TestStudio:

An environment for automatic test generation based on Design by Contract^{TM}

Diploma Thesis

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ABSTRACT

The importance of testing in the software development process is recognized as a matter of fact nowadays. However, practice shows that, in spite of on-going research in the field, testing methodologies and tools have not yet managed to provide software developers with adequate support for testing activities.

In this project, we suggest a different approach to testing: the testing process is fully automatic. Our methodology is based on Design by Contract™. Contracts are a valuable source of information regarding the intended semantics of the software. By checking that the software respects its contracts, we can ascertain its validity. Therefore, contracts provide the basis for automation of the testing process.

The goal of this project was to develop an environment for automatic generation of tests, which we call TestStudio. It has a friendly user interface and allows the user to generate, compile and run tests on the push of a button. It also allows fine tuning of the testing process.

We used this tool to test several Eiffel libraries and found bugs in them. We consider this to be clear proof of the effectiveness of the approach.

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1. INTRODUCTION

The most important quality factor of software applications is correctness, defined as “the ability of software products to perform their exact tasks, as defined by their specification” [Meyer97]. This is the first requirement that customers have and there should be no trade-off where it is concerned: software developers should never sacrifice correctness in favor of other quality factors, of meeting deadlines or of other constraints.

However, ensuring correctness is an extremely difficult task. We can group the methods for checking the correctness of software into the following categories: validation, verification, and testing. Validation means checking that the system does what it is supposed to do, while verification checks that the system does it correctly. The purpose of testing is to find faults in programs. After having identified faults (widely known as “bugs”), you must remove the errors that caused them from the program code.

In spite of its importance, testing is not performed thoroughly and exhaustively. Data from a survey [TestingSurvey] of 240 North American and European software companies conducted in 1996 shows that 8% of companies release beta versions of applications without any testing. 83% of developers don’t like testing code. 53% find testing their own code tedious. 30% don’t like testing because they find the tool support inadequate.

To address the problems outlined by this survey, we have developed an environment for automatic generation of tests based on the ideas of Design by Contract™. The information that contracts (preconditions, postconditions, class invariants, loop variants and invariants, and check instructions) provide can be used to check whether the software fulfills its intended purpose. Based on this observation, we have created an environment which we call *TestStudio* and which generates tests automatically, runs these tests using a wide range of values and offers all the benefits of an intuitive user interface.

Note: For simplicity reasons, this report uses words such as “he” and “his” to refer to unspecified persons, instead of using longer constructs such as “he or she” and “his or her”, with no connotation of gender.

2. MAIN RESULTS

The purpose of this project was to develop an environment for automatic test generation. To do so, we have extended an already existing tool, called *Test Wizard*, which implements the basic functionality for the automatic generation of tests based on contracts.

The main contributions of the current project are:

- Providing a Graphical User Interface to the Test Wizard, which allows the user to:
    - create test configurations as projects, save them and reload them again later;
    - set a wide range of test criteria and options;
    - generate and compile the test code (according to the test configuration) on a button-click;
    - run the generated test on a button-click;
    - display the test results;
- Providing a command-line facility to complement the GUI version;
- Extending and refining the test generation mechanism of the Test Wizard.

Using TestStudio we tested some Eiffel libraries, and found previously unknown bugs. We describe some of these bugs in section 8.2. We also tested examples that we created and in which we planted bugs on purpose, to assess the capabilities of TestStudio. This proved the effectiveness of the approach and showed that TestStudio does meet its intent.

3. PROJECT PLAN

We provide an outline of the objectives of the project and their priorities. We describe which objectives were reached and which still need to be done, and also some work that was done but not yet concluded.

3.1. SCOPE OF THE WORK

TestStudio is based largely on a tool that was implemented as Master’s project [Greber04] by Nicole Greber at ETH Zurich. The tool (called *Test Wizard*) automatically generates tests from contract-equipped classes. The goal of the current project was to provide a graphical user interface (GUI) for that tool and also to extend some of its existing functionality. The design and capabilities of the Test Wizard are explained briefly in section 5. Here we only outline the scope of the current project.

TestStudio is meant to address the major drawbacks of the Test Wizard, to turn it into a user-friendly tool, with all the facilities needed for effective and productive operation.

The Test Wizard takes an Eiffel library as input and generates tests, which it executes and evaluates using the contract information. No user interaction is possible, except for providing the library to be tested. Changing the test scope and criteria requires editing the source code. Another issue is that the Test Wizard does not run the generated test automatically; the user has to launch it manually. These aspects are of utmost importance in turning the Test Wizard into a user-friendly, powerful application, which can be used to automatically generate and run extensive and highly tunable tests on existing software. Therefore, this project aims to provide a user interface to the Test Wizard, while also adding some functionality and refining the existing implementation of the test generator.

3.2. INTENDED RESULTS

Implementation:

a) Developing a graphical user interface (GUI) for the Test Wizard, which allows the user to interact with the tool at the following stages:
   - Choosing the following test criteria for defining the test scenario:
     - **Scope** of the test: which clusters, classes, features should we test?
     - **Stress level**: how many times should we call each feature and should we also test features in descendants? (It will be possible to set this level globally and on a per-cluster, per-class and per-feature basis.)

        - **Context**:
            - the values used for instantiating basic types and for other types;
            - the level of randomness, defined as the number of objects of each class that we create.
        - **Tolerance**: the level of assertion checking (preconditions, postconditions, class invariants, loop invariants and variants, check instructions).
        - **Testing order**: we can perform tests
            - on one feature at a time;
            - on one class at a time;
            - on as many features as possible.

    - When we have generated the test scenario, we display it to the user to allow them to change:
        - the list of calls that will be performed (by adding or removing feature calls);
        - the order of calls;
        - the arguments used for the calls.

    - After running the tests, we display the results to the user, in a format which makes it easy to find the results for any of the tested features.

b) Automatically running the generated test code, without any intervention from the user once they have set all the test criteria.

c) Providing a storing functionality for the Test Wizard in order to:
    - Store the test scenario once it has been completely defined;
    - Store the objects that will be used in the tests;
    - Store the test results;
    - Retrieve the results of previously run tests.

d) Adding a command-line facility to complement the GUI.

e) Extending the functionality currently available with the following improvements:
    - Using several creation procedures to instantiate classes;
    - Enabling the user to change the list of modifiers that the tool automatically selects;

- Distinguishing between preconditions violated by the test case and by a feature under test;
- Outputting test results in the Gobo Eiffel Test format;
- Checking catcalls (for anchored arguments of features) in case the anchor is an attribute or function of the enclosing class;
- Enabling the user to define whether a test has passed or not in case a rescued exception occurs in the feature while running the test;
- Automatically setting the path to the compiler and the path to finish freezing (which the user must do manually in the Test Wizard);
- Enabling the user to choose the type used for instantiating generic parameters (the Test Wizard only uses the constraining type);
- Enabling the user to choose whether obsolete classes and/or features are tested.

Documentation:

Developer manual:	presents the architecture of the software, discusses issues involved in the design and implementation and lists the advantages, limitations and possible future extensions of the tool.
User manual:	explains how to install and use TestStudio.
Project report:	consists of a theoretical description of the concepts involved, the developer manual, the user manual, and presents some results obtained by running the tool.

3.3. BACKGROUND MATERIAL

READING LIST

- "Object-Oriented Software Construction" [Meyer97], in particular:
  - Chapter 1: Software quality
  - Chapter 10: Genericity
  - Chapter 11: Design by Contract: building reliable software
  - Chapter 12: When the contract is broken: exception handling
  - Chapter 14: Introduction to inheritance
  - Chapter 15: Multiple inheritance
  - Chapter 16: Inheritance techniques
  - Chapter 17: Typing
  - Chapter 26: A sense of style

- Chapter 28: The software construction process
- Chapter 32: Some OO techniques for graphical interactive applications

3.4. PROJECT MANAGEMENT

OBJECTIVES AND PRIORITIES

Objective	***Priority***
GUI development	1
Automatically running generated test	1
Storing facility	1
Using several creation procedures	2
Control on instantiating generic parameters	2
Command-line facility	2
Distinguish between preconditions violated by test case and by calling from another feature	2
Finer catcall checking	3 (if time permits)
Allow rescued exceptions in tests	3 (if time permits)
Finer selection of modifiers	3 (if time permits)
Testing obsolete classes and features	3 (if time permits)
Paths to compiler and to finish freezing	3 (if time permits)
Developer manual	1
User manual	1
Project report	1

CRITERIA FOR SUCCESS

The criteria for success is the quality of the software and the documentation. The result may be a partial implementation of the objectives without implying any penalty on the success of the project.

Quality of software:

- Use of Design by Contract
  - Routine pre- and postconditions;
  - Class invariants;
  - Loop variants and invariants.
- Careful design
  - Design patterns;
  - Extendibility;
  - Reusability;
  - Careful abstraction.
- Core principles of OOSC2 [Meyer97]
  - Command/query separation;
  - Simple interfaces;
  - Uniform access;
  - Information hiding;
  - Etc.
- Style guidelines.
- Correct and robust code.
- Readability of the source code.
- Ease of use.

Quality of documentation:

- Completeness.
- Understandability.
- Usefulness.
- Structure.

METHOD OF WORK

The technologies involved are:

- Gobo Eiffel Lint [Bezault04];
- Programming language: Eiffel [Meyer92] (EiffelStudio 5.4).

QUALITY MANAGEMENT

Quality is ensured by:

- Progress reports to the supervisor;
- Review of each milestone by the supervisor;
- Intermediary project presentations;
- Final project presentation;
- Documentation.

4. THEORETICAL BACKGROUND

4.1. TERMINOLOGY

There are several kinds of software testing, depending on the purpose. In this project we only deal with **functional testing**, defined as “validating that an application […] conforms to its specifications and correctly performs all its required functions” [TestTypes]. The word “**testing**” is used to mean “functional testing” in this document.

An **error** in the software construction process causes **faults** to appear in the application, which may lead to **failure** of the program execution [TestingCourse].

The purpose of testing is to find faults (“bugs”) in it. **Debugging** a program means trying to find and remove bugs from it [TestingCourse].

The term “**test case**” refers to a specific test. It consists of information regarding requirements testing, test steps, verification steps, prerequisites, outputs, test environment, etc. A **test suite** is a sequence of test cases. A **test driver** is a program or tool used to execute tests [TestingGlossary]. A **test oracle** defines the expected behavior of the program on running the test. A **test plan** is a “document describing the scope, approach, resources, and schedule of intended testing activities. It identifies test items, the features to be tested, the testing tasks, who will do each task and any risks requiring contingency planning” [TestingGlossary].

Black-box testing relies on the specification of the software, without any reference to its internal workings; its purpose is to test whether the software fulfills the requirements. In contrast, **white-box testing** (also known as structural testing) uses knowledge of the internal structure of the software.

4.2. THE TESTING PROCESS

The testing process consists of the following steps [TestingCourse]:

1. Choosing which elements to test (the granularity can vary from an instruction to a component or library);
2. Building test cases and test oracles;
3. Executing them;
4. Comparing actual results with expected results (as given by the oracle);
5. Measuring execution characteristics (time, memory, etc.).

Traditional approaches require the tester (or developer) to manually execute all these steps. The second one is especially cumbersome and effort- and time-consuming. It is also prone to omissions, because the tester might not consider some cases.

You can run tests at several levels [TestingCourse]:

- Unit testing – a single program unit is tested;
- Integration testing – units are assembled into a system and tested as a whole; you can do this either progressively or as “big bang” (meaning that you run the integration tests only after you have constructed the whole system);
- Regression tests – after updating software, you re-execute tests that you ran successfully in the past, to ensure that no new bugs have been introduced.

A test plan governs the testing process. It documents the decisions that are made with respect to various options [TestingCourse]:

- Who will perform the testing: developers or specialized testers?
- What resources (in terms of people, time and effort) will we allocate for the testing activity?
- At which level will we perform tests?
- Will we carry out the test manually or automatically?
- How will we save test configurations and results?
- What are the risks involved in the testing process?
- What actions will we take depending on the test results?

4.3. MANUAL VS. AUTOMATED TESTING

As suggested by the survey presented in section 1, the problems we need to address are that developers don’t like testing, find it tedious, and consider the tool support for it inadequate. However, there is another major drawback to manual testing: inevitably, some cases will remain untested, and it might be exactly the extreme ones – which the developer might not even think of testing – that cause malfunctions in the final product.

However, even when developers perform thorough tests, errors do appear in the software product. The reason why bugs escape testing can be any of the following [Whittaker00]:

- One or several combinations of input values remain untested;
- Parts of the code remain untested;
- An order in which statements can be executed remains untested;
- Tests are not run for every possible execution environment.

Automated testing does not address all of these problems. Exhaustive testing (in terms of input values tested and path coverage) is impossible, except for extremely simple programs. Still, tools which automatically generate tests can, if designed correctly, achieve much better path coverage and test a wider range of input values, some of which a tester might not even consider. Such a tool has to be highly tunable, to allow testers to adapt the testing process to their particular needs and preferences.

5. THE TEST WIZARD

The Test Wizard is a tool that was implemented at ETH Zurich by Nicole Greber as Master project [Greber04]. The goal of the current project was to extend the Test Wizard. Therefore, we briefly describe its architecture and capabilities.

5.1. FUNCTIONALITY

The Test Wizard implements the basic functionality for automatically generating black-box tests for programs written in Eiffel. It takes as input (provided as command-line argument) the path to the ace file for the system to be tested and generates and compiles the test code. Then, the user needs to run the test by hand. Result information is saved as follows: an Excel-compatible text file and an XML file containing the summary of test results for each feature, and an Excel-compatible text file containing details about the tests that failed.

We classify the results into four categories:

- Failed – the feature produced an assertion violation, some exception occurred during its execution or one or several of its calls were possible catcalls[1];
- No call was valid – no call to the feature fulfilled its precondition, so the feature does not fail the test but does not pass either – it simply was not actually tested;
- Could not be tested – the Test Wizard could issue no call to the feature, because it could not instantiate the target object or one of the arguments;
- Passed – at least one of the feature calls succeeded (fulfilled the precondition) and its execution did not produce any exceptions or assertion violations (the assertions that are actually checked during the execution of the test can be set by the user when defining the test scenario).

5.2. ARCHITECTURE

The following picture shows the architecture of the Test Wizard (there is no implementation for the items with dotted outlines) [Greber04]:

[1] A call is a catcall if some redefinition of the routine (in an heir of the class) would make it invalid because of a change of export status or argument type [Meyer97].

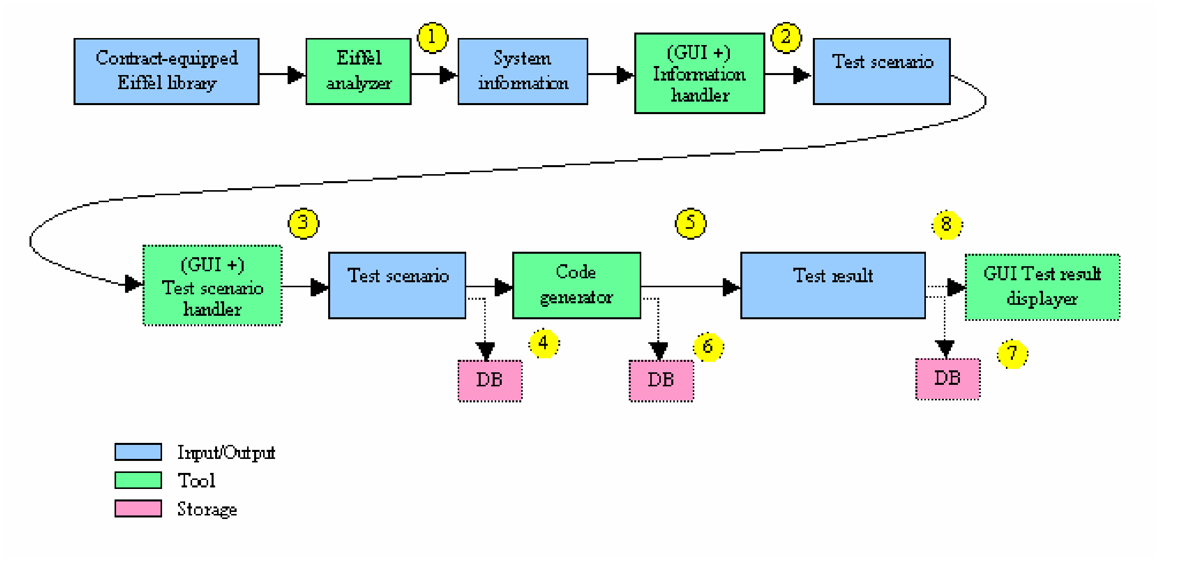


Figure 1: Architecture of the Test Wizard

The above figure shows the basic components and the data flow between them. The Test Wizard works as follows:

(1) Gather system information.

(2) Display system information and allow the user to set various test options.

(3) After generating the test scenario, allow the user to adapt it (change the order of class instantiations, the order of calls to the tested features, the arguments used, etc.)

(4) Store the test scenario.

(5) Generate a test executable corresponding to the test scenario and run it.

(6) Store information regarding the test executable.

(7) Store test results.

(8) Display the results.

The building blocks of the Test Wizard are:

- Eiffel analyzer (see section 5.2.1);
- Information handler (see section 5.2.2);
- Code generator (see section 5.2.3).

5.2.1. EIFFEL ANALYZER

The Eiffel analyzer parses the Eiffel library provided as input get the system information. It relies on the parsing tool Gobo Eiffel Lint [Bezault04], also known as *gelint*, which analyzes Eiffel source code and gathers the necessary information: the list of clusters, deferred and effective classes, their generic parameters and descendants, deferred and effective features, their arguments and result types as well as modifiers and creation procedures. It also reports errors and warnings. The Eiffel analyzer then passes this information to the information handler.

5.2.2. INFORMATION HANDLER

The information handler generates the test scenario from the system information received from the Eiffel analyzer; it also takes into account the criteria set by the user (in the Test Wizard, the user can set these criteria only by modifying the source code of the wizard). The test criteria consist of the test scope (the items that the user wants to test: clusters, classes or features), test data (the user can define values that will be used to instantiate classes), and options. We describe the test criteria in more detail in section 6.1.

Once it has set all the test parameters, the information handler defines the test scenario according to these parameters. The code generator uses this scenario to create a test executable.

5.2.3. CODE GENERATOR

The code generator has the following components:

a) Test generator - generates Eiffel code according to the test scenario and calls the Eiffel compiler, which builds the test executable;

b) Context handler – establishes how and in which order to instantiate the needed classes;

c) Context generator – creates the objects and then randomly calls modifiers on them, to create a pool of objects, which we call the “context”;

d) Call simulator – performs the calls to the features that the user wants to test. To do this, it chooses target and argument objects from the context, so that their types match the types required by the feature’s signature. It needs to wrap all feature calls in rescue blocks, so that the wizard can recover from any assertion violation or exception that occurs and report it in the test results.

6. DESIGN AND IMPLEMENTATION OF TESTSTUDIO

In this section, we describe the design and some implementation issues of TestStudio. As mentioned before, TestStudio extends an already existing tool, the Test Wizard, which we described in Chapter 5. Therefore, this chapter – unless otherwise noted –only discusses the architecture of what is added to the Test Wizard, namely the contribution of this project.

6.1. TEST SCOPE, DATA AND OPTIONS

We outline here the various test criteria that can be set by the user. These criteria are also present in the Test Wizard, but the user can only set them by modifying the source code of the Wizard, whereas in TestStudio they are set through the GUI.

We divide the test criteria into the following categories:

a) **Test scope** – defines the items that the user wants to test. TestStudio can work on different levels of granularity: the user can include whole clusters in the test (which means that all classes in these clusters with all their features will be tested), whole classes (all their features will be included in the test), or individual features.

b) **Test data** – the user can:

- Set the values used for instantiating basic types (*INTEGER*, *REAL*, *DOUBLE*, *BOOLEAN*, *CHARACTER*, *STRING*) or use the default values provided by TestStudio. This is an addition of TestStudio: the Test Wizard does not allow users to set these values.
- Add values for other types. These objects will be part of the context, but other values for their corresponding types will also be created by the context generator. To add values for non-basic types, the user has to write a function returning an object of the desired type. The GUI of TestStudio fully supports this.
- Set the stress levels for the tested elements (this feature was also not present in the Test Wizard). The user can do this globally or on a per-cluster, per-class or per-feature basis. Setting a stress level globally means setting it for all clusters included in the test, for all their classes and for all the features. Setting a stress level for a cluster will assign that stress level to all the cluster's classes and to all their features, and so on. Setting the stress level for a particular feature will override the stress level that was assigned to it from its enclosing class; likewise for classes and clusters. The stress level varies on the following scale: very low, low, moderate, high, critical. All these levels actually map to values of two parameters: the number of method calls (this is an *INTEGER* which, by default, varies with the stress level from 10 to 100) and whether features should also be tested in descendants (*BOOLEAN* parameter, which by default is **False**). The user can set the mapping between stress levels and values for these parameters.

c) **Test options**:

- Level of assertion checking: the user can specify which of the following types of assertions they want to check in the generated test:
    - Preconditions
    - Postconditions
    - Class invariants
    - Loop variants and invariants
    - Check instructions.
- Testing order – can be one of the following:
    - As many features as possible – call all features once before calling them a second time;
    - One feature at a time – perform all calls on a feature before calling the next one;
    - One class at a time – perform all calls on the features of a class before calling the features of the next one.
- Level of support for genericity – the user can choose the types which will be used for instantiating generic parameters:
    - Only the constraining type;
    - Basic types if they conform to the constraining type, otherwise only the constraining type;
    - All types conforming to the constraining type.

6.2. GRAPHICAL USER INTERFACE (GUI)

Designing and implementing the GUI of TestStudio was the biggest part of this project. We paid special attention to the design, because TestStudio allows the user to set a wide range of parameters, and this needs to be done easily and intuitively.

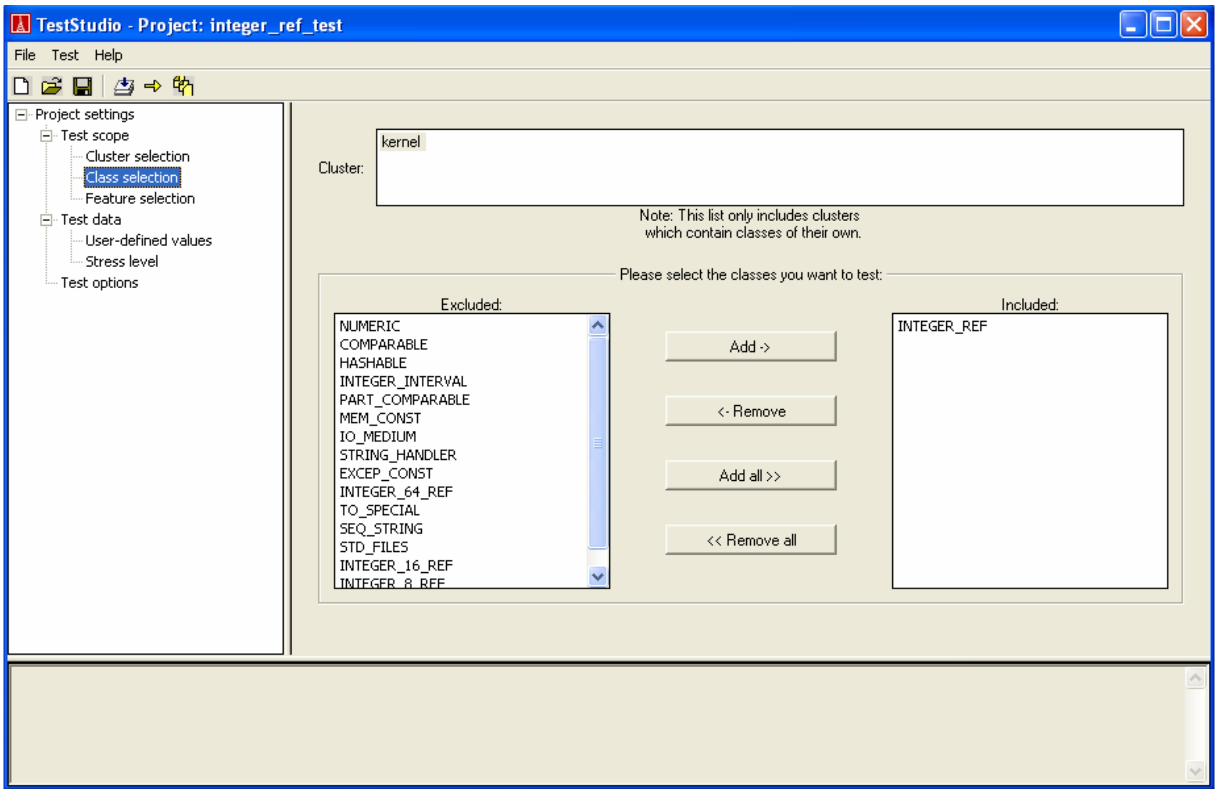
6.2.1. DESIGN OF THE GUI

The GUI of TestStudio must allow the user to:

- Set all parameters listed in section 6.1, but not force the user to do it (by providing defaults);
- Save the values that the user sets, so that it is possible to run the same test again;
- Open a previously saved test configuration;
- Generate and compile the test code, then run the executable;

- Display the test results in a format that is easy to use and to browse through.

The most important objectives in the design of the GUI were: the ease of learning how to use it, the ease of using it, its intuitiveness, but also the fact that it should fulfill all the functions listed above. Therefore, we designed a project-oriented GUI: TestStudio saves all the test information (scope, data and options) as a project, which it can then open again. The main window of TestStudio displays a browser-like tree on its left-hand side, corresponding to the structure of the project data. We will call this the *project tree browser*. By clicking on the leaves of the tree, the user can display various panels in the right-hand side of the window, which allow him to set the different test parameters. We will refer to these as *project panels*. Figure 2 shows a screenshot of the main window, with a project loaded.



Cluster: kernel

Note: This list only includes clusters which contain classes of their own.

Please select the classes you want to test:

Excluded:
NUMERIC
COMPARABLE
HASHABLE
INTEGER_INTERVAL
PART_COMPARABLE
MEM_CONST
IO_MEDIUM
STRING_HANDLER
EXCEP_CONST
INTEGER_64_REF
TO_SPECIAL
SEQ_STRING
STD_FILES
INTEGER_16_REF
INTEGER_8_REF

Included:
INTEGER_REF

Figure 2: Main window of TestStudio.

When you launch TestStudio, there is no open project. The user can either create a new project or open a previously saved one. When creating a new project, the user must enter data about the project and define the test scope. For this, we created a wizard with the following dialogs:

1. “Project name and directory” dialog - allows the user to choose the project name and directory;
2. “Input file” dialog – the user must select the ace file for the system that contains the elements which he wants to test; the user can also choose to create a log file for the project;
3. “Scope selection - clusters” dialog – the user can choose the clusters to be included in the test (by default, TestStudio includes all clusters);

4. “Scope selection - classes” dialog – the user can choose the classes (from the clusters selected at the previous step) to be included in the test (by default, TestStudio includes all classes);
5. “Scope selection - features” dialog – the user can choose the features (from the classes selected at the previous step) to be included in the test (by default, TestStudio includes all features).

The user can navigate through these dialogs with “Next” and “Back” buttons. When the execution of the wizard is finished (i.e. the user has gone through all the dialogs of the wizard), TestStudio opens the project in its main window. The user can already generate the test or set other test parameters. If he does not set values for the rest of the parameters, the default values are used.

The main window of TestStudio contains menu items and toolbar buttons for:

- Creating a new project;
- Opening a project;
- Saving an open project;
- Generating and compiling the test code;
- Running the test;
- Displaying the test results.

6.2.2. IMPLEMENTATION OF THE GUI

The main classes used for implementing the GUI of TestStudio are represented in the class diagram in Figure 3. Refer to this figure to follow the description in the text.

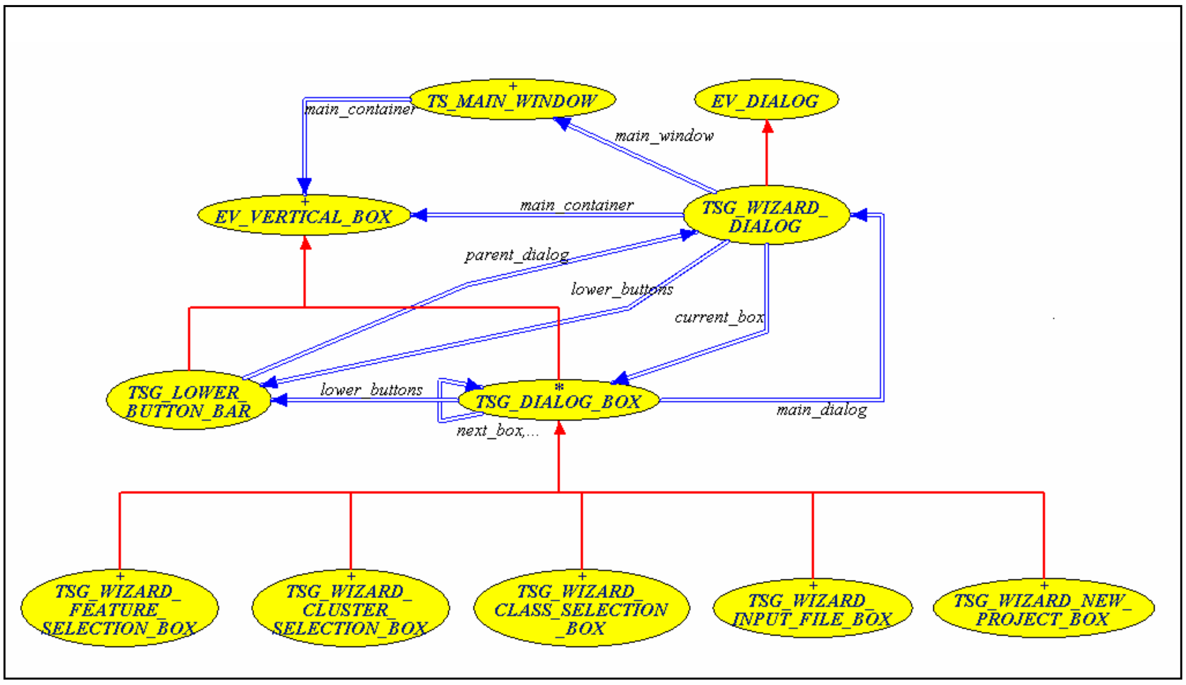


Figure 3: Diagram containing the main GUI classes of TestStudio.

Implementation of the wizard for creating a new project

The wizard for creating a new project is made of five dialogs where the user can enter information about the project and define the test scope. To achieve this, we use a dialog (implemented by class *TSG_WIZARD_DIALOG*), whose content (the box that is displayed inside it) changes when the user presses the "Next" or "Back" button.

Class *TSG_WIZARD_DIALOG* inherits from *EV_DIALOG*; its content is an instance of class *TSG_DIALOG_BOX* (not a direct instance, because the class is deferred, but an instance of one of its effective descendants). This class is the ancestor of all classes implementing boxes that can be displayed in the wizard. It inherits from *EV_VERTICAL_BOX* and any class which represents a box that can be displayed in the wizard must inherit from it.

TSG_DIALOG_BOX contains the functionality for navigating between the boxes. To do this, it keeps track of the next and previous boxes that it can display, by using the attributes *next_box* and *previous_box*, both of type *TSG_DIALOG_BOX*.

To implement the lower bar of the dialog containing buttons "Next", "Back", "Cancel" and "Help", we created class *TSG_LOWER_BUTTON_BAR*. It keeps a reference to the dialog that contains it (in attribute *parent_dialog* of type *TSG_WIZARD_DIALOG*) and has procedures that will be executed when the user presses the "Back" and "Cancel" buttons. It also contains procedure *add_new_forward_action* for adding a procedure which will be executed when the user presses the "Next" button.

Class *TSG_DIALOG_BOX* has a reference to an object of type *TSG_LOWER_BUTTON_BAR* and a deferred method *create_lower_button_bar*, which its effective descendants implement according to their specific needs.

The descendants of *TSG_DIALOG_BOX* are: *TSG_WIZARD_NEW_PROJECT_BOX*, *TSG_WIZARD_INPUT_FILE_BOX*, *TSG_WIZARD_CLUSTER_SELECTION_BOX*, *TSG_WIZARD_CLASS_SELECTION_BOX* and *TSG_WIZARD_FEATURE_SELECTION_BOX*. Each of them corresponds to one of the steps in the execution of the wizard for creating a new project. All of these classes define a procedure to be executed when the user presses the "Next" button. To add this procedure to the list of actions executed on the selection of the "Next" button, they call *add_new_forward_action* of class *TSG_LOWER_BUTTON_BAR* and pass the procedure they want to add as argument.

TSG_WIZARD_NEW_PROJECT_BOX inherits from *TSG_PROJECT_NAME_DIR_BOX*, which contains the widgets for entering a name and directory for the project. The reason for having a class *TSG_PROJECT_NAME_DIR_BOX* is that this class will also be used when the user wants to save a project under a different name and/or in another directory (the "Save as…" function of TestStudio). Class *TSG_WIZARD_NEW_PROJECT_BOX* only needs to extend it with the procedure that will be executed when the user presses the "Next" button and the implementation of the procedure for creating the lower button bar (*create_lower_button_bar*). In short, class *TSG_PROJECT_NAME_DIR_BOX* contains the functionality for setting a project name and directory, and class *TSG_WIZARD_NEW_PROJECT_BOX* just adds to it some wizard-specific behavior.

Classes *TSG_WIZARD_CLUSTER_SELECTION_BOX*, *TSG_WIZARD_CLASS_SELECTION_BOX* and *TSG_WIZARD_FEATURE_SELECTION_BOX* encapsulate instances of classes *TSG_CLUSTER_SELECTION_VERTICAL_BOX*, *TSG_CLASS_SELECTION_VERTICAL_BOX* and *TSG_FEATURE_SELECTION_VERTICAL_BOX*, respectively. These latter classes contain the widgets and functionality for selecting the clusters, classes and features that the user wants to test. The wizard classes just add to them some wizard-like functions (actions to be executed when the user presses the "Next" button, creating the lower button bar, etc.). The TestStudio main window also uses these classes when it displays the scope selection panels.

Classes *TS_TEST_DATA* and *TS_TG_TEST_RESULT*

We created a class called *TS_TEST_DATA* which holds all information about a certain project (name, directory, output directory) and about the test parameters for that project (all those listed in section 6.1, plus a reference to the instance of the test generator and the input ace file). We also need to record whether the user has specifically set the stress level for a cluster, class or feature, or if we set its stress level by copying the stress level of the more general (enclosing) element. For this we use three attributes of type *HASH_TABLE [BOOLEAN, STRING]* where the keys are names of clusters/classes/features and the values are set to **True** if the user has specifically set that element's stress level.

Class *TS_TEST_DATA* contains:

- Setter methods for all its attributes;
- A few convenience features, such as:
  - *include_all_classes* - adds all classes in the included clusters to the test;
  - *include_all_features* – adds all features of the included classes to the test;
  - *select_clusters* - receives a list of cluster names as argument and deletes the clusters whose names are not in this list from the list of included clusters;
  - *select_classes* and *select_features* - do the same for classes and features respectively;
- Features for deleting the values of some attributes (stress levels for clusters, classes and features, and the lists of included classes and features);
- Functions for checking if the values that the user wants to set are legal values for the corresponding attribute. For example, *is_valid_testing_order* checks if the *INTEGER* that it receives as argument is a legal value for the testing order; *is_valid_genericity_support_level* does the same for a level of support for genericity;
- Procedures which are not exported and which some of the features described above use as agents, e.g. for deleting an element from a list or a hash table, for deleting a cluster from the list of included clusters (this will also delete all its classes and all their features), for excluding a cluster (without excluding all its classes and their features), or for excluding a class.

Class *TS_TG_TEST_RESULT* encapsulates information about test results for each feature. It records:

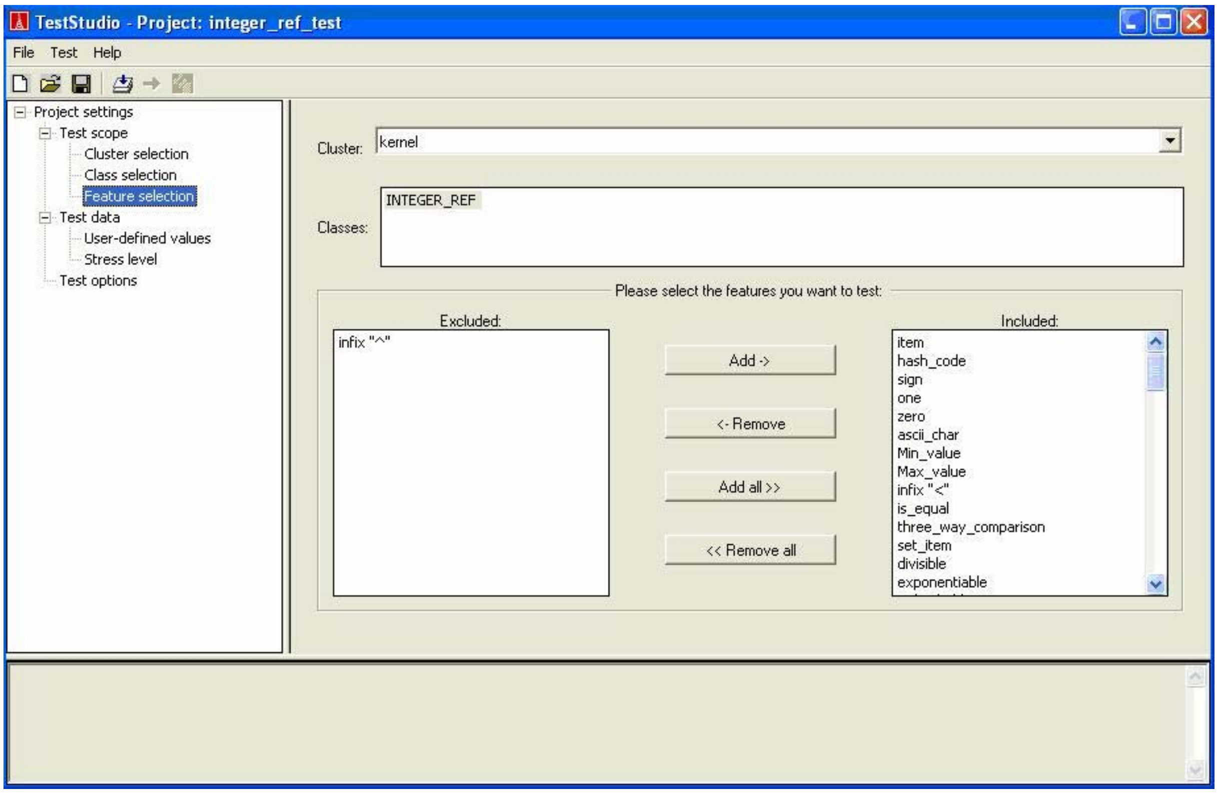
- the name of the class the feature belongs to
- the name of the feature
- the result type
- the number of calls to the feature that produced no exceptions

- the number of calls that violated the feature's preconditions[2]
- the number of calls that produced assertion violations[3]
- the number of calls that produced other exceptions
- the number of possible catcalls
- the number of calls that were attempted on a void target.

The class also contains setter routines for all these attributes.

Implementation of the TestStudio main window

The main window of TestStudio must allow the user to perform project-related operations (creating, opening, saving a project), to generate, compile and run the test, and then display test results. It must also display, when a project is open, all the information regarding it and allow the user to change it. As described in section 6.2.1, the window is split into two vertical parts (see Figure 4): a tree-like browser on the left side and a panel displaying information corresponding to the selected tree item on the right side. At the bottom of the window, there is a text area (not editable by the user) displaying the compiler output.



Cluster: kernel

Classes: INTEGER_REF

Excluded:
infix "^"

Included:
item
hash_code
sign
one
zero
ascii_char
Min_value
Max_value
infix "<"
is_equal
three_way_comparison
set_item
divisible
exponentiable

Figure 4: Screenshot of the TestStudio main window.

The window contains menu items and toolbar buttons for operations on projects and for test generation and execution. When there are both a menu item and a toolbar button for a

[2] This refers to a precondition of the feature being violated because of the test case. It does not signal a bug in the feature.

[3] This refers to assertion violations that occur during the execution of the feature, which signal the presence of bugs in the tested feature.

certain operation (which is the case for all menu options except “Save as…”, “Exit” and “Help”), they trigger the execution of the same agent. We will describe below the operation and implementation of some of these agents:

- Routines concerned with project management:
    - `create_new_project` – It is called when the user selects the menu item or the toolbar button for creating a new project. It first checks whether there is already an open project, and if so calls the procedure for closing a project (`close_project`). If closing the project was successful or if there was no open project, it launches the wizard for creating a new project (described above). When execution returns from the wizard, it checks if the project and test data have been set correctly (in other words, if the user did not interrupt the execution of the wizard at some point by pressing “Cancel”). If this check is successful, feature `create_new_project` adjusts some GUI elements of the window to reflect that now there is an open project. When the wizard finishes its execution (the user presses the “OK” button on the last screen of the wizard and all entered data is valid), it calls feature `show_test_panel`, which creates and displays the tree-like browser on the left side of the TestStudio main window.
    - `save_project` - It is called when the user selects the menu item or the toolbar button for saving a project. It first records the test information contained in the currently displayed project panel. Then it also records the information regarding values of types entered by the user, stress levels and options (we record these values when the corresponding project panels are hidden, which might not happen before saving the project). Here by “recording” we mean saving the information in an instance of class `TS_TEST_DATA`, which we keep in an attribute (called `test_data`) of `TS_MAIN_WINDOW`. If everything could be recorded successfully, it creates an instance of class `TS_XML_GENERATOR`, and calls its `save_project` procedure, passing it `test_data` as argument (we describe this routine below).
    - `save_project_as` – It is called when the user selects the “Save as…” menu item. It records the new project name and directory in `test_data` and then calls routine `save_project`.
    - `open_project` – It is called when the user selects the menu item or the toolbar button for opening a project. If there is an open project, it closes it (by calling procedure `close_project`). If closing the project was successful or if there was no open project, it creates a new instance of `TS_TEST_DATA`, by overwriting the value contained by attribute `test_data`. Then it displays the dialog for opening a project (described in section “Additional dialogs”) and after control returns from that dialog, it adjusts some elements of the graphical interface to the newly opened project.
    - `close_project` – This feature is not exported; it is only called by routines `open_project` and `create_new_project`. It first displays a dialog which asks the user whether he wants to save the project that is currently open before proceeding (the user can also cancel the operation); if the user wants to save the project, it calls procedure `save_project`, then it adjusts some graphical elements to reflect that there is currently no open project. Figure 5 shows the code of feature `close_project`.

```
close_project is
                -- Close the currently open project.
                -- (Is called by `open_project' and `create_new_project')
        local
                confirm_dialog: EV_CONFIRMATION_DIALOG
                button_labels: ARRAYED_LIST [STRING]
        do
                create confirm_dialog.make_with_text (
                                        Close_project_confirmation_text)
                create button_labels.make (0)
                button_labels.extend (Yes_button_text)
                button_labels.extend (No_button_text)
                button_labels.extend (Cancel_button_text)
                confirm_dialog.set_buttons (button_labels)
                confirm_dialog.set_default_push_button (confirm_dialog.button (
                                                                Yes_button_text))
                confirm_dialog.show_modal_to_window (Current)
                if equal (confirm_dialog.selected_button, Yes_button_text) then
                                -- Save the project that was previously open and
                                -- then close it.
                        save_project
                end
                if (equal (confirm_dialog.selected_button, Yes_button_text) and
                                save_successful) or equal (
                                confirm_dialog.selected_button, No_button_text)
                                then
                        set_title (Window_title)
                        split_area.wipe_out
                        save_menu_item.disable_sensitive
                        save_toolbar_button.disable_sensitive
                        save_as_menu_item.disable_sensitive
                        generate_test_menu_item.disable_sensitive
                        generate_test_toolbar_button.disable_sensitive
                        run_test_menu_item.disable_sensitive
                        run_test_toolbar_button.disable_sensitive
                        get_test_results_menu_item.disable_sensitive
                        get_test_results_toolbar_button.disable_sensitive
                        output_text_area.set_text ("")
                        exists_open_project := False
                        test_data := Void

                        ok_to_go_on := True
                else
                        ok_to_go_on := False
                end
        end
```

Figure 5: Feature `close_project` of class `TS_MAIN_WINDOW`.

- Routines concerned with test generation and running:
    - `generate_test` – It is called when the user selects the menu item or the toolbar button for generating and compiling the test code. It first needs to save the project information (i.e. record it in `test_data`) in the same manner as described for feature `save_project`. Then it calls procedure `generate_test` on an object of class `TS_TG_ROOT_GENERATOR`, which actually does the work of generating the test code and compiling it. Then it checks if compilation was successful by looking for an executable file of the test and displays an information dialog which lets the user know about the result of the test generation.
    - `run_test` – It is called when the user selects the menu item or the toolbar button for running the generated test executable. It calls procedure `run_test` on an object of class `TS_TG_ROOT_GENERATOR`, which actually executes the test. Then

it checks whether there is a result file in the output directory of the project, to determine if the test was run successfully, and displays an information dialog to the user.

- o `get_test_results` - It is called when the user selects the menu item or the toolbar button for displaying the test results. To generate HTML files for the results and then display them, it first creates an instance of class `TS_CSV_READER`, and calls its `get_test_results` routine. This function reads the CSV[4] file containing the test results and returns an array of instances of class `TS_TG_TEST_RESULT` (described above). If parsing the CSV file is successful, `get_test_results` generates the HTML files by calling procedure `generate_html` on an instance of class `TS_HTML_GENERATOR`. This will also display the test results in a browser. Figure 6 shows an extract from the code of routine `get_test_results`.

```
if checker.is_valid_file (test_data.output_directory + "\" +
                          test_res_cts.Results_csv_file_name) then
            -- Read the CSV file to get the test results.
      create csv_reader.make (test_data.output_directory + "\" +
                              test_res_cts.Results_csv_file_name)
      results := csv_reader.get_test_results
      if results = Void then
                  -- Display info dialog.
            create info_dialog.make_with_text (Invalid_csv_file_text)
            info_dialog.show_modal_to_window (Current)
      else
                  -- Generate HTML.
            create html_generator
            html_generator.generate_html (results, test_data.output_directory)

            create info_dialog.make_with_text (Html_results_saved_text +
                  test_data.output_directory + "\" +
                  test_res_cts.Html_results_dir_name + ".")
            info_dialog.show_modal_to_window (Current)
      end

else
            -- Display info dialog.
      create info_dialog.make_with_text ("There is no file called " +
            test_res_cts.Results_csv_file_name + " in directory " +
            test_data.output_directory + ".")
      info_dialog.show_modal_to_window (Current)
end
```

Figure 6: Extract from routine `get_test_results` of class `TS_MAIN_WINDOW`.

- Routines for displaying project panels - all these procedures work in the same way: they display the corresponding box (an instance of one of the classes described below) and add an agent to the deselect actions of the corresponding browser-tree node, agent which saves the information set through that panel. The agents for saving the test scope (clusters, classes and features) follow a typical scenario: they check if anything has really changed in the box (for example, if the list of included clusters is different from the one already recorded in `test_data`), and if that is the case they call the corresponding save routine of the box that was displayed. (Figure 7 shows an extract from the code of procedure `save_cluster_info`.) The rest of the agents do not

[4] Comma-separated values

check for changes, but just call the save procedures of the boxes (because the operations they have to perform for saving are quite simple, it is not worth to check for changes before doing the actual saving). All agents set the `save_successful BOOLEAN` attribute, to show whether the data to be saved was valid.

```
changed := False
old_cluster_list := test_data.cluster_list
if old_cluster_list.count /= cluster_selection_box.included_list.count then
        changed := True
else
        from
                old_cluster_list.start
        until
                changed or else old_cluster_list.after
        loop
                cluster_name := old_cluster_list.item.name
                        -- Look for a cluster with name `cluster_name' in the
                        -- list of included clusters of the cluster selection box.
                found := False
                from
                        cluster_selection_box.included_list.start
                until
                        found or else cluster_selection_box.included_list.after
                loop
                        if equal (cluster_selection_box.included_list.item.text,
                                        cluster_name) then
                                found := True
                        end
                        cluster_selection_box.included_list.forth
                end
                if not found then
                        changed := True
                end

                old_cluster_list.forth
        end
end

if changed then
        cluster_selection_box.save_info (test_data)
        save_successful := cluster_selection_box.save_successful
end
```

Figure 7: Extract from routine `save_cluster_info` of class `TS_MAIN_WINDOW`.

We use the lower part of the TestStudio main window (an instance of `EV_TEXT` which the user cannot edit) for displaying the output of the compiler. We will refer to this as the "output text area". To redirect the compiler output, we had to modify feature `compile` of class `TS_TG_CODE_GENERATOR`, which launches the compilation process. We use an object of `WEL_PROCESS_LAUNCHER`, on which we call routine `launch` with an agent encapsulating a procedure of class `TS_MAIN_WINDOW` as argument. This procedure displays the string it receives as argument in the output text area.

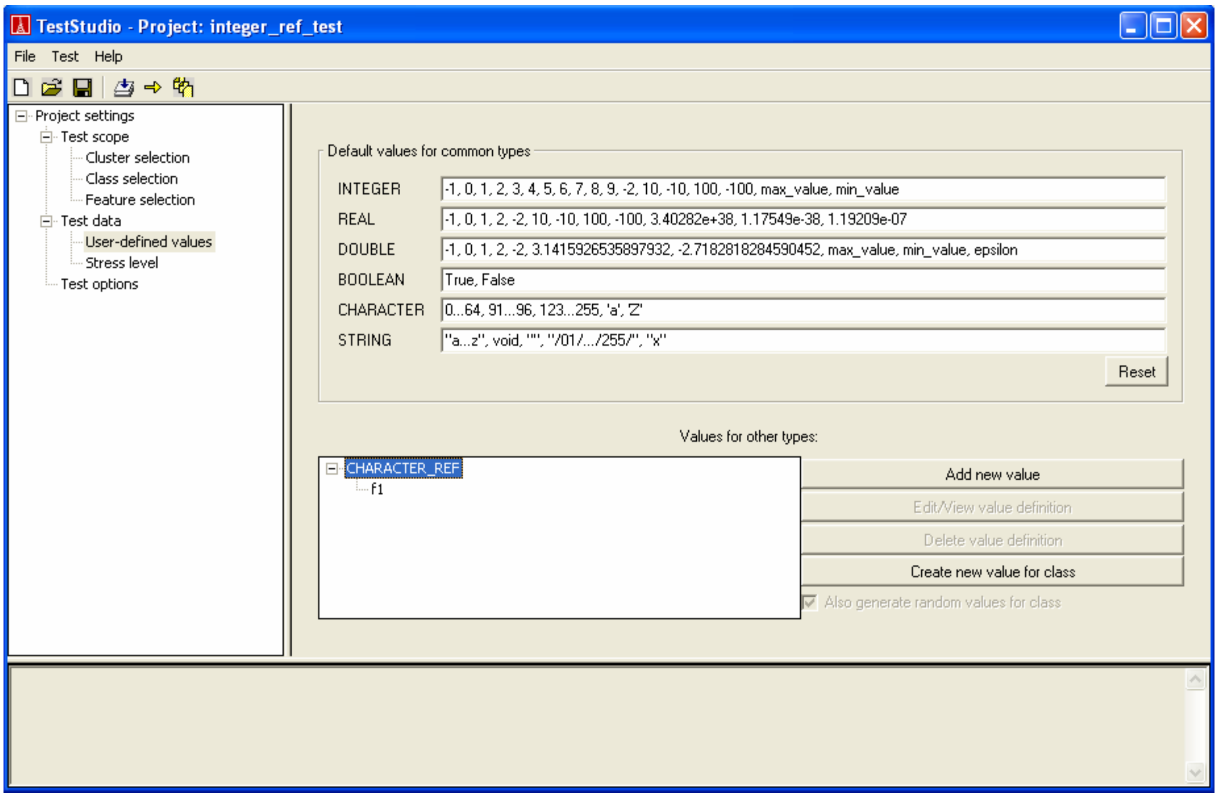
Boxes displayed in project panels

We present the classes implementing the boxes displayed when the user selects one of the leaves of the project tree browser. All of them inherit from `EV_VERTICAL_BOX` and their creation procedures receive as argument an instance of *TS_TEST_DATA*. This object contains the values for the test parameters that the user has already set, so that the widgets in the box can reflect that information (for example, the lists of clusters included in and excluded from the test must reflect the choices that the user has made; in case this is the first time that the box is displayed and the user has not made that choice yet, all clusters are included by default).

Classes *TSG_CLUSTER_SELECTION_VERTICAL_BOX*, *TSG_CLASS_SELECTION_VERTICAL_BOX* and *TSG_FEATURE_SELECTION_VERTICAL_BOX* contain the widgets and logic for setting the project scope. They need to include the functionality for moving items from one list (instance of *EV_LIST*) to another (from the list of included elements to the list of excluded elements or vice-versa), so that the user can include and exclude clusters, classes and features from the test scope. Therefore, there are routines for including and excluding one or several items. These routines operate in a similar way, but some of them also need specific behavior. For instance, the box for cluster selection displays all clusters contained in the input ace file as a tree. When the user chooses to include a cluster, we add it to the list of included clusters and we need to change its icon in the tree. Furthermore, if the user has selected the check box for including subclusters, we will also have to include all its subclusters. The boxes for selecting classes and features work only on lists (they don't use tree-like structures). They operate in a similar manner: the routines for including and excluding one or several classes or features just call a routine which implements the basic functionality for moving items between lists.

These classes also have features for saving the data set through the box in an instance of *TS_TEST_DATA*. Again, they operate in a similar manner: first they check an integrity constraint (the fact that the user has included at least one cluster/class/feature), then they set the corresponding attributes of the *test_data* object and reset the values of attributes that are influenced by the change. (For example, when the list of included clusters changes, it makes no sense to keep the lists of included classes and features that we had before; we need to reset these lists, so that they contain all classes of the included clusters and all their features). Finally, they set a *BOOLEAN* attribute called *save_successful* which shows if we could actually save the data or not (in the case that checking the integrity constraints failed).

Class *TSG_VALUES_VERTICAL_BOX* contains the functionality for setting values for basic and other types. For basic types (*INTEGER*, *REAL*, *DOUBLE*, *BOOLEAN*, *CHARACTER*, *STRING*), there are text fields where the user can enter the values that TestStudio should use when generating the test. To define values for other types, the user must write a function returning a value of the desired type. To do this, they must use some additional dialogs, which they launch by pressing the buttons in the lower right-hand side of the box. The list in the lower left-hand side of the box contains a tree-like structure, which displays the classes for which the user has entered values and the names of the features which return those values. Figure 8 shows a screenshot of the TestStudio main window with the box for entering values.



Default values for common types

INTEGER	-1, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, -2, 10, -10, 100, -100, max_value, min_value
REAL	-1, 0, 1, 2, -2, 10, -10, 100, -100, 3.40282e+38, 1.17549e-38, 1.19209e-07
DOUBLE	-1, 0, 1, 2, -2, 3.1415926535897932, -2.7182818284590452, max_value, min_value, epsilon
BOOLEAN	True, False
CHARACTER	0...64, 91...96, 123...255, 'a', 'Z'
STRING	"a...z", void, "", "/01/.../255/", "x"

Values for other types:

```
CHARACTER_REF
    f1
```

Figure 8: TestStudio screen for entering values for basic and other types.

The buttons in the lower right-hand side are enabled or disabled depending on what is selected in the tree:

- The "**Add new value**" button is always enabled. It displays a dialog (implemented by class *TSG_ADD_VALUE_DIALOG*) which allows the user to enter the name of the feature, its return type and body. When the user has entered the data, this dialog calls procedure *add_new_value* of an object of class *TSG_VALUES_VERTICAL_BOX*, which adds the new value to the tree (after checking that there is not already a feature with the same name). To do this, it looks for nodes in the tree for the same type, and if it finds one, it adds the name of the new routine under that node; otherwise, it creates a new node (root) in the tree and adds to it a child node containing the feature name.
- The "**Edit/View value definition**" button is only enabled when the name of a feature is selected in the tree. When the user clicks this button, a dialog is displayed (implemented in class *TSG_EDIT_VIEW_VALUE_DIALOG*), similar to the one for adding a new value. The only difference is that the fields for the name, return type and body of the function are filled in with those of the feature selected in the tree. This dialog allows the user to see and edit the body of the feature. If the user wants to change the name or return type of a function, he has to delete the old feature and create a new one.
- The "**Delete value definition**" button is only enabled when the name of a feature is selected in the tree. It triggers the deletion of the selected function. If there are no other features returning an object of the same type, we also delete the node for the type from the tree.
- The "**Create new value for class**" button is only enabled when the name of a class is selected in the tree. When the user selects this button, we open the dialog for adding a

new value, with the name of the selected class filled in in the text field for the return type.

- The **check box for random generation** (through which the user can choose whether he wants to generate random values for types for which he has already defined values) is selected and disabled. The reason is that currently we cannot disable random generation of values for types other than the basic ones in the context generator.

Function *save_info* of class *TSG_VALUES_VERTICAL_BOX* saves the values that the user entered (in an instance of *TS_TEST_DATA*). As described above, the user must enter the values for basic types in text fields. By getting the texts from these fields, we obtain strings which have to be parsed in ordered to get the integers, reals, etc. they contain. For this, we created a utility class called *TSU_STRING_PARSER*, which contains functions *get_ints*, *get_reals*, *get_doubles*, *get_booleans*, *get_chars*, and *get_strings* (all receiving a *STRING* as argument) for parsing a string to get different kinds of values from it. All these functions return arrays of objects of the corresponding basic type. Then we save these arrays in an instance of *TS_TEST_DATA*.

The functions of class *TSU_STRING_PARSER* use instances of special parser classes (contained in cluster *scanner*): *TSG_INTEGER_SCANNER*, *TSG_REAL_SCANNER*, *TSG_DOUBLE_SCANNER*, *TSG_CHARACTER_SCANNER* and *TSG_STRING_SCANNER*. (For booleans it's not necessary to have a special scanner class, because we can just test if the string contains a "true" substring and a "false" substring, as these are the only legal values for type *BOOLEAN*.) We generated these classes using Gobo Eiffel Lex (*gelex* [Bezault04]). *Gelex* takes as input a lex-type file which contains three sections:

- Declarations – start conditions, options, name definitions and Eiffel code which *gelex* will copy at the beginning of the generated scanner class;
- Rules – a series of rules of the form "pattern action";
- User code – Eiffel code which *gelex* will copy at the end of the generated scanner class.

For all the above-mentioned classes, the user code section contains a function called *scan_text*, which reads tokens one at a time and performs different actions depending on the type of the token that it finds. We declare the token types as constants at the end of the class.

Having intervals is allowed for characters and strings (an interval inside a string is interpreted as the string containing all characters whose codes are between the code of the character starting the interval and the code of the character ending the interval). So the parsers for characters and strings need to take this into account, and when they encounter the "…" token, actually add all elements of the interval to the array they return.

We save the values that the user enters for non-basic types, as they are, in an instance of *TS_TEST_DATA*. When we generate the test code, we assemble them into feature definitions and we copy their code as it is in the context generator class.

Class *TSG_STRESS_LEVEL_VERTICAL_BOX* contains the functionality for setting the stress levels associated with tested items, either globally, or on a per-cluster, per-class, or per-feature basis. It initially displays only the radio buttons for setting the global stress level and a button which, when it is pressed, triggers the display of the widgets used for setting the stress level for clusters, classes and features. The elements included in the test are shown in a tree-like structure, and for each element the user can set the stress level. The user can also change the values of the parameters which map to stress levels (number of method calls and whether we also test features in descendants), by selecting the “Modify stress levels parameters…” button. This button launches a dialog for setting these values (implemented in class *TSG_STRESS_LEVEL_PARAMETERS_DIALOG*).

The functions called when the user sets the stress level need to take into account the fact that setting the stress level on a more general level means setting it for all more specific elements, unless the user has expressly assigned a stress level for those elements. For example, setting a stress level of “high” for a cluster will set this stress level for all the classes of that cluster and all their features, except those classes and features to which the user has already assigned a stress level. If the user has assigned “moderate” stress level to class *C* in that cluster, this stress level will not be overwritten by setting the “high” stress level for the cluster. Therefore, class *TSG_STRESS_LEVEL_VERTICAL_BOX* needs to keep track of the elements to which the user has assigned a specific stress level. It uses attributes *clusters_stress_level_set*, *classes_stress_level_set* and *features_stress_level_set*, which are hash tables containing *BOOLEAN* values for each key (name of the corresponding element). Another set of attributes (*clusters_stress_level*, *classes_stress_level* and *features_stress_level*) records the actual stress levels set. We overwrite the values in this latter set of hash tables when the user assigns a stress level to an element (from the more general to the more specific) only if the corresponding *BOOLEAN* value for that element is not **True**. Figure 9 shows a part of the code of routine *specific_stress_level_set* (called when the user sets the stress level for a cluster, class or feature), namely the part that deals with the case when the user sets the stress level for a class.

```
class_name := tree.selected_item.text

if user_set then
        classes_stress_level_set.replace (True, class_name)
end

classes_stress_level.replace (value, class_name)

feature_names := features_stress_level.current_keys
from
        i := 1
until
        i > feature_names.count
loop
        if feature_names.item (i) /= Void then
                aux_class_name := feature_names.item (i).substring (1,
                                        feature_names.item (i).index_of ('.', 1) - 1)
                if equal (aux_class_name, class_name) then
                                -- The current feature belongs to the selected class.
                        if not (features_stress_level_set @ feature_names.item (i))
                                        then
                                features_stress_level.replace (value,
                                                                feature_names.item (i))
                        end
                end
        end

        i := i + 1
end
```

Figure 9: Part of the code of routine *specific_stress_level_set* of class *TSG_STRESS_LEVEL_VERTICAL_BOX*.

Class *TSG_STRESS_LEVEL_VERTICAL_BOX* also has a *save_info* routine which records the stress level information in an instance of *TS_TEST_DATA*. As explained above, it needs to save both the actual stress levels for each element, and whether the user set them specifically or not.

Class *TSG_TEST_OPTIONS_VERTICAL_BOX* implements the box containing the elements for setting the various project options. All this class does is to use a few other boxes, each for setting an option, and display them vertically. We describe these boxes in the following paragraph.

TSG_ASSERTION_VERTICAL_BOX contains check boxes for each type of assertions that can be checked and its *save_info* routine records this information in an instance of *TS_TEST_DATA*. Class *TSG_TESTING_ORDER_VERTICAL_BOX* contains radio buttons for setting the testing order and it also has a *save_info* procedure which saves the desired testing order in a field of attribute *test_data* of type *TS_TEST_DATA*. *TSG_OUTPUT_DIR_VERTICAL_BOX* allows the user to select the output directory for the project (the directory in which we generate test results). *TSG_GENERICITY_VERTICAL_BOX* is similar to the class for setting the testing order: it contains radio buttons for the different levels of support for genericity and its *save_info* routine sets the corresponding attribute in *test_data*.

Additional dialogs

As already mentioned, TestStudio uses a few additional dialogs for various tasks, such as editing values for types and project management. We describe these dialogs below.

Some of them are involved in entering values for types other than the basic ones. These dialogs are *TSG_ADD_VALUE_DIALOG* and *TSG_EDIT_VIEW_VALUE_DIALOG*. Both of them use an object of class *TSG_EDIT_VALUE_VERT_BOX*, which contains the text fields for entering the name, return type and body of the feature. When creating this box, the two dialogs can set the text in some of the text fields. For example, *TSG_EDIT_VIEW_VALUE_DIALOG* will set the feature name and return type and disable them, so that the user cannot edit them.

Class *TSG_OPEN_PROJECT_DIALOG* contains the functionality for opening a project. It contains a text field where the user can enter the name of (and path to) the project file and a "Browse…" button which opens a dialog for selecting a file. The name and path to the project file will be displayed in the text field. When the user presses the "OK" button, it loads the project (with a progress bar in the dialog showing the status of the loading process), and calls routine *show_test_panel* on the object of class *TS_MAIN_WINDOW*, so that the main window of TestStudio shows the open project.

Class *TSG_SAVE_PROJECT_AS_DIALOG* contains the widgets and logic for saving a project under a different name and to a possibly different directory. It uses the same box as the dialog for creating a new project, in the first step of the wizard, i.e. an object of class *TSG_PROJECT_NAME_DIR_BOX*, which contains the text fields for setting the project name and directory. Before saving the project under the new name, procedure *save_project* checks that the user entered a non-empty name and a valid directory for it. Then, for the actual saving, it calls an agent that it receives as argument (routine *save_project_as* of *TS_MAIN_WINDOW*).

6.3. COMMAND LINE

We implemented the command line facility as a separate project. For test generation, compilation and running, it basically uses the same classes as the GUI version of TestStudio, but it needs to replace the classes for graphical elements with classes that work with command-line arguments.

The root class of the command line system (called *TS_CL_ROOT*) has only one routine (*execute*), which parses the arguments, and, depending on their content, decides which of the routines of the other classes to call, or, in case there is an error in the arguments supplied, prints an error message. The first argument must always be the name of the command that the user wants to execute, i.e. one of: "create_project", "generate_compile", "run", "get_results" or "help". The rest of the arguments depend on the first one.

When creating a project, the user must specify the name and directory of the project and the ace file. He can also specify files containing the names of clusters, classes and features that should be included in the test. Unless otherwise specified, all clusters (and all classes and their features) referenced in the ace file are included in the test. When he wants to generate and compile the test, the user must only indicate the project (.tsp) file containing the test criteria. To run the test, the user must only supply the project directory. Similarly, tor display test results, he must only provide the output directory of the project (which contains the results saved when running the test).

Procedure *execute* of class *TS_CL_ROOT* checks that the command specified by the user is a valid one, then checks the arguments of the command. If any of the arguments are not valid, it prints a message explaining the correct usage of the command line tool. Otherwise, depending on the command, it calls a routine of the corresponding class. However, *execute* does not perform any checks based on the semantics of the arguments. For instance, it does not check if the argument following the "run" command is the name or path to an existing directory. It just passes the arguments as they are, as strings, to the corresponding methods.

Class *TS_CL_PROJECT_GENERATOR* contains the functionality for creating projects. Its creation procedure *make* takes as arguments the name of the ace file, the project name and directory, and the names of the files specifying the clusters, classes and features that should be included in the test. All of these arguments are strings. Any and all of the last three can be **Void**, as the user does not have to specify any of these. If the user does specify files for clusters or classes, *make* calls the helper routine *get_strings*, which parses the files to get the names of the elements. The files must contain the name of each element on one line. To get information about the features, *make* calls routine *get_feature_names*. A specialized routine is necessary for features because the format of the file is different: each line begins with the name of the class, followed by a colon and then a comma-separated list of names of features belonging to that class. In the case of creation procedures, we need to distinguish between the two statuses that they can have (creators or normal procedures). Therefore, the name of a procedure which the user wants to include in the test as a creator must be followed by the string "(creation)".

Routine *generate_tsp_file* of class *TS_CL_PROJECT_GENERATOR* contains the code to create the project and to save it to a .tsp file. It first creates an instance of *TS_TEST_DATA* in which it will record all data of the project. Then it sets its attributes referring to the ace file, project name and directory. It creates an instance of *TS_TG_ROOT_GENERATOR* by calling its *execute* routine, which will parse the ace file to get the system information. Then it sets the test scope, by first including all clusters, classes and features and then selecting only the ones specified by the user through the files, if any. It sets the global stress level and the values used for basic types to the defaults. It also sets the level of assertion checking and the testing order to the default values. Finally, it creates an instance of class *TS_XML_GENERATOR* and calls its *save_project* routine, which will write the project information to a .tsp file.

Class *TS_CL_TEST_GENERATOR* contains the functionality for generating and compiling the test code. Its most important routine is *generate_compile_test*. It uses an instance of class *TS_XML_READER* to read in the project information from the project file, then it calls the *generate_test* procedure on an instance of class *TS_TG_ROOT_GENERATOR*, which will generate and compile the test code.

The main routine of class *TS_CL_TEST_RUNNER* is *run_test*, which launches the execution of the "generated_test.exe" file in the directory "generated_test_root\EIFGEN\F_code".

Class *TS_CL_RESULT_DISPLAYER* contains the functionality for creating HTML files for the test results and displaying them in a browser. Its main routine is *get_test_results*, which uses an object of class *TS_CSV_READER* and calls its *get_test_results* function to read the results from the CSV file. If an error occurs while reading the results, it prints a message; otherwise it creates an object of *TS_HTML_GENERATOR* and calls its *generate_html* routine to create the HTML files.

6.4. STORING TEST CONFIGURATIONS

We must save all data contained in a project (test scope, data and options, and project-related information) to reuse it again later. We decided to save this information in XML format, as a single file (with the ".tsp" extension, which stands for TestStudio Project). Below is an example of such a file, for a project called "integer_ref_test", which tests some of the features of class *INTEGER_REF*.

```
  <?xml version="1.0" encoding="ISO8859-1" ?>
- <project_settings>
      <project_name>integer_ref_test</project_name>
      <project_dir>D:\Testing\projects\integer_ref_test</project_dir>
       <ace_file>D:\Testing\test_libraries\librarybase.ace</ace_file>
   - <test_scope>
      - <cluster_selection>
            <cluster>kernel</cluster>
        </cluster_selection>
      - <class_selection>
         - <cluster>
              <name>kernel</name>
            - <classes>
                 <class_name>INTEGER_REF</class_name>
              </classes>
           </cluster>
        </class_selection>
      - <feature_selection>
         - <class>
              <name>INTEGER_REF</name>
      - <features>
          <feature_name>item</feature_name>
          <feature_name>sign</feature_name>
          <feature_name>set_item</feature_name>
          <feature_name>divisible</feature_name>
          <feature_name>exponentiable</feature_name>
          <feature_name>is_valid_character_code</feature_name>
          <feature_name>abs</feature_name>
          <feature_name>infix "+"</feature_name>
          <feature_name>infix "-"</feature_name>
          <feature_name>infix "*"</feature_name>
          <feature_name>infix "/"</feature_name>
          <feature_name>prefix "+"</feature_name>
          <feature_name>prefix "-"</feature_name>
          <feature_name>infix "//"</feature_name>
          <feature_name>infix "\\"</feature_name>
          <feature_name>infix "|..|"</feature_name>
          <feature_name>infix "|"</feature_name>
          <feature_name>infix ">"</feature_name>
          <feature_name>infix ">="</feature_name>
          <feature_name>max</feature_name>
          <feature_name>min</feature_name>
        </features>
      </class>
    </feature_selection>
  </test_scope>
- <test_data>
  - <user_defined_values>
    - <basic_types>
      - <integer>
          <value>-1</value>
          <value>0</value>
          <value>1</value>
          <value>2</value>
          <value>-2</value>
          <value>10</value>
          <value>-10</value>
          <value>100</value>
          <value>-100</value>
          <value>2147483647</value>
          <value>-2147483648</value>
        </integer>
      - <real>
          <value>-1</value>
          <value>0</value>
          <value>1</value>
          <value>2</value>
          <value>-2</value>
          <value>10</value>
          <value>-10</value>
          <value>100</value>
          <value>-100</value>
          <value>3.40282e+38</value>
          <value>1.17549e-38</value>
          <value>1.19209e-07</value>
        </real>
      - <double>
          <value>-1</value>
          <value>0</value>
          <value>1</value>
          <value>2</value>
          <value>-2</value>
          <value>3.1415926535897932</value>
          <value>-2.7182818284590452</value>
          <value>1.7976931348623156e+308</value>
          <value>2.2250738585072012e-308</value>
          <value>2.2204460492503132e-16</value>
        </double>
```

```
          - <boolean>
                <value>True</value>
                <value>False</value>
            </boolean>
            <character>0...64, 91...96, 123...255, 'a', 'Z'</character>
            <string>"a...z", void, "", "/01/.../255/", "x"</string>
        </basic_types>
      - <other_values>
          - <feature>
                <feature_name>f1</feature_name>
                <return_type>CHARACTER_REF</return_type>
              - <body>
                    <line>create Result</line>
                    <line>Result.set_item ('o')</line>
                    <line />
                </body>
            </feature>
        </other_values>
    </user_defined_values>
  - <stress_level>
        <global>3</global>
        <cluster_level />
        <class_level />
        <feature_level />
      - <parameters>
          - <stress_level>
                <level>1</level>
                <number_of_method_calls>10</number_of_method_calls>
                <test_in_descendants>False</test_in_descendants>
            </stress_level>
          - <stress_level>
                <level>2</level>
                <number_of_method_calls>20</number_of_method_calls>
                <test_in_descendants>False</test_in_descendants>
            </stress_level>
          - <stress_level>
                <level>3</level>
                <number_of_method_calls>30</number_of_method_calls>
                <test_in_descendants>False</test_in_descendants>
            </stress_level>
          - <stress_level>
                <level>4</level>
                <number_of_method_calls>50</number_of_method_calls>
                <test_in_descendants>True</test_in_descendants>
            </stress_level>
          - <stress_level>
                <level>5</level>
                <number_of_method_calls>100</number_of_method_calls>
                <test_in_descendants>True</test_in_descendants>
            </stress_level>
        </parameters>
    </stress_level>
</test_data>
- <test_options>
  - <assertions>
        <preconditions>True</preconditions>
        <postconditions>True</postconditions>
        <class_invariants>True</class_invariants>
        <loop_variants_and_invariants>False</loop_variants_and_invariants>
        <check_instructions>False</check_instructions>
    </assertions>
    <testing_order>2</testing_order>
    <genericity_support_level>2</genericity_support_level>
    <output_directory>
      D:\Testing\projects\integer_ref_test\test_results
    </output_directory>
  </test_options>
</project_settings>
```

We use two classes for creating and reading this file respectively: *TS_XML_GENERATOR* and *TS_XML_READER*. These classes are part of the *xml_parser* cluster.

We generate the file sequentially, by writing each tag and its content in order. Class *TS_XML_GENERATOR* only has one exported routine, called *save_project*, which receives an object of class *TS_TEST_DATA* and writes this information to an XML file. This procedure creates the project file in the directory of the project (giving it the name of the project), writes the XML header, the project-related information (project name and directory) and the path and name of the ace file (in corresponding enclosing tags). Then it calls some helper, specialized routines for saving the test scope, data, and options. These routines operate in similar manners: they write every piece of information to the file, enclosing it in tags, as the above example illustrates.

Class *TS_XML_READER* also has only one exported feature, called *load_project*. It sequentially reads information from the file it gets as argument, and records it in an instance of *TS_TEST_DATA*. At every step, it checks if the XML file is well-formed and if its tags are correct and in the right order. If it finds any error, it calls an agent that it has received as argument, passing it a string with information about the error. This is actually a procedure of class *TS_MAIN_WINDOW*, which displays the string it receives in a dialog. Thus, the user gets very specific information about the error encountered while parsing the project XML file. Procedure *load_project* uses a few helper routines for reading specific parts of the XML file, so that the process of loading project data is modularized.

6.5. TEST GENERATION AND EXECUTION

As described in section 5, the Test Wizard implements the functionality for test case generation. TestStudio only extends this functionality.

The main drawbacks of the test generation mechanism of the Test Wizard are that it uses only one creation procedure for each class (all instances of each class are created by calling the same procedure) and that it only instantiates generic parameters by using the constraining type (or *ANY*, in the case of unconstrained genericity). Both of these deficiencies seriously affect the coverage of the tests performed. Therefore, we concentrated on eliminating these drawbacks in the test generation.

TestStudio uses several creation procedures for instantiating classes. When the context generator has to create an object, it randomly selects one of the creation procedures available for that class. Out of all creation procedures for a class, we select only the ones which fulfill all following conditions:

- They are exported to *ANY*;
- They do not use an argument of the same type (Because the only object available initially for every type is *Void*, calling a creation procedure that takes it as argument would probably not produce an interesting new object. In fact, in most cases it would fail, because the preconditions of such features require the argument not to be *Void*.);

- They do not use pointers. (The policy that the Test Wizard uses regarding pointers is explained in more detail in section 7.2.)

This process of random selection is very similar to the one performed on modifiers. As soon as we have two objects of a certain type (we need two because, as mentioned above, the first object is always *Void*), we randomly call modifiers on them. Currently, TestStudio automatically tags as modifiers all routines without a return type (based on the *Command-Query Separation* principle [Meyer97]). In Eiffel, creation procedures have double status: they are both procedures used for instantiating classes and regular procedures. For this reason, TestStudio records them twice (if the export status allows it, of course) and gives the user the possibility of choosing to include them as either creation, or regular procedures, or both. This double status of creation routines means that they will also be selected as modifiers (since they don't have a return type). Figure 10 shows the generated code for creating an object of type *ARRAY [ANY]*.

```
create_arrayed_list_ANY_object is
            -- Create an object.
      local
            arrayed_list_ANY_variable: ARRAYED_LIST [ANY]
            failure: INTEGER
      do
            if (failure < 10) then
                  random.forth
                  inspect (random.item \\ 3)
                  when 0 then
                        create arrayed_list_ANY_variable.make (
                                                      context_integer)
                  when 1 then
                        create
                              arrayed_list_ANY_variable.make_filled (
                                                      context_integer)
                  when 2 then
                        create
                              arrayed_list_ANY_variable.make_from_array (
                                                      context_array_ANY)
                  end

                  arrayed_list_ANY_objects.force (arrayed_list_ANY_variable)
            else
                  print  (  "Couldn't  create  object  of  class  ARRAYED_LIST
[ANY]%N")
            end
      rescue
            failure := failure + 1
            retry
      end
```

Figure 10: Generated code to create an object of type *ARRAY [ANY]*.

Another important direction in extending the test generation capabilities of the Test Wizard was to improve its support for genericity, by using for generic parameters direct instances of any type conforming to the constraining type[5]. The user can choose one of three levels:

- using only instances of the constraining type (or of its effective descendants, if it is deferred);

[5] Here we also include the case of unconstrained genericity, with *ANY* being the constraining type.

- using basic types if they conform to the constraining type;
- using all types that conform to the constraining type.

In the second and third case, the context generator needs to create instances for the type with all possible generic parameters. When we receive a request for one of these objects, we randomly select an object of a conforming type. For instance, if the test application needs an object of type `ARRAYED_LIST [ANY]` and the user has selected the option for using basic types to instantiate generic parameters, we will randomly select an object of type `ARRAYED_LIST [ANY]`, `ARRAYED_LIST [INTEGER_REF]`, `ARRAYED_LIST [INTEGER_8_REF]`, `ARRAYED_LIST [INTEGER_16_REF]`, `ARRAYED_LIST [INTEGER_64_REF]`, `ARRAYED_LIST [REAL_REF]`, `ARRAYED_LIST [DOUBLE_REF]`, `ARRAYED_LIST [CHARACTER_REF]`, or `ARRAYED_LIST [BOOLEAN_REF]`.

Implementing this required several changes in the test generation mechanism. First, we had to modify how the context is built. Whenever we add a class with formal generic parameters to the context, we must also add classes that are generically derived from it. The routine that does this is `add_generically_derived_classes_to_context` from class `TS_TG_INFORMATION_HANDLER`. It first determines the types that conform to the constraining type of each generic parameter, and then adds them to the context. We also add to the context an instance of `TS_OBJECT`[6] for each of the possible combinations of generic parameters. We also need to record for each object which its conforming objects are. Thus, we add the `conforming_objects` attribute to class `TS_OBJECT`, which is an `ARRAYED_LIST [TS_OBJECT]`.

When we add a feature to the context, we also add its arguments. Here again, we must check if each argument has generic parameters, and if so, add the types conforming to the argument type to the context. To achieve this, procedure `add_feature_to_context` of class `TS_TG_INFORMATION_HANDLER` calls routine `add_generically_derived_types_to_context`, which works similarly to `add_generically_derived_classes_to_context`. It first determines the types that can be used for the actual generic parameters of the type provided as argument, adds the classes of these types and their instances to the context, and then adds these objects to the list of conforming objects of the initial type's object.

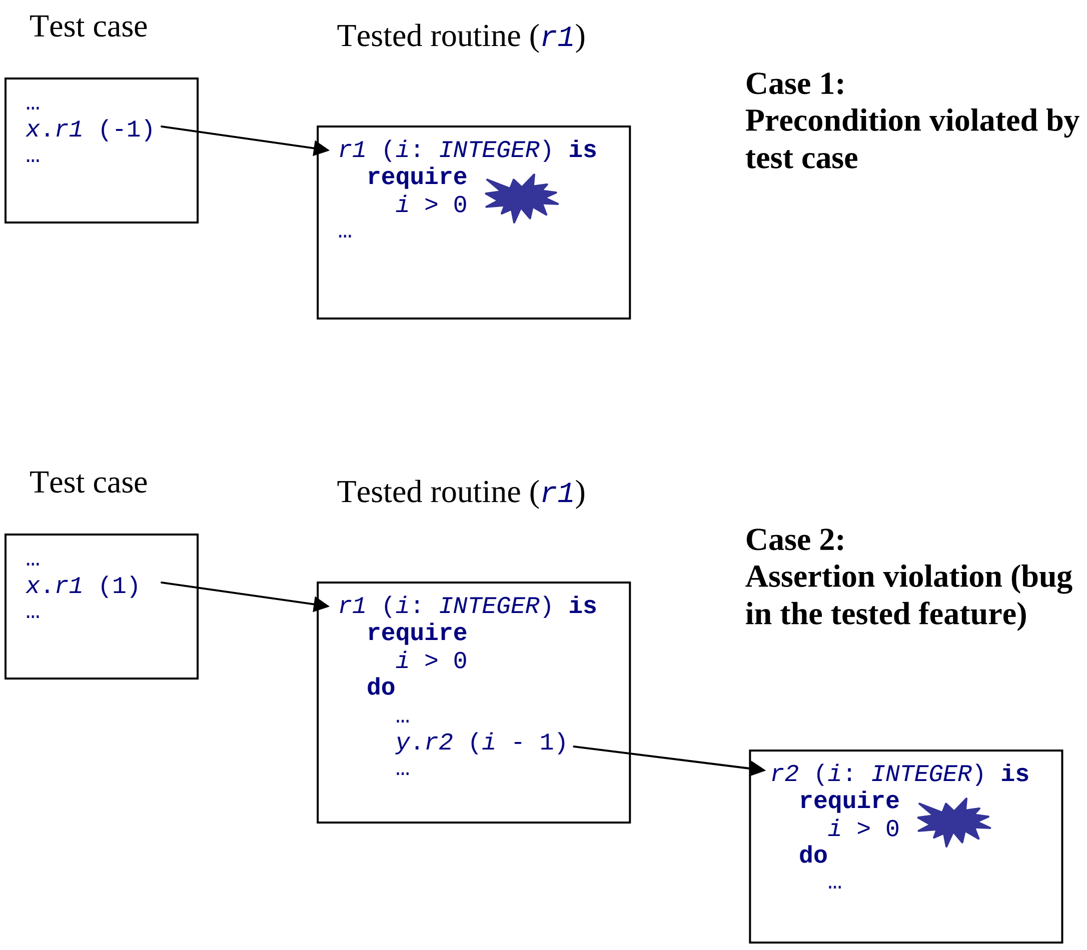
We also had to change the generation of access methods[7] for the context, because now we don't necessarily return an object of that type, but we can also return any object whose actual generic parameters conform to the generic parameters of the requested object. We do the selection randomly. To generate it, we use the `conforming_objects` attribute of class `TS_OBJECT`.

There were some other aspects of the test generation that had to be improved. One of them was reporting of precondition violations. We must distinguish between two cases[8]:

- when the test case (directly) calls a feature, it might violate its precondition because of the values used;
- a precondition violation can also occur at any other place in the call chain, for instance if a tested feature (`r1`) calls another routine (`r2`) and this call violates `r2`'s precondition.

[6] The class used by the Test Wizard for storing meta-information about objects in the test context.
[7] Access methods are called on the context in the generated test whenever an object of a certain type is needed, and they randomly return one of the objects in the container for that type.
[8] This idea was first suggested by Per Madsen, Aalborg University, Denmark.

Figure 11 depicts these two cases. The first is a problem in the test case, whereas the second is a bug in the tested routine, and should be reported as such. The Test Wizard did not make this difference, which is clearly an error. We fixed this in TestStudio, so that, when we generate test result information, the first case is reported as “precondition violation”, and the second as “assertion violation”.


Test case
Tested routine (r1)
Case 1:
Precondition violated by test case
Test case
Tested routine (r1)
Case 2:
Assertion violation (bug in the tested feature)

```
…
x.r1 (-1)
…
```

```
r1 (i: INTEGER) is
  require
    i > 0
…
```

```
…
x.r1 (1)
…
```

```
r1 (i: INTEGER) is
  require
    i > 0
  do
    …
    y.r2 (i - 1)
    …
```

```
r2 (i: INTEGER) is
  require
    i > 0
  do
    …
```

Figure 11: Distinguishing between preconditions violated by the test case and by a feature under test.

To make this distinction, we had to change the generated **rescue** clause of routine *run* of class *TSGEN_TEST*. This class is deferred and all the classes that are generated for testing each feature inherit from it, effecting its *test_feature* routine (by calling the corresponding feature). All that *run* does is to call *test_feature*, and then take care of exception handling. To have access to detailed information about the exception that the tested feature might have thrown, class *TSGEN_TEST* is an heir of *EXCEPTIONS*. The **rescue** clause of feature *run* tests the *original_exception* attribute to get the type of the exception. If it was a precondition violation, we have to check *recipient_name*. If it is equal to the name of the tested feature, then we are dealing with case 1, so we report a precondition violation. Otherwise, we have found a bug in the tested feature, and we report an assertion violation.

Another disadvantage of the Test Wizard is that it doesn’t test creation procedures. To be more precise, it doesn’t test them with the creation status (as shown above, we add creation procedures to the test scope both as creation and as regular routines). We considered this to be an error, so we added testing of creation procedures as part of the extension of the test generation mechanism in TestStudio.

TestStudio cannot currently handle infinite loops in the features it tests. If the execution of a feature does not finish, the execution of the test doesn't finish, so the TestStudio window becomes blocked. There is no way of interrupting the execution of the test as a whole or of the feature. This drawback is also present in the Test Wizard.

We tried several approaches for eliminating this disadvantage, but the work is not finished yet. The idea we wanted to implement was to stop the execution of a feature after a certain time, which could be set by the user or could be a default value, such as one or several minutes. This means that we must launch the execution of the feature in a separate thread. We time the execution of the thread and stop it if it does not finish before the set time interval elapses.

To implement this, we first tried using the EiffelThread library. However, there is no way of stopping a thread in this library. We then tried to use e-POSIX [DeBoer04], the Eiffel library providing access to the POSIX API. The problem with this was that interrupting the execution of a thread at any random point can cause runtime panic. Another possible solution that we looked at was to use external calls to C routines, which would have allowed us to use the thread mechanism from C. Although this seemed like a possible solution, we did not have time to fully implement and test it.

Future versions of TestStudio should fix this problem, as it can be a serious drawback in automatic test execution.

In the Test Wizard, the user has to manually set the paths to the Eiffel compiler and to finish freezing (in the corresponding attributes of class *TS_TG_CODE_GENERATOR*). TestStudio eliminates this disadvantage, by using the value associated with the $ISE_EIFFEL environment variable. The locations of the compiler and finish freezing executables are fixed relative to the ISE Eiffel installation directory. Therefore, assuming that the user has set the $ISE_EIFFEL environment variable, from the value of this variable we can deduce the paths to the compiler and to finish freezing.

7. ADVANTAGES AND LIMITATIONS OF TESTSTUDIO

7.1. BENEFITS OF USING TESTSTUDIO

TestStudio is an environment for **automatic generation of tests** for contract-equipped classes. The presence of contracts is of utmost importance for the test generation process. By taking advantage of the information contained in contracts, TestStudio can automatically decide if a feature fulfills its task. This is the greatest advantage that TestStudio brings: the testing process is completely automatic; the user only has to specify what he wants to test, and TestStudio performs the rest of the process (creating tests, compiling them, running them and then displaying the result information). Traditional approaches to testing require the user to write at least the tests and the test oracles. Writing the test code can be automated, but, without contracts, there is no way for the tool to know if the tests are successful (if the tested features work according to specification) or not, so the user is required to specify this manually.

TestStudio implements the idea of push-button testing: once the user has specified the test scope, test generation and compilation is done on the push of a button. Running the test and then getting the test results also require only a button-push. Test generation and running is completely automatic, and this is the greatest advantage of using TestStudio.

However, the tool must allow the user to **adapt the testing process** to his own needs and preferences. This is especially important since the tests are generated automatically, without any intervention from the user; therefore, the user must be able to adjust the test configuration before the actual code generation begins.

TestStudio allows the user to set a wide range of parameters of the test configuration:

- test scope: which clusters, classes, and features it will test – there are no restrictions here, except that the ace file that the user supplies must include all tested elements (and any other elements they need);
- test data:
  - o what values TestStudio will use for basic types (*INTEGER*, *REAL*, *DOUBLE*, *BOOLEAN*, *CHARACTER*, *STRING*) and for other types (however, for other types, TestStudio will also randomly generate objects, in addition to those that the user creates);
  - o the stress level associated with each cluster, class and feature (this actually maps to two other parameters: the number of calls performed on a feature and whether we also test it in descendants);
- various options:
  - o testing order;
  - o which assertions we monitor in the test;
  - o level of support for genericity.

All these parameters allow great flexibility in setting up a configuration for which TestStudio then generates the test code. The user does not have to set all these options, because TestStudio provides defaults for all of them.

Naturally, the graphical user interface for setting these options has to be intuitive and easy to use. The studio-like design of our application accomplishes this task. The user can navigate between the various parameters using a browser. Selecting items in the browser displays different panels, for setting one or several related parameters of the test configuration. Some of these panels communicate between them if the information set in one influences the data displayed in another. For example, if the selection of clusters included in the test changes, the panels for selecting classes and features also change, because we include all classes (and all their features) by default. In addition to the GUI, TestStudio also has a command-line version.

Another great benefit that TestStudio brings is the possibility of saving test configurations and using them again later. For this, it uses the notion of “project”. A project incorporates all the above-mentioned data about a test and it can be saved and reloaded.

Although the testing process is completely automatic, it must be thorough and produce relevant information. To achieve this, TestStudio uses a wide range of values on which it runs tests, to ensure that it covers as many cases as possible. The user provides the values used for basic types (or can use the defaults that TestStudio supplies), and for the other types the context creator generates objects randomly (by first calling random creation procedures and then random modifiers on the objects just created). The user can also specify values for non-basic types. Although this method of creating objects has some disadvantages (described in detail in section 8.3) and does not guarantee the diversity of the test data, practice has shown that we actually test a wide range of cases, some of which developers do not think of including in the tests they write. (See section 8 for a discussion of test results obtained using TestStudio.)

The information the user gets about test results is also important. The user must know at least if the test of a feature failed or succeeded, and, in the case of failure, what was the reason for it. TestStudio offers this information: the test results it saves contain, for each feature, the number of feature calls which produced no exception, a precondition violation, an assertion violation, another exception, the number of calls that were possible catcalls and the number of calls attempted on a void target object. For the features that fail, if the cause of the failure is an assertion violation, we also record the tag of that assertion. However, saving test results can still be improved, as shown in section 7.2.

The level of support for genericity that TestStudio provides is advanced. The user can choose between three levels (as explained in section 6.5). If he chooses the highest level, objects of any type conforming to the constraining type will be used for actual generic parameters. In this case, when a request for an object of a generically-derived type arrives, we randomly select an object of a conforming type. Again, the reason for this is to try to test as many cases as possible.

7.2. LIMITATIONS

Future versions will have to improve several features of TestStudio, especially regarding the test generation process. An important point is that we cannot automatically test features in descendants of a class, unless the user explicitly includes them in the test. This is a serious disadvantage, because of polymorphism and dynamic binding. The user should have the option of turning on or off the testing of features in descendant classes.

When the user specifies values for non-basic types, we also generate random values for those types. When we need an object of that type during test running, we randomly select one of the available objects. This means that there is actually no guarantee that we will use the objects the user supplied in the test. Therefore, the user should have the possibility to enable and disable automatic generation of objects for the types for which he has already defined values. If he disables automatic generation, the only objects used in the test will be the ones he creates. This gives a further degree of control of the testing process. The current version of TestStudio does not allow disabling automatic generation of objects. The panel which allows the user to enter values for basic and non-basic types in the TestStudio main window contains a check box for this purpose, but the test generator does not support the required functionality, so the check box is always set and disabled, so that the user cannot change its setting.

Another serious drawback of TestStudio is that it cannot save the randomly generated values used in a test. If we run a generated test several times, the same values will be used, but, if we generate the test again for the same configuration, new values will also be generated, making it impossible to run the exact same tests. Being able to save these values is also important for regression testing. If anything changes in the software and we want to run the same tests on it, this will require a new generation of the test code, and, as shown above, other values will be used. This means that we are actually not running the same tests, so we are not doing regression testing. However, if we were able to save these values, this is all we would need to have real regression testing. All the other necessary support is already there in TestStudio.

TestStudio cannot generate tests if the input ace file lists several clusters with the same name (even if the names of the parent clusters are different). Therefore, the user needs to pay special attention to the way they name clusters, so that there are no name clashes.

A feature which would be useful in TestStudio is an “import” facility, allowing the user to get some settings from a project and reuse them in another project. Thus it would be possible to set the test scope by importing it from another project, to use the same values (for basic and non-basic types) as in another project, to copy the stress levels (if the test scopes match) or the stress level parameters used in another project, or to set the same test options as in another project.

In the current version of TestStudio, we map stress levels to two parameters: the number of method calls and whether or not we test features in descendants. Another parameter that is connected to the notion of stress level is the number of objects of each type that we create. Currently, the user cannot set this number. A default value is used for all types in the context. It would be important for the user to be able to set it, possibly as part of the stress level, if not as a separate parameter.

Future versions can add various improvements to TestStudio in terms of the degree of control it allows, in order to make the testing process even more flexible. For instance, it should be possible to specify which assertions are checked on a cluster- or class-level, so that the user is able to check different types of assertions for different classes or clusters. Finer-grained control of the level of support for genericity would also improve the testing process: the user would be able to assign different levels to different classes (or clusters), depending on what he wants to test more thoroughly.

TestStudio cannot handle nested genericity. Although nested genericity is not too common in practice (in the EiffelBase library, there is only one class which uses it, plus its descendants), this can still be a serious disadvantage, which later versions of TestStudio need to fix.

Currently, the test results that TestStudio saves do not contain any information about the objects (target objects for feature calls and argument objects) for which calls fail. This is valuable information. Without it, the user must actually debug the generated code to see which values caused the failure, identify the bug and then fix it. Therefore, future versions of TestStudio should save at least this information, if not even more data about the state of the system when the failure occurred.

A feature that would be useful in TestStudio is the possibility of displaying diagrams for test results, so that the information gathered from the test results is represented in a graphical manner. For instance, we could have charts showing the number of features that passed the test and the number of features that failed. We could also show how many feature calls triggered precondition violations, opposed to how many were valid. This kind of information can easily be represented with graphs, charts or diagrams, so that the user can have a quick overview of the obtained results.

Limitations "inherited" from the Test Wizard

There are several limitations of the Test Wizard which TestStudio inherits and does not fix. Some of them are inherent to automatic testing, others we can eliminate.

TestStudio cannot test a few classes like *FILE*, *POINTER*, *EXCEPTIONS* and their heirs. For the first two, the reason is that it is dangerous to randomly call their routines. Users probably would not want TestStudio to start creating and deleting random files on their systems. Randomly allocating pointers and randomly calling routines on them is also dangerous and very likely to fail. TestStudio tries to avoid pointers as much as possible, by excluding creation procedures and modifiers which use them. However, it is allowed to test routines having pointer arguments and routines calling other routines which use pointers. This will not be a problem anymore once we can turn off random generation of values, so that only the values given by the user are used for certain types. The problem with class *EXCEPTIONS* is only its *die* routine, because TestStudio terminates when it calls that routine. The user can still test the class if he excludes procedure *die* from the test.

TestStudio cannot test expanded types. The reason for this is that routines which have an anchored type as argument can cause panic if they receive an expanded type for the argument. A more detailed explanation of this is available in [Greber04], section 5.2.

TestStudio cannot handle features calling C routines. If such a feature fails, it causes runtime panic, and TestStudio cannot recover from it.

If a routine goes into an infinite loop, TestStudio also cannot recover. Of course, the user still has the option of debugging the generated code and seeing where the loop occurs, but the studio provides no support for this. It cannot detect infinite loops and take measures to stop their execution. We describe some work done on this (but not completed) in section 6.5.

TestStudio does catcall checking only if the anchor refers to an argument of the routine or to **Current**. This means that it overlooks the case of anchored types referring to a feature of the enclosing class.

TestStudio automatically selects modifiers for each class by choosing routines with no return type (according to the command-query separation principle [Meyer97]). However, some of these routines do not modify the state of the target object. The code of the routines could be analyzed to determine if they actually modify the state of the object.

8. RESULTS

8.1. TEST RESULTS

We tested TestStudio by running it on some Eiffel libraries (ISE EiffelBase, EiffelTime, EiffelLex, EiffelParse) and on smaller examples we created. This showed some of the limitations of TestStudio listed in section 7.2 and some advantages and disadvantages of automatic test generation (we discuss disadvantages in section 8.3).

From running these tests, we can say that the test generation and compilation works well, but running automatically generated tests poses problems (see section 8.3). Nevertheless, automatic generation of tests is a big advantage because the user can manually run the generated code and see, if he encounters problems, what the cause is and remove it. We discuss possible improvements and extensions of TestStudio in detail in sections 7.2 and 9.

8.2. EXAMPLES OF FOUND BUGS

We tested some Eiffel libraries with TestStudio and found bugs. As developers had thoroughly tested these libraries, TestStudio's ability to find bugs proves the value of automatic test generation.

Many of the bugs we discovered had to do with using "extreme" values for types, such as the minimum and maximum values for integers. We provide an example of such a bug below.

The tests we ran often fail because of the failure of creation procedure *`make`* of class *`ARRAY`*, whose code is shown in Figure 12.

```
make (min_index, max_index: INTEGER) is
            -- Allocate array; set index interval to
            -- `min_index' .. `max_index'; set all values to default.
            -- (Make array empty if `min_index' = `max_index' + 1).
      require
            valid_bounds: min_index <= max_index + 1
      do
            lower := min_index
            upper := max_index
            if min_index <= max_index then
                  make_area (max_index - min_index + 1)
            else
                  make_area (0)
            end
      ensure
            lower_set: lower = min_index
            upper_set: upper = max_index
            items_set: all_default
      end
```

Figure 12: Creation procedure *make* of class *ARRAY*.

The bug in this routine appears, for example, when we call it with values -2147483648 (the minimum value an integer can have) and 10 for arguments *min_index* and *max_index*, respectively. The precondition is fulfilled, because -2147483648 <= 10 + 1, so *make* is executed. Since -2147483648 <= 10, we will execute the call to *make_area* with the argument given by *max_index – min_index + 1*. However, when this number is calculated, the result exceeds the maximum representable integer number. Consequently, it is interpreted as being a negative integer and *make_area* is called with the value -2147483639 as argument.

Figure 13 shows the code of feature *make_area* of class *TO_SPECIAL [T]*.

```
make_area (n: INTEGER) is
            -- Creates a special object for `n' entries.
      require
            non_negative_argument: n >= 0
      do
            create area.make (n)
      ensure
            area_allocated: area /= Void and then area.count = n
      end
```

Figure 13: Routine *make_area* of class *TO_SPECIAL [T]*.

The precondition of *make_area* states that the argument it receives should not be negative. Therefore, when feature *make* of class *ARRAY* calls *make_area* with value -2147483639, the precondition is violated. However, this is not the fault of *make*'s client, because the precondition of *make* is fulfilled. Thus, we have found a bug in creation procedure *make* of class *ARRAY*.

One way to correct this bug would be to change the precondition of *make* to *max_index – min_index + 1 >= 0*. In this case, values -2147483648 and 10 would not fulfill *make*'s precondition, so the user would not be able to call it with these values.

We found a similar bug while testing class `INTEGER_REF`. The test results that TestStudio saved showed that feature `infix “//”` failed because one of the calls generated an exception and feature `infix “|…|”` failed because two calls produced assertion violations.

We will look at feature `infix “//”` first. Its code is shown in Figure 14.

```
infix "//" (other: like Current): like Current is
			-- Integer division of Current by `other'
		require -- from NUMERIC
			other_exists: other /= Void
			good_divisor: divisible (other)
		do
			create Result
			Result.set_item (item // other.item)
		ensure -- from NUMERIC
			result_exists: Result /= Void
		end
```

Figure 14: Routine `infix “//”` of class `INTEGER_REF`.

This routine throws an exception when attribute `item` of the `INTEGER_REF` target object is -2147483648 and `other.item` is -1. When calling `Result.set_item (item // other.item)`, an unhandled exception is generated. The reason is that the result of dividing `item` by `other.item` should be 2147483648, but this number is greater than the maximum representable integer (2147483647).

Routine `infix “|…|”` also produces an assertion violation when it is called with the maximum value for `INTEGER`. Figure 15 shows its code.

```
infix "|..|" (other: INTEGER): INTEGER_INTERVAL is
			-- Interval from current element to `other'
			-- (empty if `other' less than current integer)
		do
			create Result.make (item, other)
		end
```

Figure 15: Routine `infix “|…|”` of class `INTEGER_REF`.

When `infix “|…|”` is called with a value of 2147483647 for `other` and the value of the `item` attribute of the target object is -1, the feature produces a violation of the class invariant of `INTEGER_INTERVAL`, more precisely of the assertion with tag `non_negative_count`. This invariant clause is inherited from `INDEXABLE` and states that `count >= 0`. Figure 16 shows the definition of `count`.

```
count: INTEGER is
            -- Number of items in interval
        do
            check
                finite: upper_defined and lower_defined
            end
            if upper_defined and lower_defined then
                Result := upper - lower + 1
            end
        ensure then
            definition: Result = upper - lower + 1
        end
```

Figure 16: Function `count` of class `INTEGER_INTERVAL`.

What happens is that routine `infix "|..|"` tries to create an integer interval from -1 to 2147483647, but the size of this interval (2147483647 – (-1) + 1) exceeds the maximum value for `INTEGER`, so that again, it is interpreted as a negative number. Therefore, the invariant of class `INTEGER_INTERVAL` is broken.

8.3. PROBLEMS ENCOUNTERED WHEN RUNNING TESTS

As outlined in section 8.1, although test generation and compilation work well, running the automatically generated tests poses several problems, mainly due to using completely random values.

A problem that arises constantly has to do with routines that allocate memory. When they need to allocate very large amounts of memory, they often cause runtime panic. An example is feature `force` of class `ARRAY`, whose code is shown in Figure 17.

```
force (v: like item; i: INTEGER) is
            -- Assign item `v' to `i'-th entry.
            -- Always applicable: resize the array if `i'
            -- falls out of
            -- currently defined bounds; preserve existing
            -- items.
        do
            if i < lower then
                auto_resize (i, upper)
            elseif i > upper then
                auto_resize (lower, i)
            end
            put (v, i)
        ensure
            inserted: item (i) = v
            higher_count: count >= old count
        end
```

Figure 17: Procedure `force` of class `ARRAY`.

When *force* is called with 2147483647 as the value for its *INTEGER* argument, *lower* having value 1, it will need to resize the array, so that its indexes go from 1 to 2147483647. For this, it calls *auto_resize* (1, 2147483647), which causes panic when *auto_resize* cannot allocate so much memory for the array. As we showed in section 7.2, TestStudio cannot recover from features which cause panic, so running the test fails. This is something that happened often in the tests we ran for features similar to *force*, which have to allocate memory. One can restrict the values used for type *INTEGER* to some smaller numbers, so that these features do not have to allocate very big chunks of memory. However, this means that only these values will be used for integers when testing other features.

We got multiple precondition violations when running the tests. Naturally, this is bound to happen if we use completely random values. However, since we randomly generate objects, it might happen that none of the objects we generate satisfies the precondition of a feature we have to test. Consequently, we cannot test that feature. We discuss this problem and possible solutions to it in section 9.

9. DIRECTIONS FOR FUTURE WORK

We described some limitations of TestStudio in section 7.2. Those were close to the implementation level. In this section we discuss other features which can be improved or added to TestStudio. Some of them are topics for on-going research.

As shown in section 8.3, one of the biggest problems when using TestStudio arises when running the tests and using totally random values. Such values can cause various problems when calling some features, such as when memory allocation is involved or when the precondition of a feature is not met by any of the available objects. Furthermore, some values for a type can be more interesting for testing a certain feature, while others are more useful for testing another feature. Therefore, we should adapt object creation to the needs of the tested features.

In the current version of TestStudio, we generate objects completely randomly. When we need an object of a certain type, we select it from a pool of available objects of that type. This selection is also completely random. No information about the called feature is used either in the creation or in the selection. The random nature of the process causes all the problems listed above.

The solution is to have an "intelligent" object factory, which can adapt object creation and selection to the requirements of the tested features. This kind of object creator would be able to analyze the precondition of each feature and return objects which satisfy it. In addition, it would also be able to produce "interesting" objects for test cases, objects which could bring a lot of information if used in the tests.

As mentioned in section 8.3, a lot of precondition violations occur when running the automatically generated tests. This means that many useless calls are made. In some cases, we can't even test a feature because none of the calls fulfills its precondition. The "intelligent" object creator could solve both problems, by looking at the preconditions and supplying only objects that fulfill them. This is an area of research that is currently being pursued by Andreas Leitner at the Technical University of Graz, Austria. The goal is to provide TestStudio with a means of creating objects that do not violate the preconditions of features.

An idea related to having "interesting" objects to run tests on was introduced by Per Madsen, from Aalborg University, Denmark [Madsen04]. This idea is based on using equivalence partitioning to determine "classes" (categories) of objects on which to run tests. For instance, if input values for a feature must be in the interval [*a*..*b*], we could define the categories of values as being

- values less than *a*;
- values between *a* and *b*;
- values greater than b.

Hence, we should test one value that is less than *a*, one that is between *a* and *b*, one that is greater than *b*, and also *a* and *b*. The user can specify partitions or we can deduce them from class invariants.

Another direction for the further development of TestStudio is going from black box to white box testing. The testing strategy that the studio currently uses is black box. However, knowledge about the internal structure of the software can bring great benefits, such as the ones listed above: parsing of preconditions so that we can create objects that satisfy them, parsing class invariants in order to determine partitions. White box testing would also allow us to check the path coverage of the tests and adapt them to test (if possible) all branches of the code. This would be an important extension of TestStudio because currently we cannot tell anything about the coverage of the tests we run.

10. USER MANUAL

10.1. SYSTEM REQUIREMENTS

Currently, the only operating system that TestStudio supports is Windows. We have only tested it on Windows XP, but expect that it should also run on Windows 2000. Future versions will be available for other platforms too.

Version 5.4 (or later) of EiffelStudio is required to run TestStudio. This version is needed for assertion checking to be enabled and disabled correctly [Greber04].

10.2. INSTALLATION

To install TestStudio, you need to follow the instructions below:

1. Download the file “TestStudio.zip”. It contains:
    - the source code of TestStudio (for both the GUI and command line versions) in the “src” directory;
    - executables for the GUI and command line versions in the “bin” directory;
    - the user manual in the “doc” directory;
    - the Gobo Eiffel library under the “library” directory;
    - file “License.txt” containing the license for the software;
    - file “Readme.txt” containing important information about TestStudio, its installation and the contents of the delivery;
    - file “Release_notes.txt” containing information about the requirements for running TestStudio.
2. Unzip its content to a directory of your choice and set the $TEST_STUDIO environment variable to point to that directory.
3. Unzip the package “gobo33.zip” provided with this release and set the $GOBO environment variable so that it points to the directory where you unzipped the file.

10.3. HOW TO USE TESTSTUDIO

10.3.1. HOW TO USE THE GUI VERSION OF TESTSTUDIO

Launching TestStudio

When you launch TestStudio, its main window appears (see Figure 18). There is no open project, so you have to either create a new project or open a previously saved project.

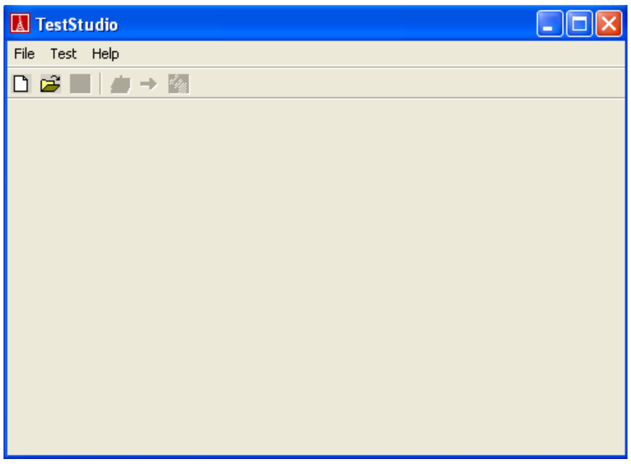
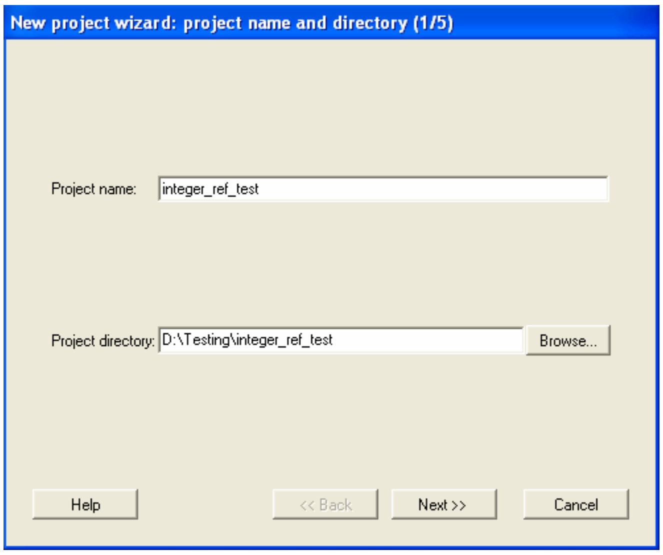


Figure 18: Main window of TestStudio, when no project is open.

Creating a new project

To create a new project, you can use either the “New” option under the “File” menu, the corresponding toolbar button, or the Ctrl+N shortcut keys. This launches a wizard for creating a project.

The first dialog of the wizard asks you to enter the project name and the project directory (see Figure 19). By default, the project directory is the current directory. You can change it either by typing in the path to the desired directory or by choosing the directory from a dialog, launched by pressing the “Browse” button. To go to the next dialog of the wizard, you must press the “Next” button. The wizard performs some validity checks before going on to the next dialog: the project must have a non-empty name and an existing directory. If these conditions are not fulfilled, the wizard brings up a dialog telling you what is wrong and it does not display the next dialog until the entered information is correct.

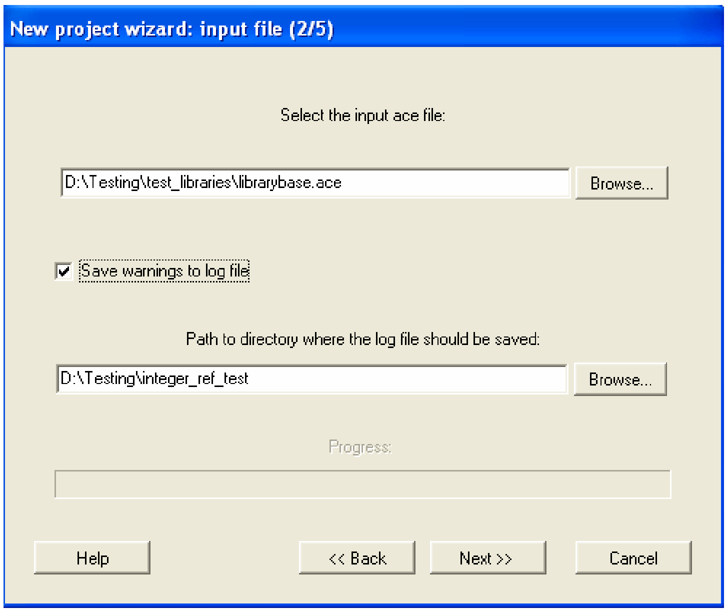

New project wizard: project name and directory (1/5)

Project name: integer_ref_test

Project directory: D:\Testing\integer_ref_test

Figure 19: First dialog of the wizard for creating a new project.

The second dialog asks you to indicate the input ace file containing the clusters that you want to test and any other clusters that they need (see Figure 20). You can type in the full path to this file in the text field or use the "Browse" button. This dialog also allows you to specify whether you want to save warnings to a log file. If you select the corresponding check box, the text field for entering the path to the directory where the log file should be saved is enabled. By default, this directory is the project directory. You can change it (only if you have selected the check box) by either typing in the path to the directory or by using the "Browse" button. The name of the log file is fixed ("test_studio_log.txt"). TestStudio will create this file under the directory that you specify.


New project wizard: input file (2/5)

Select the input ace file:

D:\Testing\test_libraries\librarybase.ace

[✓] Save warnings to log file

Path to directory where the log file should be saved:

D:\Testing\integer_ref_test

Progress:

Figure 20: Wizard dialog for entering the ace file.

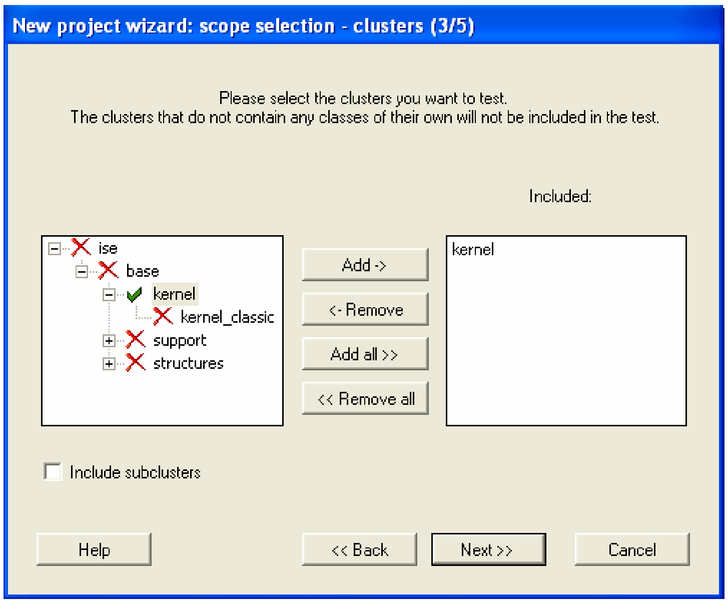
The only warnings that TestStudio currently produces are related to the classes that it cannot test, which it determines when parsing the ace file. TestStudio cannot test a class if either of the following occurs:

- *gelint* finds errors when parsing or compiling it;
- it is obsolete;
- it has no creation procedure exported to *ANY*.

Therefore, it you select the option, information about the excluded classes will be saved to the log file.

The progress bar in the lower part of the dialog is enabled when you press the "Next" button. If the information entered in this dialog is valid (the ace file exists and, if the check box is selected, the directory for the log file is valid), *gelint* parses the ace file to get the system information. It updates the progress bar according to the progress of the compilation.

When compilation is finished, the wizard displays the next dialog. Figure 21 shows this dialog. This and the subsequent wizard dialogs allow you to define the test scope. The current dialog deals with the clusters that will be included in the test. By default, all clusters in the given ace file are included.

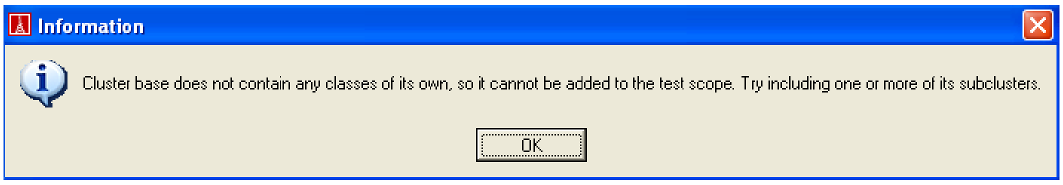

New project wizard: scope selection - clusters (3/5)

Please select the clusters you want to test.
The clusters that do not contain any classes of their own will not be included in the test.

Figure 21: Wizard dialog for selecting the clusters that will be tested.

The box on the left side of this dialog lists all available clusters (the ones included in the ace file), in a tree-like structure. The icons next to the cluster names indicate their status: the check sign marks included clusters, whereas the "X" sign marks the rest of the clusters. Included clusters are also recorded in the list on the right side of the dialog. You can add clusters to the included list or remove clusters from it by using the "Add", "Add all", "Remove" and "Remove all" buttons. Additionally, if you have selected the "Include subclusters" check box, when you select a certain cluster and then press "Add", all the subclusters of that cluster are also included.

You cannot include test clusters which have no classes of their own. In the example shown in Figure 21, clusters *ise* or *base* can't be included. If you select one of them and press "Add", a dialog similar to the one shown in Figure 22 is displayed. The reason for this is that it does not make sense to include such a cluster without any of its subclusters that actually contain classes because there is nothing to test.

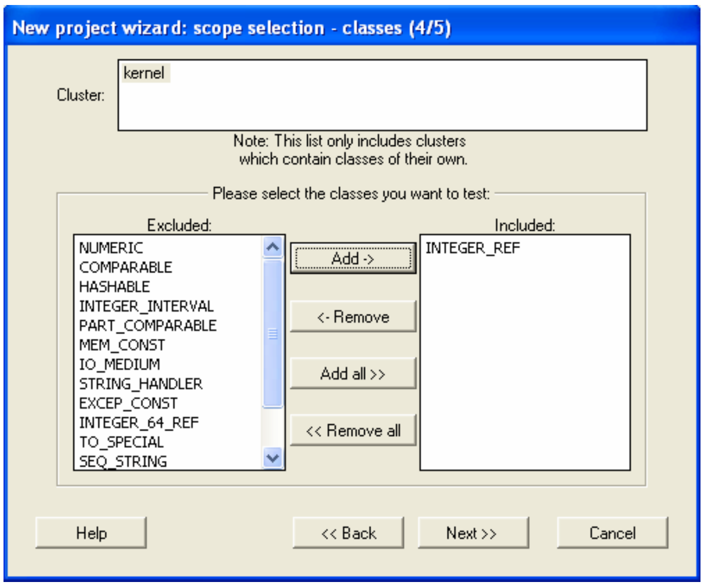

Information

Cluster base does not contain any classes of its own, so it cannot be added to the test scope. Try including one or more of its subclusters.

Figure 22: Information dialog displayed to the user when attempting to include a cluster with no class of its own.

When you press the "Next" button, the dialog checks that at least one cluster is included and that at least one of the included clusters contains classes of its own. If one of these conditions is not fulfilled, a dialog is displayed telling you what the problem is and how to fix it. If the check succeeds, the next dialog of the wizard appears.

The fourth dialog of the wizard (shown in Figure 23) allows you to select the classes that will be included in the test. The list in the upper part of the dialog window contains the clusters included at the previous step. When you select one of these clusters, its classes are displayed in the lower lists. By default, all classes of all clusters are included.


New project wizard: scope selection - classes (4/5)

Cluster: kernel

Note: This list only includes clusters which contain classes of their own.

Please select the classes you want to test:

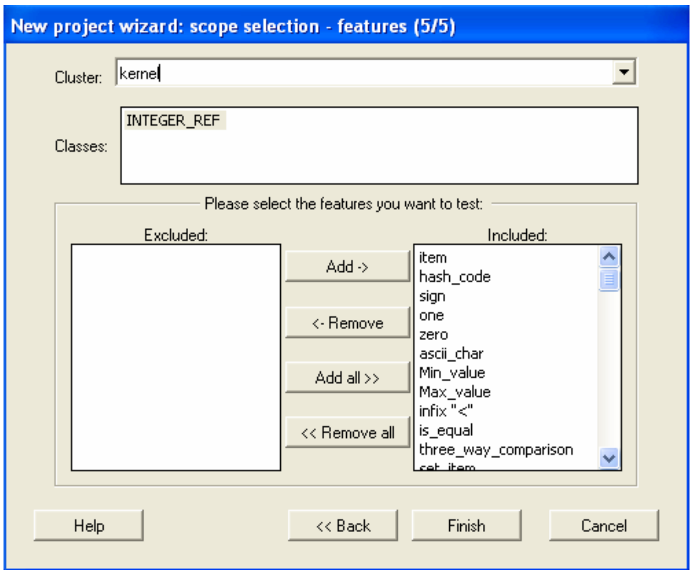
Excluded:
NUMERIC
COMPARABLE
HASHABLE
INTEGER_INTERVAL
PART_COMPARABLE
MEM_CONST
IO_MEDIUM
STRING_HANDLER
EXCEP_CONST
INTEGER_64_REF
TO_SPECIAL
SEQ_STRING

Included:
INTEGER_REF

Figure 23: Wizard dialog for selecting the classes to be included in the test.

The lower two lists in the dialog contain the excluded and included classes. To move classes between these lists, use the “Add”, “Add all”, “Remove” and “Remove all” buttons. When you press “Next”, the wizard checks if you have included at least one class in the test. If this is not the case, it displays a dialog informing you about the problem; otherwise, it shows the next dialog.

The final dialog in the wizard (Figure 24) lets you select the features that you want to test. By default, all features of all classes under test are included.


New project wizard: scope selection - features (5/5)

Cluster: kernel

Classes: INTEGER_REF

Please select the features you want to test:

Excluded:

Included:
item
hash_code
sign
one
zero
ascii_char
Min_value
Max_value
infix "<"
is_equal
three_way_comparison
set_item

Figure 24: Wizard dialog for selecting the features that will be tested.

The combo box at the top of the window contains the clusters under test. The list underneath contains the classes of the selected cluster which have been included in the test. The lower two lists contain the excluded and included features for the selected class. You can move classes between these lists using the “Add”, “Add all”, “Remove” and “Remove all” buttons. As explained in section 6.2, we list creation procedures twice, because they have two statuses: they can be used to create objects or they can be called as normal procedures. To distinguish between these two cases, we add the string “ (creation)” to the name of the procedure if it should be treated as a creator. For instance, feature *make* of class *STRING* would appear twice in the list, once as “make” and once as “make (creation)”. You can include the creation procedure separately from the normal one, and also the other way around. The two statuses of the procedure do not influence each other.

Pressing the “Finish” button will end the execution of the wizard. First the wizard checks if you have included at least one feature in the test. If this is not the case, it displays an information dialog, otherwise the wizard dialog is closed and TestStudio opens the newly created project in its main window, as shown in Figure 25.

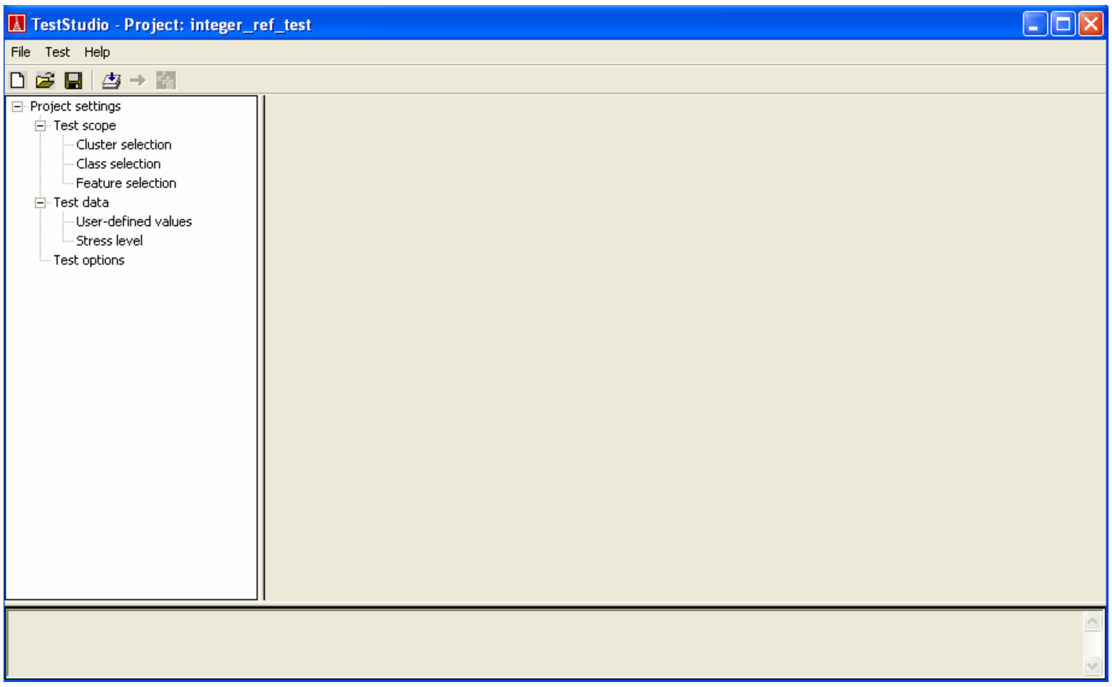
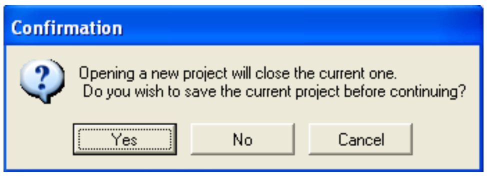


Figure 25: Main window of TestStudio after creating a new project with the project wizard.

Opening a project

To open a previously saved project, select “Open…” in the “File” menu, the corresponding toolbar button or use the Ctrl+O shortcut keys.

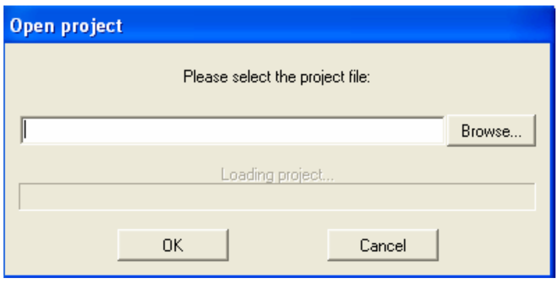
If there is already an open project, the dialog shown in Figure 26 appears. You can either cancel the action (not open another project), or open a project with or without saving the one that is currently open. If you choose to save the project, a dialog is displayed informing you about the success or failure of the operation. We discuss saving projects in more detail in section “Saving a project”.


Confirmation

Opening a new project will close the current one.
Do you wish to save the current project before continuing?

Figure 26: Dialog shown when the user wants to open a project and there is already an open project.

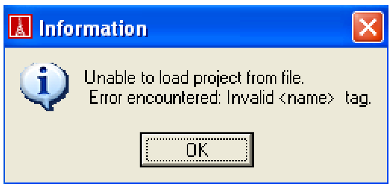
Then an open project dialog is displayed (Figure 27), asking you to enter the path to the project (.tsp) file. You can either type it in the text field or use the “Browse” button, which opens an “open file” dialog.


Open project

Please select the project file:

Figure 27: Dialog to open a project.

When you click “OK”, the dialog first checks if the project file exists, then loads the information it contains. If it encounters any errors when reading the project file, it displays a dialog, informing you about what went wrong, and it does not load the project. Figure 28 shows such a dialog.


Information

Unable to load project from file.
Error encountered: Invalid <name> tag.

Figure 28: Example of a dialog displayed when an error is encountered while loading a project.

Otherwise, the project is opened (the progress bar becomes enabled and reflects the progress of loading the project) and displayed in the main window of TestStudio.

Saving a project

To save a project, select “Save” in the “File” menu, the corresponding toolbar button, or use the Ctrl+S shortcut keys. This will instruct TestStudio to write all the information about the project to a project file (having the same name as the project and the .tsp extension) in the project directory. Before saving the project, TestStudio performs some integrity checks on the information. We describe them in the next section. In case some of the entered information is invalid, it displays a dialog informing you about the problem and it does not save the project. If, on the contrary, the save operation is successful, a dialog like the one in Figure 29 is shown.

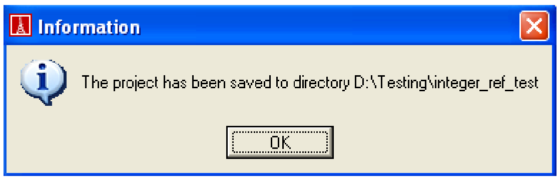

Information
The project has been saved to directory D:\Testing\integer_ref_test
OK

Figure 29: Dialog shown when a project is saved successfully.

Saving a project under a different name and/or directory

To save a project under a different name and/or in a different directory, use the "Save As" option from the "File" menu. This will display the dialog shown in Figure 30.

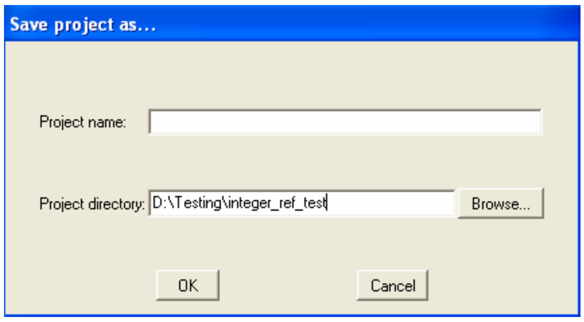


Figure 30: Dialog to save a project under a different name and/or directory.

You must enter the project name in the first text field and the project directory in the second. To specify the directory, you can also use the "Browse" button, which displays a dialog for selecting a directory. When you press "OK", TestStudio first checks if the information is valid (the project name is not empty and the directory exists). If the check is successful, TestStudio saves the project with the given name in the specified directory and opens it in the main window; otherwise, it displays a dialog informing you about the problem.

Working with an open project

We will now look at ways of specifying the test scope, data and options in an open project.

When there is an open project, the browser on the left side of the TestStudio main window shows the various categories of information that the project contains. Figure 31 shows the browser.

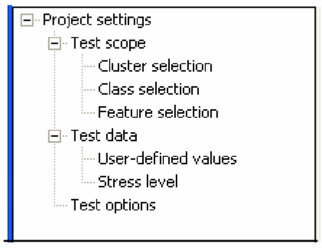
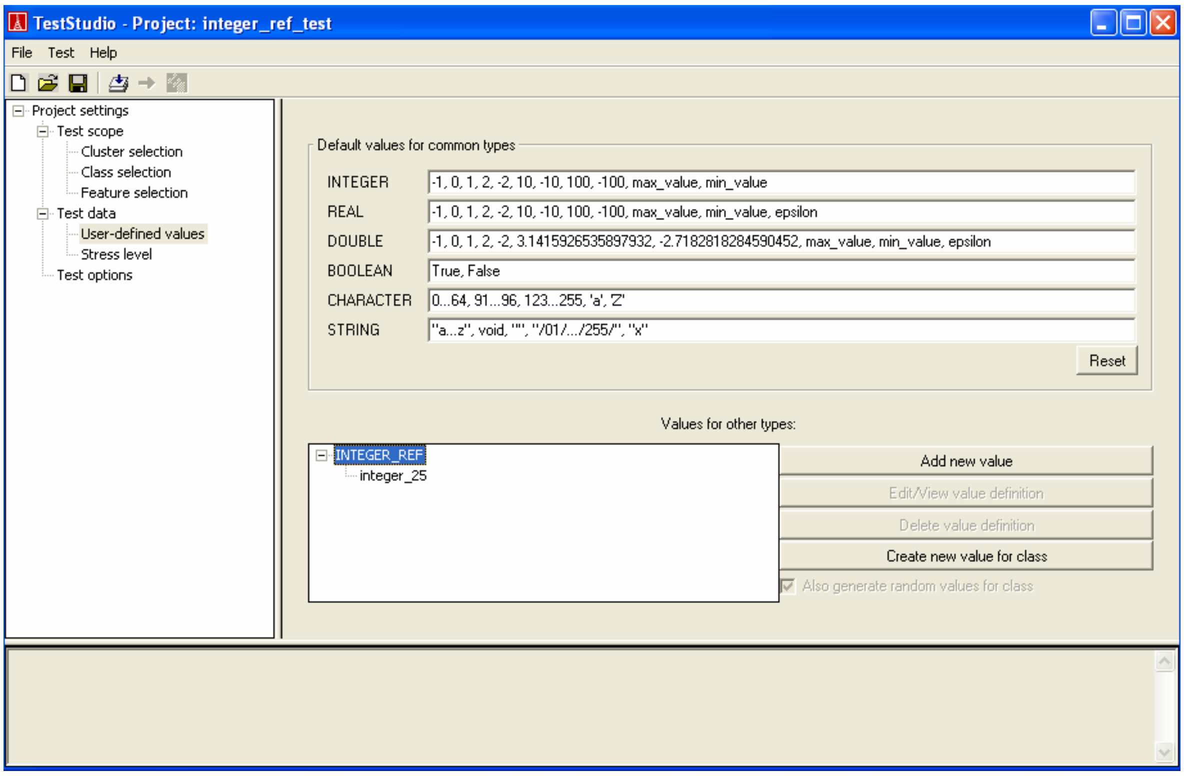


Figure 31: Tree-like browser displaying the categories of information contained in a project.

The project settings are grouped into three categories: test scope, data, and options. The test scope contains the selection of clusters, classes and features under test, and the test data refers to values for basic and non-basic types and stress levels. Selecting any of the leaves of the tree-like browser displays the corresponding panel on the right side of the TestStudio main window.

The panels used for cluster, class and feature selection are similar to the ones used by the wizard for creating a new project. See section "Creating a new project" for detailed information about them. The difference here is that they are not displayed in a wizard-like manner (i.e. in a sequence); however, the selection of clusters must influence the selection of classes, and the selection of classes must influence the selection of features. Therefore, when something changes in the cluster selection, we also update the panels for class and feature selection, so that all classes and all their features are included. Similarly, when something changes in the class selection, we update the panel for feature selection, so that all the features of the classes under test are included.

Figure 32 shows the panel to enter values for types. The upper part of the panel contains text fields for entering the values that TestStudio will use to instantiate basic types (*`INTEGER`*, *`REAL`*, *`DOUBLE`*, *`BOOLEAN`*, *`CHARACTER`* and *`STRING`*). Only the values that you enter in these fields will be used for basic types.



Default values for common types

INTEGER	-1, 0, 1, 2, -2, 10, -10, 100, -100, max_value, min_value
REAL	-1, 0, 1, 2, -2, 10, -10, 100, -100, max_value, min_value, epsilon
DOUBLE	-1, 0, 1, 2, -2, 3.1415926535897932, -2.7182818284590452, max_value, min_value, epsilon
BOOLEAN	True, False
CHARACTER	0...64, 91...96, 123...255, 'a', 'Z'
STRING	"a...z", void, "", "/01/.../255/", "x"

Figure 32: Main window of TestStudio, showing the panel to enter values for types.

You can also use some predefined names for special values, such as *min_value* and *max_value* for the minimum and respectively maximum values for a type (*`INTEGER`*, *`REAL`*, or *`DOUBLE`*) and *epsilon* for the minimum positive value of a type (*`REAL`* or *`DOUBLE`*). Strings can also be **`Void`**, as opposed to the rest of the basic types. To indicate that you also want to use **`Void`** as a value for strings, just enter *Void* in the corresponding text field.

For characters and strings, it is also possible to enter intervals of values. For characters, an interval of the form ‘a’…‘f’ defines all character values between ‘a’ and ‘f’. For strings, an interval means that the string contains all characters in the interval. For instance, a string defined as “ae…imn” is equivalent to “aefghimn”.

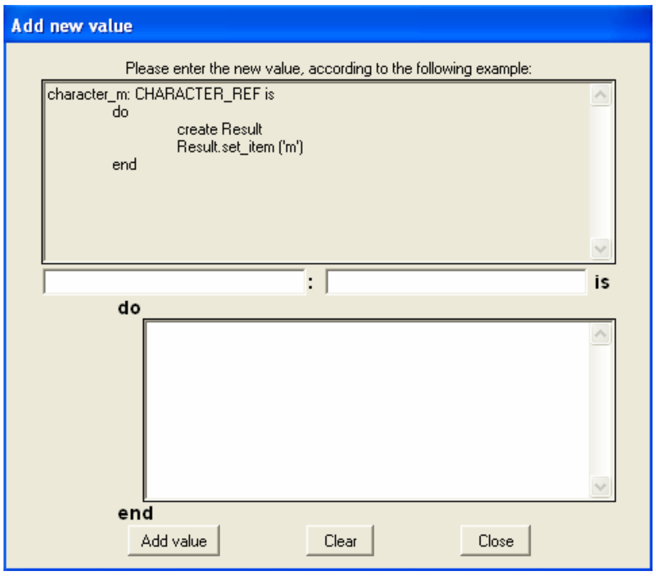
For both characters and strings, you can use the ASCII code of a character, so that you can also test non-printable characters. In the case of characters, you can insert the corresponding code directly in the text field, instead of the character itself (as shown in Figure 32). For strings, if you use a code instead of a character, you must insert it between slashes, as in “/10/”. This case is also represented in Figure 32.

The lower part of the panel allows you to enter values for non-basic types. To define a value that will be used for any other type than *INTEGER*, *REAL*, *DOUBLE*, *BOOLEAN*, *CHARACTER* and *STRING*, you must write a function returning that value. An example of such a function is the following:

```
character_m: CHARACTER_REF is
   do
         create Result
         Result.set_item ('m')
   end
```

The code that you write for the function is inserted without change in the generated test code.

To write such a function, click the “Add new value” button. This will display the dialog shown in Figure 33. The upper part of the dialog provides an example of how to write the function (the same example as the one given above). You must enter a name for the feature (this name has to be unique among the names for all features that you define), a return type and a body. When you click the “Add value” button, TestStudio checks that the feature name, return type and body are not empty, but it does not compile the code you write. Therefore, if there are errors in the function, TestStudio will only report them when it generates and compiles the test code.


Add new value

Please enter the new value, according to the following example:

```
character_m: CHARACTER_REF is
        do
                create Result
                Result.set_item ('m')
        end
```

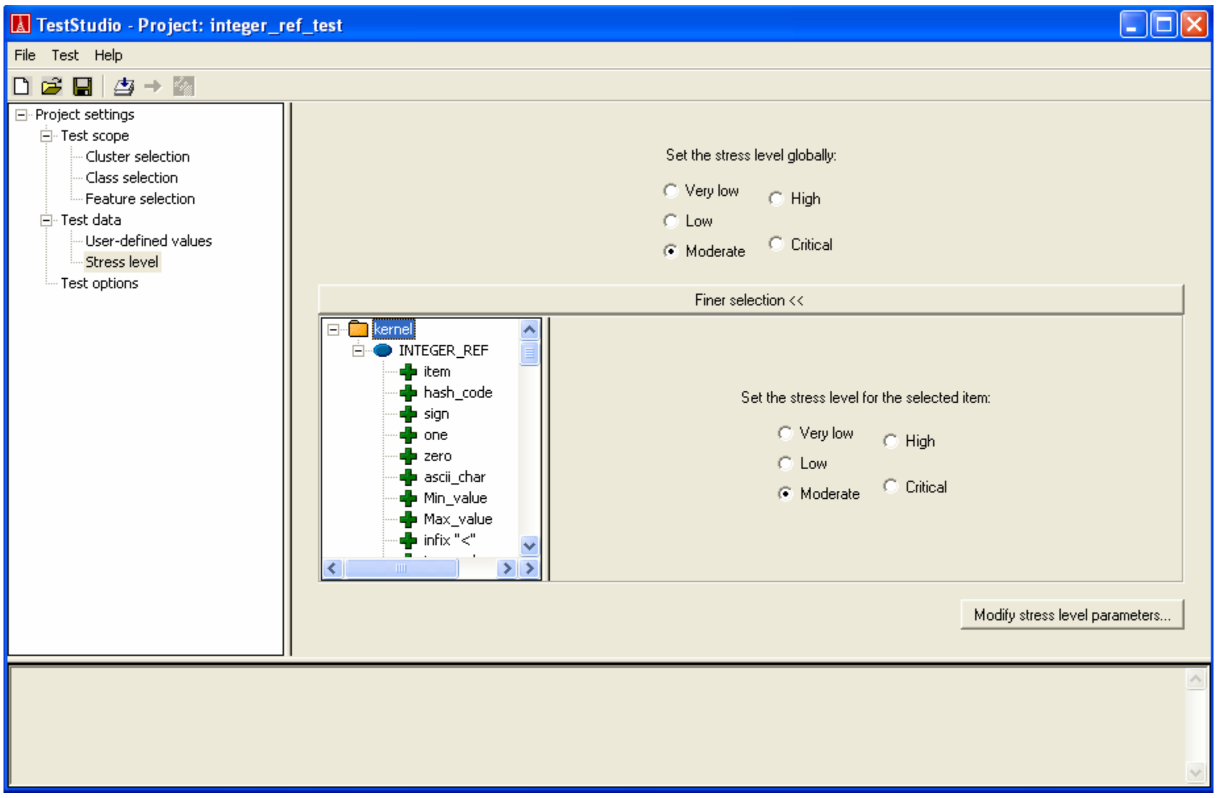
Figure 33: Dialog for entering a value for a non-basic type.

After you add a value for a non-basic type, it will be displayed in the tree on the left. The roots of the tree are type names for which values have been defined. Feature names are grouped under the type names.

When a type name is selected in the tree, the “Create new value for class” button is enabled. Pressing it displays a dialog similar to the one in Figure 33, only with the class name filled in. When a feature name is selected, the “Edit/view value definition” and “Delete value definition” buttons are enabled. The former displays a dialog similar to the one shown in Figure 33, but with the feature name and return type filled in and disabled, so that you can only change the feature body. If you want to change the name or return type, you must delete the old feature (by using the “Delete value definition button”) and write a new one. When you delete a value, TestStudio checks if there are any other values for that type. If this is not the case, it also removes the node containing the type name from the tree.

This panel also contains a check box that enables or disables random generation of values for types for which you have already defined at least one value. This check box is currently selected and disabled, so it cannot be deselected. The reason for this is that currently TestStudio cannot turn random generation of values off. This will be fixed in a future version and then the check box will be enabled.

Figure 34 shows the panel for setting the stress level. When the “stress level” tree node is selected in the browser, the panel that is displayed contains only the radio buttons for setting the global stress level. The “Finer selection” subpanel is hidden. Pressing the button expands it, pressing it again hides it.



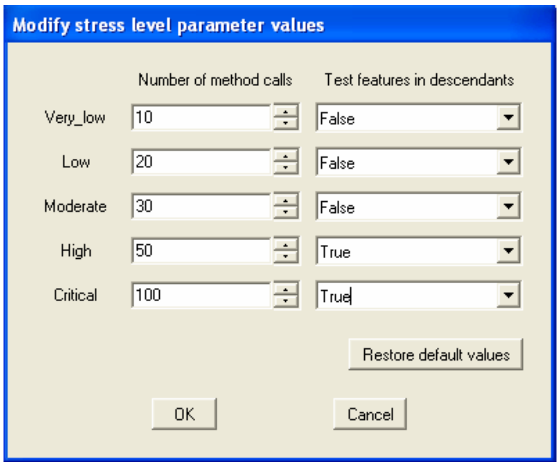
Set the stress level globally: Very low, Low, [✓ Moderate], High, Critical

Set the stress level for the selected item: Very low, Low, [✓ Moderate], High, Critical

Figure 34: Main window of TestStudio showing the panel for setting the stress level.

You can set the stress level globally or on a per-cluster, per-class, or per-feature level. To set it globally, use the upper group of radio buttons. Otherwise, the “Finer selection” subpanel must be expanded and you must select (in the tree on the left side) the element (cluster, class or feature) for which you want to set a specific stress level. Setting the stress level for more specific elements overrides the setting obtained from more general elements. For instance, if you set the stress level of cluster *kernel* to “low”, this stress level will be set for all its classes and all their features. If you now set the stress level of class `INTEGER_REF` to "high", this will override the setting at the cluster level, so that `INTEGER_REF`'s stress level will be "high", whereas for the rest of the classes in the cluster it will be "low". Because you have set the stress level of the class, the same stress level will be attributed to all its features. If you now set the stress level of feature `item` to "critical", this will override the stress level that was set to it by the class. So, the stress level for `item` will be "critical", and for the rest of the features of `INTEGER_REF` it will be "high".

This panel also allows you to change the mapping between the stress levels and the underlying parameters: the number of calls performed on each feature and whether or not we test features in descendants. Pressing the "Modify stress level parameters…" button brings up the dialog shown in Figure 35. The new parameter values will only be used in the current project. New projects will use the default values.



Modify stress level parameter values

	Number of method calls	Test features in descendants
Very_low	10	False
Low	20	False
Moderate	30	False
High	50	True
Critical	100	True

Figure 35: Dialog for changing the mapping between stress levels and underlying parameters.

Figure 36 shows the panel for setting the test options. These are:

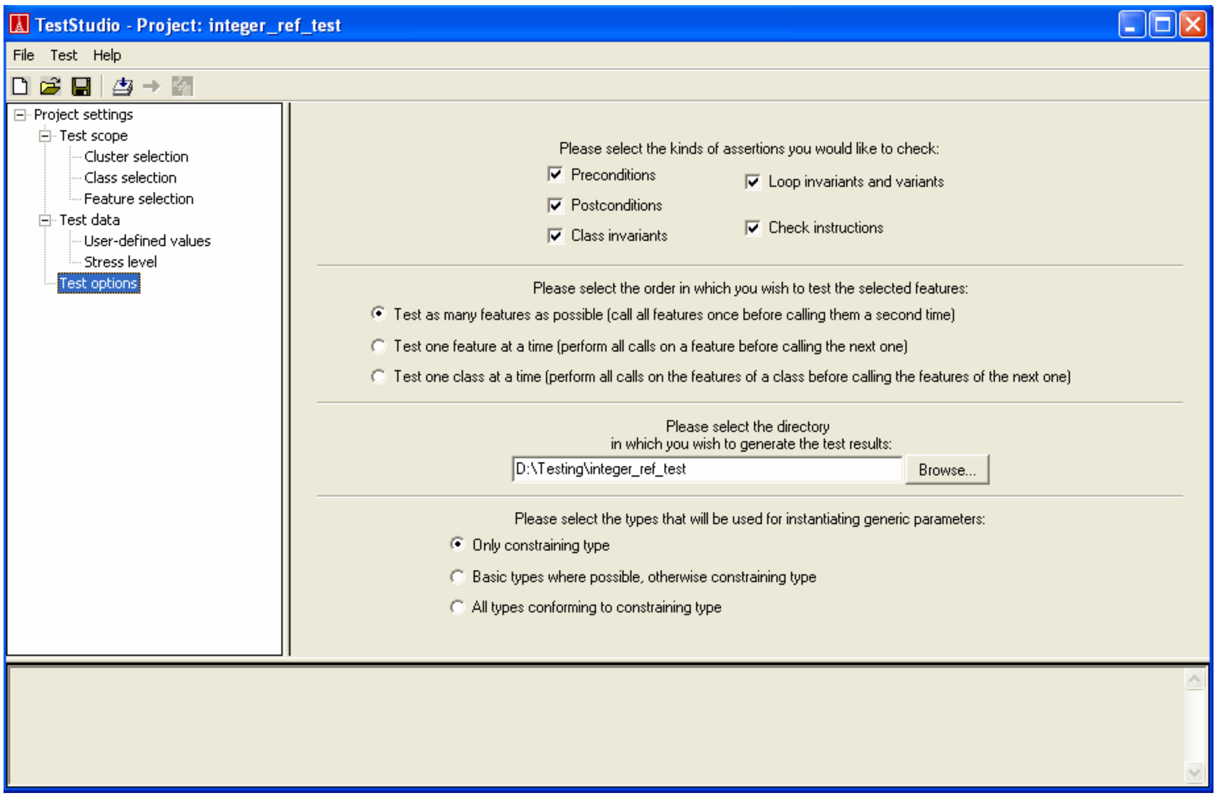
- Level of assertion checking: which types of assertions (preconditions, postconditions, class invariants, loop variants and invariants, and check instructions) we will monitor in the generated test. You can choose any combination of these by selecting the appropriate check boxes. By default, we check all types of assertions.
- Testing order: the order of feature calls. It can be one of the following:
  - As many features as possible – call all features once before calling them a second time (this is the default level);
  - One feature at a time – perform all calls on a feature before calling the next one;
  - One class at a time – perform all calls on the features of a class before calling the features of the next class under test.
- Level of support for genericity: which types we use for instantiating generic parameters. It can be one of the following:
  - Use only direct instances of the constraining type[9] if it is not deferred; otherwise, use instances of its effective descendants (this is the default level);

[9] We also include unconstrained genericity here, with `ANY` as the constraining type.

- Use instances of basic types if they conform to the constraining type, and instances of the constraining type;
- Use instances of any types that conform to the constraining type.

- Output directory: the directory in which TestStudio will save the test results.

The only check that TestStudio performs when saving the information contained in this panel is that the output directory is valid.



Please select the kinds of assertions you would like to check:

✓ Preconditions
✓ Postconditions
✓ Class invariants
✓ Loop invariants and variants
✓ Check instructions

Please select the order in which you wish to test the selected features:

● Test as many features as possible (call all features once before calling them a second time)
○ Test one feature at a time (perform all calls on a feature before calling the next one)
○ Test one class at a time (perform all calls on the features of a class before calling the features of the next one)

Please select the directory
in which you wish to generate the test results:
D:\Testing\integer_ref_test

Please select the types that will be used for instantiating generic parameters:

● Only constraining type
○ Basic types where possible, otherwise constraining type
○ All types conforming to constraining type

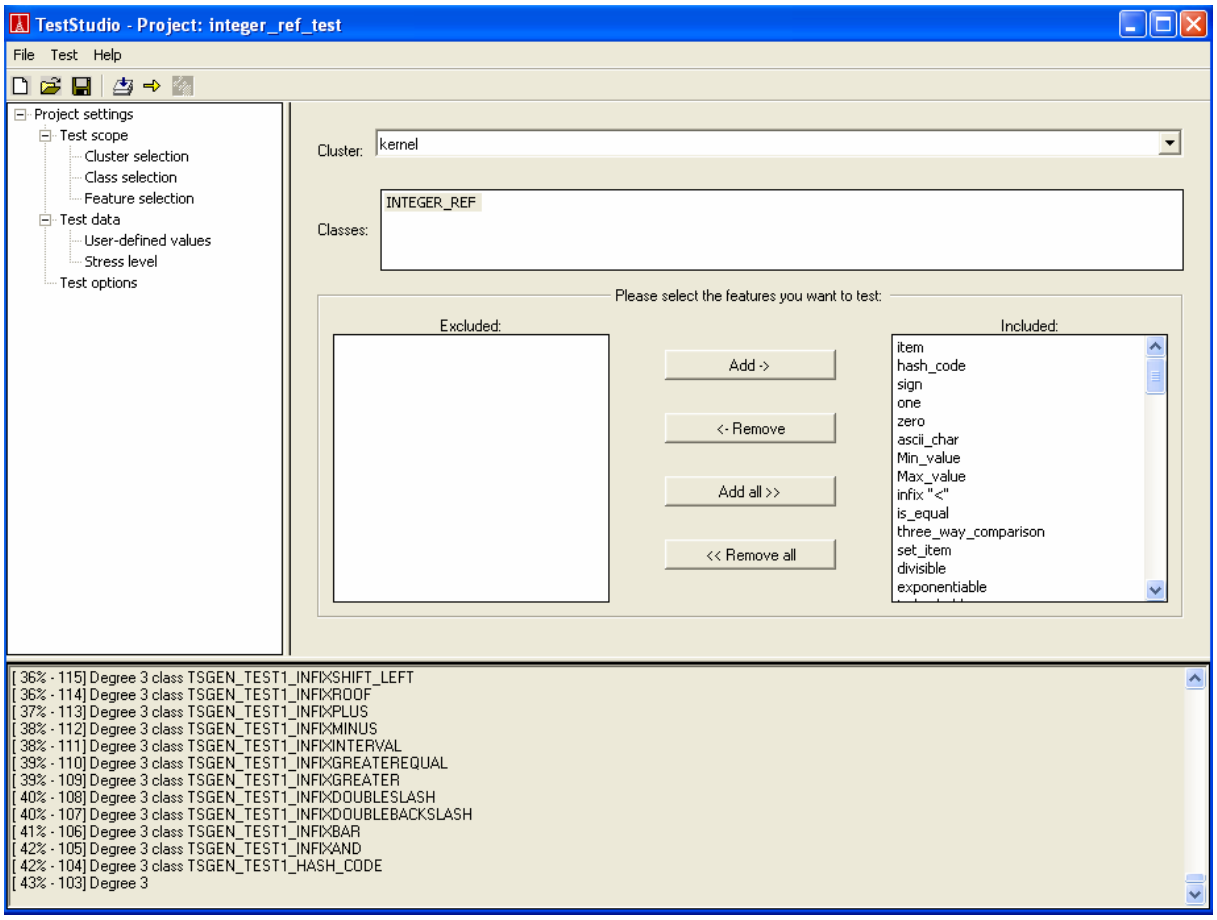
Figure 36: Main window of TestStudio showing the panel for setting test options.

Generating, compiling and running tests, and displaying test results

Once a project is open, you can already generate the test according to the criteria contained in it. Therefore, when you create a new project, after the execution of the wizard is finished, you can already start test generation, because all test criteria that are not set through the wizard have defaults, so you don't have to set them explicitly.

The "Test" menu contains options to work with tests. To generate and compile a test, use the "Generate test" option, the corresponding toolbar button, or the Ctrl+G shortcut keys. Before actually generating the test code, TestStudio updates the project information with the data set in the last panel that you modified. For example, if you change something in the feature selection panel, then select the menu option for generating the test, TestStudio will update the project information with the new feature selection. It will also perform some checks on it: in this case, whether at least one feature is included in the test. If the checks succeed, the test generation starts; otherwise, a dialog is displayed informing you about the problem and the test is not generated until the information is valid.

Test generation actually consists of two steps: automatic generation of the test code and compilation. The output of the compiler is displayed in the lower part of the TestStudio main window, as shown in Figure 37. We compile the test code in finalization mode and then run finish freezing on it.



Cluster: kernel

Classes: INTEGER_REF

Please select the features you want to test:

Excluded:

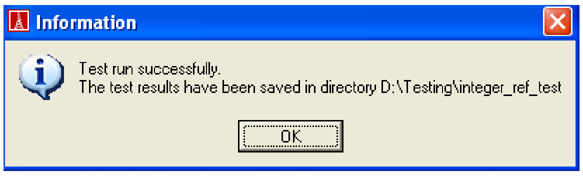
Included:
item
hash_code
sign
one
zero
ascii_char
Min_value
Max_value
infix "<"
is_equal
three_way_comparison
set_item
divisible
exponentiable

```
[ 36% - 115] Degree 3 class TSGEN_TEST1_INFIXSHIFT_LEFT
[ 36% - 114] Degree 3 class TSGEN_TEST1_INFIXROOF
[ 37% - 113] Degree 3 class TSGEN_TEST1_INFIXPLUS
[ 38% - 112] Degree 3 class TSGEN_TEST1_INFIXMINUS
[ 38% - 111] Degree 3 class TSGEN_TEST1_INFIXINTERVAL
[ 39% - 110] Degree 3 class TSGEN_TEST1_INFIXGREATEREQUAL
[ 39% - 109] Degree 3 class TSGEN_TEST1_INFIXGREATER
[ 40% - 108] Degree 3 class TSGEN_TEST1_INFIXDOUBLESLASH
[ 40% - 107] Degree 3 class TSGEN_TEST1_INFIXDOUBLEBACKSLASH
[ 41% - 106] Degree 3 class TSGEN_TEST1_INFIXBAR
[ 42% - 105] Degree 3 class TSGEN_TEST1_INFIXAND
[ 42% - 104] Degree 3 class TSGEN_TEST1_HASH_CODE
[ 43% - 103] Degree 3
```

Figure 37: TestStudio main window, showing the compilation progress for the generated test.

If any errors occur during compilation, they will be displayed as part of the compiler output and TestStudio will also bring up a dialog telling you that there were problems during test compilation.

Once there is an executable for the test, the menu item (“Run Test”) and corresponding toolbar button are enabled. You can also use the Ctrl+R shortcut keys to run the test. When you load a project, TestStudio checks if there is an executable (called “generated_test.exe”) in the project directory (under the path “generated_test_root\EIFGEN\F_code”). If it finds the executable, it enables the widgets to run the test. The reason for this check is that the user might have already generated the test code for a project. When he reopens that project, he will not need to generate the test code again. If the test is run successfully, a dialog like the one in Figure 38 appears.



Test run successfully.
The test results have been saved in directory D:\Testing\integer_ref_test

Figure 38: Dialog displayed when test running succeeds.

If running the test fails (for example, if one of the feature calls generates runtime panic, from which TestStudio cannot recover), a dialog is shown informing you about the failure of the operation.

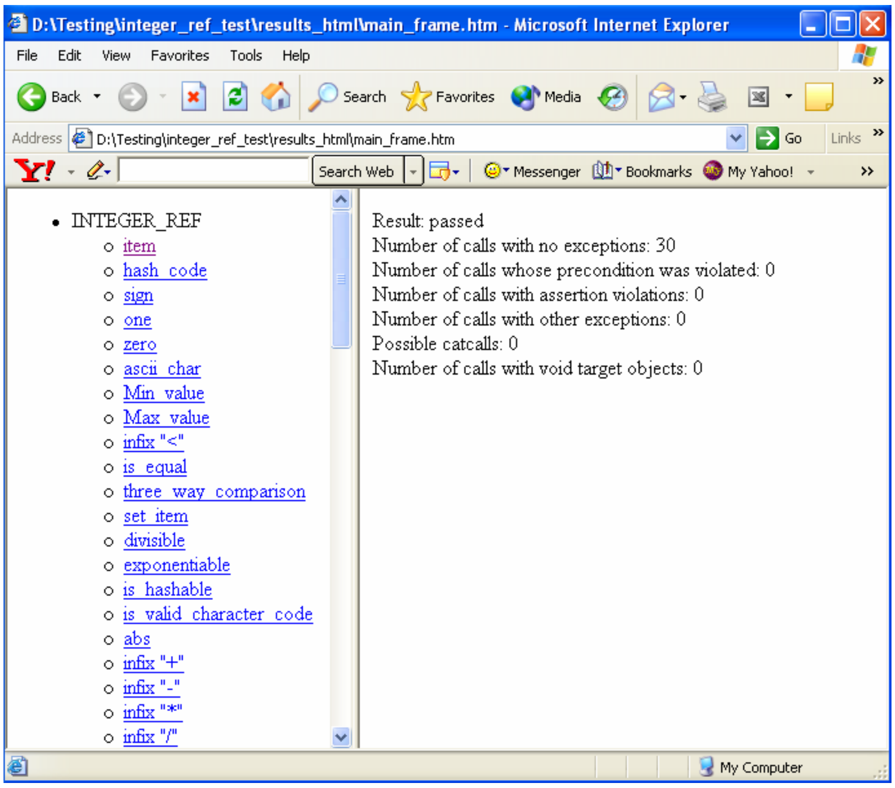
When running the test is successful, test results are saved in several files:

- "results.csv", "results.txt" and "results.xml" contain the same information in various formats (comma-separated values, text and XML). These files contain the following information for each tested feature:
    - The result type:
        - Failed – a feature fails if any of its calls causes an assertion violation or another exception or is a possible catcall;
        - No call was valid – none of the calls to the feature fulfilled its precondition;
        - Could not be tested – it was not possible to call the feature, because we could not instantiate the target object or one of the arguments;
        - Passed – the feature was executed at least once and none of its calls produced assertion violations or other kinds of exceptions or were possible catcalls.
    - Number of calls that produced no exceptions;
    - Number of calls that violated the feature's precondition;
    - Number of calls that produced assertion violations;
    - Number of calls that produced other exceptions;
    - Number of calls that were possible catcalls;
    - Number of calls that were tried on void target objects.
- "details.txt" – for all features whose precondition was violated by the test case or which produced assertion violations, it records the class and name of the feature, the type of assertion that was violated and the tag of that assertion.

All these files are created in the output directory specified in the project.

The number of calls performed on a feature is set internally by TestStudio (currently to 30). In future versions of the tool, it will be possible for the user to set this number. The calls that violate the feature's precondition are not counted, so that only calls that actually lead to the feature being executed increase the number of performed calls.

Successfully running a test will produce a "results.csv" file. TestStudio looks for this file (in the project output directory) and, if it finds it, enables the menu option ("Get Test Results") and toolbar button for displaying test results in HTML format. You can also use the Ctrl+T shortcut keys for the same purpose. This will save the information contained in file "results.csv" in HTML format and display it in a browser (see Figure 39). The HTML files are created in the output directory of the project, in the "results_html" directory. A dialog (similar to the one in Figure 40) is also displayed, informing you about the success of the operation.

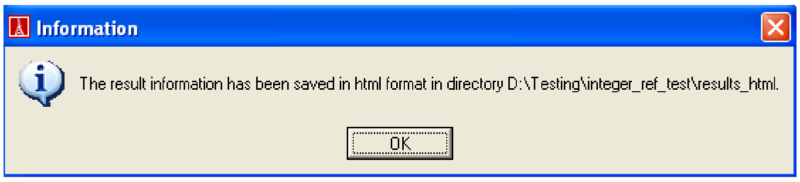

D:\Testing\integer_ref_test\results_html\main_frame.htm - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Search Favorites Media
Address D:\Testing\integer_ref_test\results_html\main_frame.htm Go Links
Search Web Messenger Bookmarks My Yahoo!
My Computer

- INTEGER_REF
  - item
  - hash_code
  - sign
  - one
  - zero
  - ascii_char
  - Min_value
  - Max_value
  - infix "<"
  - is_equal
  - three_way_comparison
  - set_item
  - divisible
  - exponentiable
  - is_hashable
  - is_valid_character_code
  - abs
  - infix "+"
  - infix "-"
  - infix "*"
  - infix "/"

```
Result: passed
Number of calls with no exceptions: 30
Number of calls whose precondition was violated: 0
Number of calls with assertion violations: 0
Number of calls with other exceptions: 0
Possible catcalls: 0
Number of calls with void target objects: 0
```

Figure 39: Test results saved in HTML format displayed inside a browser.

We use an HTML menu (shown on the left side of the window) to display the results. It contains the features that were tested and groups features belonging to the same class under the name of that class. Clicking on the name of a feature displays the results for it in the right panel of the window.



The result information has been saved in html format in directory D:\Testing\integer_ref_test\results_html.

Figure 40: Dialog informing the user about the results being saved in HTML format.

10.3.2. HOW TO USE THE COMMAND LINE VERSION OF TESTSTUDIO

The command line version of TestStudio takes several arguments, depending on what the user wants to do. We will call the first of these arguments the “command”. It can be one of the following: “`create_project`”, “`generate_compile`”, “`run`”, “`get_results`”, or “`help`”. The number and semantics of the rest of the arguments depends on the command. We will describe each of them.

If you want to create a new project, you must use the “`create_project`” command. This command must be followed by arguments according to the following pattern:

```
test_studio_cl create_project <ace_file> <project_name> <project_directory>
{-clusters <file_name>} {-classes <file_name>} {-features <file_name>}
```

The items included between `{}` are optional. None, one or several of them can be present. The semantics of the arguments is the following:

- `<ace_file>` – path to the ace file containing the information about the system that will be tested;
- `<project_name>` – name of the project;
- `<project_directory>` – directory where the project will be created;
- `-clusters <file_name>` - `file_name` is the path to the file containing the names of the clusters under test;
- `-classes <file_name>` - `file_name` is the path to the file containing the names of the classes under test;
- `-features <file_name>` - `file_name` is the path to the file containing the names of the features under test.

The files containing the names of clusters and classes must have the following format: the name of each element should appear on one line. For the features, you must also specify the class to which they belong (because features cannot be identified by name only). So, the format of the file specifying the features under test must be the following: each line of the file must begin with the name of the class, followed by a colon and then a comma-separated list of names of features belonging to that class. Creation features can have two statuses, as shown above: they can be included either as creators or as regular procedures. To include a procedure as creator, you must append the string " (creation)" to its name. Here is an example:

```
STRING:  make_filled  (creation),  make,  prune,  prune_all,  keep_head,
keep_tail
```

The "`create_project`" command will create a project (.tsp) file. If not otherwise specified, it will include all clusters, classes and features by default. If you provide a cluster file, only the clusters mentioned in it will be included; likewise for classes and features. The rest of the test criteria (stress level, values for basic types, level of assertion checking, testing order, and output directory) are set to defaults. If you want to change any of these defaults, you must modify the generated .tsp file.

The "`generate_compile`" command takes a single argument, i.e. the path to the .tsp file:

```
test_studio_cl generate_compile <tsp_file>
```

It will load the project from the given file and generate and compile the test code for it. It will save the test code in the project directory under the "generated_test_code" and "generated_test_root" directories.

To run the generated test, use the "`run`" command. It needs the path to the project directory as argument:

```
test_studio_cl run <project_directory>
```

This will also create the result files ("results.csv", "results.txt", "results.xml" and "details.txt") in the output directory of the project.

Finally, the "`get_results`" command needs the path to the project output directory as argument:

```
test_studio_cl get_results <project_output_directory>
```

It saves the test results in HTML format in the "results_html" directory under the project directory and displays them in a browser window.

The "`help`" command takes no arguments. It prints a message informing you about the correct usage of the command line facility.

10.4. EXAMPLES

The delivery for TestStudio includes the "examples" directory, which contains an example for using the GUI version of TestStudio and one for the command line. We describe these examples in the following.

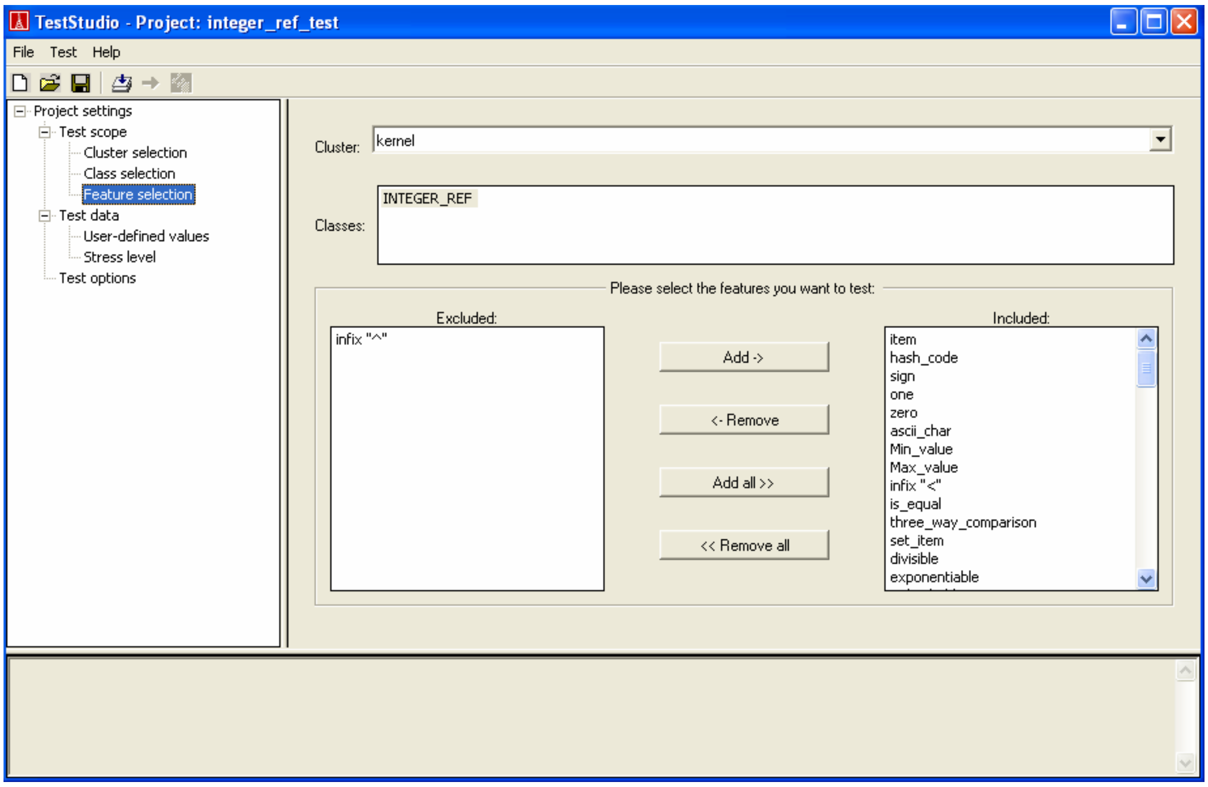
10.4.1. EXAMPLE FOR THE GUI VERSION OF TESTSTUDIO

The example for using the graphical version of TestStudio is located under the "examples\GUI\integer_ref_test" directory. Before using the example you need to modify the project file ("integer_ref_test.tsp"):

- Change the project directory (contained inside the "`<project_dir>`" tags) so that it points to the directory where the project file is actually located (this will be the installation directory for TestStudio, concatenated with the string "\examples\GUI\integer_ref_test");
- Change the path to the ace file (contained inside the "`<ace_file>`" tags) so that it points to the "librarybase.ace" file located in the "examples\test_libraries" directory;
- Change the project output directory (contained inside the "`<output_directory>`" tags) to any directory you want. TestStudio will save the test results in this directory.

To run this example, launch TestStudio (by using the executable located in the "bin" directory) and then select "Open…" in the "File" menu, the corresponding toolbar button, or use the Ctrl+O shortcut keys. In the dialog that appears, select the "integer_ref_test.tsp" project file, then click "OK". This opens the project in the main window of TestStudio.

Figure 41 shows a screenshot of the TestStudio main window, with the integer_ref_test project open. Using the tree-browser on the left side of the window, you can navigate between the various project options that you can set.



Cluster: kernel

Classes: INTEGER_REF

Please select the features you want to test:

Excluded:
infix "^"

Included:
item
hash_code
sign
one
zero
ascii_char
Min_value
Max_value
infix "<"
is_equal
three_way_comparison
set_item
divisible
exponentiable

Figure 41: Main window of TestStudio, showing the features included in the test.

To generate test code, select “Generate Test” in the “Test” menu, the corresponding toolbar button, or use the Ctrl+G shortcut keys. This generates the test code under the “generated_test_code” and “generated_test_root” directories in the project directory.

To run the test, select “Run Test” in the “Test” menu, the corresponding toolbar button, or use the Ctrl+R shortcut keys. This saves several files containing the test results in the output directory of the project.

To display the test results, select “Get Test Results” in the “Test” menu, the corresponding toolbar button, or use the Ctrl+T shortcut keys. This displays the result information in a browser and saves the HTML files in the “results_html” directory under the output directory.

10.4.2. EXAMPLE FOR THE COMMAND LINE

The example for using the command line is located in the “examples\command_line” directory. This directory contains four executable files (with the “.bat” extension), each having the name of one the commands that you can issue and containing the corresponding command and necessary arguments. In order to use these files, you have to change the relative path information that they contain. However, the examples bring useful information about using the command line facility. The directory also contains three text files, which are used for creating a project. Each of them provides an example for how to specify the clusters, classes and respectively features under test.

11. CONCLUSIONS

The goal of this project was to extend a tool for automatic generation of tests with a graphical user interface and several other functionalities. The resulting application is called TestStudio and it is an environment that allows the user to automatically generate tests for contract-equipped classes, compile these tests, run them and get the results. The user can also set a wide range of parameters, which enables him to finely adapt the testing process to his own needs and preferences.

TestStudio is a proof of concept for push-button testing. It shows that, in the presence of contracts, a fully automatic testing process is possible. In fact, it is not only possible, but also effective and efficient. By using TestStudio, we discovered several bugs in Eiffel libraries, bugs that had escaped thorough manual testing performed by library developers.

Contracts are vital to the success of our approach. They express the intended semantics of the software. Only in their presence can it be checked automatically that the software performs its required functions. However, the correctness of the test results is highly dependent on the quality of the contracts. If contracts are not accurate enough, the test results will also not be accurate. For example, if the postcondition of a feature does not specify one of its intended effects, TestStudio will not be able to test the feature for that particular outcome. Therefore, another benefit of using contracts for testing is that it leads to several guidelines for writing contracts, which could be developed into a full methodology.

Although much work remains to be done on TestStudio, the results we have obtained so far are very encouraging. The success of the approach also proves the importance of contracts in the design and implementation of software systems. It proves that they are an integral part of the software and provide valuable information about it, information without which automatic testing would not be possible.

12. REFERENCES

[Arnout03]	Karine Arnout, Xavier Rousselot, Bertrand Meyer: *Test Wizard: Automatic Test Case Generation Based on Design by Contract™*, draft report, ETH Zurich, June 2003, http://se.inf.ethz.ch/people/arnout/arnout_rousselot_meyer_test_wizard.pdf
[Bezault04]	Eric Bezault: *Gobo Eiffel Project*, http://www.gobosoft.com
[DeBoer04]	Berend de Boer: *e-POSIX, the Complete Eiffel to POSIX Binding*, http://www.berenddeboer.net/eposix/
[Greber04]	Nicole Greber: *Test Wizard: Automatic Test Generation Based on Design by Contract™*, Master thesis, ETH Zurich, January 2004, http://se.inf.ethz.ch/projects/nicole_greber/tw_final_report.pdf
[Madsen04]	Per Madsen: *Enhancing Design by Contract with Knowledge of Equivalence Partitions*, Journal of Object Technology (Special issue published for TOOLS USA 2003), volume 3, no 4, April 2004, http://www.jot.fm/issues/issue_2004_04/article1.pdf
[Meyer92]	Bertrand Meyer: *Eiffel: The Language*, Prentice Hall, 1992
[Meyer97]	Bertrand Meyer: *Object-Oriented Software Construction, 2nd edition*, Prentice Hall, 1997
[TestingCourse]	Bertrand Meyer: *Quality Assurance*, lecture held at ETH Zurich, June 2004, http://se.inf.ethz.ch/teaching/ss2004/0004/slides/25_testing_1up.pdf
[TestingGlossary]	*Software Testing Glossary*, http://www.aptest.com/glossary.html
[TestingSurvey]	*Software Quality: Facts & Stats*, http://www.computerworld.com/news/1997/story/0,11280,17522,00.html
[TestTypes]	*Software Testing Types*, http://www.aptest.com/testtypes.html
[Whittaker00]	James A. Whittaker: *What Is Software Testing? And Why Is It So Hard?*, IEEE Software, January/February 2000, pp. 70 - 79