYPE = MixedChars: SLENGTH VS. RLEN = sLength=rlen: SLENGTH VS. RLEN = sLength<rlen: SLENGTH VS. RLEN = sLength=0: RLEN = rlen>sLength: RLEN = rlen<0: </pre>	<pre> ODD_DIGIT = odd_digit=[0-15] RLEN = rlen=0: RLEN = 0<rlen<sLength SLENGTH VS. RLEN = sLength>rlen SCHARTYPE = allValid: SCHARTYPE = N/A: SCHARTYPE = allInvalid: SCHARTYPE = MixedChars: SLENGTH VS. RLEN = sLength=rlen: SLENGTH VS. RLEN = sLength<rlen: SLENGTH VS. RLEN = sLength=0: RLEN = rlen>sLength: RLEN = rlen<0: </pre>
---	---

Some of them are actually identified in the tree but they have a number of instances equal to zero (rules 3, 4, 7, and 8). Rules 3 and 4 are feasible combinations and indicate missing test cases (Case 2.2). Rules 7 and 8 are unfeasible combinations of choices (Case 3.1), because choice $sLength < rlen$ of rule 7 and choice $sLength = 0$ of rule 8 is in contradiction with the choice $0 < rlen \leq sLength$. The decision tree also shows a missing choice ($rlen < 0$) and is due to missing test cases (Case 2.2).

<pre> ODD_DIGIT = odd_digit=-1 RLEN = rlen=0: -1.0 (2.0) RLEN = 0<rlen<=sLength SLENGTH VS. RLEN = sLength>rlen SCHARTYPE = allValid: S[rlen-1] (5.0/2.0) SCHARTYPE = N/A: -1.0 (0.0) SCHARTYPE = allInvalid: -1.0 (0.0) SCHARTYPE = MixedChars: -1.0 (12.0/5.0) SLENGTH VS. RLEN = sLength=rlen: -1.0 (2.0) SLENGTH VS. RLEN = sLength<rlen: -1.0 (0.0) SLENGTH VS. RLEN = sLength=0: -1.0 (0.0) RLEN = rlen>sLength: -2.0 (1.0) ODD_DIGIT = odd_digit=[0-15] SLENGTH = OddLength: odd_digit (1.0) SLENGTH = EvenLength: -1.0 (3.0/1.0) SLENGTH = Empty: odd_digit (2.0) ODD_DIGIT = odd_digit>15: -3.0 (2.0) ODD_DIGIT = odd_digit<-1: -3.0 (1.0) === Confusion Matrix === a b c d e <-- classified as 13 0 0 2 0 a = -1.0 0 3 0 0 0 b = odd_digit 0 0 3 0 0 c = -3.0 6 0 0 3 0 d = S[rlen-1] 0 0 0 0 1 e = -2.0 </pre>	<pre> Rule 1 Rule 2 Rule 3 Rule 4 Rule 5 Rule 6 Rule 7 Rule 8 Rule 9 Rule 10 Rule 11 Rule 12 Rule 13 Rule 14 </pre>
---	---

Figure 16 Student B's TS + B's CP – Iteration 1

We first add the missing category to the student's CP (the same category as for student A). Once the abstract test cases are (automatically) re-created from the updated Category-Partition, the execution of C4.5 produces the decision tree of Figure 17 with 10 rules.

The tree in Figure 17 shows one rule with no instance (rule 3): this is an unfeasible combination of choices (Case 3.1), because the number of first `rlen` characters of string `s` can not be even (“#RLENCCHARS = EVEN”) if `rlen` is zero (`rlen=0`). The tree also suggests that the following eight combinations of choices are potentially missing:

ODD_DIGIT = odd_digit=-1 #RLENCCHARS = Zero: RLEN = rlen=0: RLEN = 0<rlen<=sLength: #RLENCCHARS = Odd: RLEN = 0<rlen<=sLength:	ODD_DIGIT = odd_digit=[0-15] #RLENCCHARS = Zero: RLEN = rlen=0: RLEN = 0<rlen<=sLength: RLEN = rlen<0: #RLENCCHARS = Odd: RLEN = 0<rlen<=sLength: #RLENCCHARS = Even: RLEN = 0<rlen<=sLength:
---	---

Looking at the test suite shows that none of the above combinations have been already exercised.

ODD_DIGIT = odd_digit=-1 #RLENCCHARS = Zero: -1.0 (6.0) #RLENCCHARS = Odd: S[rlen-1] (8.0) #RLENCCHARS = Even RLEN = rlen=0: -1.0 (0.0) RLEN = 0<rlen<sLength: -1.0 (7.0) RLEN = rlen>sLength: -2.0 (1.0)	Rule 1 Rule 2 Rule 3 Rule 4 Rule 5
ODD_DIGIT = odd_digit=[0-15] #RLENCCHARS = Zero: odd_digit (3.0) #RLENCCHARS = Odd: -1.0 (2.0) #RLENCCHARS = Even: S[rlen-1] (1.0) ODD_DIGIT = odd_digit>15: -3.0 (2.0) ODD_DIGIT = odd_digit<-1: -3.0 (1.0)	Rule 6 Rule 7 Rule 8 Rule 9 Rule 10

Figure 17 Student B's TS + B's CP – Iteration 2

We therefore create eight test cases; (automatically) produce the corresponding abstract test cases and re-run C4.5, which returns the decision tree in Figure 18 with

14 rules. The tree shows potentially missing choice combinations (rules 3, 6, and 9): rules 3 and 6 are unfeasible combinations of choices, because the number of first `rLen` characters of string `s` can not be even (“#RLENCHARS = EVEN”) if `rLen` is zero (`rLen=0`) or if `rLen` is negative (`rLen<0`). Rule 9 is feasible but involves an error condition (`rLen>sLength`) which already appears in another rule. The tree also suggests missing combinations of choices. However, they are already exercised by the test suite and do not appear in the tree for the same reasons as for Student A. The tree shows rules with a number of instances larger than one (rules 1, 2, 4, 7, 8, 11, 12, and 13), possibly suggesting redundant test cases.

ODD_DIGIT = odd_digit=-1	
#RLENCHARS = Zero: -1.0 (8.0)	Rule 1
#RLENCHARS = Odd: S[rLen-1] (9.0)	Rule 2
#RLENCHARS = Even	
RLEN = rLen=0: -1.0 (0.0)	Rule 3
RLEN = 0<rLen<=sLength: -1.0 (7.0)	Rule 4
RLEN = rLen>sLength: -2.0 (1.0)	Rule 5
RLEN = rLen<0: -1.0 (0.0)	Rule 6
ODD_DIGIT = odd_digit=[0-15]	
#RLENCHARS = Zero	
RLEN = rLen=0: odd_digit (3.0)	Rule 7
RLEN = 0<rLen<=sLength: odd_digit (2.0)	Rule 8
RLEN = rLen>sLength: odd_digit (0.0)	Rule 9
RLEN = rLen<0: -2.0 (1.0)	Rule 10
#RLENCHARS = Odd: -1.0 (3.0)	Rule 11
#RLENCHARS = Even: S[rLen-1] (2.0)	Rule 12
ODD_DIGIT = odd_digit>15: -3.0 (2.0)	Rule 13
ODD_DIGIT = odd_digit<-1: -3.0 (1.0)	Rule 14

Figure 18 Student B's TS + B's CP – Iteration 3

We removed some of the test cases in those rules (randomly selected), keeping one test case for each rule except for rule 12, because removing any further test case will result in reduced code coverage, thus maintaining the same code coverage. When re-running C4.5, we obtain a tree with the same rules as in Figure 18 except that the number of instances for each rule (except rule 12) is now one. The final CP, which

contains nine categories and 23 choices of which categories 1, 2, 3, 4, and 8 (i.e. five categories and eleven choices) are used in the tree, is equivalent to the expert CP (Section 5.4.1).

5.5.3 Student C's CP and TS

Student C's test suite contains 19 test cases. Using C's CP specifications (Appendix A.5), 19 abstract test cases are created. After executing C4.5 on these abstract test cases, we obtain the decision tree (and confusion matrix) in Figure 19. The decision tree shows two misclassified test cases: rules 4 and 10 (Case 1). This again is due to the student failing to recognize that the program compacts the first `RLEN` hexadecimal characters in the input string, resulting in a missing category in student C's CP (Case 1.1). There are no missing combinations of choices in the decision tree (Case 3, according to the heuristic described in Section 4.4). Rules 2 and 8 are unfeasible combinations of choices (Case 3.1), since it is not feasible to have "`SCHARTYPE=N/A`" and "`RLEN = [1...SLength]`" at the same time.

```

ODD_DIGIT = ODD_DIGIT=-1
| RLEN = RLEN=0: -1.0 (2.0) Rule 1
| RLEN = RLEN=[1...Slength]
| | SCHARTYPE = N/A: -1.0 (0.0) Rule 2
| | SCHARTYPE = AllValid: S[rLEN-1] (2.0) Rule 3
| | SCHARTYPE = Mixed: -1.0 (2.0/1.0) Rule 4
| | SCHARTYPE = AllInvalid: -1.0 (2.0) Rule 5
| RLEN = RLEN=INVALID: -2.0 (1.0) Rule 6
ODD_DIGIT = ODD_DIGIT=[0...15]
| RLEN = RLEN=0: odd_digit (2.0) Rule 7
| RLEN = RLEN=[1...Slength]
| | SCHARTYPE = N/A: -1.0 (0.0) Rule 8
| | SCHARTYPE = AllValid: -1.0 (2.0) Rule 9
| | SCHARTYPE = Mixed: -1.0 (2.0/1.0) Rule 10
| | SCHARTYPE = AllInvalid: odd_digit (2.0) Rule 11
| RLEN = RLEN=INVALID: -2.0 (1.0) Rule 12
ODD_DIGIT = ODD_DIGIT=INVALID: -3.0 (1.0) Rule 13

=== Confusion Matrix ===

a b c d e <-- classified as
8 0 0 0 0 | a = -1.0
1 4 0 0 0 | b = odd_digit
0 0 1 0 0 | c = -3.0
1 0 0 2 0 | d = S[rLEN-1]
0 0 0 0 2 | e = -2.0

```

Figure 19 Student C's TS + C's CP – Iteration 1

We first add the missing category to the student's CP (the same category as for student A). Once the abstract test cases are (automatically) re-created from the updated CP, the execution of C4.5 produces the decision tree of Figure 20 with nine rules. The decision tree shows a missing choice (#RLENCCHARS=Even) which is due to missing test cases (Case 2.2). Using the heuristic described in section 4.4 for adding choice combinations, the tree also suggests that the following six combinations of choices are potentially missing, among which only the two identified with a '*' are not already exercised by the test suite:

<pre> ODD_DIGIT = odd_digit ==-1 #RLENCHARS= Zero: RLEN = rlen=0: RLEN = rlen =[1...Slength]: #RLENCHARS= Even RLEN = rlen =[1...Slength]: </pre>	<pre> ODD_DIGIT = odd_digit =[0...15] #RLENCHARS= Zero: RLEN = rlen =0: RLEN = rlen =[1...Slength]: #RLENCHARS= Even RLEN = rlen =[1...Slength]: </pre>
*	*

The tree also shows two rules (rules 2 and 6) with no instances: these are unfeasible combinations of choices (Case 3.1), because if the number of first hexadecimal characters in string *s* is odd (#RLENCHARS=Odd) then it is not possible for *rlen* to be zero (RLEN=0).

<pre> ODD_DIGIT = ODD_DIGIT==-1 #RLENCHARS = Zero: -1.0 (5.0) #RLENCHARS = Odd RLEN = RLEN=0: S[rlen-1] (0.0) RLEN = RLEN=[1...Slength]: S[rlen-1] (3.0) RLEN = RLEN=INVALID: -2.0 (1.0) ODD_DIGIT = ODD_DIGIT=[0...15] #RLENCHARS = Zero: odd_digit (5.0) #RLENCHARS = Odd RLEN = RLEN=0: -1.0 (0.0) RLEN = RLEN=[1...Slength]: -1.0 (3.0) RLEN = RLEN=INVALID: -2.0 (1.0) ODD_DIGIT = ODD_DIGIT=INVALID: -3.0 (1.0) </pre>	<p>Rule 1</p> <p>Rule 2</p> <p>Rule 3</p> <p>Rule 4</p> <p>Rule 5</p> <p>Rule 6</p> <p>Rule 7</p> <p>Rule 8</p> <p>Rule 9</p>
--	--

Figure 20 Student C's TS + C's CP – Iteration 2

We therefore create two test cases, for the two missing combinations, (automatically) produce the corresponding abstract test cases and re-run C4.5, which returns the decision tree in Figure 21 with 13 rules. This tree shows three rules (rules 6, 9, and 12) with no instances: these rules are feasible but involve an error condition (odd_digit=INVALID) which already appears in another rule (rule 3). Following the heuristic described in Section 4.4, there are no combinations of choices missing in the decision tree. The tree suggests redundancy, since rules 1, 2, 4, 5, 7, 8, and 13 cover more than one instance.

RLEN = rlen=0	
ODD_DIGIT = odd_digit=-1: -1.0 (2.0)	Rule 1
ODD_DIGIT = odd_digit=[0...15]: odd_digit (2.0)	Rule 2
ODD_DIGIT = odd_digit=INVALID: -3.0 (1.0)	Rule 3
RLEN = rlen=[1...sLength]	
#RLENCHARS = Zero	
ODD_DIGIT = odd_digit=-1: -1.0 (3.0)	Rule 4
ODD_DIGIT = odd_digit=[0...15]: odd_digit (3.0)	Rule 5
ODD_DIGIT = odd_digit=INVALID: -1.0 (0.0)	Rule 6
#RLENCHARS = Odd	
ODD_DIGIT = odd_digit=-1: S[rlen-1] (3.0)	Rule 7
ODD_DIGIT = odd_digit=[0...15]: -1.0 (3.0)	Rule 8
ODD_DIGIT = odd_digit=INVALID: -1.0 (0.0)	Rule 9
#RLENCHARS = Even	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 10
ODD_DIGIT = odd_digit=[0...15]: S[rlen-1] (1.0)	Rule 11
ODD_DIGIT = odd_digit=INVALID: -1.0 (0.0)	Rule 12
RLEN = rlen=INVALID: -2.0 (2.0)	Rule 13

Figure 21 Student C's TS + C's CP – Iteration 3

We remove redundant test cases and obtain the tree in Figure 22 with 13 rules. No occurrence of the problems discussed in section 4.2 can be found and the iterative process of Figure 4 stops. The final CP, which contains five categories and 14 choices of which categories 1, 2, and 5 (i.e., three categories and nine choices) are used in the tree, is equivalent to the Expert CP (Section 5.4.1).

RLEN = rlen=0	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 1
ODD_DIGIT = odd_digit=[0...15]: odd_digit (1.0)	Rule 2
ODD_DIGIT = odd_digit=INVALID: -3.0 (1.0)	Rule 3
RLEN = rlen=[1...sLength]	
#RLENCHARS = Zero	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 4
ODD_DIGIT = odd_digit=[0...15]: odd_digit (1.0)	Rule 5
ODD_DIGIT = odd_digit=INVALID: -1.0 (0.0)	Rule 6
#RLENCHARS = Odd	
ODD_DIGIT = odd_digit=-1: S[rlen-1] (1.0)	Rule 7
ODD_DIGIT = odd_digit=[0...15]: -1.0 (1.0)	Rule 8
ODD_DIGIT = odd_digit=INVALID: -1.0 (0.0)	Rule 9
#RLENCHARS = Even	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 10
ODD_DIGIT = odd_digit=[0...15]: S[rlen-1] (1.0)	Rule 11
ODD_DIGIT = odd_digit=INVALID: -1.0 (0.0)	Rule 12
RLEN = rlen=INVALID: -2.0 (1.0)	Rule 13

Figure 22 Student C's TS + C's CP – Final Tree

5.6 Results with the Expert CP – OSS Context

Note that since we use our CP to classify the student test cases we have $CP = CP'$ in our definition of category partition specification comparison (Section 5.4.1. We still compare CP_{DT1} and CP_{DT2} using the definition in section 5.4.

5.6.1 Student X's TS with the Expert CP

After creating abstract test cases for student X's test suite (15 test cases) using the Expert CP, and running C4.5, we obtain the decision tree in Figure 23 with five rules. The tree shows no misclassified instance (test case). This is expected as we use the Expert CP: a complete set of categories and well-defined choices should result into correct classifications. However, the tree shows a number of issues: (1) not all the categories of the Expert CP appear in the tree (Case 2), specifically, categories 5, 7, 8, 9, 10, and 11 are missing (Appendix A.2); (2) some choices (in the remaining, used categories) are missing (Case 2), specifically choices c3, c7, c8, c9, and c14 (Appendix A.2); (3) There are missing combinations of choices (Case 3), specifically, using the heuristic described in Section 4.4 for adding combinations, the tree suggests that the following 16 combinations of choices are potentially missing, among which two (identified with a '*') are already exercised by the test suite:


```

RLEN = rlen=[1...sLength]
| S CHAR TYPE IN [0...RLEN] = AllHexadecimal
| | ODD_DIGIT = odd_digit=<-1
| | ODD_DIGIT = odd_digit=[a...f]:
| | ODD_DIGIT = odd_digit=[A...F]:
| S CHAR TYPE IN [0...RLEN] = AllNonHexadecimal
| | ODD_DIGIT = odd_digit=-1:
| | ODD_DIGIT = odd_digit=[0...9]:
| | ODD_DIGIT = odd_digit=[a...f]:
| | ODD_DIGIT = odd_digit=[A...F]:
| S CHAR TYPE IN [0...RLEN] = MixedChars
| | ODD_DIGIT = odd_digit=-1: *
| | ODD_DIGIT = odd_digit=[0...9]:
| | ODD_DIGIT = odd_digit=[a...f]:
| | ODD_DIGIT = odd_digit=[A...F]:

RLEN = rlen=0
| | ODD_DIGIT = odd_digit=-1: *
| | ODD_DIGIT = odd_digit=[0...9]:
| | ODD_DIGIT = odd_digit=[a...f]:
| | ODD_DIGIT = odd_digit=[A...F]:

RLEN = rlen<0
| ODD_DIGIT = odd_digit=[0...9]:

```

RLEN = rlen>sLength: -2.0 (8.0)	
RLEN = rlen=[1...sLength]	
SCHARSTYPE IN [0...RLEN] = AllHexadecimal	
ODD_DIGIT = odd_digit=-1: -1.0 (3.0)	Rule 1
ODD_DIGIT = odd_digit>15: -3.0 (1.0)	Rule 2
ODD_DIGIT = odd_digit=[0...9]: -1.0 (1.0)	
SCHARSTYPE IN [0...RLEN] = N/A: -1.0 (0.0)	Rule 3
SCHARSTYPE IN [0...RLEN] =MixedChars:S[rlen-1] (1.0)	Rule 4
RLEN = rlen=0: odd_digit (1.0)	Rule 5

Figure 23 X's TS + Expert CP – Iteration 1

This initial use of C4.5 therefore allows us to improve the test suite. Fourteen new test cases are created and transformed into abstract test cases, and C4.5 is re-executed with a total of 29 abstract test cases (15 initial ones and 14 new ones). The result is the decision tree of Figure 24 with 28 rules. This tree shows potentially missing choice combinations ((0.0) in bold face—rules 3, 5, 8, 12, 13, 17, 19, 23, and 25): rules 8, 12, and 13 are feasible and cover no test case, rules 3, 5, 17, 19, 23, and 25 are combinations of choices that are feasible but involve an error condition which already appears in another rule (rules 9 and 11). The tree also suggests the following

19 missing combinations of choices, among which eleven (identified with a “*”) are not already covered by the test suite:

```

RLEN = rlen=[1...sLength]
|   NUM HEX CHARS IN [0...RLEN] = Even
|   |   NON HEX CHAR POSTION IN [0..RLEN] = N/A
|   |   |   ODD_DIGIT = odd_digit=-1:
|   |   |   ODD_DIGIT = odd_digit=[0...9]:          (*)
|   |   |   ODD_DIGIT = odd_digit=[a...f]:
|   |   |   ODD_DIGIT = odd_digit=[A...F]:
|   NUM HEX CHARS IN [0...RLEN] = Odd
|   |   NHC POSTION IN [0..RLEN] = N/A
|   |   |   ODD_DIGIT = odd_digit=-1:          (*)
|   |   |   ODD_DIGIT = odd_digit=[a...f]:      (*)
|   |   |   ODD_DIGIT = odd_digit=[A...F]:      (*)
|   |   NHC POSTION IN [0..RLEN] = First:
|   |   |   ODD_DIGIT = odd_digit=-1:
|   |   |   ODD_DIGIT = odd_digit=[0...9]:      (*)
|   |   |   ODD_DIGIT = odd_digit=[a...f]:      (*)
|   |   |   ODD_DIGIT = odd_digit=[A...F]:      (*)
|   |   NHC POSTION IN [0..RLEN] = Middle:
|   |   |   ODD_DIGIT = odd_digit=-1:          (*)
|   |   |   ODD_DIGIT = odd_digit=[0...9]:      (*)
|   |   |   ODD_DIGIT = odd_digit=[a...f]:      (*)
|   |   |   ODD_DIGIT = odd_digit=[A...F]:
|   |   NHC POSTION IN [0..RLEN] = Last:
|   |   |   ODD_DIGIT = odd_digit=-1:
|   |   |   ODD_DIGIT = odd_digit=[0...9]:      (*)
|   |   |   ODD_DIGIT = odd_digit=[a...f]:
|   |   |   ODD_DIGIT = odd_digit=[A...F]:

```

RLEN = rlen>sLength: -2.0 (8.0)	Rule 1
RLEN = rlen=[1...sLength]	
NUM HEX CHARS IN [0...RLEN] = Even	
ODD_DIGIT = odd_digit=-1: -1.0 (3.0)	Rule 2
ODD_DIGIT = odd_digit>15: S[rLEN-1] (0.0)	Rule 3
ODD_DIGIT = odd_digit=[0...9]: S[rLEN-1] (1.0)	Rule 4
ODD_DIGIT = odd_digit<-1: S[rLEN-1] (0.0)	Rule 5
ODD_DIGIT = odd_digit=[a...f]: S[rLEN-1] (2.0)	Rule 6
ODD_DIGIT = odd_digit=[A...F]: S[rLEN-1] (1.0)	Rule 7
NUM HEX CHARS IN [0...RLEN] = Odd	
NHC POSTION IN [0..RLEN] = N/A	
ODD_DIGIT = odd_digit=-1: -3.0 (0.0)	Rule 8
ODD_DIGIT = odd_digit>15: -3.0 (1.0)	Rule 9
ODD_DIGIT = odd_digit=[0...9]: -1.0 (1.0)	Rule 10
ODD_DIGIT = odd_digit<-1: -3.0 (1.0)	Rule 11
ODD_DIGIT = odd_digit=[a...f]: -3.0 (0.0)	Rule 12
ODD_DIGIT = odd_digit=[A...F]: -3.0 (0.0)	Rule 13
NHC POSTION IN [0..RLEN] = First: S[rLEN-1] (1.0)	Rule 14
NHC POSTION IN [0..RLEN] = Middle: -1.0 (1.0)	Rule 15
NUM HEX CHARS IN [0...RLEN] = Zero	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 16
ODD_DIGIT = odd_digit>15: odd_digit (0.0)	Rule 17
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 18
ODD_DIGIT = odd_digit<-1: odd_digit (0.0)	Rule 19
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 20
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 21
RLEN = rlen=0	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 22
ODD_DIGIT = odd_digit>15: odd_digit (0.0)	Rule 23
ODD_DIGIT = odd_digit=[0...9]: odd_digit (2.0)	Rule 24
ODD_DIGIT = odd_digit<-1: odd_digit (0.0)	Rule 25
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 26
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 27
RLEN = rlen<0: -2.0 (1.0)	Rule 28

Figure 24 X's TS + Expert CP – Iteration 2

After having added eleven test cases, automatically produced the corresponding abstract test cases and re-run C4.5, we obtain the tree in Figure 25 with 26 rules. Rules 3, 5, 15, 17, 21, and 23 are combinations of choices that are feasible but involve error conditions which already appear in rules 9 and 11: there is no need to add test cases. Some rules in Figure 25 contain a large number of instances (test cases): e.g. rule 1. According to the decision tree, these test cases trigger the same input-output relationship in the program.

RLEN = rlen>sLength: -2.0 (8.0)	Rule 1
RLEN = rlen=[1...sLength]	
NUM HEX CHARS IN [0...RLEN] = Even	
ODD_DIGIT = odd_digit=-1: -1.0 (3.0)	Rule 2
ODD_DIGIT = odd_digit>15: S[rlen-1] (0.0)	Rule 3
ODD_DIGIT = odd_digit=[0...9]: S[rlen-1] (2.0)	Rule 4
ODD_DIGIT = odd_digit<-1: S[rlen-1] (0.0)	Rule 5
ODD_DIGIT = odd_digit=[a...f]: S[rlen-1] (2.0)	Rule 6
ODD_DIGIT = odd_digit=[A...F]: S[rlen-1] (1.0)	Rule 7
NUM HEX CHARS IN [0...RLEN] = Odd	
ODD_DIGIT = odd_digit=-1: S[rlen-1] (3.0)	Rule 8
ODD_DIGIT = odd_digit>15: -3.0 (1.0)	Rule 9
ODD_DIGIT = odd_digit=[0...9]: -1.0 (4.0)	Rule 10
ODD_DIGIT = odd_digit<-1: -3.0 (1.0)	Rule 11
ODD_DIGIT = odd_digit=[a...f]: -1.0 (3.0)	Rule 12
ODD_DIGIT = odd_digit=[A...F]: -1.0 (3.0)	Rule 13
NUM HEX CHARS IN [0...RLEN] = Zero	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 14
ODD_DIGIT = odd_digit>15: odd_digit (0.0)	Rule 15
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 16
ODD_DIGIT = odd_digit<-1: odd_digit (0.0)	Rule 17
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 18
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 19
RLEN = rlen=0	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 20
ODD_DIGIT = odd_digit>15: odd_digit (0.0)	Rule 21
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 22
ODD_DIGIT = odd_digit<-1: odd_digit (0.0)	Rule 23
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 24
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 25
RLEN = rlen<0: -2.0 (1.0)	Rule 26

Figure 25 X's TS + Expert CP – Iteration 3

We remove some of those test cases (randomly selected) and only keep one of them per rule unless code coverage is affected. We obtain a test suite of 20 test cases. The tree in Figure 26 with 26 rules is similar to the one in Figure 25 except that the number of instances for all rules becomes 1. No occurrence of the problems discussed in Section 4.2 can be found and the iterative process of Figure 4 stops. It is worth mentioning that the decision tree we obtain with student X's TS and Expert CP uses the same categories and choices as when using the Expert's CP and the Expert's test suite together (Appendix C.1): the two CPs are therefore equivalent.

```

RLEN = rlen>sLength: -2.0 (1.0)
RLEN = rlen=[1...sLength]
| NUM HEX CHARS IN [0...RLEN] = Even
| | ODD_DIGIT = odd_digit=-1: -1.0 (1.0)
| | ODD_DIGIT = odd_digit>15: S[rLEN-1] (0.0)
| | ODD_DIGIT = odd_digit=[0...9]: S[rLEN-1] (1.0)
| | ODD_DIGIT = odd_digit<-1: S[rLEN-1] (0.0)
| | ODD_DIGIT = odd_digit=[a...f]: S[rLEN-1] (1.0)
| | ODD_DIGIT = odd_digit=[A...F]: S[rLEN-1] (1.0)
| NUM HEX CHARS IN [0...RLEN] = Odd
| | ODD_DIGIT = odd_digit=-1: S[rLEN-1] (1.0)
| | ODD_DIGIT = odd_digit>15: -3.0 (1.0)
| | ODD_DIGIT = odd_digit=[0...9]: -1.0 (1.0)
| | ODD_DIGIT = odd_digit<-1: -3.0 (1.0)
| | ODD_DIGIT = odd_digit=[a...f]: -1.0 (1.0)
| | ODD_DIGIT = odd_digit=[A...F]: -1.0 (1.0)
| NUM HEX CHARS IN [0...RLEN] = Zero
| | ODD_DIGIT = odd_digit=-1: -1.0 (1.0)
| | ODD_DIGIT = odd_digit>15: odd_digit (0.0)
| | ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit<-1: odd_digit (0.0)
| | ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)
RLEN = rlen=0
| ODD_DIGIT = odd_digit=-1: -1.0 (1.0)
| ODD_DIGIT = odd_digit>15: odd_digit (0.0)
| ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)
| ODD_DIGIT = odd_digit<-1: odd_digit (0.0)
| ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)
| ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)
RLEN = rlen<0: -2.0 (1.0)

```

Figure 26 X's TS + Expert CP – Final Tree

5.6.2 Student Y's TS with the Expert CP

Student Y's test suite contains 20 test cases. The corresponding abstract test cases are used as inputs to C4.5 which generates the decision tree in Figure 27 with nine rules. Similarly to X's TS, the decision tree shows no misclassification but some categories are missing (Categories 5, 6, 7, 8, 10, and 11) and some choices of used categories are missing (specifically, c7 and c9): Case 2 in Section 4.2. The tree shows potentially missing choice combinations (rule 3): rule 3 is feasible and covers no test case. Using the heuristic described in Section 4.4 for adding choice combinations, the tree also

suggests the following 15 missing combinations of choices, among which only three are already exercised by the test suite (identified with a ‘*’ in the list below):

```

RLEN = rlen=[1...sLength]
| ODD_DIGIT = odd_digit<-1
| | NUM HEX CHARS IN [0...RLEN] = Zero:
| ODD_DIGIT = odd_digit=-1
| | NUM HEX CHARS IN [0...RLEN] = Zero:
| ODD_DIGIT = odd_digit=[0...9]:
| | NUM HEX CHARS IN [0...RLEN] = Even:
| | NUM HEX CHARS IN [0...RLEN] = Odd: *
| | NUM HEX CHARS IN [0...RLEN] = Zero:
| ODD_DIGIT = odd_digit=[a...f]:
| | NUM HEX CHARS IN [0...RLEN] = Even: *
| | NUM HEX CHARS IN [0...RLEN] = Odd:
| | NUM HEX CHARS IN [0...RLEN] = Zero:
| ODD_DIGIT = odd_digit=[A...F]:
| | NUM HEX CHARS IN [0...RLEN] = Even:
| | NUM HEX CHARS IN [0...RLEN] = Odd:
| | NUM HEX CHARS IN [0...RLEN] = Zero:

RLEN = rlen=0:
| ODD_DIGIT = odd_digit=-1
| | NUM HEX CHARS IN [0...RLEN] = Zero: *
| ODD_DIGIT = odd_digit=[0...9]:
| | NUM HEX CHARS IN [0...RLEN] = Zero:
| ODD_DIGIT = odd_digit=[a...f]:
| | NUM HEX CHARS IN [0...RLEN] = Zero:
| ODD_DIGIT = odd_digit=[A...F]:
| | NUM HEX CHARS IN [0...RLEN] = Zero:

```

RLEN = rlen=[1...sLength]	
ODD_DIGIT = odd_digit=-1	
HEX CHARS IN [0...RLEN] = Even: -1.0 (3.0)	Rule 1
HEX CHARS IN [0...RLEN] = Odd: S[rLEN-1] (7.0)	Rule 2
HEX CHARS IN [0...RLEN] = Zero: S[rLEN-1] (0.0)	Rule 3
ODD_DIGIT = odd_digit>15: -3.0 (1.0)	Rule 4
ODD_DIGIT = odd_digit=[0...9]: -1.0 (2.0)	Rule 5
ODD_DIGIT = odd_digit=[a...f]: S[rLEN-1] (1.0)	Rule 6
RLEN = rlen=0: -1.0 (4.0)	Rule 7
RLEN = rlen>sLength: -2.0 (1.0)	Rule 8
RLEN = rlen<0: -2.0 (1.0)	Rule 9

Figure 27 Y’s TS + Expert CP – Iteration 1

This initial use of C4.5 therefore allows us to improve the test suite: Step 4 in Figure 4. 12 new test cases are transformed into abstract test cases, and C4.5 is re-executed with a total of 32 abstract test cases (20 original and 12 new ones). The result is the tree of Figure 28 with 26 rules. In this tree, rules 8, 12, 14, 18, 20, and 24 are

combinations of choices that are feasible but involve an error condition which already appears in rules 2 and 6. Rule 10, on the other hand, is a feasible combination of choices that covers no test case.

RLEN = rlen=[1...sLength]	
HEX CHARS IN [0...RLEN] = Even	
ODD_DIGIT = odd_digit=-1: -1.0 (3.0)	Rule 1
ODD_DIGIT = odd_digit>15: -3.0 (1.0)	Rule 2
ODD_DIGIT = odd_digit=[0...9]: S[rlen-1] (1.0)	Rule 3
ODD_DIGIT = odd_digit=[a...f]: S[rlen-1] (1.0)	Rule 4
ODD_DIGIT = odd_digit=[A...F]: S[rlen-1] (1.0)	Rule 5
ODD_DIGIT = odd_digit<-1: -3.0 (1.0)	Rule 6
CHARS IN [0...RLEN] = Odd	
ODD_DIGIT = odd_digit=-1: S[rlen-1] (7.0)	Rule 7
ODD_DIGIT = odd_digit>15: S[rlen-1] (0.0)	Rule 8
ODD_DIGIT = odd_digit=[0...9]: -1.0 (3.0)	Rule 9
ODD_DIGIT = odd_digit=[a...f]: S[rlen-1] (0.0)	Rule 10
ODD_DIGIT = odd_digit=[A...F]: -1.0 (1.0)	Rule 11
ODD_DIGIT = odd_digit<-1: S[rlen-1] (0.0)	Rule 12
CHARS IN [0...RLEN] = Zero	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 13
ODD_DIGIT = odd_digit>15: odd_digit (0.0)	Rule 14
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 15
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 16
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 17
ODD_DIGIT = odd_digit<-1: odd_digit (0.0)	Rule 18
RLEN = rlen=0	
ODD_DIGIT = odd_digit=-1: -1.0 (4.0)	Rule 19
ODD_DIGIT = odd_digit>15: -1.0 (0.0)	Rule 20
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 21
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 22
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 23
ODD_DIGIT = odd_digit<-1: -1.0 (0.0)	Rule 24
RLEN = rlen>sLength: -2.0 (1.0)	Rule 25
RLEN = rlen<0: -2.0 (1.0)	Rule 26

Figure 28 Y's TS + Expert CP – Iteration 2

We therefore create one new test case, (automatically) produce the corresponding abstract test case and re-run C4.5 with a total of 33 abstract test cases, which returns the decision tree in Figure 29 with 26 rules. The tree shows six rules with no instances (rules 8, 12, 14, 18, 20, and 24): these are feasible combinations of choices but involves an error condition which already appears in rules 2 and 6. Additionally, some rules in Figure 29 contain a large number of instances (test cases).

RLEN = rlen=[1...sLength]	
NUM HEX CHARS IN [0...RLEN] = Even	
ODD_DIGIT = odd_digit=-1: -1.0 (3.0)	Rule 1
ODD_DIGIT = odd_digit>15: -3.0 (1.0)	Rule 2
ODD_DIGIT = odd_digit=[0...9]: S[rlen-1] (1.0)	Rule 3
ODD_DIGIT = odd_digit=[a...f]: S[rlen-1] (1.0)	Rule 4
ODD_DIGIT = odd_digit=[A...F]: S[rlen-1] (1.0)	Rule 5
ODD_DIGIT = odd_digit<-1: -3.0 (1.0)	Rule 6
NUM HEX CHARS IN [0...RLEN] = Odd	
ODD_DIGIT = odd_digit=-1: S[rlen-1] (7.0)	Rule 7
ODD_DIGIT = odd_digit>15: S[rlen-1] (0.0)	Rule 8
ODD_DIGIT = odd_digit=[0...9]: -1.0 (3.0)	Rule 9
ODD_DIGIT = odd_digit=[a...f]: -1.0 (1.0)	Rule 10
ODD_DIGIT = odd_digit=[A...F]: -1.0 (1.0)	Rule 11
ODD_DIGIT = odd_digit<-1: S[rlen-1] (0.0)	Rule 12
NUM HEX CHARS IN [0...RLEN] = Zero	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 13
ODD_DIGIT = odd_digit>15: odd_digit (0.0)	Rule 14
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 15
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 16
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 17
ODD_DIGIT = odd_digit<-1: odd_digit (0.0)	Rule 18
RLEN = rlen=0	
ODD_DIGIT = odd_digit=-1: -1.0 (4.0)	Rule 19
ODD_DIGIT = odd_digit>15: -1.0 (0.0)	Rule 20
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 21
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 22
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 23
ODD_DIGIT = odd_digit<-1: -1.0 (0.0)	Rule 24
RLEN = rlen>sLength: -2.0 (1.0)	Rule 25
RLEN = rlen<0: -2.0 (1.0)	Rule 26

Figure 29 Y's TS + Expert CP – Iteration 3

We remove some of those test cases (randomly selected) and only keep one per rule without affecting the code coverage. We therefore obtain a test suite of 20 test cases, and a tree similar to the one in Figure 29 except that the number of instances for all feasible rules becomes one. No occurrence of the problems discussed in Section 4.2 can be found and the iterative process of Figure 4 stops. The decision tree we obtain with student Y's TS and Expert CP uses the same categories and choices as when using the Expert's CP and the Expert's test suite together (Appendix C.1): the CPs are equivalent. Keep also in mind that the test suite we obtained in Iteration 3 and the reduced test suite have the same code coverage.

5.6.3 Student Z's TS with the Expert CP

Student Z's test suite contains eleven test cases. The corresponding abstract test cases are used as inputs to C4.5 which generates the decision tree in Figure 30 with 13 rules. Similarly to X's DT, the decision tree shows no misclassification but some categories are missing (Categories 5, 6, 7, 9, 10, and 11 in Appendix A.2) and some choices of used categories are missing (specifically, c7): Case 2. This tree shows potentially missing choice combinations (rules 4, 5, 6, and 7): these are four feasible rules that cover no test case. Using the heuristic described in Section 4.4 for adding choice combinations, the tree also suggests the following 36 missing combinations of choices, among which four combinations (identified with a '*') are already exercised by the test suite:

<pre> ODD_DIGIT=odd_digit= -1 BOUNDARY VALUE IN [0..RLEN]=Contains[0]: BOUNDARY VALUE IN [0..RLEN]=Contains[9]: BOUNDARY VALUE IN [0..RLEN]=Contains[a]: BOUNDARY VALUE IN [0..RLEN]=Contains[f]: BOUNDARY VALUE IN [0..RLEN]=ContainsMixed: ODD_DIGIT=odd_digit= [0...9] BOUNDARY VALUE IN [0..RLEN]=Contains[0]: BOUNDARY VALUE IN [0..RLEN]=Contains[9]: BOUNDARY VALUE IN [0..RLEN]=Contains[a]: BOUNDARY VALUE IN [0..RLEN]=Contains[f]: BOUNDARY VALUE IN [0..RLEN]=Contains[A]: BOUNDARY VALUE IN [0..RLEN]=Contains[F]: BOUNDARY VALUE IN [0..RLEN]=ContainsMixed: BOUNDARY VALUE IN [0..RLEN]=ContainsNone: ODD_DIGIT=odd_digit= [a...f] BOUNDARY VALUE IN [0..RLEN]=Contains[0]: BOUNDARY VALUE IN [0..RLEN]=Contains[9]: BOUNDARY VALUE IN [0..RLEN]=Contains[a]: BOUNDARY VALUE IN [0..RLEN]=Contains[f]: BOUNDARY VALUE IN [0..RLEN]=Contains[A]: BOUNDARY VALUE IN [0..RLEN]=Contains[F]: BOUNDARY VALUE IN [0..RLEN]=ContainsMixed: BOUNDARY VALUE IN [0..RLEN]=ContainsNone: </pre>	<pre> ODD_DIGIT=odd_digit= [A...F] BOUNDARY VALUE IN [0..RLEN]=Contains[0]: BOUNDARY VALUE IN [0..RLEN]=Contains[9]: BOUNDARY VALUE IN [0..RLEN]=Contains[a]: BOUNDARY VALUE IN [0..RLEN]=Contains[f]: BOUNDARY VALUE IN [0..RLEN]=Contains[A]: BOUNDARY VALUE IN [0..RLEN]=Contains[F]: BOUNDARY VALUE IN [0..RLEN]=ContainsMixed: BOUNDARY VALUE IN [0..RLEN]=ContainsNone: ODD_DIGIT=odd_digit=-1 RLEN=rLEN=0: * RLEN=rLEN=[1...sLength]: * ODD_DIGIT=odd_digit=[0...9] RLEN=rLEN=0: ODD_DIGIT=odd_digit=[a...f]: RLEN=rLEN=0: RLEN=rLEN=[1...sLength]: * ODD_DIGIT=odd_digit=[A...F]: RLEN=rLEN=0: RLEN=rLEN=[1...sLength]: * </pre>
---	--

ODD_DIGIT = odd_digit=-1	
BOUNDARY VALUE IN [0..RLEN] = ContainsNone: -1.0 (2.0)	Rule 1
BOUNDARY VALUE IN [0..RLEN] = Contains[A]: -1.0 (1.0)	Rule 2
BOUNDARY VALUE IN [0..RLEN] = Contains[F]: S[rLEN-1] (1.0)	Rule 3
BOUNDARY VALUE IN [0..RLEN] = Contains[f]-: -1.0 (0.0)	Rule 4
BOUNDARY VALUE IN [0..RLEN] = Contains[a]-: -1.0 (0.0)	Rule 5
BOUNDARY VALUE IN [0..RLEN] = ContainsMixed: -1.0 (0.0)	Rule 6
ODD_DIGIT = odd_digit=[0...9]	
RLEN = rlen=0: -2.0 (0.0)	Rule 7
RLEN = rlen=[1...sLength]: S[rLEN-1] (1.0)	Rule 8
RLEN = rlen<0: -2.0 (1.0)	Rule 9
RLEN = rlen>sLength: -2.0 (2.0)	Rule 10
ODD_DIGIT = odd_digit=[a...f]: S[rLEN-1] (1.0)	Rule 11
ODD_DIGIT = odd_digit<-1: -3.0 (1.0)	Rule 12
ODD_DIGIT = odd_digit>15: -3.0 (1.0)	Rule 13

Figure 30 Z's TS + Expert CP – Iteration 1

We refine the test suite by adding 32 new test cases. They are transformed into abstract test cases, and C4.5 is re-executed with a total of 43 abstract test cases (11 original and 32 new ones). The result is the tree of Figure 31 with 21 rules. This tree shows potentially missing choice combinations (rules, 4, 5, 11, 17, and 18): rules 5 and 18 are feasible combinations of choices but involve an error condition which already appears in rule 12. Rules 4, 11, and 17 are also feasible combinations of choices and involve the same error condition (odd_digit<-1) for which there is no test case. In the end, using our heuristic, the tree suggests the following five missing combinations of choices of which none is exercised by the test suite:

RLEN = rlen=[1...sLength]
NUM HEX CHARS IN [0..RLEN] = Zero:
ODD_DIGIT = odd_digit=-1:
ODD_DIGIT = odd_digit=[0...9]:
ODD_DIGIT = odd_digit=[a...f]:
ODD_DIGIT = odd_digit=[A...F]:
NUM HEX CHARS IN [0..RLEN] = Even
ODD_DIGIT = odd_digit<-1:

RLEN = rlen=0	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 1
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 2
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 3
ODD_DIGIT = odd_digit<-1: odd_digit (0.0)	Rule 4
ODD_DIGIT = odd_digit>15: odd_digit (0.0)	Rule 5
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 6
RLEN = rlen=[1...sLength]	
NUM HEX CHARS IN [0...RLEN] = Zero: -3.0 (1.0)	Rule 7
NUM HEX CHARS IN [0...RLEN] = Even	
ODD_DIGIT = odd_digit=-1: -1.0 (4.0)	Rule 8
ODD_DIGIT = odd_digit=[0...9]: S[rlen-1] (8.0)	Rule 9
ODD_DIGIT = odd_digit=[a...f]: S[rlen-1] (7.0)	Rule 10
ODD_DIGIT = odd_digit<-1: S[rlen-1] (0.0)	Rule 11
ODD_DIGIT = odd_digit>15: -3.0 (1.0)	Rule 12
ODD_DIGIT = odd_digit=[A...F]: S[rlen-1] (6.0)	Rule 13
NUM HEX CHARS IN [0...RLEN] = Odd	
ODD_DIGIT = odd_digit=-1: S[rlen-1] (4.0)	Rule 14
ODD_DIGIT = odd_digit=[0...9]: -1.0 (1.0)	Rule 15
ODD_DIGIT = odd_digit=[a...f]: -1.0 (2.0)	Rule 16
ODD_DIGIT = odd_digit<-1: -1.0 (0.0)	Rule 17
ODD_DIGIT = odd_digit>15: -1.0 (0.0)	Rule 18
ODD_DIGIT = odd_digit=[A...F]: -1.0 (2.0)	Rule 19
RLEN = rlen<0: -2.0 (1.0)	Rule 20
RLEN = rlen>sLength: -2.0 (2.0)	Rule 21

Figure 31 Z's TS + Expert CP – Iteration 2

We therefore create five test cases, (automatically) produce the corresponding abstract test cases and re-run C4.5 with a total of 48 abstract test cases (43 from Iteration 2 and five new ones) which returns the decision tree in Figure 32 with 26 rules. This tree shows five rules (rules 4, 5, 11, 22, and 23): these are feasible combinations of choices involving an error condition which already appears in rules 16 and 17. Some rules contain a large number of instances (test cases), e.g. rule 14.

RLEN = rlen=0	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 1
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 2
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 3
ODD_DIGIT = odd_digit<-1: odd_digit (0.0)	Rule 4
ODD_DIGIT = odd_digit>15: odd_digit (0.0)	Rule 5
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 6
RLEN = rlen=[1...sLength]	
NUM HEX CHARS IN [0...RLEN] = Zero	
ODD_DIGIT = odd_digit=-1: -1.0 (1.0)	Rule 7
ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)	Rule 8
ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)	Rule 9
ODD_DIGIT = odd_digit<-1: -3.0 (1.0)	Rule 10
ODD_DIGIT = odd_digit>15: odd_digit (0.0)	Rule 11
ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)	Rule 12
NUM HEX CHARS IN [0...RLEN] = Even	
ODD_DIGIT = odd_digit=-1: -1.0 (4.0)	Rule 13
ODD_DIGIT = odd_digit=[0...9]: S[rlen-1] (8.0)	Rule 14
ODD_DIGIT = odd_digit=[a...f]: S[rlen-1] (7.0)	Rule 15
ODD_DIGIT = odd_digit<-1: -3.0 (1.0)	Rule 16
ODD_DIGIT = odd_digit>15: -3.0 (1.0)	Rule 17
ODD_DIGIT = odd_digit=[A...F]: S[rlen-1] (6.0)	Rule 18
NUM HEX CHARS IN [0...RLEN] = Odd	
ODD_DIGIT = odd_digit=-1: S[rlen-1] (4.0)	Rule 19
ODD_DIGIT = odd_digit=[0...9]: -1.0 (1.0)	Rule 20
ODD_DIGIT = odd_digit=[a...f]: -1.0 (2.0)	Rule 21
ODD_DIGIT = odd_digit<-1: -1.0 (0.0)	Rule 22
ODD_DIGIT = odd_digit>15: -1.0 (0.0)	Rule 23
ODD_DIGIT = odd_digit=[A...F]: -1.0 (2.0)	Rule 24
RLEN = rlen<0: -2.0 (1.0)	Rule 25
RLEN = rlen>sLength: -2.0 (2.0)	Rule 26

Figure 32 Z's TS + Expert CP – Iteration 3

We remove some of those test cases (randomly selected) and only keep one per rule unless code coverage is affected. We therefore obtain a test suite of 21 test cases, and a tree similar to the one in Figure 32 except that the number of instance for all feasible rules becomes one. No occurrence of the problems discussed in Section 4.2 can be found and the iterative process of Figure 4 stops. The decision tree we obtain with student Z's TS and Expert CP uses the same categories and choices as when using the Expert's CP and the Expert's test suite together (Appendix C.1): the CPs are equivalent.

5.7 Assessing the fault detection effectiveness of improved test suites

To show the effectiveness of the improved test suites, we use method level mutation operators discussed in Section 5.7.1 using MuJava—a mutation system for java. The results are discussed in Section 5.7.2.

5.7.1 Mutation Testing

Mutation testing [30] is a fault based testing strategy that measures the quality/adequacy of test cases by examining whether they can reveal certain types of faults [31]. *Mutation operators* are applied to introduce single faults into the original program thereby creating a set of faulty versions, called *mutants*. Mutation operators describe syntactical changes to the program [32]. A mutant is said to be *killed* if a test set can differentiate a mutant from the original program, the mutant is called *alive* otherwise. A mutant may stay alive either because it is an *equivalent mutant*, i.e. it always produces the same output as the original program but is syntactically different, or the test suite is inadequate. A test suite that can kill all non-equivalent mutants is called an *adequate* test suite.

Our interest in using mutants is to assess the fault detection effectiveness of the improved test suites. Mutants have indeed been used to evaluate or compare test suites and testing techniques [33, 34].

MuJava [32], a mutation system for Java, is used to generate mutants for the PackHexChar program. A total of 254 mutants were generated of which 231 are non equivalent mutants (We consider a mutant as equivalent if it is not killed by the

Expert TS). Figure 33 shows the number of mutants (equivalent and non equivalent) generated for each mutation operator. Note that there are no mutants for mutation operators COD, LOR, LOD, ASR, because the generated mutants were syntactically incorrect. MuJava uses both method and class-level mutation operators. Method-level mutation operators modify expression by replacing, deleting, and inserting primitive operators, whereas class-level mutation operators handle object-oriented specific features such as inheritance, polymorphism and dynamic binding [32]. We are interested in method-level mutation operators that modify expressions by replacing, deleting, and inserting primitive operators. (The PackHexChar program only has one class, therefore operators targeting inheritance, polymorphism ... are not adequate.) Table 2 lists all the method level operators implemented in MuJava. They are all used to generate mutants for the case study:

Operator	Description
AOR	Arithmetic Operator Replacement
AOD	Arithmetic operator Deletion
AOI	Arithmetic operator Insertion
ROR	Relational Operator Replacement
COR	Conditional Operator Replacement
COD	Conditional operator Deletion
COI	Conditional operator Insertion
SOR	Shift Operator Replacement
LOR	Logical Operator Replacement
LOD	Logical operator Deletion
LOI	Logical operator Insertion
ASR	Assignment Operator Replacement

Table 2 Method-Level Mutation Operators for Java.

Figure 33 Number of (non-) Equivalent Mutants for each Mutation Operator

To show whether the improved test suites kill more mutants than the original test suite, we use mutated versions i.e. faulty version of the PackHexChar program, we then compare the size of the initial, improved and reduced test suites together with the number of mutants each one kills. We also investigate reasons why mutants remain alive by conducting a qualitative analysis.

5.7.2 Results

Table 3 shows the students ID and Iteration number (iteration 1 is the original student test suite), the size of the test suite (i.e., number of test cases), the number of mutants killed by the test suite (with percentage) and the coverage achieved by the test suite – Recall from Section 5.3 that we use statement coverage. (The exact mutants not killed by the different students test suites can be found in Table 6, Appendix D.)

First we can note differences between students initial test suites. Though the students all applied category partition from the same specification description, during the same amount of time, results show varying numbers of test cases with varying effectivenesses. Effectiveness varies between 75.3% (student X) and 97.8% (student Z), and size varies between 11 (student Z) and 31 (student A). Student Z test suite was very cost effective, whereas Students B and C test suites are the worst.

Student ID	Test Suite ID	Test Suite Size	Mutants Detected	% Of Mutants Detected	% Of Statement Coverage
X	Iteration 1	15	174/231	75.3%	88%
	Iteration 2	29	224/231	97%	100%
	Iteration 3	40	227/231	98.3%	100%
	Iteration 4	20	225/231	97.4%	100%
Y	Iteration 1	20	225/231	97.4%	100%
	Iteration 2	32	227/231	98.3%	100%
	Iteration 3	33	227/231	98.3%	100%
	Iteration 4	20	226/231	97.8%	100%
Z	Iteration 1	11	226/231	97.8%	100%
	Iteration 2	43	230/231	99.6%	100%
	Iteration 3	48	230/231	99.6%	100%
	Iteration 4	21	230/231	99.6%	100%
A	Iteration 1	20	225/231	97.4%	100%
	Iteration 2	26	226/231	97.8%	100%
	Iteration 3	11	222/231	96.1%	100%
B	Iteration 1	31	200/231	86.6%	94%
	Iteration 2	39	207/231	89.6%	95%
	Iteration 3	12	205/231	88.7%	95%
C	Iteration 1	19	185/231	80.1%	90%
	Iteration 2	21	200/231	86.6%	94%
	Iteration 3	10	200/231	86.6%	94%
Our CP+TS	Iteration 1	221	231/231	100%	100%
	Iteration 2	21	223/231	96.5%	100%

Table 3 Mutants killed and coverage by each test suite

Student X's original test suite (TS) contains 15 test cases which kill 75.3% of the mutants. After having improved the test suite in the second and third iterations with a test suite of 29 (resp. 40) test cases, 97% (resp. 98.3%) of the mutants are killed, which is quite an improvement, compared to the initial 75.3%. Four mutants (ROR11, ROR18, ROR21, and ROR28) remain alive though, which is further discussed in Section 5.8. After having reduced student X's TS to 20 test cases, the number of

mutants killed drops to 225 (97.4%). By removing 50% of the test cases, the number of killed mutants drops only by two. The two mutants that are not killed by the reduced test suite are AOIU3 and AORB14 (see descriptions in Table 7, Appendix D). In order to kill AOIU3, a test case must map to the following choices of the Expert CP where feasible: C1, any choice in category 3, C12, C13 or C14, C17 or C18, any choice in category 8, C28 or C29, any choice in category 10 or 11. For instance a test case with `r1en = 3`, `odd_digit=-1`, and `S="0a1"`, which maps to C2, C5, C12, C13, C19, C20, and C28, will kill AOIU3. Note that the conditions to kill those mutants appear in the categories and choices of the Expert CP (which is used with student X's test suite—recall Section 5.6.1) but during (random) test suite reduction the test cases that killed those mutants were unluckily selected and removed, further discussion on why this is the case is discussed in Section 5.8.

Student Y's original TS kills 97.4% of the mutants. The test suite improvement process increases this value to 98.7% at iteration 2 (no further improvement at iteration 3). Four mutants (AOIS102, ROR8 ROR18, and ROR28) remain alive at the end of the improvement process, a discussion on why these mutants remain alive is given in Section 5.8. After having reduced the TS by 13 test cases, the percentage of mutants killed drops to 97.8% (two mutants survive), which is not a significant drop. The two mutants that are not killed after test suite reduction, shown in Table 8 (Appendix D), are for the same reason as for student X -see Section 5.8 for further discussion.

Student Z's original TS kills 97.8% of the mutants. The test suite improvement process increases this value to 99.6% at iteration 2: One mutant (AOIS102) remains

alive. The reduced test suites kill 99.6% of the mutants as well. There is no such test case in the reduced test suite that will kill this mutant. The reason why this mutant stays alive is further discussed in Section 5.8.

Student A's original test suite kills 97.4% of the mutants. The test suite improvement process increases this value to 97.8%. Four mutants (shown in Table 6) remain alive at the end of the improvement process, this is further discussed in Section 5.8. Student A's reduced test suite with eleven test cases kills 96.1% of the mutants. The four mutants that are not killed after test suite reduction are shown in Table 10 (Appendix D). The reason these mutants are not killed is because the test suite does not contain test cases that kill these mutant and we further discuss the reason in Section 5.8.

Student B's original test suite kills 86.6% of the mutants. The test suite improvement process increases this value to 89.6%. Twenty four mutants (shown in Table 6) remain alive at the end of the improvement process, this is further discussed in Section 5.8. The reduced test suite with 12 test cases kills 88.7% of the mutants, which is slightly smaller than the number of mutants killed by the test suite before reduction (89.6%). The twenty six mutants that are not killed after test suite reduction are shown in Table 11 (Appendix D).

Student C's original test suite kills 80.1% of the mutants. The test suite improvement process increases this value to 86.6%. Thirty one mutants (shown in Table 6) remain alive at the end of the improvement process; this is further discussed in Section 5.8. The reduced test suite that contains ten test cases kills 86.6% of the mutants, which is

the same as the test suite at the end of the improvement process, which contains 21 test cases.

Using expert CP and TS, all 231 mutants are killed (100%), after having reduced the expert TS to 21 test cases (90% of reduction), the number of mutants killed drops to 96.5% (8 mutants less). The 8 mutants that are not killed after test suite reduction are shown in Table 12 (Appendix D). Recall that based on our test removal strategy (Section 4.4.2), test cases are randomly removed for each leaf (rule) unless the percentage of code coverage drops. We further discuss next our reduction strategy and why the number of alive mutant increases when test cases are removed.

The reason these mutants were not killed is because test cases satisfying some categories and choices related to the content of the input string s , i.e. not necessary to determine the output equivalence class, are not used in the tree and hence not used in the DT.

5.8 Analysis of alive mutants after test suite improvement/reduction

In Section 5.7.2, we noticed some issues with the improvement strategy as well the test suite reduction process. In this section, we explain why this happens and suggest a possible alternative.

5.8.1 OSS Context

We first discuss the context where we use a student TS with the Expert CP (OSS Context). Recall that in Section 4.4.1 two solutions are discussed for adding test cases. The first is to follow the CP method and build all the feasible (according to properties

and selectors) combinations of choices and select the ones that are missing in the abstract test suite and the second is to identify which combinations of choices may be relevant to determine the output class and could be missing from the test suite by using the decision tree. We decided to use the second solution: this heuristic is advantageous for it uses the information provided by the tree, when the tester intends to cover new choices, she does not have only the expensive option to exercise all the feasible combinations of choices, but can focus on combinations that are likely to affect the output. But by using the second solution when adding test cases we are potentially missing out some choices combinations that could potentially kill mutants that would otherwise not be killed by the first alternative since issuing choice combinations would be identified not only based on the tree but also on the CP specification. Therefore, the number of mutants killed by using the first solution would be higher than the second solution. For instance, the main reason why mutants remain alive is that the test inputs do not contain boundary values⁹. In the case of Student X, four mutants (ROR11, ROR18, ROR21, ROR28) have not been killed by the improved test suite, and will only be killed if there are test cases where the first `rlen` characters in the input string contained an "a", "A", "f", or "F". Similarly, Student Y's improved test suite could have killed the mutants that involved boundary values (ROR8, ROR18, ROR28) if the first `rlen` characters in the input string contained 9, F, or f. By using the first solution, these mutants would have been killed.

⁹ The input String may contains valid hex chars between [0...9], [a...f], and [A...F], where 0, 9, a, f, A, and F are boundary values in the input string.

Recall that in Section 4.4.2, we proposed a strategy for removing test cases to minimize functional test suites and ad hoc test suites which often turn out to contain redundancy. Following the heuristic described in Section 4.4.2, test cases are randomly removed per leaf (rule) unless the percentage of code coverage (we use statement coverage) drops. Obviously statement coverage was not a sufficient criteria for ensuring the reduced test suite kills the same number of mutants as would the initial test suite. One improvement to this strategy would be to combine Statement Coverage with Condition Coverage, which reports the true or false outcome of each boolean sub-expression, since most of the mutants that are not killed involve boundary values in the conditional statements. As discussed in Section 5.7.2, the nine mutants that are not killed by the expert reduced test suite are AOIS102, ROR1, ROR8, ROR11, ROR18, ROR21, ROR28, ROR31, and AOIS31 (see descriptions in Table 13, Appendix D). If condition coverage is used, during the reduction process only two (AOIS102, AOIS31) would have not been killed which is an improvement to our initial strategy. We currently further investigate other strategies to improve this process.

5.8.2 Evolution Context

We now discuss the context where we use a student TS with the student CP (Evolution Context). As discussed in Section 4.4.1 and the previous section, two solutions are discussed for adding test cases: The first one is to follow the CP method and build all the feasible (according to properties and selectors) combinations of choices and select the ones that are missing in the abstract test suite, and the second is to identify which combinations of choices may be relevant to determine the output

class and could be missing from the test suite by using the decision tree. None of the two solutions is inherently better than the other in this context. The reason is that the student CPs' do not have the necessary categories and choices which can be used to add test cases that will kill mutants that would have been killed otherwise. But the argument for using the first solution is that it will result in a larger test suite, meaning that the resultant test suite will have a higher possibility of killing more mutants. An alternative to these two techniques will be investigated in our future work.

When removing test cases, the solution discussed for the OSS context applies to the evolution context as well. For instance, the four mutants (ROR5, ROR13, ROR14, and ROR36) that are not killed by student A's reduced test suite would have been killed if we use condition and statement coverage together.

5.9 Discussions

The previous sections illustrated the MELBA iterative process in two different application contexts: (1) when Category-Partition specifications are used to generate an initial, possibly incomplete test suite, (2) when no Category-Partition specification exists and must be reverse-engineered independently from the test suites, based on an intuitive functional understanding of the system under test. In both situations, we showed that using MELBA we were able to identify instances of problems in the decision trees and use this information to improve both test suites and Category-Partition specifications. The iterative process stopped when no problem could be identified in the trees, at which point the test suites and Category-Partition specifications were reaching a quality level that would likely have been achieved by

an expert and that was in any case equivalent to the best Category-Partition specifications we could derive.

From the case study, we can also conclude that our taxonomies of decision tree problems and their possible root causes (Sections 4.2 and 4.3) are complete with respect to the PackHexChar program. With the case study performed not all problem-cause pairs were covered. For instance, we did not have a scenario where a misclassification led to too many test cases for a rule. We also did not have a scenario where a category is not used because of ill-defined choices.

The resulting test suites for students obtained in section 5.5 and section 5.6 are smaller than the expert TS. There are two reasons why this is the case: the first is that in the heuristic described in section 4.4.1, test cases are added only when needed not based on the Category-Partition, the second reason is that expert CP has categories and choices that do not impact the output but results in a larger test suite.

Furthermore, we have seen that based on our students' test suites, who can be considered competent testers in terms of training, we could achieve a final Category-Partition specification and test suite in two to three improvement steps.

Recall the two solutions discussed in Section 4.4.1 for adding test cases and the solution for removing test cases in Section 4.4.2 have deficiencies as discussed in Section 5.8. The main reason why we were unable to kill all mutants at the end of the improvement process is because our improvement strategy added test cases based on the information provided by the tree and not the CP. The problem with the reduction strategy is that when removing test cases we only consider Statement Coverage,

which does not seem to be sufficient. One improvement to this strategy would be to consider other code coverage condition such as Condition Coverage.

Of the two application contexts discussed, the evolution context (Section 5.5) requires upfront investment in creating a CP. However, the improvement process is the same for both OSS and Evolution context. The reduction process requires a lot of time since everytime test cases are removed we have to check the code coverage information and keep doing so until we reach a test suite with minimum number of test cases but still have the same code coverage as the improved test suite.

CHAPTER 6 CASE STUDY TWO: SPACE PROGRAM

In this section, we first describe the second system used for the case study (Section 6.1). We then present the design of the case study (Section 6.2) and describe the results of applying C4.5 decision trees to drive the improvement of the test specification and test suite (Sections 6.3 and 6.4). Lastly, we discuss the results in section 6.6.

6.1 The Space Program

The Space program [35] was originally developed by the European Space Agency, and was first used in a software engineering study by Pasquini *et al.* [35]. It has subsequently been used in other experiments. Space allows users to describe the configuration of an array of antennas using a specific array definition language (ADL). It reads a text file containing ADL statements, checks its conformance to the ADL grammar as well as specific consistency rules, and performs other computations. It is a 5905-NBNC¹⁰-LOC C program. (See [36] for further details.) Vokolos and Frankl [37] used the program for a study in which they compared the effectiveness of regression test selection strategies. For that study, they generated 10,000 test cases using a randomized input generation tool. Rothermel *et al.* [38] later added enough test cases to ensure that each executable decision was covered by at least 30 test cases in each direction; this procedure added 3,585 test cases to the pool.

¹⁰ NBNC: Non-blank line, non-comments statements.

Note that this suggests that the test suite contains redundant test cases. The resulting test pool covers 90, 85, 85, and 80 percent of all blocks, decisions, c-uses, and p-uses present in the program, respectively. The total number of blocks, decisions, c-uses, and p-uses are 2995, 1191, 3733, and 1707, respectively.

During the course of their research, Rothermel *et al.* [38] identified and eliminated five more faults, bringing the total number of versions of the program to 38; however, they found that three of the original versions did not exhibit faulty behavior, reducing the number of non-equivalent versions to 35. We obtained the program, and test pool from the Galileo Research Group Subject Infrastructure Repository at the University of Nebraska – Lincoln. In this case study, we used the Space program [35], and test cases generated by the authors of [35, 38, 39] directly.

In our method, we use the category partition technique to characterize test cases instead of using this technique to devise test cases. Therefore, it is not necessary to identify constraints on choices as suggested by the category-partition technique [6]. The CP specification available from [23] contains 207 parameters, 83 categories, and 582 choices (Appendix E.1). Since the Space program is a language processing program, it is not surprising that such a large number of categories and choices are defined.

6.2 Design of the Experiment

Recall from Figure 4 that the MELBA method we propose can be applied in two broad contexts: The reuse, validation, and integration of open source software and software evolution. The Space program lies in the evolution context. We can however

further distinguish two situations (in the evolution context) that require we perform two slightly different types of experiments (Sections 6.3 and 6.4), because of the specifics of the test suite of the Space program. In the first experiment (Sections 6.3) we use the CP specification with the original test suite (13,585 test cases) to generate the decision tree. In the second experiment (Section 6.4) we use a much smaller test suite (56 test cases) to go through the improvement process. The 56 test cases have been obtained from the original test suite by randomly removing test cases from the original test suite until the statement coverage of the test suite drops. The main reason is that, as suggested by the way the original test suite has been built, the test suite contains a lot of redundant test cases. So we expect to discover many rules with a lot of instances during the first experiment, and we therefore want to exercise the Melba procedure on a more realistic test suite.

Since the output equivalence classes have not been defined for the space program in [23], we have to define them. The experiments are carried out in Sections 6.3 and 6.4 using the following output equivalent classes, which are all the possible (error) messages the Space program returns (please refer to Space program for detailed descriptions of these errors):

- i. INV_GEOMETRY_DEF: ERROR 34: Incorrect element GEOMETRY definition.
- ii. INV_PHASE_EXC_DEF: ERROR 80: Incorrect PHASE excitation definition.
- iii. INV_PORTS_DEF: ERROR 49: Incorrect element PORTS definition
- iv. INV_AMP_EXC_DEF: ERROR 79: Incorrect AMPLITUDE excitation definition.

- v. INV_ADD/REMOVE_DEF: ERROR 64: Incorrect ADD or REMOVE statement.
- vi. INV_GRID_DEF: ERROR 67: Missing ELEMENT definition after GRID definition.
- vii. INV_POLARIZATION_DEF: ERROR 31: Incorrect element LINEAR polarization definition.
- viii. NULL_POINTER
- ix. SEC_ORD_NOT_ALLOWED_ON_IRREG_GROUPS: ERROR B5: SECOND ORDER law not allowed on irregular groups.
- x. ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM: ERROR B8: Error in group geometry
- xi. RECT_NOT_ALLOWED_ON_HEX: ERROR B3: RECTANGULAR element not allowed on HEXAGONAL grid in GROUP
- xii. GRID_ANG_OUTOF_NON_AMBIG_RANGE: ERROR B4: GRID angle out of non ambiguity range
- xiii. SEQ_ROT_NOT_ALLOWED_ON_IRREG_GROUPS: ERROR B11: SEQUENTIAL ROTATION not allowed on irregular shaped groups.
- xiv. SEQ_ROT_NOT_ALLOWED_ON_MULTIPORT_ELEM: ERROR B10: SEQUENTIAL ROTATION not allowed to multiport elements.
- xv. FILE_ERROR: File related errors occur when the file does not exist, the file is empty or an incorrect number of parameters is passed
- xvi. VALID_INPUT: The test case input is valid and the space program produces an output.

We then try to identify occurrences of problems using the heuristics described in Figure 4. We go through the iterative improvement process illustrated in Figure 4. Both the test suite and the CP specification were iteratively improved using the patterns we specified in Section 4.3 for analyzing decision trees and their potential relationships to problems in the test suite or CP specification. Since we also require

code coverage information when removing test cases, Coverage Validator¹¹, for measuring and reporting C code coverage, is used for our purpose. Coverage Validator supports statement coverage. The results of applying C4.5 are reported in Section 6.3 and 6.4 for the two experiments, respectively.

6.3 Experiment one

In this experiment we use the complete Space test suite (13,585 test cases) with the original Space CP and our 16 output equivalence classes (Section 6.2). We generate the corresponding abstract test suite, and after running C4.5, we obtain the decision tree in Figure 35: this is only an excerpt of the decision tree, which contains a total of 6,892 rules; the confusion matrix is also very large and is not shown here. There are a number of issues with the tree. First, there are 125 misclassifications, which is relatively small considering that we have 13,585 test cases: 0.9% of them are misclassified. This suggests that our CP specification, including output equivalence classes is relatively good at specifying Space's functionalities. Second the tree is quite large and therefore difficult to analyze. This suggests that on such a large CP test suite and CP specification, tool support for Melba is warranted. There is redundancy in the test suite, as discussed earlier, and therefore, as expected, many rules cover more than one test case. The minimum and maximum numbers of test cases in rules are 0 and 339, respectively. Figure 34 shows the distribution of numbers of rules with specific numbers of test cases: more than 4000 (~60%) rules

¹¹ <http://www.softwareverify.com/cpp/coverage/index.htm>

have one test case, but a large number of rules have more than 10 test cases; 309 rules have more than 30 test cases (recall that each edge and node in the source code control flow graph is covered by at least 30 test cases, but apparently these white box test cases do not correspond to unique combinations of input/output combinations from our CP specification); redundancy may also ggestsu misclassification (Section 4.3.6).

Figure 34 Normal distribution of test cases per rule

A careful analysis of the (huge) tree shows that the tree suggests some combinations of choices are not exercised by the complete test suite. We also make such an observation during the second experiment that we further discuss in the following section. On the one hand this is surprising considering the size of the test suite, and the way (redundancy) it was built. On the other hand, test cases where added to the test suite to increase the amount of code coverage (recall Section 6.1), but coverage of statements, edges, and data flow does not necessarily correspond to combinations of choices which is a functional aspect rather than structural one: we believe that combinations of choices better correspond to paths in the code than simple structural elements as the ones mentioned above.

In the first scenario we do not report on the complete application of the Melba process since we quickly (first decision tree) reach the limits of the manual application of the process. This also justifies our second experiment, where we apply Melba on a reduced test suite, and the construction of tool support, which is left to future work.

```

Elem_Port_Amp_Unit = MissingValue
| Grexc_Gramp_Exec_Unit = MissingValue
| | Grexc_Gramp_Exec_Val5 = N/A
| | | Grexc_Grpha_Exec_Val4 = N/A
| | | | Grexc_Grpha_Def = ROTATION
| | | | | Elem_Port_Number = MissingValue
| | | | | | Grgeo_Additional_Def = BLOCK
| | | | | | | Elem_Geometry_Val2 = MissingValue
| | | | | | | | Elem_Polar_Def = RH
| | | | | | | | | Grexc_Grpha_Exec_Def = CCW
| | | | | | | | | | Grid_Elem_Def = InvalidValue: INV_GRID_DEF (2.0)
| | | | | | | | | | Grid_Elem_Def = STEP: INV_GRID_DEF (30.0)
| | | | | | | | | | Grid_Elem_Def = MissingValue: INV_POLARIZATION_DEF (1.0)
...

```

Figure 35 DT with complete TS and Original CP – 16 Equivalence classes

This experiment was also carried out in two different other scenarios where we used two different sets of (coarser grained) output equivalence classes. In one scenario we used only three output equivalence classes: VAL_INPUT, INV_INPUT (representing 14 of the classes of Section 6.2) and FILE_ERROR. In the other scenario, we used only four output equivalence classes: VAL_INPUT, INV_SYNTAX (representing seven, i.e., i-vii, of the classes of Section 6.2), INV_SEMANTICS (representing seven, i.e., viii-xiv of the classes of Section 6.2) and FILE_ERROR. In each scenario, we generated the corresponding abstract test suite, and after running C4.5, we obtained a decision tree with a very large number of rules (3100 and 3292, respectively), with larger numbers of instances per rule (the minimum and maximum numbers of test cases in rules are 0 and 817, and 0 and 814, respectively), which also showed misclassifications (73 and 74 respectively, i.e., 0.5% of the complete test

suite in each case). Since these scenarios did not change our previous observations, we do not report on them. In addition, although the number of rules and misclassified instances in trees generated with those coarser grained output equivalence classes is almost half of that of the tree generated with 16 equivalence classes, we believe that the benefit of having a refined analysis with 16 classes provides in depth understanding of the system and better exposure to paths that are not excerscised in the test suite. This will have to be confirmed by additional studies.

6.4 Experiment two

In this experiment we use a reduced test suite (56 test cases) with the original Space CP and our 16 output equivalence classes (Section 6.2). We generated the corresponding abstract test suite and followed the Melba process.

6.4.1 First Iteration

After running C4.5 we obtain the decision tree (and confusion matrix) in Figure 36 with 55 rules. The tree in Figure 36 explicitly shows that 23 combinations of choices are missing (Case 3), as they correspond to rules with no instances (identified by (*)).

Grexc_Grpha_Exec = PHASE	
Elem_Port_Amp_Unit = MissingValue	
Grexc_Gramp_Exec_Val2 = N/A	
Elem_Geometry_Def = CIRCULAR	
Grexc_Grpha_Exec_Def = N/A	
Grgeo_Additional_Int_Val2 = MissingValue	
Grid_Elem_Triang_Val2 = <0: VALID_INPUT (1.0)	Rule 1
Grid_Elem_Triang_Val2 = N/A	
Grid_Elem_Def = PX: VALID_INPUT (0.0)	Rule 2(*)
Grid_Elem_Def = STEP: VALID_INPUT (2.0)	Rule 3
Grid_Elem_Def = MissingValue: VALID_INPUT (4.0)	Rule 4
Grid_Elem_Def = ANGLE: VALID_INPUT (1.0)	Rule 5
Grid_Elem_Def = PSTEP: INV_GRID_DEF (2.0)	Rule 6
Grid_Elem_Triang_Val2 = MissingValue: VALID_INPUT (0.0)	Rule 7(*)
Grid_Elem_Triang_Val2 = >0: INV_GRID_DEF (2.0)	Rule 8
Grgeo_Additional_Int_Val2 = Combination	
Grid_Def = TRIANGULAR: VALID_INPUT (2.0)	Rule 9
Grid_Def = HEXAGONAL	
Grgeo_Add_Real_Val1 = N/A: VALID_INPUT (2.0)	Rule 10


```

| | | | | Grgeo_Add_Real_Val1 = >0: VALID_INPUT (0.0) Rule 11(*)
| | | | | Grgeo_Add_Real_Val1 = MissingValue: INV_ADD/REMOVE_DEF (1.0) Rule 12
| | | | | Grid_Def = RECTANGULAR: INV_ADD/REMOVE_DEF (1.0) Rule 13
| | | | | Grid_Def = SQUARE: VALID_INPUT (0.0) Rule 14(*)
| | | | | Grid_Def = MissingValue: VALID_INPUT (0.0) Rule 15(*)
| | | | | Grgeo_Additional_Int_Val2 = >0: INV_ADD/REMOVE_DEF (1.0) Rule 16
| | | | | Grgeo_Additional_Int_Val2 = <0: VALID_INPUT (0.0) Rule 17(*)
| | | | | Grexc_Grpha_Exec_Def = MissingValue
| | | | | Grid_Elem_Def = PX: INV_PHASE_EXC_DEF (0.0) Rule 18(*)
| | | | | Grid_Elem_Def = STEP: INV_PHASE_EXC_DEF (0.0) Rule 19(*)
| | | | | Grid_Elem_Def = MissingValue: INV_PHASE_EXC_DEF (2.0) Rule 20
| | | | | Grid_Elem_Def = ANGLE: INV_PHASE_EXC_DEF (0.0) Rule 21(*)
| | | | | Grid_Elem_Def = PSTEP
| | | | | Grid_Elem_Val1 = N/A: INV_ADD/REMOVE_DEF (0.0) Rule 22(*)
| | | | | Grid_Elem_Val1 = >0: INV_ADD/REMOVE_DEF (1.0) Rule 23
| | | | | Grid_Elem_Val1 = MissingValue: INV_ADD/REMOVE_DEF (0.0) Rule 24(*)
| | | | | Grid_Elem_Val1 = <0: INV_GRID_DEF (1.0) Rule 25
| | | | | Elem_Geometry_Def = InvalidValue: INV_GEOMETRY_DEF (1.0) Rule 26
| | | | | Elem_Geometry_Def = RECTANGULAR
| | | | | Grid_Elem_Def = PX: ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM (0.0) Rule 27(*)
| | | | | Grid_Elem_Def = STEP: RECT_NOT_ALLOWED_ON_HEX (1.0) Rule 28
| | | | | Grid_Elem_Def = MissingValue
| | | | | Grexc_Grpha_Exec_Val5 = <0: ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM (4.0) Rule 29
| | | | | Grexc_Grpha_Exec_Val5 = >0: VALID_INPUT (2.0) Rule 30
| | | | | Grexc_Grpha_Exec_Val5=MissingValue:ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM(0.0) Rule 31(*)
| | | | | Grexc_Grpha_Exec_Val5=ErrorMissing:ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM(0.0) Rule 32(*)
| | | | | Grid_Elem_Def = ANGLE: ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM (0.0) Rule 33(*)
| | | | | Grid_Elem_Def = PSTEP: INV_GEOMETRY_DEF (1.0) Rule 34
| | | | | Elem_Geometry_Def = MissingValue: VALID_INPUT (0.0) Rule 35(*)
| | | | | Grexc_Gramp_Exec_Val2 = >0
| | | | | Grid_Elem_Triang_Val1 = <0: VALID_INPUT (0.0) Rule 36(*)
| | | | | Grid_Elem_Triang_Val1 = N/A
| | | | | Elem_Geometry_Def = CIRCULAR: SEC_ORD_NOT_ALLOWED_ON_IRREG_GROUPS (1.0) Rule 37
| | | | | Elem_Geometry_Def = InvalidValue: VALID_INPUT (0.0) Rule 38(*)
| | | | | Elem_Geometry_Def = RECTANGULAR
| | | | | Grexc_Grpha_Exec_Unit2 = MissingValue: VALID_INPUT (3.0) Rule 39
| | | | | Grexc_Grpha_Exec_Unit2 = N/A: VALID_INPUT (1.0) Rule 40
| | | | | Grexc_Grpha_Exec_Unit2 = deg: RECT_NOT_ALLOWED_ON_HEX (1.0) Rule 41
| | | | | Elem_Geometry_Def = MissingValue: VALID_INPUT (0.0) Rule 42(*)
| | | | | Grid_Elem_Triang_Val1 = MissingValue: NULL_POINTER (1.0) Rule 43
| | | | | Grid_Elem_Triang_Val1 = >0: INV_PHASE_EXC_DEF (1.0) Rule 44
| | | | | Grid_Elem_Triang_Val1 = non_number: VALID_INPUT (0.0) Rule 45(*)
| | | | | Grexc_Gramp_Exec_Val2 = MissingValue: INV_AMP_EXC_DEF (2.0) Rule 46
| | | | | Elem_Port_Amp_Unit = Combination
| | | | | Elem_Port_Orient_UNIT = MissingValue: INV_PORTS_DEF (4.0) Rule 47
| | | | | Elem_Port_Orient_UNIT = Combination: INV_POLARIZATION_DEF (1.0) Rule 48
| | | | | Elem_Port_Orient_UNIT = N/A: INV_PORTS_DEF (0.0) Rule 49(*)
| | | | | Elem_Port_Amp_Unit = dB: GRID_ANG_OUTOF_NON_AMBIG_RANGE (1.0) Rule 50
| | | | | Grexc_Grpha_Exec = InvalidValue
| | | | | Elem_Geometry_Unit = MissingValue: INV_AMP_EXC_DEF (2.0) Rule 51
| | | | | Elem_Geometry_Unit = dm: INV_AMP_EXC_DEF (0.0) Rule 52(*)
| | | | | Elem_Geometry_Unit = mm: INV_PORTS_DEF (1.0) Rule 53
| | | | | Elem_Geometry_Unit = cm: INV_AMP_EXC_DEF (0.0) Rule 54(*)
| | | | | Grexc_Grpha_Exec = MissingValue: FILE_ERROR (5.0) Rule 55

```

```

Number of Leaves : 55
Size of the tree : 74

```

=== Confusion Matrix ===

```

a b c d e f g h i j k l m n <-- classified as
18 0 0 0 0 0 0 0 0 0 0 0 0 0 0 | a = VALID_INPUT
0 2 0 0 0 0 0 0 0 0 0 0 0 0 0 | b = INV_GEOMETRY_DEF
0 0 3 0 0 0 0 0 0 0 0 0 0 0 0 | c = INV_PHASE_EXC_DEF
0 0 0 5 0 0 0 0 0 0 0 0 0 0 0 | d = INV_PORTS_DEF
0 0 0 0 4 0 0 0 0 0 0 0 0 0 0 | e = INV_AMP_EXC_DEF
0 0 0 0 0 4 0 0 0 0 0 0 0 0 0 | f = INV_ADD/REMOVE_DEF
0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 | g = NULL_POINTER
0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 | h = SEC_ORD_NOT_ALLOWED_ON_IRREG_GROUPS
0 0 0 0 0 0 0 0 4 0 0 0 0 0 0 | i = ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM

```

0	0	0	0	0	0	0	0	0	2	0	0	0	0		j	=	RECT_NOT_ALLOWED_ON_HEX
0	0	0	0	0	0	0	0	0	0	1	0	0	0		k	=	INV_POLARIZATION_DEF
0	0	0	0	0	0	0	0	0	0	0	5	0	0		l	=	INV_GRID_DEF
0	0	0	0	0	0	0	0	0	0	0	0	1	0		m	=	GRID_ANG_OUTOF_NON_AMBIG_RANGE
0	0	0	0	0	0	0	0	0	0	0	0	0	5		n	=	FILE_ERROR

Figure 36 DT with reduced TS and Original CP – 16 Equivalence classes

Following the heuristic described in Section 4.4.1 for adding test cases results in the identification of approximately 8,239,381 missing combinations of choices. We consider this number to be too large and probably an indication that our heuristic for improving the test suite is probably not very adequate for large CP specification and test suite like Space's. Therefore, we lean towards a new heuristic based on the CP specification and decision tree, instead of a heuristic solely based on the decision tree. This new heuristic relies on the notion of base-choice (or nominal choice) which is a notion introduced in the original Category-Partition technique. The heuristic assumes that a base choice, or nominal choice, be defined for each category in the CP specification. (Base choices for the Space CP specification are available in Appendix E.) Category-Partition then defines a number of criteria for selecting combinations of choices to exercise. One of them, the All Combinations criterion, is to try all the feasible combinations of choices: one value for every choice of every category must be combined with one value of every choice of every other category (as long as the combination satisfies constraints). Another criterion, namely Base Choice, requires that a first base test be formed by using all the base choices for categories. Subsequent tests are chosen by holding all but one base choice constant (i.e., we select a non-base choice for one category) and forming choice combinations by covering all non-base choices of the selected category. This is repeated for each

category. Instead of All Combinations, which leads to a too large number of test cases, we decided to use Base choice coverage.

Keep in mind, though, that we still want to rely on the information provided in the decision tree. Therefore, we only use categories and choices selected by the tree. Our heuristic is therefore defined as follows. We first identify combinations of choices that the tree suggests are missing (this is similar to the first heuristic discussed in Section 4.4.1). We then only add a test case for a combination if the combination has at most one non base choice.

Following the heuristic described above, we add a test case for a missing combination of choices only if the combination of choices it triggers (as indicated by the tree) contains at most one non base choice – there are 12 such instances. Of the 12 new choice combinations, only two abstract test cases matching the choice combinations were found in the complete Space test suite. Test cases for the remaining ten choice combinations identified in Figure 37 were added and the Abstract Test Cases generated.

```

Grexc_Grpha_Exec = PHASE
|   Elem_Port_Amp_Unit = Combination
|   |   Grexc_Gramp_Exec_Val2 = >0
|   |   |   Elem_Geometry_Def = CIRCULAR
|   |   |   |   Grexc_Grpha_Exec_Def = CW
|   |   |   |   |   Grgeo_Additional_Int_Val2 = >0
|   |   |   |   |   |   Grid_Def = RECTANGULAR
|   |   |   |   |   |   |   Grgeo_Add_Real_Val1 = >0
Grexc_Grpha_Exec = PHASE
|   Elem_Port_Amp_Unit = dB
|   |   Grexc_Gramp_Exec_Val2 = >0
|   |   |   Elem_Geometry_Def = CIRCULAR
|   |   |   |   Grexc_Grpha_Exec_Def = CW
|   |   |   |   |   Grgeo_Additional_Int_Val2 = >0
|   |   |   |   |   |   Grid_Def = RECTANGULAR
|   |   |   |   |   |   |   Grgeo_Add_Real_Val1 = >0
Grexc_Grpha_Exec = PHASE
|   Elem_Port_Amp_Unit = dm
|   |   Grexc_Gramp_Exec_Val2 = >0
|   |   |   Elem_Geometry_Def = CIRCULAR
|   |   |   |   Grexc_Grpha_Exec_Def = CW
|   |   |   |   |   Grgeo_Additional_Int_Val2 = >0
|   |   |   |   |   |   Grid_Def = RECTANGULAR

```


complete test set, instead of creating test cases from scratch, we reused the complete test set as follows: (i) We identified the test cases in the complete test set that exercise each missing combination of choices; (ii) We randomly selected one such test case for each missing combination. For the ten missing combinations (Figure 37) that are not exercised by the complete test set, we specifically created test cases from scratch. The results are shown in the 2nd iteration.

It is worth recalling that test cases in the test suite are mostly white-box test cases (e.g., to cover several times specific control and data flow elements) and therefore do not necessarily exercise specific functional aspects of the system, as specified by choice combinations. This first iteration of the Melba process does illustrate the fact that the process can lead to improvements to an industrially developed test suite: we found new interesting functional test cases for Space.

6.4.2 Second Iteration

Once the $56 + 12 = 68$ abstract test cases are (automatically) re-created from the improved TS, the execution of C4.5 produces the decision tree of Figure 38 made of 80 rules. The tree shows that some choice combinations are missing (Case 3), 39 of them being explicitly identified in rules with no instance (identified with a (*)), with some combinations feasible and some unfeasible.

Elem_Port_set_num = 0.0	
Grexc_Grpha_Exec_Def = N/A	
Elem_Geometry_Def = CIRCULAR	
Grexc_Gramp_Exec_Def = UNIFORM	
Grexc_Grpha_Exec = PHASE	
Grgeo_Additional_Int_Val3 = MissingValue	
Grexc_Grpha_Def = UNIFORM	
Grid_Elem_Val2 = N/A: VALID_INPUT (7.0)	Rule 1
Grid_Elem_Val2 = MissingValue: VALID_INPUT (3.0)	Rule 2
Grid_Elem_Val2 = >0: VALID_INPUT (1.0)	Rule 3
Grid_Elem_Val2 = ErrorMissing: INV_GRID_DEF (1.0)	Rule 4
Grid_Elem_Val2 = <0: INV_GRID_DEF (1.0)	Rule 5

Grexc_Grpha_Def = InvalidValue: VALID_INPUT (0.0)	Rule 6 (*)
Grexc_Grpha_Def = SECOND: INV_GRID_DEF (1.0)	Rule 7
Grexc_Grpha_Def = ROTATION: VALID_INPUT (0.0)	Rule 8 (*)
Grexc_Grpha_Def = MissingValue: VALID_INPUT (0.0)	Rule 9 (*)
Grgeo_Additional_Int_Val3 = Combination	
Grid_Elem_Triang_Val1 = <0: VALID_INPUT (0.0)	Rule 10(*)
Grid_Elem_Triang_Val1 = N/A	
Grid_Elem_Def = PX: INV_ADD/REMOVE_DEF (0.0)	Rule 11(*)
Grid_Elem_Def = STEP: VALID_INPUT (1.0)	Rule 12
Grid_Elem_Def = MissingValue: INV_ADD/REMOVE_DEF (2.0)	Rule 13
Grid_Elem_Def = ANGLE: INV_ADD/REMOVE_DEF (0.0)	Rule 14(*)
Grid_Elem_Def = PSTEP: INV_ADD/REMOVE_DEF (1.0)	Rule 15
Grid_Elem_Triang_Val1 = MissingValue: VALID_INPUT (2.0)	Rule 16
Grid_Elem_Triang_Val1 = >0: VALID_INPUT (0.0)	Rule 17(*)
Grid_Elem_Triang_Val1 = non_number: VALID_INPUT (0.0)	Rule 18(*)
Grgeo_Additional_Int_Val3 = <0: VALID_INPUT (1.0)	Rule 19
Grgeo_Additional_Int_Val3 = >0: VALID_INPUT (0.0)	Rule 20(*)
Grgeo_Additional_Int_Val3 = 0.0: VALID_INPUT (0.0)	Rule 21(*)
Grexc_Grpha_Exec = InvalidValue: INV_AMP_EXC_DEF (1.0)	Rule 22
Grexc_Grpha_Exec = MissingValue: VALID_INPUT (0.0)	Rule 23(*)
Grexc_Gramp_Exec_Def = SECOND	
Elem_Polar_Def = ORIENTATION: SEC_ORD_NOT_ALLOWED_ON_IRREG_GROUPS (1.0)	Rule 24
Elem_Polar_Def = MissingValue: INV_AMP_EXC_DEF (2.0)	Rule 25
Elem_Polar_Def = LH: INV_AMP_EXC_DEF (0.0)	Rule 26(*)
Elem_Polar_Def = RH: INV_AMP_EXC_DEF (0.0)	Rule 27(*)
Grexc_Gramp_Exec_Def = InvalidValue: VALID_INPUT (0.0)	Rule 28(*)
Grexc_Gramp_Exec_Def = MissingValue: VALID_INPUT (0.0)	Rule 29(*)
Elem_Geometry_Def = InvalidValue: INV_GEOMETRY_DEF (1.0)	Rule 30
Elem_Geometry_Def = RECTANGULAR	
Elem_Polarization_Spec = LINEAR	
Grid_Elem_Def = PX: ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM (0.0)	Rule 31(*)
Grid_Elem_Def = STEP: VALID_INPUT (1.0)	Rule 32
Grid_Elem_Def = MissingValue: ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM (3.0)	Rule 33
Grid_Elem_Def = ANGLE: ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM (0.0)	Rule 34(*)
Grid_Elem_Def = PSTEP: ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM (0.0)	Rule 35(*)
Elem_Polarization_Spec = MissingValue	
Grgeo_Add_Int_Val2 = >0: RECT_NOT_ALLOWED_ON_HEX (2.0)	Rule 36
Grgeo_Add_Int_Val2 = <0: VALID_INPUT (1.0)	Rule 37
Grgeo_Add_Int_Val2 = 0.0: VALID_INPUT (2.0)	Rule 38
Grgeo_Add_Int_Val2 = non_number: VALID_INPUT (0.0)	Rule 39(*)
Grgeo_Add_Int_Val2 = MissingValue: VALID_INPUT (0.0)	Rule 40(*)
Elem_Polarization_Spec = CIRCULAR: VALID_INPUT (0.0)	Rule 41(*)
Elem_Geometry_Def = MissingValue: VALID_INPUT (0.0)	Rule 42(*)
Grexc_Grpha_Exec_Def = MissingValue	
Elem_Port_Number = MissingValue	
Grid_Elem_Unit = MissingValue	
Grid_Elem_Angle_Unit = N/A	
Elem_Geometry_Def = CIRCULAR: INV_PHASE_EXC_DEF (3.0)	Rule 43
Elem_Geometry_Def = InvalidValue: INV_PHASE_EXC_DEF (0.0)	Rule 44(*)
Elem_Geometry_Def = RECTANGULAR: VALID_INPUT (1.0)	Rule 45
Elem_Geometry_Def = MissingValue: INV_PHASE_EXC_DEF (0.0)	Rule 46(*)
Grid_Elem_Angle_Unit = MissingValue: NULL_POINTER (1.0)	Rule 47
Grid_Elem_Angle_Unit = deg: INV_PHASE_EXC_DEF (0.0)	Rule 48(*)
Grid_Elem_Unit = N/A: INV_PHASE_EXC_DEF (0.0)	Rule 49(*)
Grid_Elem_Unit = m: INV_PHASE_EXC_DEF (0.0)	Rule 50(*)
Grid_Elem_Unit = mm: INV_GRID_DEF (1.0)	Rule 51
Grid_Elem_Unit = cm: INV_PHASE_EXC_DEF (0.0)	Rule 52(*)
Elem_Port_Number = [1-998]: SEQ_ROT_NOT_ALLOWED_ON_IRREG_GROUPS (0.0)	Rule 53(*)
Elem_Port_Number = >999: SEQ_ROT_NOT_ALLOWED_ON_IRREG_GROUPS (0.0)	Rule 54(*)
Elem_Port_Number = MissingValue	
Grexc_Gramp_Exec_Def = UNIFORM	
Grid_Elem_Val1 = N/A: SEQ_ROT_NOT_ALLOWED_ON_IRREG_GROUPS (3.0)	Rule 55
Grid_Elem_Val1 = >0: SEQ_ROT_NOT_ALLOWED_ON_IRREG_GROUPS (3.0)	Rule 56
Grid_Elem_Val1 = MissingValue: VALID_INPUT (1.0)	Rule 57
Grid_Elem_Val1 = <0: SEQ_ROT_NOT_ALLOWED_ON_IRREG_GROUPS (0.0)	Rule 58(*)
Grexc_Gramp_Exec_Def = SECOND: GRID_ANG_OUTOF_NON_AMBIG_RANGE (1.0)	Rule 59
Grexc_Gramp_Exec_Def = InvalidValue: SEQ_ROT_NOT_ALLOWED_ON_IRREG_GROUPS (0.0)	Rule 60(*)
Grexc_Gramp_Exec_Def = MissingValue: SEQ_ROT_NOT_ALLOWED_ON_IRREG_GROUPS (0.0)	Rule 61(*)
Grexc_Grpha_Exec_Def = CW: SEC_ORD_NOT_ALLOWED_ON_IRREG_GROUPS (1.0)	Rule 62
Elem_Port_set_num = 8.0	
Elem_Geometry_Def = CIRCULAR: INV_PORTS_DEF (3.0)	Rule 63

Elem_Geometry_Def = InvalidValue: INV_PORTS_DEF (0.0)	Rule 64(*)
Elem_Geometry_Def = RECTANGULAR: ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM (1.0)	Rule 65
Elem_Geometry_Def = MissingValue: INV_PORTS_DEF (0.0)	Rule 66(*)
Elem_Port_set_num = 3.0	
Elem_Geometry_Def = CIRCULAR: INV_PORTS_DEF (2.0)	Rule 67
Elem_Geometry_Def = InvalidValue: INV_PORTS_DEF (0.0)	Rule 68(*)
Elem_Geometry_Def = RECTANGULAR: INV_AMP_EXC_DEF (1.0)	Rule 69
Elem_Geometry_Def = MissingValue: INV_PORTS_DEF (0.0)	Rule 70(*)
Elem_Port_set_num = 4.0: VALID_INPUT (1.0)	Rule 71
Elem_Port_set_num = 7.0: INV_GEOMETRY_DEF (1.0)	Rule 72
Elem_Port_set_num = 6.0: INV_POLARIZATION_DEF (1.0)	Rule 73
Elem_Port_set_num = 1.0	
Grid_Elem_Triang_Vall = <0: GRID_ANG_OUTOF_NON_AMBIG_RANGE (1.0)	Rule 74
Grid_Elem_Triang_Vall = N/A: INV_GRID_DEF (0.0)	Rule 75(*)
Grid_Elem_Triang_Vall = MissingValue: INV_GRID_DEF (0.0)	Rule 76(*)
Grid_Elem_Triang_Vall = >0: INV_GRID_DEF (0.0)	Rule 77(*)
Grid_Elem_Triang_Vall = non_number: INV_GRID_DEF (1.0)	Rule 78
Elem_Port_set_num = 5.0: INV_ADD/REMOVE_DEF (1.0)	Rule 79
Elem_Port_set_num = MissingValue: FILE_ERROR (5.0)	Rule 80
Number of Leaves : 80	
Size of the tree : 103	
=== Confusion Matrix ===	
a b c d e f g h i j k l m n o	<-- classified as
22 0 0 0 0 0 0 0 0 0 0 0 0 0 0	a = VALID_INPUT
0 2 0 0 0 0 0 0 0 0 0 0 0 0 0	b = INV_GEOMETRY_DEF
0 0 3 0 0 0 0 0 0 0 0 0 0 0 0	c = INV_PHASE_EXC_DEF
0 0 0 5 0 0 0 0 0 0 0 0 0 0 0	d = INV_PORTS_DEF
0 0 0 0 4 0 0 0 0 0 0 0 0 0 0	e = INV_AMP_EXC_DEF
0 0 0 0 0 4 0 0 0 0 0 0 0 0 0	f = INV_ADD/REMOVE_DEF
0 0 0 0 0 0 1 0 0 0 0 0 0 0 0	g = NULL_POINTER
0 0 0 0 0 0 0 2 0 0 0 0 0 0 0	h = SEC_ORD_NOT_ALLOWED_ON_IRREG_GROUPS
0 0 0 0 0 0 0 0 4 0 0 0 0 0 0	i = ADD_HEX_NOT_ALLOWED_ON_RECT_GEOM
0 0 0 0 0 0 0 0 0 2 0 0 0 0 0	j = RECT_NOT_ALLOWED_ON_HEX
0 0 0 0 0 0 0 0 0 0 1 0 0 0 0	k = INV_POLARIZATION_DEF
0 0 0 0 0 0 0 0 0 0 0 5 0 0 0	l = INV_GRID_DEF
0 0 0 0 0 0 0 0 0 0 0 0 2 0 0	m = GRID_ANG_OUTOF_NON_AMBIG_RANGE
0 0 0 0 0 0 0 0 0 0 0 0 0 5 0	n = FILE_ERROR
0 0 0 0 0 0 0 0 0 0 0 0 0 0 6	o = SEQ_ROT_NOT_ALLOWED_ON_IRREG_GROUPS

Figure 38 Space Decision Tree – Second Iteration

In order to reach the final iteration where no occurrence of the problems discussed in Section 4.2 can be found in the resultant decision tree, we believe that it would require quite a large number of iterations, which appears to be unfeasible without tool support in the context of this thesis. Therefore, we stopped at that stage of the application of the Melba process.

6.5 Melba Process Automation – PackHexChar and Space

As indicated in Figure 4, activity 1 is fully automated. In our case study, we automated this activity through custom tools written in Java using Eclipse IDE. For each case study, a tool takes as input the CP specification and the raw test data; the tool then generates the abstract test cases by mapping each value in the test case to the appropriate choice(s) in the CP specification. The output file is a comma delimited (.csv) file where the last column indicates the output equivalence class, this file is referred to as the abstract test suite (ATS).

The file (ATS) generated in Activity 1 is in the format acceptable by the WEKA tool, which implements C4.5 to generate the DT (In Activity 2). For the packhexchar case study, it took less than a second for WEKA to generate a decision tree whereas it took eight seconds to generate a tree based on 13,585 abstract test cases for Space. (The execution times are reported on a PC with windows XP, AMD Athlon 4200+ processor, and a 2 GB RAM)

Activities 3, 4 and 5 are not automated at this point, as they rely on the know-how and expertise of the tester. However, we provide guidance to help identify which categories/choices need to be refined and which abstract test cases need to be defined. Test suite amendment (Activity 4) requires an effort that is anyway incurred if one is improving a test suite. Note however that this effort (e.g., building the test harness that include drivers and oracles) will only involve the newly created test cases: the tester will be able to reuse drivers and oracles for existing test cases.

6.6 Discussions

The experiments on the Space program are carried out on a much larger problem than in CHAPTER 5: much larger test suite (though it contains redundancy) and much larger CP specification. We conducted in fact two different experiments in the Space program.

In the first experiment, we used the complete test suite (with 13,585 test cases). After the first iteration of the Melba process, the decision tree suggested that there are category-choice combinations missing in the test suite, potentially indicating that some paths are not exercised by the initial (complete) test suite.

In the second experiment we reduce the complete test suite by randomly removing test cases until further test suite reduction causes statement coverage to drop: we obtain a smaller test suite, equivalent to the initial, large one in terms of statement coverage. We then justify test case addition using the CP method and the Base-Choice (Nominal-Choice) criterion. During the first iteration of MELBA we were able to identify instances of problems in the decision trees and use this information to improve the test suite. In particular, the decision tree pointed to missing combinations of choices, some of which are not even exercised by the complete test suite (with 13,585 test cases). With retrospect, this is not entirely surprising since the complete test suite mostly contains white-box test cases (e.g., to cover several times specific control and data flow elements) and therefore does not necessarily exercise specific functional aspects of the system, as specified by choice combinations.

In both experiments, due to lack of tool support for the Melba process, we limited our investigation: the problem is too large to be handled manually. We stopped early in the Melba process and were unable to show the final iteration where no problem could be identified in the generated trees.

Not all problem-cause pairs are illustrated in this case study. Better tool support will help reduce manual intervention and will enable applying our technique to applications with larger CP specifications. Tool support for Melba is the purpose of future work.

CHAPTER 7 CONSLUSIONS AND FUTURE WORK

This thesis proposed the MELBA automated iterative method, based on machine learning, to help software engineers analyze the weaknesses of test specifications and test suites so as to be able to iteratively improve them.

The MELBA method takes as inputs the test suite and specifications to be re-engineered, the latter following the Category-Partition (CP) strategy. Based on the Category-Partitions specification, test cases are transformed into abstract test cases which are tuples of pairs (category, choice) associated with an output equivalence class (instead of raw inputs/outputs). A machine learning algorithm (in our case, C4.5) is used to learn rules that relate pairs (category, choice), modeling input properties, to output equivalence classes. These rules are in turn analyzed to determine potential improvements of the test suite (e.g., redundant test cases, need for additional test cases) as well as improvements of the Category-Partition specification (e.g., need to add a category or choice).

We have illustrated the main aspects of the MELBA method on a running example (the Triangle program), and evaluated its effectiveness on test suites and Category-Partition specifications created by fully trained 4th year students on a small size but logically complex program. The study showed that the iterative process can indeed improve both the test suite and the Category-Partition specification to a level that is equivalent to what an expert would likely produce within two to three improvement cycles. An evaluation of the (improved) test suite effectiveness at finding faults (i.e.,

killing mutants) showed that the improved test suites kill more mutants than the original test suites. When removing redundant test cases though, the reduced test suite may not always detect the same faults as the improved test suite (though the drop is small), thus suggesting a trade-off between test cost and effectiveness. But as discussed in section 5.9, in our future work, we look into improving the test suite reduction heuristic by looking at different code coverage techniques (we used statement coverage as it is simple to apply, though it is known to not be sufficient—it has to be completed with edge coverage and/or some data flow coverage criterion).

We performed a second evaluation of the MELBA method on a more complex, industrial program, the Space program. The Space program originally had 13,585 test cases. In the first experiment, using 16 output equivalence classes defined in section 6.2, we generated a decision tree with 6892 rules based on the expert CP and complete TS. This appears to be too much if handled manually, as it was the case in this thesis. Tool support for Melba is warranted. In order to show the effectiveness of our technique, we then reduced the test suite to 56 test cases by randomly removing test cases while still keeping the original code coverage (i.e. statement coverage). Due to the lack of tool support, we only show one iteration of the improvement process in this second experiment. The decision tree suggests improvements to the test suite: there are missing combinations of choices that require the addition of test cases. To add the missing test cases, we selected adequate test cases (i.e., that would exercise the missing combinations) from the complete test suite. One interesting result is that some of the missing combinations of choices, as indicated by the decision tree appear to be missing in the complete test suite (i.e., none of the 13,585 test cases exercise

them). This is not entirely surprising since the complete test suite mostly contains white-box test cases (e.g., to cover several times specific control and data flow elements) and therefore does not necessarily exercise specific functional aspects of the system, as specified by choice combinations. This shows that even on this larger problem, with a very large test suite that has been built with care by other researchers, the Melba process is able to suggest improvements to the test suite.

Future work will include investigating other black-box specifications than Category-Partition, such as Boolean expressions and statecharts, additional evaluations of the iterative process on programs of varying sizes and complexities to illustrate the problem-causes pairs (Figure 7) that are not illustrated in our case studies, as well as user-friendly automated tool support. (Recall that most of the activities of the MELBA method are automated.) Other strategies to remove redundancy in a test suite will also be investigated, thereby trying to not lose in terms of effectiveness. As noticed during the case studies when adding test cases, not all mutants were killed. Since our test cases addition is based on the decision tree, therefore, not all categories and choices are considered when adding test cases. Therefore, a new approach is to be investigated where both the decision tree and the CP specification are used when adding test cases, instead of solely using the decision tree.

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Appendix A CP Specifications

A.1 Triangle Program

A.1.1 Description

The input values (a , b , c) characterize the length of triangle sides. We use Category-Partition and define properties and relationships between sides. We then perform the mapping between the test cases and Category-Partition in order to generate an abstract test suite. Based on the abstract test suite, the learning algorithm will be able to determine whether the triangle is Equilateral, Isosceles, Irregular, not a triangle, or a null triangle.

A.1.2 CP Specifications

Parameter a

Category 1—values for a

Choice C1: $a > 0$

Choice C2: $a \leq 0$

Category 2— a compared to b

Choice C3: $a = b$

Choice C4: $a \neq b$

Category 3— a compared to b and c

Choice C5: $a \leq b + c$

Choice C6: $a > b + c$

Parameter b

Category 4—values for b

Choice C7: $b > 0$

Choice C8: $b \leq 0$

Category 5— b compared to c

Choice C9: $b = c$

Choice C10: $b \neq c$

Category 6— b compared to a and c

Choice C11: $b \leq a + c$

Choice C12: $b > a + c$

Parameter c

Category 7—values for c

Choice C13: $c > 0$

Choice C14: $c \leq 0$

Category 8— c compared to a

Choice C15: $c = a$

Choice C16: $c \neq a$

Category 9— c compared to a and b

Choice C17: $c \leq a + b$
 Choice C18: $c > a + b$

A.1.3 Triangle Decision Tree

```
(a vs. b) = a=b
| (b vs. c) = b=c
| | (a) = a>0: Equilateral (54.0)
| | (a) = a<=0: null (6.0)
| (b vs. c) = b!=c
| | (c) = c>0
| | | (c vs. a+b) = c<=a+b: Isosceles (22.0)
| | | (c vs. a+b) = c>a+b: Not_Triangle (2.0)
| | (c) = c<=0: null (2.0)
(a vs. b) = a!=b
| (c vs. a+b) = c<=a+b
| | (a vs. b+c) = a<=b+c
| | | (b vs. a+c) = b<=a+c
| | | | (b vs. c) = b=c: Isosceles (22.0)
| | | | (b vs. c) = b!=c
| | | | | (c vs. a) = c=a: Isosceles (22.0)
| | | | | (c vs. a) = c!=a: Irregular (60.0)
| | | (b vs. a+c) = b>a+c: Not_Triangle (20.0)
| | (a vs. b+c) = a>b+c: Not_Triangle (20.0)
| (c vs. a+b) = c>a+b
| | (a) = a>0
| | | (b) = b>0: Not_Triangle (18.0)
| | | (b) = b<=0: null (2.0)
| | (a) = a<=0: null (2.0)
```

Number of Leaves: 13
 Size of the tree: 25

Correctly Classified Instances 252 100%
 Incorrectly Classified Instances 0 0%

=== Confusion Matrix ===

```
a b c d e <-- classified as
54 0 0 0 0 | a = Equilateral
0 66 0 0 0 | b = Isosceles
0 0 60 0 0 | c = Irregular
0 0 0 60 0 | d = Not_Triangle
0 0 0 0 12 | e = null
```

A.1.4 Test Suite for the Triangle program

(a)	(b)	(c)	(Class)
1	1	1	Equilateral
1	1	2	Isosceles
6	6	10	Isosceles
8	9	9	Isosceles
1	1.5	2	Irregular
3	5	7	Irregular
1	1	2.5	Not Triangle
0.5	1	2.5	Not Triangle
-1	1	1	null

Table 4 Test Cases for the Triangle Program

(a)	(b)	(c)	(a vs. b)	(b vs. c)	(c vs. a)	(a vs. b+c)	(b vs. a+c)	(c vs. a+b)	Class
a>0	b>0	c>0	a=b	b=c	c=a	a<=b+c	b<=a+c	c<=a+b	Equilateral
a>0	b>0	c>0	a=b	b!=c	c!=a	a<=b+c	b<=a+c	c<=a+b	Isosceles
a>0	b>0	c>0	a=b	b!=c	c!=a	a<=b+c	b<=a+c	c<=a+b	Isosceles
a>0	b>0	c>0	a!=b	b=c	c!=a	a<=b+c	b<=a+c	c<=a+b	Isosceles
a>0	b>0	c>0	a!=b	b!=c	c!=a	a<=b+c	b<=a+c	c<=a+b	Irregular
a>0	b>0	c>0	a!=b	b!=c	c!=a	a<=b+c	b<=a+c	c<=a+b	Irregular
a>0	b>0	c>0	a=b	b!=c	c!=a	a<=b+c	b<=a+c	c>a+b	Not Triangle
a>0	b>0	c>0	a!=b	b!=c	c!=a	a<=b+c	b<=a+c	c>a+b	Not Triangle
a<=0	b>0	c>0	a!=b	b=c	c!=a	a<=b+c	b>a+c	c>a+b	null

Table 5 Abstract Test Cases using the Test Cases of Table 4 and CP specification of Section A.1.2

A.2 PackHexChar: CP Specifications

Parameter RLEN

CATEGORY 1—Valid values for rlen

C1:	rlen = 0	[Property rlen0]
C2:	rlen = [1...sLength]	[Property rlen1ToS]

CATEGORY 2—Invalid values for rlen

C3:	rlen < 0	[Error] [Single] [Property rlenLT0]
C4:	rlen > sLength	[Error] [Single]

Parameter ODD_DIGIT

CATEGORY 3—Valid values for odd_digit

C5:	odd_digit = -1
C6:	odd_digit = [0...9]
C7:	odd_digit = [A...F]
C8:	odd_digit = [a...f]

CATEGORY 4—Invalid values for odd_digit

C9:	odd_digit < -1	[Error] [Single]
C10:	odd_digit > 15	[Error] [Single]

Parameter String S

CATEGORY 5—Length of S

C11:	sLength = 0	[Property S0]
C12:	sLength > 0	[Property SGT0]

CATEGORY 6—Type of characters in the first rlen characters of S

C13:	AllHexadecimal	[Property allHD] [if SGT0 AND not rlen0 AND not rlenLT0]
C14:	AllNonHexadecimal	[Property allNHD] [if SGT0 AND not rlen0 AND not rlenLT0]
C15:	MixedChars	[Property Mixed] [if SGT0 AND not rlen0 AND not rlenLT0]

CATEGORY 7- Case of chars in the first rlen chars of the string S

C16:	allNumbers	[if not allNHD AND not rlen0 AND not rlenLT0]
C17:	allLowerCase	[if not allNHD AND not rlen0 AND not rlenLT0]
C18:	allUpperCase	[if not allNHD AND not rlen0 AND not rlenLT0]
C19:	MixedCase	[if not allNHD AND not rlen0 AND not rlenLT0]

CATEGORY 8- The first rlen characters of the string contains boundary Value [0, 9, a, f, A, F]

C20:	Contains [0]	[Single] [if MixedCase]
C21:	Contains [9]	[Single] [if MixedCase]
C22:	Contains [a]	[Single] [if MixedCase]
C23:	Contains [f]	[Single] [if MixedCase]
C24:	Contains [A]	[Single] [if MixedCase]
C25:	Contains [F]	[Single] [if MixedCase]
C26:	ContainsMixed	[Single] [if MixedCase]
C27:	ContainsNone	

CATEGORY 9—Number of hexadecimal characters in the first rlen characters of S

C28:	Odd	[if not rlenLT0]
C29:	Even	[if not rlenLT0]

C30: Zero

CATEGORY 10—Position of the first non-hexadecimal character in the first rlen characters of S

C31:	First	[Single] [if SGT0 AND Mixed]
C32:	Middle	[Single] [if SGT0 AND Mixed]
C33:	Last	[Single] [if SGT0 AND Mixed]

CATEGORY 11—Consecutive non-hexadecimal characters in the first rlen characters of S

C34:	Yes	[if SGT0 AND not allHD]
C35:	No	[if SGT0 AND not rlen0 AND not rlenLT0]

A.2.1 Note on PackHexChar CP Specifications:

Given the selectors on the choices, some combinations may not be feasible; in some cases a whole category will be skipped. For instance when `rlen < 0` then the following categories 6, 7, 8, and 9 are skipped, instead a value of N/A is placed in the ATS. Or for instance, if the string S contains all hexadecimal characters then category 8 does not apply since there are no non-hexadecimal characters and therefore a N/A is placed in the ATS to indicate that a category was skipped because of the selectors on the choices.

A.2.2 Mapping between Abstract Test Suite and CP

Categories in the CP	Choices in the CP	Output Equivalence Class
Category 1: Contains choices for all the valid values of RLEN	C1: RLEN = 0 C2: RLEN is between 1 and the length of S	RLEN
Category 2: Contains all invalid values of RLEN	C3: RLEN < 0 C4: RLEN is greater than the length of String	
Category 3: Contains choices for all valid values for ODD_DIGIT	C5: Odd_digit = -1 C6: Odd_digit is between 0 and 9 C7: Odd_digit is between a and f C8: Odd_digit is between A and F	ODD_DIGIT
Category 4: Contains choices for all invalid values for ODD_DIGIT	C9: Odd_digit is less than 0 C10: Odd_digit is greater than 15	
Category 5: Contains choices for the length of the String	C11: String is empty C12: String is not empty	S LENGTH
Category 6: Contains choices for the type of the first rlen character in the string S (Applies only when C2 or C4 holds)	C13: All rlen characters are hexadecimal C14: All rlen characters are non hexadecimal C15: rlen characters are a mix of hexadecimal and non hexadecimal characters	S CHAR TYPE IN [0...RLEN]
CATEGORY 7: Case of chars in the first rlen chars of the string S	C16: First rlen characters of the string S are all numbers C17: First rlen characters of the string S are all lower case letters C18: First rlen characters of the string S are all upper case letters C19: First rlen characters of the string S is a mix of numbers, lower case letters and upper case letters (combination of either C16 and C17 or C16 and C18 or C17 and C18 or C16, C17 and C18)	CHAR CASE IN [0...RLEN]
CATEGORY 8- The first rlen characters of the string contains boundary Value [0, 9, a, f, A, F]	C20: The first rlen chars of the string S contain 0 but no other boundary value. C21: The first rlen chars of the string S contain 9 but no other boundary value. C22: The first rlen chars of the string S contain "a" but no other boundary value. C23: The first rlen chars of the string S contain f but no other boundary value. C24: The first rlen chars of the string S contain A, but no other boundary value. C25: The first rlen chars of the	BOUNDARY VALUE IN [0...RLEN]

	<p>string S contain F but no other boundary value.</p> <p>C26: The first rlen chars of the string S contain a mix of (either all or some) of the boundary values</p> <p>C27: The first rlen chars of the string S contain no boundary value</p>	
<p>Category 9: Contains choices for whether the number of hexadecimal characters in the first rlen characters of the String S is Odd, Even or Zero. This category holds if rlen not 0.</p>	<p>C28: Number of hexadecimal characters in the first rlen characters of the String S is Odd</p> <p>C29: Number of hexadecimal characters in the first rlen characters of the String S is Even</p> <p>C30: Number of hexadecimal characters in the first rlen characters of the String S is Zero</p>	<p>NUM HEX CHARS IN [0...RLEN]</p>
<p>Category 10: Contains value for the position of the first non-hexadecimal character in the first rlen characters of S. This category only applies if C12 and C15 hold.</p>	<p>C31: The position of the first non hexadecimal character is in the first position of the first rlen characters of the string S.</p> <p>C32: The position of the first non hexadecimal character is in the middle of the first rlen characters of the string S.</p> <p>C33: The position of the first non hexadecimal character is in the last position of the first rlen characters of the String S.</p>	<p>NON HEX CHAR POSTION IN [0...RLEN]</p>
<p>Category 11: This category contains choices for whether there are consecutive non-hexadecimal characters in the first rlen characters of S. Applies if C3 does not hold.</p>	<p>C34: There are consecutive non hexadecimal characters in the first rlen characters of the string S.</p> <p>C35: There are no consecutive non hexadecimal characters in the first rlen characters of the string S.</p>	<p>CONSECUTIVE NON HEX CHARS IN [0...RLEN]</p>

A.3 Student A: CP Specification

Parameter RLEN

Category 1: In Range

- Choice 1: {0} [if not OutOfRange]
- Choice 2: Length of S – 1 [if not OutOfRange]

Category 2: Out of Range

- Choice 3: Negative [Property OutOfRangeNeg] [Error]
- Choice 4: Length of S [Property OutOfRangePos] [Error]

Parameter ODD_DIGIT

Category 3: No Odd Digit

- Choice 5: {-1} [Property OddDigit] [Single]
- Choice 6: [0-15] [if not OutOfRange] [if not OddDigit]

Category 4: Out of Range

- Choice 7: {-2} [Error]
- Choice 8: {16} [Property OutOfRange] [Error]

Parameter S

Category 5: Length

- Choice 9: Odd
- Choice 10: Even
- Choice 11: Empty

Category 6: Valid or Invalid Characters

- Choice 12: Valid
- Choice 13: Invalid (By Invalid the student means Mixe of valid and invalid)

//This category is added to fix student A's CP

Category 7: Number of valid hex characters from 0 to rlen

- Choice 14: Odd
- Choice 15: Even
- Choice 16: Zero

A.4 Student B: CP Specifications

Parameter: rlen

Category 1: Legal

Choice 1: 0 [Property noCharToPack, isLegal] [single]
Choice 2: <S [Property isLegal]

Category 2: Not Legal

Choice 3: <0 [Property not isLegal] [error]
Choice 4: >S [error] [Property not isLegal] [error]

Parameter: odd_digit

Category 3: Legal

Choice 5: -1 [Property digitIsLegal]
Choice 6: [0-15] [Property digitIsLegal]

Category 4: Not Legal

Choice 7: < -1 [Property not digitIsLegal] [error]
Choice 8: > 15 [Property not digitIsLegal] [error]

Parameter: string

Category 5: Case of characters

Choice 9: uppercase [if not noCharInString] [single]
Choice 10: uppercase & lowercase [if not noCharInString]
Choice 11: lowercase [if not noCharInString]

Category 6: Type of characters

Choice 12: valid [if not noCharInString]
Choice 13: valid & invalid [if not noCharInString]
Choice 14: invalid [if not noCharInString] [single]

Category 7: length of string

Choice 15: zero [Property noCharInString]
Choice 16: < rlen [error] [if not noCharToPack]
Choice 17: = rlen
Choice 18: > rlen

Category 8: # characters in string

Choice 19: even
Choice 20: odd

//This category is added to fix student A's CP

Category 9: Number of valid hex characters from 0 to rlen

Choice 21: Odd
Choice 22: Even
Choice 23: Zero

A.5 Student C: CP Specifications

Parameter: rlen

Category 1: number of characters to read

- Choice 1: {0} [property readNone]
- Choice 2: -1 - s.length [property readSome]
- Choice 3: anything else [property readTooMany][error]

Parameter: odd_digit

Category 2: Extra digit to parse

- Choice 4: {-1}
- Choice 5: -0 - 15]
- Choice 6: anything else [error]

Parameter: s

Category 3: length of string

- Choice 7: {0} [if readNone and if not readSome and if not readTooMany]
- Choice 8: anything else [if not readTooMany]

Category 4: number of invalid characters

- Choice 9: none [if not readNone and if not readTooMany]
- Choice 10: several [if not readNone and if not readTooMany]
- Choice 11: maximum [if not readNone and if not readTooMany][single]

//This category is added to fix student A's CP

Category 5: Number of valid hex characters from 0 to rlen

- Choice 12: Odd
- Choice 13: Even
- Choice 14: Zero

Appendix B Mapping of Categories/Choices of Expert CP and Student CPs

The tuple (cat_i, ch_i) represents a choice ch_i of category cat_i . The three table below represents Categories and choices in the CP_{sub} s. Student A, and B's CP_{sub} s can be compared to the Expert CP_{sub} in the same way as student C's CP_{sub} was compared to the expert CP_{sub} in section 5.4.1.

Expert CP	Relation	Student A CP
(Cat1, Ch1)	=	(Cat1, Ch1)
(Cat1, Ch2)	=	(Cat1, Ch2)
(Cat2, Ch3)	=	(Cat2, Ch3)
(Cat2, Ch4)	=	(Cat2, Ch4)
(Cat3, Ch5)	=	(Cat3, Ch5)
(Cat3, Ch6)	$\subset$	(Cat3, Ch6)
(Cat3, Ch7)	$\subset$	(Cat3, Ch6)
(Cat3, Ch8)	$\subset$	(Cat3, Ch6)
(Cat4, Ch9)	=	(Cat4, Ch7)
(Cat4, Ch10)	=	(Cat4, Ch8)
(Cat9, Ch28)	=	(Cat7, Ch14)
(Cat9, Ch29)	=	(Cat7, Ch15)
(Cat9, Ch30)	=	(Cat7, Ch16)

Expert CP	Relation	Student B CP
(Cat1, Ch1)	=	(Cat1, Ch1)
(Cat1, Ch2)	=	(Cat1, Ch2)
(Cat2, Ch3)	=	(Cat2, Ch3)
(Cat2, Ch4)	=	(Cat2, Ch4)
(Cat3, Ch5)	=	(Cat3, Ch5)
(Cat3, Ch6)	$\subset$	(Cat3, Ch6)
(Cat3, Ch7)	$\subset$	(Cat3, Ch6)
(Cat3, Ch8)	$\subset$	(Cat3, Ch6)
(Cat4, Ch9)	=	(Cat4, Ch7)
(Cat4, Ch10)	=	(Cat4, Ch8)
(Cat9, Ch28)	=	(Cat9, Ch14)
(Cat9, Ch29)	=	(Cat9, Ch15)
(Cat9, Ch30)	=	(Cat9, Ch16)

Expert CP	Relation	Student C CP
(Cat1, Ch1)	=	(Cat1, Ch1)
(Cat1, Ch2)	=	(Cat1, Ch2)
(Cat2, Ch3)	$\subset$	(Cat1, Ch3)
(Cat2, Ch4)	$\subset$	(Cat1, Ch3)
(Cat3, Ch5)	=	(Cat2, Ch4)
(Cat3, Ch6)	$\subset$	(Cat2, Ch5)
(Cat3, Ch7)	$\subset$	(Cat2, Ch5)
(Cat3, Ch8)	$\subset$	(Cat2, Ch5)
(Cat4, Ch9)	$\subset$	(Cat2, Ch6)
(Cat4, Ch10)	$\subset$	(Cat2, Ch6)
(Cat9, Ch28)	=	(Cat5, Ch12)
(Cat9, Ch29)	=	(Cat5, Ch13)
(Cat9, Ch30)	=	(Cat5, Ch14)

Appendix C PackHexChar: Decision Trees before TS

Reduction

C.1 Expert CP and Expert TS

```
RLEN = rlen=0
| ODD_DIGIT = odd_digit=-1: -1.0 (2.0)
| ODD_DIGIT = odd_digit=[0...9]: odd_digit (2.0)
| ODD_DIGIT = odd_digit=[A...F]: odd_digit (2.0)
| ODD_DIGIT = odd_digit=[a...f]: odd_digit (2.0)
| ODD_DIGIT = odd_digit<-1: odd_digit (0.0)
| ODD_DIGIT = odd_digit>15: odd_digit (0.0)
RLEN = rlen=[1...sLength]
| NUM HEX CHARS IN [0...RLEN] = Zero
| | ODD_DIGIT = odd_digit=-1: -1.0 (1.0)
| | ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit<-1: odd_digit (0.0)
| | ODD_DIGIT = odd_digit>15: odd_digit (0.0)
| NUM HEX CHARS IN [0...RLEN] = Odd
| | ODD_DIGIT = odd_digit=-1: S[rlen-1] (28.0)
| | ODD_DIGIT = odd_digit=[0...9]: -1.0 (27.0)
| | ODD_DIGIT = odd_digit=[A...F]: -1.0 (27.0)
| | ODD_DIGIT = odd_digit=[a...f]: -1.0 (23.0)
| | ODD_DIGIT = odd_digit<-1: -1.0 (0.0)
| | ODD_DIGIT = odd_digit>15: -1.0 (0.0)
| NUM HEX CHARS IN [0...RLEN] = Even
| | ODD_DIGIT = odd_digit=-1: -1.0 (27.0)
| | ODD_DIGIT = odd_digit=[0...9]: S[rlen-1] (27.0)
| | ODD_DIGIT = odd_digit=[A...F]: S[rlen-1] (27.0)
| | ODD_DIGIT = odd_digit=[a...f]: S[rlen-1] (19.0)
| | ODD_DIGIT = odd_digit<-1: -3.0 (1.0)
| | ODD_DIGIT = odd_digit>15: -3.0 (1.0)
RLEN = rlen<0: -2.0 (1.0)
RLEN = rlen>sLength: -2.0 (1.0)
```

C.2 Expert CP and Student X TS (Iteration 3)

```
RLEN = rlen>sLength: -2.0 (8.0)
RLEN = rlen=[1...sLength]
| NUM HEX CHARS IN [0...RLEN] = Even
| | ODD_DIGIT = odd_digit=-1: -1.0 (3.0)
| | ODD_DIGIT = odd_digit>15: S[rlen-1] (0.0)
| | ODD_DIGIT = odd_digit=[0...9]: S[rlen-1] (2.0)
| | ODD_DIGIT = odd_digit<-1: S[rlen-1] (0.0)
| | ODD_DIGIT = odd_digit=[a...f]: S[rlen-1] (2.0)
| | ODD_DIGIT = odd_digit=[A...F]: S[rlen-1] (1.0)
| NUM HEX CHARS IN [0...RLEN] = Odd
| | ODD_DIGIT = odd_digit=-1: S[rlen-1] (3.0)
| | ODD_DIGIT = odd_digit>15: -3.0 (1.0)
| | ODD_DIGIT = odd_digit=[0...9]: -1.0 (4.0)
| | ODD_DIGIT = odd_digit<-1: -3.0 (1.0)
| | ODD_DIGIT = odd_digit=[a...f]: -1.0 (3.0)
| | ODD_DIGIT = odd_digit=[A...F]: -1.0 (3.0)
| NUM HEX CHARS IN [0...RLEN] = Zero
| | ODD_DIGIT = odd_digit=-1: -1.0 (1.0)
| | ODD_DIGIT = odd_digit>15: odd_digit (0.0)
| | ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit<-1: odd_digit (0.0)
| | ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)
RLEN = rlen=0
| ODD_DIGIT = odd_digit=-1: -1.0 (1.0)
| ODD_DIGIT = odd_digit>15: odd_digit (0.0)
| ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)
| ODD_DIGIT = odd_digit<-1: odd_digit (0.0)
| ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)
| ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)
RLEN = rlen<0: -2.0 (1.0)
```

C.3 Expert CP and Student Y TS (Iteration 3)

```
RLEN = rlen=[1...sLength]
| NUM HEX CHARS IN [0...RLEN] = Even
| | ODD_DIGIT = odd_digit=-1: -1.0 (3.0)
| | ODD_DIGIT = odd_digit>15: -3.0 (1.0)
| | ODD_DIGIT = odd_digit=[0...9]: S[rLEN-1] (1.0)
| | ODD_DIGIT = odd_digit=[a...f]: S[rLEN-1] (1.0)
| | ODD_DIGIT = odd_digit=[A...F]: S[rLEN-1] (1.0)
| | ODD_DIGIT = odd_digit<-1: -3.0 (1.0)
| NUM HEX CHARS IN [0...RLEN] = Odd
| | ODD_DIGIT = odd_digit=-1: S[rLEN-1] (7.0)
| | ODD_DIGIT = odd_digit>15: S[rLEN-1] (0.0)
| | ODD_DIGIT = odd_digit=[0...9]: -1.0 (3.0)
| | ODD_DIGIT = odd_digit=[a...f]: -1.0 (1.0)
| | ODD_DIGIT = odd_digit=[A...F]: -1.0 (1.0)
| | ODD_DIGIT = odd_digit<-1: S[rLEN-1] (0.0)
| NUM HEX CHARS IN [0...RLEN] = Zero
| | ODD_DIGIT = odd_digit=-1: -1.0 (1.0)
| | ODD_DIGIT = odd_digit>15: odd_digit (0.0)
| | ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit<-1: odd_digit (0.0)
RLEN = rlen=0
| ODD_DIGIT = odd_digit=-1: -1.0 (4.0)
| ODD_DIGIT = odd_digit>15: -1.0 (0.0)
| ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)
| ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)
| ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)
| ODD_DIGIT = odd_digit<-1: -1.0 (0.0)
RLEN = rlen>sLength: -2.0 (1.0)
RLEN = rlen<0: -2.0 (1.0)
```

C.4 Expert CP and Student Z TS (Iteration 3)

```
RLEN = rlen=0
| ODD_DIGIT = odd_digit=-1: -1.0 (1.0)
| ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)
| ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)
| ODD_DIGIT = odd_digit<-1: odd_digit (0.0)
| ODD_DIGIT = odd_digit>15: odd_digit (0.0)
| ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)
RLEN = rlen=[1...sLength]
| NUM_HEX_CHARS IN [0...RLEN] = Zero
| | ODD_DIGIT = odd_digit=-1: -1.0 (1.0)
| | ODD_DIGIT = odd_digit=[0...9]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit=[a...f]: odd_digit (1.0)
| | ODD_DIGIT = odd_digit<-1: -3.0 (1.0)
| | ODD_DIGIT = odd_digit>15: odd_digit (0.0)
| | ODD_DIGIT = odd_digit=[A...F]: odd_digit (1.0)
| NUM_HEX_CHARS IN [0...RLEN] = Even
| | ODD_DIGIT = odd_digit=-1: -1.0 (4.0)
| | ODD_DIGIT = odd_digit=[0...9]: S[rlen-1] (8.0)
| | ODD_DIGIT = odd_digit=[a...f]: S[rlen-1] (7.0)
| | ODD_DIGIT = odd_digit<-1: -3.0 (1.0)
| | ODD_DIGIT = odd_digit>15: -3.0 (1.0)
| | ODD_DIGIT = odd_digit=[A...F]: S[rlen-1] (6.0)
| NUM_HEX_CHARS IN [0...RLEN] = Odd
| | ODD_DIGIT = odd_digit=-1: S[rlen-1] (4.0)
| | ODD_DIGIT = odd_digit=[0...9]: -1.0 (1.0)
| | ODD_DIGIT = odd_digit=[a...f]: -1.0 (2.0)
| | ODD_DIGIT = odd_digit<-1: -1.0 (0.0)
| | ODD_DIGIT = odd_digit>15: -1.0 (0.0)
| | ODD_DIGIT = odd_digit=[A...F]: -1.0 (2.0)
RLEN = rlen<0: -2.0 (1.0)
RLEN = rlen>sLength: -2.0 (2.0)
```

C.5 Student A CP and TS (Iteration 3)

```
ODD_DIGIT = odd_digit=-1
| #RLENCHARS = Even
| | RLEN = rlen=[1...sLength]: -1.0 (3.0)
| | RLEN = rlen=0: -1.0 (0.0)
| | RLEN = rlen>sLength: -2.0 (1.0)
| | RLEN = rlen<0: -1.0 (0.0)
| #RLENCHARS = Odd: S[rlen-1] (7.0)
| #RLENCHARS = Zero
| | RLEN = rlen=[1...sLength]: -1.0 (1.0)
| | RLEN = rlen=0: -1.0 (4.0)
| | RLEN = rlen>sLength: -1.0 (0.0)
| | RLEN = rlen<0: -2.0 (1.0)
ODD_DIGIT = odd_digit>=16: -3.0 (1.0)
ODD_DIGIT = odd_digit=[0...15]
| #RLENCHARS = Even: S[rlen-1] (1.0)
| #RLENCHARS = Odd: -1.0 (2.0)
| #RLENCHARS = Zero: odd_digit (4.0)
ODD_DIGIT = odd_digit<=-2: -3.0 (1.0)
```


C.6 Student B CP and TS (Iteration 3)

```
ODD_DIGIT = odd_digit=-1
| #RLENCHARS = Zero: -1.0 (8.0)
| #RLENCHARS = Odd: S[rlen-1] (9.0)
| #RLENCHARS = Even
| | RLEN = rlen=0: -1.0 (0.0)
| | RLEN = 0<rlen<=sLength: -1.0 (7.0)
| | RLEN = rlen>sLength: -2.0 (1.0)
| | RLEN = rlen<0: -1.0 (0.0)
ODD_DIGIT = odd_digit=[0-15]
| #RLENCHARS = Zero
| | RLEN = rlen=0: odd_digit (3.0)
| | RLEN = 0<rlen<=sLength: odd_digit (2.0)
| | RLEN = rlen>sLength: odd_digit (0.0)
| | RLEN = rlen<0: -2.0 (1.0)
| #RLENCHARS = Odd: -1.0 (3.0)
| #RLENCHARS = Even: S[rlen-1] (2.0)
ODD_DIGIT = odd_digit>15: -3.0 (2.0)
ODD_DIGIT = odd_digit<-1: -3.0 (1.0)
```

C.7 Student C CP and TS (Iteration 3)

```
ODD_DIGIT = odd_digit=-1
| #RLENCHARS = Zero: -1.0 (5.0)
| #RLENCHARS = Odd
| | RLEN = rlen=0: S[rlen-1] (0.0)
| | RLEN = rlen=[1...sLength]: S[rlen-1] (3.0)
| | RLEN = rlen>sLength: -2.0 (1.0)
| | RLEN = rlen<0: S[rlen-1] (0.0)
| #RLENCHARS = Even: -1.0 (1.0)
ODD_DIGIT = odd_digit=[0...15]
| #RLENCHARS = Zero
| | RLEN = rlen=0: odd_digit (2.0)
| | RLEN = rlen=[1...sLength]: odd_digit (3.0)
| | RLEN = rlen>sLength: odd_digit (0.0)
| | RLEN = rlen<0: -2.0 (1.0)
| #RLENCHARS = Odd
| | RLEN = rlen=0: -1.0 (0.0)
| | RLEN = rlen=[1...sLength]: -1.0 (3.0)
| | RLEN = rlen>sLength: -2.0 (1.0)
| | RLEN = rlen<0: -1.0 (0.0)
| #RLENCHARS = Even: S[rlen-1] (1.0)
ODD_DIGIT = odd_digit=INVALID: -3.0 (2.0)
```

Appendix D Mutation Results—PackHexChar Program

Student ID	Test Suite ID	Mutant ID (Not killed)
X	Iteration 3	ROR11, ROR18, ROR21, ROR28
	Iteration 4	AOIU3, AORB14, ROR11, ROR18, ROR21, ROR28
Y	Iteration 3	AOIS102, ROR8 ROR18, ROR28
	Iteration 4	AOIS102, ROR8, ROR14, ROR18, ROR28
Z	Iteration 3	AOIS102
	Iteration 4	AOIS102
A	Iteration 3	AOIS102, ROR1, ROR8, ROR18, ROR28
	Iteration 4	AOIS102, ROR1, ROR5, ROR8, ROR13, ROR14, ROR18, ROR28, ROR36
B	Iteration 3	AOIS102, AOIS37, AOIS39, AOIS40, AOIS41, AOIS42, AOIS43, AOIS44, AOIU3, AORB13, AORB14, AORB16, AORB17, AORB18, AORB19, AORB20, LOI12, ROR8, ROR18, ROR21, ROR24, ROR28, ROR29, ROR36
	Iteration 4	OIS102, AOIS31, AOIS37, AOIS39, AOIS40, AOIS41, AOIS42, AOIS43, AOIS44, AOIU3, AORB13, AORB14, AORB16, AORB17, AORB18, AORB19, AORB20, LOI12, ROR18, ROR8, ROR21, ROR24, ROR28, ROR29, ROR31, ROR36
C	Iteration 3	AOIS37, AOIS38, AOIS39, AOIS40, AOIS41, AOIS42, AOIS43, AOIS44, AOIU3, AORB13, AORB14, AORB16, AORB17, AORB18, AORB19, AORB20, COI9, LOI11, LOI12, ROR8, ROR18, ROR21, ROR24, ROR26, ROR27, ROR28, ROR29, ROR3, ROR30, ROR36, ROR4
	Iteration 4	AOIS37, AOIS38, AOIS39, AOIS40, AOIS41, AOIS42, AOIS43, AOIS44, AOIU3, AORB13, AORB14, AORB16, AORB17, AORB18, AORB19, AORB20, COI9, LOI11, LOI12, ROR8, ROR18, ROR21, ROR24, ROR26, ROR27, ROR28, ROR29, ROR3, ROR30, ROR36, ROR4
Our CP+TS	Iteration 1	N/A
	Iteration 2	AOIS102, ROR1, ROR11, ROR18, ROR21, ROR28, ROR31, ROR8

Table 6 Mutants not killed in the last two iterations for all students

Mutant Name	Mutation Operator	How to Kill?
AOIU3	+ → - (sign change)	The first rlen characters of the string S must contain one or more hex char between [a...f] but not at the 0 th index. e.g. "0a1"
AORB14	- → /	The first rlen characters of the string S must contain a hex char between [a...f] other than b. e.g. "a31"

Table 7 Mutants not killed by reduced student X TS

Mutant Name	Mutation Operator	How to Kill?
ROR14	$\geq \rightarrow ==$	The first rlen characters of the string S must contain one or more hex chars between [B...F].
ROR18	$\leq \rightarrow <$	The first rlen characters of the string S must contain F.

Table 8 Mutants not killed by reduced student Y TS

Mutant Name	Mutation Operator	How to Kill?
AOIS102	Post decrement(--)	The number of hex chars in the first rlen characters of the string is more than one where the last character is 0.

Table 9 Mutants not killed by reduced student Z TS

Mutant Name	Mutation Operator	How to Kill?
ROR5	$\geq \rightarrow !=$	The first rlen characters of the string S must contain one or more characters whose value is less than 48 (0)
ROR13	$\geq \rightarrow \leq$	The first rlen characters of the string S must contain one or more characters whose value is less than 65 (A) and is not between [0...9]
ROR14	$\geq \rightarrow ==$	The first rlen characters of the string S must contain one or more hex chars between [B...F]
ROR36	$> \rightarrow \leq$	Odd digit must have a value 15.

Table 10 Mutants not killed by reduced student A TS

Mutant Name	Mutation Operator	How to Kill?
AOIS37	Pre-Increment (++)	The first rlen characters of the string S contains one or more characters in [a...f], and if the last letter in the first rlen characters of the Sring S is between [a...f] then the following letter should not be the same one.
AOIS39	Post-Incremen(++)	The first rlen characters of the string S contains one or more characters in [a...f], and if the last letter in the first rlen characters of the Sring S is between [a...f] then the following letter should not be the same one.
AOIS40	Post-Decremen(--)	The first rlen characters of the string S contains one or more characters in [a...f]
AOIS41	Pre-Increment (++)	The first rlen characters of the string S contains one or more characters in [a...f], and if the last letter in the first rlen characters of the Sring S is between [a...f] then the following letter should not be the same one.
AOIS42	Pre-Decrement(--)	The first rlen characters of the string S contains one or more characters in [a...f]
AOIS43	Post-Increment(++)	The first rlen characters of the string S contains one or more characters in [a...f], and if the last letter in the first rlen characters of the Sring S is between [a...f] then the following letter should not be the same one.
AOIS44		
AOIS102	Post decrement(--)	The number of hex chars in the first rlen characters of the string is more than one where the last character is 0.
AOIU3	+ → -	The first rlen characters of the string S contains one or more characters in [a...f] anywhere except at index 0
AORB13	- → *	The first rlen characters of the string S contains one or more characters in [a...f]
AORB14	- → /	The first rlen characters of the string S contains the char a.
AORB16	- → +	The first rlen characters of the string S contains one or more characters in [a...f]
AORB17	+ → *	The first rlen characters of the string S contains one or more characters in [a...f]
AORB18	+ → /	The first rlen characters of the string S contains one or more characters in [a...f]
AORB19	+ → %	The first rlen characters of the string S contains one or more characters in [a...f]
AORB20	+ → -	The first rlen characters of the string S contains one or more characters in [a...f]
ROR8	<= → <	The first rlen characters of the string S must contain 9.
ROR18	<= → <	The first rlen characters of the string S must contain F.
ROR21	>= → >	The first rlen characters of the string S must contain a.
ROR24	>= → ==	The first rlen characters of the string S contains one or more characters in [b...f]
ROR28	<= → <	The first rlen characters of the string S must contain F.
ROR29	<= → ==	The first rlen characters of the string S contains one or more characters in [a...e]
ROR36		

Table 11 Mutants not killed by reduced student B TS

Mutant Name	Mutation Operator	How to Kill?
AOIS37	Pre-Increment (++)	The first rlen characters of the string S contains one or more characters in [a...f], and if the last letter in the first rlen characters of the Sring S is between [a...f] then the following letter should not be the same one.
AOIS38	Pre-Decrement (--)	The first rlen characters of the string S contains one or more characters in [a...f]
AOIS39	Post-Incremen(++)	The first rlen characters of the string S contains one or more characters in [a...f], and if the last letter in the first rlen characters of the Sring S is between [a...f] then the following letter should not be the same one.
AOIS40	Post-Decremen(--)	The first rlen characters of the string S contains one or more characters in [a...f]
AOIS41	Pre-Increment (++)	The first rlen characters of the string S contains one or more characters in [a...f], and if the last letter in the first rlen characters of the Sring S is between [a...f] then the following letter should not be the same one.
AOIS42	Pre-Decrement(--)	The first rlen characters of the string S contains one or more characters in [a...f]
AOIS43	Post-Increment(++)	The first rlen characters of the string S contains one or more characters in [a...f], and if the last letter in the first rlen characters of the Sring S is between [a...f] then the following letter should not be the same one.
AOIU3	+ → -	The first rlen characters of the string S contains one or more characters in [a...f] anywhere except at index 0
AORB13	- → *	The first rlen characters of the string S contains one or more characters in [a...f]
AORB14	- → /	The first rlen characters of the string S contains the char a.
AORB16	- → +	The first rlen characters of the string S contains one or more characters in [a...f]
AORB17	+ → *	The first rlen characters of the string S contains one or more characters in [a...f]
AORB18	+ → /	The first rlen characters of the string S contains one or more characters in [a...f]
AORB19	+ → %	The first rlen characters of the string S contains one or more characters in [a...f]
AORB20	+ → -	The first rlen characters of the string S contains one or more characters in [a...f]
COI9	! (Condtion Negated)	The first rlen characters of the string S contains one or more characters in [a...f]
LOI11	~	The first rlen characters of the string S contains one or more characters in [a...f]
LOI12	~	The first rlen characters of the string S contains one or more characters in [a...f]

ROR3	$\geq \rightarrow \leq$	The first rlen characters of the string S contains one or more characters in [1...9]
ROR4	$\geq \rightarrow ==$	The first rlen characters of the string S contains one or more characters in [1...9]
ROR8	$\leq \rightarrow <$	The first rlen characters of the string S must contain 9.
ROR18	$\leq \rightarrow <$	The first rlen characters of the string S must contain F.
ROR21	$\geq \rightarrow >$	The first rlen characters of the string S must contain a.
ROR24	$\geq \rightarrow ==$	The first rlen characters of the string S contains one or more characters in [b...f]
ROR26	$\leq \rightarrow >$	The first rlen characters of the string S contains one or more characters in [a...f]
ROR27	$\leq \rightarrow \geq$	The first rlen characters of the string S contains one or more characters in [a...e]
ROR28	$\leq \rightarrow <$	The first rlen characters of the string S must contain F.
ROR29	$\leq \rightarrow ==$	The first rlen characters of the string S contains one or more characters in [a...e]
ROR30	$\leq \rightarrow !=$	The first rlen characters of the string S must contain F.

Table 12 Mutants not killed by reduced student C TS

Mutant Name	Mutation Operator	How to Kill?
AOIS102	-- (decrement)	The number of hex chars in the first rlen characters of the string is more than one and the last character is 0
ROR1	$\geq \rightarrow >$	The first rlen characters of the string S must contain 0.
ROR8	$\leq \rightarrow <$	The first rlen characters of the string S must contain 9.
ROR11	$\geq \rightarrow >$	The first rlen characters of the string S must contain A.
ROR18	$\leq \rightarrow <$	The first rlen characters of the string S must contain F.
ROR21	$\geq \rightarrow >$	The first rlen characters of the string S must contain a.
ROR28	$\leq \rightarrow <$	The first rlen characters of the string S must contain F.
ROR31	$> \rightarrow \geq$	The first rlen characters of the string S must contain f.
AOIS31	Increment (++)	The first rlen characters of the string S must contain two or more consecutive hex chars with any but the last between [A...F]

Table 13 Mutants not killed by reduced Expert TS

Appendix E The Space Program

E.1 CP Definition for the Space Program

PA00	Input Parameter			
	CA0001	Valid Input		
B		CH000101	ValidFile	[property valid File]
		CH000102	EmptyFile	[ERROR]
	CA0002	Invalid File		
		CH000201	Nonexist_File	[ERROR]
		CH000202	Wrong_Parameter_N um	[ERROR]
PA01	Group Name			
	CA0101	Length of name		
		CH010101	length=0	[property no name]
B		CH010102	length[1..29]	[property gname]
		CH010103	length>=30	[property too long gname]
	CA0102	Context of name		
B		CH020101	start with Alpha	[if gname]
		CH020102	start with Number	[if gname]
		CH020103	start_with_Other_ Char	[if gname]
		CH020104	in Keyword_list	[if gname]
		CH020105	missingValue	[if no name]
PA02	GRID Def			
	CA0201	definition in { SQUARE, RECTANGULAR, HEXAGONAL, TRIANGULAR}		
		CH020101	SQUARE	[property G Square]
B		CH020102	RECTANGULAR	[property G Rectangular]
		CH020103	HEXAGONAL	[property G Hexagonal]
		CH020104	TRIANGULAR	[property G Triangular]
	CA0202	other nominal value		
		CH020201	INVALID VALUE	[ERROR]
B		CH020202	missingValue	[property G Missing]
PA03	Grid Elem Def			
	CA0301	definition in { STEP, PSTEP, ANGLE, PX}		
		CH030101	STEP	[if G_Square or G_Hexagonal, property step]
B		CH030102	PSTEP	[if G_Rectangular or G_Triangular, property pstep]
		CH030103	ANGLE	[if G_Triangular, property angle]
		CH030104	PX	[if G_Triangular, property lateral]
	CA0301	Other value		
		CH030201	INVALID VALUE	[ERROR]
B		CH030202	missingValue	[if G Missing]
PA04	Grid Elem Vall			
	CA0401	valid value		
		CH040101	=0	[if step or pstep or angle]
B		CH040102	>0	[if step or pstep or angle]
		CH040103	missingValue	[if G Missing or lateral]
	CA0402	invalid value		
		CH040201	<0	[ERROR][if step or pstep or angle]
		CH040202	non-number	[ERROR][if step or pstep or angle]

B		CH040203	ErrorMissing	[ERROR][if step or pstep or angle]
PA05	Grid Elem Val2			
	CA0501	valid value		
		CH050101	=0	[if pstep or angle]
B		CH050102	>0	[if pstep or angle]
		CH050103	missingValue	[if step or lateral]
	CA0502	invalid value		
B		CH050201	<0	[ERROR][if pstep or angle]
		CH050202	non-number	[ERROR][if pstep or angle]
		CH050203	ErrorMissing	[ERROR][if G Square or lateral]
PA06	Grid Elem Triang Val1			
	CA0601	number		
		CH060101	=0	[if angle or literal]
		CH060102	>0	[if angle or literal]
		CH060103	<0	[if angle or literal]
B		CH060104	missingValue	[if not (angle or literal)]
	CA0602	non number		
		CH060201	non-number	[ERROR][if angle or literal]
B		CH060202	ErrorMissing	[ERROR][if angle or literal]
PA07	Grid Elem Triang Val2			
	CA0701	number		
		CH070101	=0	[if literal]
B		CH070102	>0	[if literal]
		CH070103	<0	[if literal]
		CH070104	missingValue	[if not literal]
	CA0702	non number		
		CH070201	non-number	[ERROR][if literal]
B		CH070202	ErrorMissing	[ERROR][if literal]
PA08	Grid Elem Triang Val3			
	CA0801	number		
		CH080101	=0	[if literal]
B		CH080102	>0	[if literal]
		CH080103	<0	[if literal]
		CH080104	missingValue	[if not literal]
	CA0802	non number		
B		CH080201	non-number	[ERROR][if literal]
		CH080202	ErrorMissing	[ERROR][if literal]
PA09	Grid Elem Triang Val3			
	CA0901	number		
		CH090101	=0	[if literal]
B		CH090102	>0	[if literal]
		CH090103	<0	[if literal]
		CH090104	missingValue	[if not literal]
	CA0902	non number		
		CH090201	non-number	[ERROR][if literal]
B		CH090202	ErrorMissing	[ERROR][if literal]
PA10	Grid Elem Unit			
	CA1001	Definition in { dm, cm, mm, m }		
		CH100101	dm	[if step or pstep]
B		CH100102	cm	[if step or pstep]
		CH100103	mm	[if step or pstep]
		CH100104	m	[if step or pstep]
	CA1002	Other value		
		CH100201	INVALID VALUE	[if step or pstep]

B		CH100202	MissingValue	
PA11	Grid Elem Angle Unit			
	CA1101	Definition in {deg, rad}		
		CH110101	deg	[if angle]
B		CH110102	rad	[if angle]
	CA1102	Other value		
		CH110201	INVALID VALUE	[if angle]
B		CH110202	missingValue	
PA12	Element Name			
	CA1201	Definition in {GEOMETRY}		
B		CH120101	GEOMETRY	[property geometry]
	CA1202	length of string		
		CH120201	length=0	[if not geometry, property missing Name]
B		CH120202	length[1..29]	[if not geometry, property E Name]
		CH120203	length>=30	[if not geometry, property long Name]
	CA1203	context of name		
B		CH120301	start with Alpha	[if E Name]
		CH120302	start with Number	[if E Name]
		CH120303	start_with_Other_Char	[if E Name]
		CH120304	in Keyword list	[if E Name]
PA13	Elem Geometry Def			
	CA1301	Definition in {CIRCULAR, RECTANGULAR }		
B		CH130101	CIRCULAR	[if geometry, property E Circular]
		CH130102	RECTANGULAR	[if geometry, property E Rectangular]
	CA1302	Other value		
B		CH130201	INVALID VALUE	[if geometry, property wrong E Def]
		CH130202	missingValue	[if missing Name]
PA14	Elem Geometry Val1			
	CA1401	unsigned real number		
		CH140101	=0	[if E Circular or E Rectangular]
B		CH140102	>0	[if E Circular or E Rectangular]
	CA1402	wrong value		
B		CH140201	<0	[ERROR][if E_Circular or E Rectangular]
		CH140202	non-number	[ERROR][if E_Circular or E Rectangular]
		CH140203	missingValue	[if wrong E Def or not geometry]
PA15	Elem Geometry Val2			
	CA1501	unsigned real number		
		CH150101	=0	[if E Rectangular]
B		CH150102	> 0	[if E Rectangular]
	CA1502	wrong value		
		CH150201	<0	[ERROR][if E Rectangular]
		CH150202	non-number	[ERROR][if E Rectangular]
B		CH150203	ErrorMissing	[ERROR][if E Rectangular]
		CH150204	missingValue	[if not E Rectangular]
PA16	Elem Geometry Unit			
	CA1601	Definition in {dm,cm,mm,m}		
		CH160101	dm	[if E Circular or E Rectangular]
		CH160102	cm	[if E Circular or E Rectangular]

B		CH160103	mm	[if E Circular or E Rectangular]
		CH160104	m	[if E Circular or E Rectangular]
	CA1602	Other value		
		CH160201	INVALID_VALUE	[ERROR][if E Circular or E Rectangular]
B		CH160202	missingValue	
PA17	Elem Polarization Spec			
	CA1701	Definition in { LINEAR, CIRCULAR}		
B		CH170101	LINEAR	[if geometry, property E P linear]
		CH170102	CIRCULAR	[if geometry, property E P circular]
	CA1702	Other value		
		CH170201	INVALID_VALUE	[ERROR]
B		CH170202	missingValue	
PA18	Elem Polar Def			
	CA1801	Definition in {ORIENTATION, LH, RH }		
B		CH180101	ORIENTATION	[if E_P_linear, property E P orientation]
		CH180102	LH	[if E P circular]
		CH180103	RH	[if E P circular]
	CA1802	Other value		
B		CH180201	INVALID_VALUE	[ERROR][if E_P_linear or E P circular]
		CH180202	missingValue	
PA19	Elem Polar LinePol Val			
	CA1901	Definition in {X, Y}		
B		CH190101	X	[if E P orientation]
		CH190102	Y	[if E P orientation]
	CA1902	real number		
		CH190201	=0	[if E P orientation]
B		CH190202	>0	[if E P orientation]
		CH190203	<0	[if E P linear]
	CA1903	Other value		
		CH190301	INVALID_VALUE	[ERROR][if E P orientation]
		CH190302	errorMissing	[ERROR][if E P orientation]
B		CH190302	missingValue	
PA20	Elem Polar LinePol Unit			
	CA2001	Definition in {deg, rad}		
B		CH200101	deg	[if E P orientation]
		CH200102	rad	[if E P orientation]
	CA2002	null value		
B		CH200201	INVALID_VALUE	[ERROR][if E P orientation]
		CH200202	missingValue	
PA21	Elem Port Number			
	CA2101	Natural number		
		CH210101	=0	[if geometry, property no Port]
B		CH210102	[1, 998]	[if geometry, property medium Size Port]
		CH210103	=999	[if geometry, property large Size Port]
	CA2102	other number		
		CH210201	>999	[ERROR][if geometry]
B		CH210202	<0	[ERROR][if geometry]

		CH210203	real number	[ERROR][if geometry]
	CA2103	other value		
		CH210301	INVALID VALUE	[ERROR][if geometry]
B		CH210302	missingValue	
PA22	Elem Port Set ENum			
	CA2201	number of the element		
		CH220101	=0	[if no_Port, property missingPortDef]
		CH220102	=1	[if medium_Size_Port, property onePortDef]
B		CH220103	>1	[if medium_Size_Port or large Size_Port]
PA23	Elem Port Orient Val			
	CA2301	content of the set		
		CH230101	X	[if not missingPortDef]
		CH230102	Y	[if not missingPortDef]
B		CH230103	>0	[if not missingPortDef]
		CH230104	=0	[if not missingPortDef]
		CH230105	<0	[if not missingPortDef]
		CH230106	combination	[if not (missingPortDef or onePortDef)]
		CH230107	ContainInvalid	[if not (missingPortDef or onePortDef)]
		CH230108	allInvalid	[if not missingPortDef]
		CH230109	missingValue	
PA24	Elem Port Orient UNIT			
	CA2401	content of the set		
		CH240101	deg	[if not missingPortDef]
		CH240102	rad	[if not missingPortDef]
B		CH240103	combination	[if not (missingPortDef or onePortDef)]
		CH240104	mixedValue	[if not (missingPortDef or onePortDef)]
		CH240105	allInvalid	[if not missingPortDef]
		CH240106	missingValue	
PA25	Elem Port Amp Val			
	CA2501	content of the set		
		CH250101	>0	[if not missingPortDef]
		CH250102	=0	[if not missingPortDef]
		CH250103	<0	[if not missingPortDef]
B		CH250104	combination	[if not (missingPortDef or onePortDef)]
		CH250105	ContainInvalid	[if not (missingPortDef or onePortDef)]
		CH250106	allInvalid	[if not missingPortDef]
		CH250107	missingValue	
PA26	Elem Port Amp Unit			
	CA2601	content of the set		
		CH260101	dm	[if not missingPortDef]
		CH260102	mm	[if not missingPortDef]
		CH260103	cm	[if not missingPortDef]
		CH260104	m	[if not missingPortDef]
		CH260105	dB	[if not missingPortDef]
		CH260106	POWER	[if not missingPortDef]
B		CH260107	LINEAR	[if not missingPortDef]

		CH260108	combination	[if not (missingPortDef or onePortDef)]
		CH260109	ContainInvalid	[if not (missingPortDef or onePortDef)]
		CH260110	allInvalid	[if not missingPortDef]
		CH260111	missingValue	
PA27	Elem Port Shdef Val			
	CA2701	content of the set		
		CH270101	>0	[if not missingPortDef]
		CH270102	=0	[if not missingPortDef]
		CH270103	<0	[if not missingPortDef]
B		CH270104	combination	[if not (missingPortDef or onePortDef)]
		CH270105	ContainInvalid	[if not (missingPortDef or onePortDef)]
		CH270106	allInvalid	[if not missingPortDef]
		CH270107	MissingValue	
PA28	Elem Port Shdef Unit			
	CA2801	content of the set		
		CH280101	deg	[if not missingPortDef]
B		CH280102	rad	[if not missingPortDef]
		CH280103	combination	[if not (missingPortDef or onePortDef)]
		CH280104	ContainInvalid	[if not (missingPortDef or onePortDef)]
		CH280105	allInvalid	[if not missingPortDef]
		CH280106	missingValue	
PA29	Elem Port Scdef Val			
	CA2901	content of the set		
		CH290101	>0	[if not missingPortDef]
		CH290102	=0	[if not missingPortDef]
		CH290103	<0	[if not missingPortDef]
B		CH290104	combination	[if not (missingPortDef or onePortDef)]
		CH290105	ContainInvalid	[if not (missingPortDef or onePortDef)]
		CH290106	allInvalid	[if not missingPortDef]
		CH290107	missingValue	
PA30	Elem Port Scdef Unit			
	CA3001	content of the set		
		CH300101	deg	[if not missingPortDef]
B		CH300102	rad	[if not missingPortDef]
		CH300103	combination	[if not (missingPortDef or onePortDef)]
		CH300104	ContainInvalid	[if not (missingPortDef or onePortDef)]
		CH300105	allInvalid	[if not missingPortDef]
PA31	Elem Port Padef Val			
	CA3101	content of the set		
		CH310101	>0	[if not missingPortDef]
		CH310102	=0	[if not missingPortDef]
		CH310103	<0	[if not missingPortDef]
		CH310104	combination	[if not (missingPortDef or onePortDef)]
		CH310105	ContainInvalid	[if not (missingPortDef or

				onePortDef))]
		CH310106	allInvalid	[if not missingPortDef]
		CH310107	missingValue	
PA32	Elem Port PadeF Unit			
	CA3201	content of the set		
		CH320101	deg	[if not missingPortDef]
B		CH320102	rad	[if not missingPortDef]
		CH320103	combination	[if not (missingPortDef or onePortDef)]
		CH320104	ContainInvalid	[if not (missingPortDef or onePortDef)]
		CH320105	allInvalid	[if not missingPortDef]
PA33	Grgeo Add Def			
	CA3301	Definition in {HEXAGON, BLOCK, NODE, POLYGON}		
B		CH330101	NODE	[property node]
		CH330102	HEXAGON	[property hexagon]
		CH330103	BLOCK	[property block]
		CH330104	POLYGON	[property polygon]
	CA3302	Other value		
		CH330201	INVALID VALUE	[ERROR]
		CH330202	errorMissing	[ERROR]
PA34	Grgeo Add Int Vall			
	CA3401	integer		
		CH340101	<0	[if node or hexagon or block or polygon]
		CH340102	=0	[if node or hexagon or block or polygon]
B		CH340103	>0	[if node or hexagon or block or polygon]
	CA3402	Other value		
		CH340201	real number	[ERROR][if node or hexagon or block or polygon]
		CH340202	non-number	[ERROR][if node or hexagon or block or polygon]
B		CH340203	errorMissing	[ERROR][if node or hexagon or block or polygon]
PA35	Grgeo Add Int Val2			
	CA3501	integer		
		CH350101	<0	[if node or hexagon or block or polygon]
		CH350102	=0	[if node or hexagon or block or polygon]
B		CH350103	>0	[if node or hexagon or block or polygon]
	CA3502	Other value		
B		CH350201	real number	[ERROR][if node or hexagon or block or polygon]
		CH350202	non-number	[ERROR][if node or hexagon or block or polygon]
		CH350203	errorMissing	[ERROR][if node or hexagon or block or polygon]
PA36	Grgeo Add Int Val3			
	CA3601	integer		
		CH360101	<0	[if block or polygon]
		CH360102	=0	[if block or polygon]

B		CH360103	>0	[if block or polygon]
	CA3602	Other value		
		CH360201	real number	[ERROR][if block or polygon]
		CH360202	non-number	[ERROR][if block or polygon]
		CH360203	errorMissing	[ERROR][if block or polygon]
B		CH360204	missingValue	[if not(block or polygon)]
PA37	Grgeo Add Int Val4			
	CA3701	integer		
		CH370101	<0	[if block or polygon]
		CH370102	=0	[if block or polygon]
B		CH370103	>0	[if block or polygon]
	CA3702	Other value		
		CH370201	real number	[ERROR][if block or polygon]
		CH370202	non-number	[ERROR][if block or polygon]
B		CH370203	errorMissing	[ERROR][if block or polygon]
		CH370204	missingValue	[if not(block or polygon)]
PA38	Grgeo Add Int Val5			
	CA3801	integer		
		CH380101	<0	[if polygon]
		CH380102	=0	[if polygon]
B		CH380103	>0	[if polygon]
	CA3802	Other value		
		CH380201	real number	[ERROR][if polygon]
		CH380202	non-number	[ERROR][if polygon]
		CH380203	errorMissing	[ERROR][if polygon]
B		CH380204	missingValue	[if not(polygon)]
PA39	Grgeo Add Int Val6			
	CA3901	integer		
		CH390101	<0	[if polygon]
		CH390102	=0	[if polygon]
B		CH390103	>0	[if polygon]
	CA3802	Other value		
		CH390201	real number	[ERROR][if polygon]
B		CH390202	non-number	[ERROR][if polygon]
		CH390203	errorMissing	[ERROR][if polygon]
		CH390204	missingValue	[if not(polygon)]
PA40	Grgeo Add Real Val1			
	CA4001	real number		
		CH400101	<0	[if node]
		CH400102	=0	[if node]
B		CH400103	>0	[if node]
	CA4002	Other value		
		CH400201	non-number	[ERROR][if node]
B		CH400202	missingValue	
PA41	Grgeo Add Real Val2			
	CA4101	real number		
		CH410101	<0	[if node]
		CH410102	=0	[if node]
B		CH410103	>0	[if node]
	CA4102	Other value		
		CH410201	non-number	[ERROR][if node]
B		CH410202	missingValue	
PA42	Grgeo Add Real Val3			

	CA4201	real number		
		CH420101	<0	[if node]
		CH420102	=0	[if node]
B		CH420103	>0	[if node]
	CA4202	Other value		
B		CH420201	non-number	[ERROR][if node]
		CH420202	missingValue	
PA43	Grgeo Add Unit			
	CA4301	Definition in {deg, rad}		
B		CH430101	deg	[if node]
		CH430102	rad	[if node]
	CA4302	other value		
		CH430201	INVALID VALUE	[ERROR][if node]
B		CH430202	missingValue	
PA44	Grgeo Additional def			
	CA4401	number of set element		
		CH440101	=0	[property missingAddSet]
B		CH440102	=1	[property singleAddSet]
		CH440103	>1	[property moreAddElem]
	CA4402	content of the set		
B		CH440201	NODE	[if singleAddSet]
		CH440202	BLOCK	[if singleAddSet]
		CH440203	HEXAGON	[if singleAddSet]
		CH440204	combination	[if moreAddElem]
		CH440205	missingValue	[if missingAddSet]
PA45	Grgeo Additional Int Val1			
	CA4501	content of the set		
B		CH450101	>0	[if not missingAddSet]
		CH450102	<0	[if not missingAddSet]
		CH450103	=0	[if not missingAddSet]
		CH450104	combination	[if not missingAddSet]
		CH450105	InvalidValue	[if not missingAddSet]
		CH450106	missingValue	
PA46	Grgeo Additional Int Val2			
	CA4601	content of the set		
B		CH460101	>0	[if not missingAddSet]
		CH460102	<0	[if not missingAddSet]
		CH460103	=0	[if not missingAddSet]
		CH460104	combination	[if not missingAddSet]
		CH460105	InvalidValue	[if not missingAddSet]
		CH460106	missingValue	
PA47	Grgeo Additional Int Val3			
	CA4701	content of the set		
B		CH470101	>0	[if not missingAddSet]
		CH470102	<0	[if not missingAddSet]
		CH470103	=0	[if not missingAddSet]
		CH470104	combination	[if not missingAddSet]
		CH470105	InvalidValue	[if not missingAddSet]
		CH470106	missingValue	
PA48	Grgeo Additional Int Val4			
	CA4801	content of the set		
B		CH480101	>0	[if not missingAddSet]
		CH480102	<0	[if not missingAddSet]

		CH480103	=0	[if not missingAddSet]
		CH480104	combination	[if not missingAddSet]
		CH480105	InvalidValue	[if not missingAddSet]
		CH480106	missingValue	
PA49	Grgeo Additional Int Val5			
	CA4901	content of the set		
B		CH490101	>0	[if not missingAddSet]
		CH490102	<0	[if not missingAddSet]
		CH490103	=0	[if not missingAddSet]
		CH490104	combination	[if not missingAddSet]
		CH490105	InvalidValue	[if not missingAddSet]
		CH490106	missingValue	
PA50	Grgeo Additional Int Val6			
	CA5001	content of the set		
B		CH500101	>0	[if not missingAddSet]
		CH500102	<0	[if not missingAddSet]
		CH500103	=0	[if not missingAddSet]
		CH500104	combination	[if not missingAddSet]
		CH500105	InvalidValue	[if not missingAddSet]
		CH500106	missingValue	
PA51	Grgeo Additional Real Val1			
	CA5101	content of the set		
B		CH510101	>0	[if not missingAddSet]
		CH510102	<0	[if not missingAddSet]
		CH510103	=0	[if not missingAddSet]
		CH510104	combination	[if not missingAddSet]
		CH510105	InvalidValue	[if not missingAddSet]
		CH510106	missingValue	
PA52	Grgeo Additional Real Val2			
	CA5201	content of the set		
B		CH520101	>0	[if not missingAddSet]
		CH520102	<0	[if not missingAddSet]
		CH520103	=0	[if not missingAddSet]
		CH520104	combination	[if not missingAddSet]
		CH520105	InvalidValue	[if not missingAddSet]
		CH520106	missingValue	
PA53	Grgeo Additional Real Val3			
	CA5301	content of the set		
B		CH530101	>0	[if not missingAddSet]
		CH530102	<0	[if not missingAddSet]
		CH530103	=0	[if not missingAddSet]
		CH530104	combination	[if not missingAddSet]
		CH530105	InvalidValue	[if not missingAddSet]
		CH530106	missingValue	
PA54	Grgeo Additional Unit			
	CA5401	content of the set		
B		CH540101	deg	[if not missingAddSet]
		CH540102	rad	[if not missingAddSet]
		CH540103	combination	[if not missingAddSet]
		CH540104	InvalidValue	[if not missingAddSet]
		CH540105	missingValue	
PA55	Group Grexc Def			
	CA5501	Definition in {GROUP_EXCITATION}		
		CH550101	GROUP_EXCITATION	[property G Excitation]

	CA5502	other value		
B		CH550201	INVALID VALUE	[ERROR]
		CH550202	errorMissing	[ERROR]
PA56	Grexc Gramp Exec			
	CA5601	Definition in { AMPLITUDE }		
B		CH560101	AMPLITUDE	[property G Amplitude]
	CA5602	other value		
		CH560201	INVALID VALUE	[ERROR]
B		CH560202	errorMissing	[ERROR]
PA57	Grexc Gramp Exec Def			
	CA5701	Definition in { UNIFORM, SECOND }		
B		CH570101	UNIFORM	[if G_Amplitude, property gramp uniform]
		CH570102	SECOND	[if G_Amplitude, property gramp second]
	CA5702	other value		
		CH570201	INVALID VALUE	[ERROR][if G Amplitude]
B		CH570202	errorMissing	[ERROR][if G Amplitude]
PA58	Grexc Gramp Exec Val1			
	CA5801	real number		
		CH580101	=0	[if gramp uniform or gramp second]
B		CH580102	>0	[if gramp uniform or gramp second]
		CH580103	<0	[if gramp uniform or gramp second]
	CA5802	Other value		
		CH580201	non-number	[ERROR][if gramp_uniform or gramp second]
		CH580202	errorMissing	[ERROR][if gramp second]
B		CH580203	missingValue	[if gramp uniform]
PA59	Grexc Gramp Exec Def2			
	CA5901	Definition in { P1 VAL }		
B		CH590101	P1 VAL	[if gramp second]
	CA5902	Other value		
		CH590201	INVALID VALUE	[ERROR][if gramp second]
B		CH590202	errorMissing	[ERROR][if gramp second]
		CH590203	missingValue	
PA60	Grexc Gramp Exec Val2			
	CA6001	real number		
		CH600101	=0	[if gramp second]
B		CH600102	>0	[if gramp second]
		CH600103	<0	[if gramp second]
	CA6002	Other value		
		CH600201	non-number	[ERROR][if gramp second]
B		CH600202	errorMissing	[ERROR][if gramp second]
		CH600203	missingValue	
PA61	Grexc Gramp Exec Def3			
	CA6101	Definition in { P2 VAL }		
B		CH610101	P2 VAL	[if gramp second]
	CA6102	Other value		
		CH610201	INVALID VALUE	[ERROR][if gramp second]
B		CH610202	errorMissing	[ERROR][if gramp second]
		CH610203	missingValue	
PA62	Grexc Gramp Exec Val3			
	CA6201	real number		

		CH620101	=0	[if gramp second]
B		CH620102	>0	[if gramp second]
		CH620103	<0	[if gramp second]
	CA6202	Other value		
		CH620201	non-number	[ERROR][if gramp second]
		CH620202	errorMissing	[ERROR][if gramp second]
B		CH620203	missingValue	
PA63	Grexc Gramp Exec Def4			
	CA6301	Definition in { Q1 VAL }		
B		CH630101	Q1 VAL	[if gramp second]
	CA6302	Other value		
		CH630201	INVALID VALUE	[ERROR][if gramp second]
		CH630202	errorMissing	[ERROR][if gramp second]
B		CH630203	missingValue	
PA64	Grexc Gramp Exec Val4			
	CA6401	real number		
		CH640101	=0	[if gramp second]
B		CH640102	>0	[if gramp second]
		CH640103	<0	[if gramp second]
	CA6402	Other value		
		CH640201	non-number	[ERROR][if gramp second]
		CH640202	errorMissing	[ERROR][if gramp second]
B		CH640203	missingValue	
PA65	Grexc Gramp Exec Def5			
	CA6501	Definition in { Q2 VAL }		
		CH650101	Q2 VAL	[if gramp second]
	CA6502	Other value		
		CH650201	INVALID VALUE	[if gramp second]
B		CH650202	missingValue	
PA66	Grexc Gramp Exec Val5			
	CA6601	real number		
		CH660101	=0	[if gramp second]
B		CH660102	>0	[if gramp second]
		CH660103	<0	[if gramp second]
	CA6602	Other value		
		CH660201	non-number	[ERROR][if gramp second]
		CH660202	errorMissing	[ERROR][if gramp second]
B		CH660203	missingValue	
PA67	Grexc Gramp Exec Unit			
	CA6701	Definition in { m,mm,dm,cm LINEAR, POWER, dB }		
B		CH670101	LINEAR	[if gramp uniform]
		CH670102	POWER	[if gramp uniform]
		CH670103	dB	[if gramp uniform]
		CH670104	mm	[if gramp second]
		CH670105	dm	[if gramp second]
		CH670106	cm	[if gramp second]
		CH670107	m	[if gramp second]
	CA6702	Other value		
		CH670201	INVALID_VALUE	[ERROR][if gramp_uniform or gramp second]
B		CH670202	missingValue	
PA68	Grexc Grpha Exec			
	CA6801	Definition in { PHASE }		

B		CH680101	PHASE	[property phase]
	CA6802	other value		
B		CH680201	INVALID VALUE	[ERROR]
PA69	Grexc Grpha Def			
	CA6901	Definition in { UNIFORM, SECOND, ROTATION, POINTING }		
B		CH690101	UNIFORM	[property grpha uniform]
		CH690102	SECOND	[property grpha second]
		CH690103	ROTATION	[property grpha rotation]
		CH690104	POINTING	[property grpha pointing]
	CA6902	other value		
		CH690201	INVALID VALUE	
B		CH690202	errorMissing	
PA70	Grexc Grpha Exec Def			
	CA7001	Definition in { CW, CCW, U, THETA }		
B		CH700101	CW	[if grpha rotation]
		CH700102	CCW	[if grpha rotation]
		CH700103	U	[if grpha_pointing, property pointing axis]
		CH700104	THETA	[if grpha_pointing, property pointing angle]
	CA7002	other value		
		CH700201	INVALID VALUE	[ERROR]
B		CH700202	missingValue	
PA71	Grexc Grpha Exec Val1			
	CA7101	values in[-1.1]		
		CH710101	=0	[if not grpha uniform]
		CH710102	=-1	[if pointing axis]
		CH710103	=1	[if pointing axis]
		CH710104	(-1, 0)	[if pointing axis]
B		CH710105	(0, 1)	[if pointing axis]
	CA7102	real number		
B		CH710201	>0	[if not (grpha uniform or pointing axis)]
		CH710202	<0	[if not (grpha uniform or pointing axis)]
	CA7103	other value		
		CH710301	<-1	[ERROR][if pointing axis]
B		CH710302	>1	[ERROR][if pointing axis]
		CH710303	non-number	[ERROR][if not grpha uniform]
		CH710304	missingValue	
PA72	Grexc Grpha Exec Def1			
	CA7201	Definition in {P1 VAL, STEP, V, PHI }		
B		CH720101	P1 VAL	[if grpha second]
		CH720102	STEP	[if grpha rotation]
		CH720103	V	[if pointing axis]
		CH720104	PHI	[if pointing angle]
	CA7202	other value		
		CH720201	INVALID VALUE	[ERROR]
B		CH720202	missingValue	
PA73	Grexc Grpha Exec Val2			
	CA7301	values in[-1.1]		
		CH730101	=0	[if not (grpha uniform or pointing angle)]
		CH730102	=-1	[if pointing axis]

		CH730103	=1	[if pointing axis]
B		CH730104	(-1, 0)	[if pointing axis]
		CH730105	(0, 1)	[if pointing axis]
	CA7302	real number		
B		CH730201	>0	[if not (grpha_uniform or grpha_pointing)]
		CH730202	<0	[if not (grpha_uniform or grpha_pointing)]
	CA7303	other value		
		CH730301	<-1	[ERROR][if pointing axis]
B		CH730302	>1	[ERROR][if pointing axis]
		CH730303	non-number	[ERROR][if not (grpha_uniform or pointing_angle)]
		CH730304	missingValue	
PA74	Grexc Grpha Exec Unit1			
	CA7401	Definition in {deg, rad}		
B		CH740101	deg	[if grpha rotation]
		CH740102	rad	[if grpha rotation]
	CA7402	other value		
		CH740201	INVALID VALUE	[ERROR]
B		CH740202	missingValue	
PA75	Grexc Grpha Exec Def2			
	CA7501	Definition in {P2 VAL, START}		
		CH750101	P2 VAL	[if grpha second]
B		CH750102	START	[if grpha rotation]
	CA7502	other value		
		CH750201	INVALID VALUE	[ERROR]
B		CH750202	missingValue	
PA76	Grexc Grpha Exec Val3			
	CA7601	real number		
		CH760101	=0	[if not (grpha_uniform or grpha_pointing)]
B		CH760102	>0	[if not (grpha_uniform or grpha_pointing)]
		CH760103	<0	[if not (grpha_uniform or grpha_pointing)]
	CA7602	other value		
		CH760201	non-number	[ERROR][if not (grpha_uniform or grpha_pointing)]
B		CH760202	missingValue	
PA77	Grexc Grpha Exec Def3			
	CA7701	Definition in {Q1 VAL, STEP }		
		CH770101	Q1 VAL	[if grpha second]
B		CH770102	STEP	[if grpha rotation]
	CA7702	other nominal value		
		CH770201	INVALID VALUE	[ERROR]
B		CH770202	missingValue	
PA78	Grexc Grpha Exec Val4			
	CA7801	real number		
		CH780101	=0	[if not (grpha_uniform or grpha rotation or grpha_pointing)]
B		CH780102	>0	[if not (grpha_uniform or grpha rotation or grpha_pointing)]
		CH780103	<0	[if not (grpha_uniform or grpha rotation or grpha_pointing)]

	CA7802	other value		
		CH780201	non-number	[ERROR][if not (grpha_uniform or grpha rotation or grpha pointing)]
B		CH780202	missingValue	
PA79	Grexc Grpha Exec Def4			
	CA7901	Definition in { Q2_VAL }		
B		CH790101	Q2_VAL	[if grpha_second]
	CA7902	other value		
		CH790201	INVALID VALUE	[ERROR]
		CH790202	ErrorMissing	[ERROR]
B		CH790202	missingValue	
PA80	Grexc Grpha Exec Val5			
	CA8001	real number		
		CH800101	=0	[if not pointing axis]
B		CH800102	>0	[if not pointing axis]
		CH800103	<0	[if not pointing axis]
	CA8002	other value		
		CH800201	non-number	[ERROR][if not pointing axis]
B		CH800202	missingValue	
PA81	Grexc Grpha Exec Unit2			
	CA8101	Definition in { deg, rad }		
		CH810101	deg	[if not pointing axis]
B		CH810102	rad	[if not pointing axis]
	CA8102	other value		
		CH810201	INVALID VALUE	[ERROR]
B		CH810202	missingValue	
PA82	Recursive Def			
	CA8201	Definition in {NONE, TRIANG, POLAR, POL ORIENT, PHASE}		
		CH820101	NONE	
		CH820102	TRIANG	
		CH820103	POLAR	
B		CH820104	POL ORIENT	
		CH820105	PHASE	
	CA8202	other value		
		CH820201	INVALID VALUE	[ERROR]
B		CH820202	missingValue	
PA83	Test Case Syntax			
	CA8301	Is the input syntactically and symantically correct		
		CH830101	Yes	
		CH830102	No	
PA84	Test Result			
	CA8401	Test result of the case		
		CH840101	INV INPUT	
		CH830102	VAL INPUT	
		CH840103	FILE ERROR	
		CH840104	NULL POINTER	