TOWARDS TEST FOCUS SELECTION FOR INTEGRATION TESTING USING SOFTWARE METRICS

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ABSTRACT

Object-oriented software systems contain a large number of modules which make the unit testing, integration testing, and system testing very difficult and challenging. While the aim of the unit testing is to show that individual modules are working properly and the aim of the system testing is to determine whether the whole system meets its specifications, the aim of integration testing is to uncover errors in the interactions between system modules. Correct functioning of object-oriented software depends upon the successful integration of classes. While individual classes may function correctly, several faults can arise when these classes are integrated together. However, it is generally impossible to test all the connections between modules because of time and cost constraints. Thus, it is important to focus the testing on the connections presumed to be more error-prone.

The general goal of this research is to let testers know where in a software system to focus when they perform integration testing to save time and resources. In this work, we propose a new approach to predict and rank error-prone connections in object-oriented systems. We define method level metrics that can be used for test focus selection in integration testing. In addition, we build a tool which calculates the metrics automatically. We performed experiments on several Java applications taken from different domains. Both error seeding technique and mutation testing were used for evaluation. The experimental results showed that our approach is very effective for selecting the test focus in integration testing.

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CHAPTER 1. INTRODUCTION

1.1. Background

Software is a fundamental component in many of the devices and the systems that are available in modern life. It is used to control many critical functions of different machines such as spaceships, aircrafts, and pacemakers. All of these machines are running software systems that overly optimistic users assume will never fail. Software failure can cause serious problems such as loss of human life. In addition, software failure can have a major impact on economics. For example, software errors cost the United States economy around 60 billion dollars annually according to a study conducted by the National Institute of Standards and Technology [64]. Therefore, creating a reliable software system and increasing the confidence of the correctness of a software system are very important. Even though there are many methods that can be used to provide assurance that the software is of high quality and reliability, software testing is the primary method which is used to evaluate software under development.

Software testing is the process of executing a program or system with the intent of finding errors [49]. Software testing is very costly. It requires approximately 50% of software development cost [49]. Much software contains large number of errors. One reason these errors persist through the software development life cycle is the restriction of testing resources. These resources are restricted by many factors such as time (e.g., the software should be delivered in specific time) and cost (e.g., testing the whole software system requires a large team). Thus, if testing effort can be focused on the parts of a software system where errors are most likely to occur, then the available resources can be used more effectively, and the produced software system will be more reliable at lower cost.

Object-oriented software is a burgeoning form of software. Object-oriented software systems contain large number of modules which make the unit testing, integration testing,

and system testing very difficult and challenging. While the aim of the unit testing is to show that the individual modules are correct and the aim of the system testing is to determine whether the whole system meets its specifications, the aim of integration testing is to test that the interactions between system modules are correct. Correct functioning of object-oriented software depends upon the successful integration of classes. While individual classes may function correctly, several new faults can arise when these classes are integrated together. However, it is usually impossible to test all the connections between classes. Therefore, it is important to focus the testing on the connections presumed to be more error-prone.

Errors that happen when integrating two components can be very costly. An example of one public failure that happened because of disagreement of assumptions was the Mars Climate Orbiter. In September 1999, the communication with the spacecraft was lost as the spacecraft went into orbital insertion due to a misunderstanding in the units of measure used by two modules created by different software groups. One module computed data in English units of pound-seconds and forwarded the data to a module that expected data in metric units of Newtonseconds. The Mars Climate Orbiter went out of radio contact when the spacecraft passed behind Mars 49 seconds earlier than expected, and communication was never reestablished. This is a very typical integration error, but the error costs millions of dollars [62].

The goal of this research is to reduce the cost and the time required for integration testing by ranking the connections between modules and then the test cases are targeted to test the highly ranked connections. We are aiming to provide testers with an accurate assessment of which connections are most likely to contain errors, so they can regulate the testing efforts to target these connections. Our assumption is that using a small number of test cases to test the highly ranked error-prone connections will detect the maximum number of integration errors. This work presents an approach to select the test focus in

integration testing. It uses method-level software metrics to specify and rank the error-prone connections between modules of systems under test.

1.2. Motivation

Integration testing is a very important process in software testing. Software testing cannot be effective without performing integration testing. Around 40% of software errors are discovered during integration testing [67]. The complexity of integration testing increases as the number of interactions increases. A full integration testing of a large system may take long time to complete. Integration testing of large software systems consumes time and resources. Applying the same testing effort to all connections of a system is not a good approach. An effective approach to reduce time and cost of integration testing is to focus the testing effort on parts of the program that are more likely to contain errors.

The goal of test focus selection is to select the parts of the system that have to be tested more widely. The test focus selection is important because of time and budget constraints. The assumption is that the integration testing process should focus on the parts of the system that are more error-prone. Several approaches to predict error-prone components have been proposed by researchers [7, 14, 24]. Though, these approaches focus only on individual modules. For that reason, they can be used for unit testing but they cannot be used for integration testing because integration testing tests the connections between modules. Thus, predicting error-prone connections is necessary for test focus selection in integration testing. As a result, new approaches for test focus selection in integration testing are needed. In this work, we present a new approach to predict and rank error-prone connections in object-oriented systems. We give a weight for each connection using method level metrics. Then we predict the number of test cases needed to test each connection. The general goal of this research is to tell testers where in a software system to focus when they perform integration testing to save time and resources.

1.3. Terminology

This section presents a number of terms that are important in software testing and that will be used in this work. We use definitions of software error, software fault, software failure, test case, metric, integration testing, and object-oriented language from IEEE standard 610.12-1990 [57].

- Software fault: An incorrect step, process, or data definition in a computer program that can happen at any stage during the software development life cycle. Usually, the terms ”error” and ”bug” are used to express this meaning. Faults in software system may cause the system to fail in performing as required.

- Software error: The difference between a computed, observed, or measured value or condition and the correct value.

- Software failure: The inability of a system or component to perform its required functions within specified performance requirements.

- Test case: A set of test inputs, execution conditions, and expected results developed for a particular objective, such as to exercise a particular program path or to verify compliance with a specific requirement.

- Metric: A quantitative measure of the degree to which a system, component, or process possesses a given attribute.

- Object-oriented language: A programming language that allows the user to express a program in terms of objects and messages between those objects such as C++ and Java.

- Integration testing: Testing in which software components, hardware components, or both are combined and tested to evaluate the interaction between them.

1.4. Problem Statement and Objectives

This dissertation addresses one main problem: How to reduce cost and time required for integration testing while keeping its effectiveness in revealing errors. We want to test our hypothesis that the degree of dependency between methods is a good indicator of the number of integration errors in the interaction between methods. We assume that a developer usually makes more mistakes if two methods have strong dependencies. We also assume that developer makes more mistakes if methods are complex. Therefore, we give a weight for each connection based on both the degree of dependency and the internal complexity of the methods. In our work, we define method level dependency metrics to measure the degree of dependency between methods. We are just interested in computing dependencies between methods that belong to different classes. Dependencies between methods in the same class may be needed in unit testing but they are not needed in integration testing.

The objective of this work is to develop a new approach for integration testing that reduces cost and time of integration testing through reducing the number of test cases needed while still detecting at least 80% of integration errors. The number of test cases can be reduced by focusing the testing on the error-prone connections. We want to write test cases that cover small number of connections while these test cases uncover most of the integration errors. Integration testing can never recompense for inadequate unit testing. In our approach, we assume that all of the classes have gone through adequate unit testing.

1.5. Contributions

This dissertation makes the following contributions:

1. Define method-level object-oriented metrics. We define metrics that can be used for test focus selection in integration testing. Our metrics are defined and selected according to the following two assumptions: 1) the degree of dependencies between the two methods that have an interaction are strongly correlated with the number of

integration errors between the methods; 2) the internal complexity of the two method that have an interaction are strongly correlated with the number of integration errors in the interaction between them. We define four method level dependency metrics and three method level internal complexity metrics. We also define metrics on both method-pair and class-pair levels.

2. Build a tool to calculate the metrics automatically. We develop a tool using the R language to compute the metrics automatically from both the source code and the byte code. The tool produces four files in CSV format: 1) method level metrics file, which shows the metrics values for each method in the system under test; 2) method-pair level metrics file, which shows the metrics values for each method-pair such that (m_1 and m_2) is a method-pair if method m_1 calls method m_2 or vice verse; 3) class-pair level file, which shows the metrics values for each class-pair such that (c_1 and c_2) is a class-pair if any method in class c_1 calls any method in class c_2 or vice verse.

3. Propose an approach to reduce cost and time of integration testing. We use a combination of object-oriented metrics to give a weight for each method-pair connection. Then, we predict the number of test cases needed to test each connection. The objective is to reduce the number of test cases needed to a large degree while still detecting at least 80% of integration errors.

4. Conduct an experimental study on several Java applications taken from different domains. In order to evaluate the proposed approach, we use both error seeding and mutation analysis techniques.

1.6. Dissertation Outline

The rest of the dissertation is organized as follows: Chapter 2 starts by introducing some areas that are related to the dissertation and then it discusses related work. Chapter 3 describes the proposed approach. The chapter starts by defining a representation for a

software system. Then, it explains the steps of the proposed approach. After that, a section presents the tool that we developed for implementing the proposed approach. The chapter ends with a toy example to explain the proposed approach. The experimental evaluation and discussion are presented in Chapter 4. Chapter 5 concludes the dissertation and talks about future directions.

CHAPTER 2. LITERATURE REVIEW

2.1. Background

This research is related to software dependencies, coupling, software testing, and integration testing. This section introduces background material of these areas.

2.1.1. Software Dependencies

A dependency is a relationship between two components where changes to one may have an impact that will require changes to the other [70]. For example, Figure 1 shows a relationship between two components A and B. We say that component A depends on component B. We also say that A has outbound dependency and B has inbound dependency. A component is a dependent to another component if it has outbound dependency on that component. A component is a dependee to another component if it has inbound dependency from that component. In Figure 1, component A is a dependent and component B is a dependee.

Figure 1: The dependency relationship between component A and component B.

In general, there are two main types of dependencies according to the dependency extraction method namely static and dynamic. Static dependencies are extracted from binary files while dynamic dependencies are extracted during run-time. In our work, we extract the static dependencies.

Software metrics are quantitative measures of some properties of a part of software. They are widely used to control the software development and to assess the quality of software products. Coupling and cohesion are most likely the best known metrics that are used to measure dependencies. Coupling is used to measure the dependencies between

different modules, while cohesion is used to measure the dependencies inside a single module. Modules are considered highly coupled when there are many connections between them. A connection is a reference from one module to another. Low coupling and high cohesion are required to produce a good software system. In this work, we investigate the use of coupling measures for test focus selection. One reason to use coupling is that high coupling between two modules increases the connections between them and increases the chance that a fault in one module affect the other module. Another reason is that faults are found during integration testing exactly where couplings typically occur [33].

2.1.2. Coupling

Coupling is one of the measures that is used for measuring the performance of software at different phases such as design phase. Coupling is defined as the degree to which each program module depends on the other modules. Low coupling is desired among the modules of an object-oriented application and it is a sign for a good design. High coupling may lower the understandability and the maintainability of a software system [33]. There are twelve ordered coupling levels that are used to assess the complexity of software system design. It has been found that twelve levels of coupling are not required for testing [33]. For testing, four unordered types are needed. These four coupling types were used to define coupling-based testing criteria for integration testing. The four types are defined between pairs of units (A and B) as follows [33].

- Call coupling refers to calls between units (unit A calls unit B or unit B calls unit A) and there are no parameters, common variable references, or common references to external media between the two units.
- Parameter coupling refers to all parameter passing.
- Shared data coupling refers to procedures that both refer to the same data objects.

- External device coupling refers to procedures that both access the same external medium.

2.1.3. Software Testing

Software testing is any activity aimed at evaluating an attribute or capability of a program or system and determining that it meets its required results [30]. The testing process is divided into several levels to enhance the quality of software testing. Software testing activities have been categorized into levels. The levels of testing have a hierarchical structure that builds up from the bottom to the top where higher levels of testing assume successful completion of the lower levels of testing. Figure 2 shows the ”V” model of software testing. The levels of testing are described below:

- Unit testing: A unit is the smallest piece of a software system. A unit is presented as a function or a procedure in a procedural programming language while it is presented as a method or a class in an object-oriented programming language. Individual units are tested independently. Unit testing tries to find if the implementation of the unit satisfies the functional specification. The goal is to identify faults related to logic and implementation in each unit. If these faults are not detected, they may cause system failure when running the system. This type of testing is usually performed by the developers because it requires deep understanding of the functional specification of the system under test. The developer usually writes test cases to test the system after he/she finishes the implementation. Unit testing is the lowest testing level. It is required to be done before integration testing which is required to be done before system testing and acceptance testing.

- Integration testing: Integration testing assumes that each unit of the system is already passes through unit testing. At this level, different units are integrated together to form a working subsystem. Even though units are working individually, they

may not work properly when they interact with each other. Therefore, the goal of integration testing is to ensure that the interactions between system units are correct and no faults are introduced by the interactions. As in unit testing, integration testing is usually performed by system developers. Software testing cannot be effective without performing integration testing. Around 40% of software errors are detected during integration testing [67].

- System testing: The software system is tested as a whole. It is designed to decide whether the system meets its specification. System testing is usually performed on a system test machine while it simulates the end user environment. There are many types of testing that should be considered when writing test cases to test the system. Some of these categories are facility testing, volume testing, stress testing, usability testing, and security testing [49].

- Acceptance testing: The software system is tested to assess it with respect to requirements i.e. to be sure that the user is satisfied with the system. Acceptance testing depends completely on users and therefore it is usually performed by the users in an environment which is similar to the deployment environment.

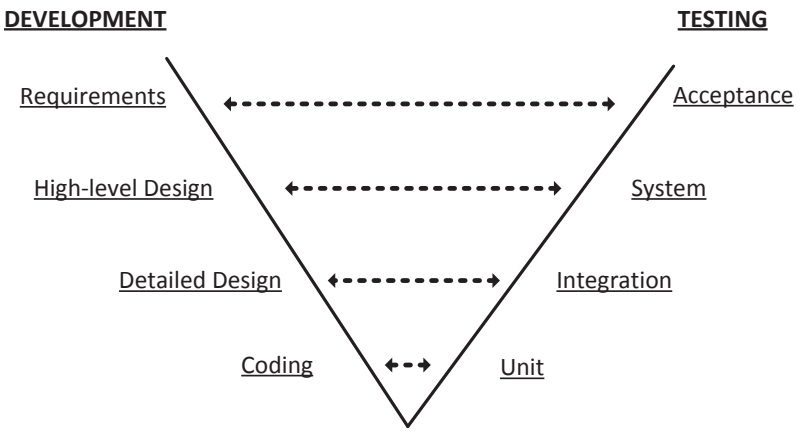


Figure 2: The ”V” model of software testing.

It is noteworthy to mention that some researchers use other variations of these levels in object-oriented software testing. Intra-method testing is used when tests are created for individual methods. Inter-method testing is used when pairs of methods in the same class are tested together. Intra-class testing is used when tests are created for a single class and inter-class testing is used when more than one class is tested at the same time [4].

An important testing level that spans through the testing phase is regression testing. Regression testing is performed when the system is modified either by adding new components during testing or by fixing errors. Regression testing seeks to uncover new software errors in a system after changes, such as enhancements, have been made to it.

2.1.4. Test Coverage

Test coverage tries to answer questions about when to stop testing or what is the the amount of testing which is enough for a program. Coverage analysis is used to assure the quality of the test cases to test a program. Code coverage defines the degree to which the source code of a program has been exercised by the set of test cases. Many coverage criteria have been used in the last fifty decades. Some common coverage criteria include:

- Statement coverage: Statement coverage is the basic form of code coverage. A statement is covered if it is executed. It is also known as line coverage or basic-block coverage.

- Branch coverage: It ensures that every branch in the source code is executed at least once by the set of test cases. It is also known as decision coverage.

- Condition/Multiple conditions coverage: Condition coverage requires that each condition be evaluated as true and false at least once by the test cases. Multiple conditions coverage requires that all true-false combinations of simple conditions be exercised at least once by the set of test cases.

Figure 3 shows an example of achieving these coverage criteria. Statement coverage is achieved by executing only test case (a), branch coverage is achieved by executing test cases (a) and (b), while condition coverage is achieved by executing test cases (b) and (c).

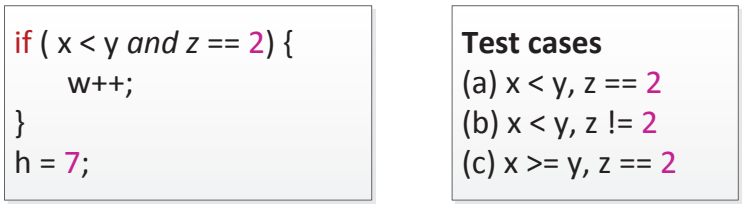


Figure 3: An example of coverage criteria.

2.1.5. Software Testing Techniques

In software testing, there are three categories of testing techniques based on the source of tests: specifications-based, program-based, and fault-based testing [53]. In this section, we present these main testing techniques.

- Specification Based Testing: The goal of specification-based testing techniques is to test the software functionality according to the appropriate requirements [36]. Tests are derived from software specifications and requirements. It uses descriptions of software containing specifications, requirements, and designs to derive test cases. It is called black-box testing because the tests are derived without examining the source code. Next, we present briefly two specification based techniques: equivalence partitioning and boundary value analysis.

  - Equivalence partitioning: Equivalence partitioning (EP) is a technique that divides the input data of software into partitions of data. Then, test cases can be derived from these partitions. The idea is to test all the domains of software instead of selecting part of the domains. Also, similar input domain can be

tested once. So, the result of testing any value from a partition is considered to be representative of the whole partition. As a result, this technique reduces the total number of test cases that should be developed. One of the main advantages of this approach is time reduction due to the smaller number of developed test cases.

  - Boundary value analysis: Boundary value analysis (BVA) is a special case of the equivalence partitioning technique where values that lie at the edge of an equivalence partition are called boundary values. The idea is that developers usually make errors near the boundaries of input domains, i.e., errors which exceed the boundary by one (if a condition is written as $x \leq 100$ where it should be $x < 100$). In the previous example, a value of 100 is valid where it should be invalid.

- Program based testing: In program-based testing, tests are derived from the source code of software. It is also called white-box testing because tests are derived from the internal structure of software. The aim is to identify input data which covers the structure of software. Different code coverage measures are used to measure the degree to which the source code of a program has been tested. There are two main types of code coverage criteria namely data-flow coverage and control-flow coverage.

  Both data-flow and control-flow testing use control flow graphs as test models which give an abstract representation of the code. Control-flow testing techniques use a directed control flow graph which represents code segments and their sequencing in a program. Each node in the graph represents a code segment. An edge between two nodes represents a conditional transfer of control between the two nodes.

  The goal of data-flow testing techniques is to ensure that data dependencies are correct. It examines how values of data affect the execution of programs e.g., data values are not available when they are required. Test cases are derived from both

flow graph and data dependency analysis. Data-flow testing selects paths to be tested based on the operations of the program. A def is a data definition (i.e., data creation, initialization, and assignment). A use is a data use (i.e., data used in computation). A definition clear (def-clear) path p with respect to a variable y is a path where y is not defined in the intermediate nodes. Data-flow testing tracks the definition and use of a variable (def-use pair), in which abnormal actions could happen, during program execution. Some data flow coverage criteria are described below:

  - All definitions (all-defs) criterion: It requires that for each definition of a variable, the set of paths executed by the test set contains a def-clear path from the definition to at least one use of the variable.
  - All uses criterion: It requires that for each definition of a variable, and for each use of the variable reachable from the definition, there is def-clear path from the definition to the use node.
  - All definition-use-paths criterion: Require that for each definition of a variable, and for each use of the variable reachable from the definition, all def-clear paths from the definition to the use node must be covered.

- Fault-based testing: Fault-based testing assumed that ”a program can only be incorrect in a limited fashion specified by associating alternate expressions with program expressions [48]”. Alternative versions of a program is generated by seeding faults to these programs. Then test cases are generated which try to distinguish between the program and the faulty versions. The effectiveness of a test case in finding real faults are measured by the number of seeded errors detected. The assumption is that seeded bugs are representative of real bugs. Two common fault-based techniques are mutation testing and error seeding techniques.

– Mutation testing: Mutation testing is used to measure the quality of testing by investigating whether test cases can uncover faults in the program. The assumption of mutation testing is that if test cases can reveal simple errors, it can also reveal more complex errors [20, 5]. Previous work found that mutation testing is a reliable way of assessing the fault-finding effectiveness of test cases and the generated mutants are similar to real faults [6]. Artificial faults are inserted into programs by creating many versions of the program; each version contains one simple fault. For a program, P, the mutation testing system creates many versions of P and inserts a simple fault in each version, these versions $(P_1, P_2, \cdots, P_k)$ are called mutants. Then, test cases are executed on the mutants to make it fail. If the test case uncover the fault in mutant P_1, we say that the mutant is killed which means that the fault that produced the mutant is distinguished by the test case. If the test case does not distinguish the mutant from the program, we say that the mutant is still alive. According to [20], a mutant may be live for one of the two reasons:

  1. the test case is not adequate to distinguish the mutant from the original program.
  2. the error which is inserted to the mutant is not an error and the program and its mutant are the same.

  The mutants are created using mutation operators. There are three types of mutation operators namely statement level mutation, method level mutation and class level mutation operators. Statement level mutation operators produce a mutation by inserting a single syntactic change to a program statement. Statement level mutation operators are mainly used in unit testing. Method level mutation operators are classified into two types namely intra-method and inter-method [52]. Intra-method level faults happen when the functionality of a

method is not as expected. Traditional mutation operators are used to create the mutants. Method level mutation operators are used in both unit testing and integration testing. Inter-method level faults occur on the connections between methods pairs. Interface mutation is applicable to this level. Class level mutation operators are also classified into two levels namely intra-class and inter-class. Intra-class testing is performed to check the functionality of the class. Inter-class testing [27] is performed to check the interactions between methods which belong to different classes. This level of testing is necessary when integrating many classes together to form a working subsystem. Kim et al. [34] defined thirteen class mutation operators to test object oriented features. The operators are extended by Chevalley [17] who added three operators. Ma et al. [42] identified six groups of inter-class mutation operators for Java. The first four groups are based on the features of object oriented languages. The fifth group of mutation operators includes features that are specific to Java, and the last group are based on common programming mistakes in object oriented languages.

– Seeding techniques: Many faulty versions of a program are created by inserting artificial faults into a program. A fault is considered detected if a test case makes it to fail. The seeding approach depends on the assumption that if a known number of seeded errors are inserted and then the number of detected seeded errors is measured, the detection rate of seeded errors could be used to predict the number of real errors. The number of real errors can be computed using the following formula [55]:

$$\frac{s}{S} = \frac{n}{N} \rightarrow N = \frac{nS}{s} \tag{1}$$

where

S: the number of seeded faults

N: the number of original faults in the code

s: the number of seeded faults detected

n: the number of original faults detected

The formula assumed that the seeded faults are representative of the real faults in terms of severity and occurrence likelihood. In our work, we use error seeding to evaluate our approach. A third party inserted integration errors according to the categorization of integration faults [38].

2.1.6. Integration Testing

Integration testing is one of the main testing activities for object-oriented systems. Nowadays, object-oriented systems are very large and complex. It contains huge number of modules and components and their interactions. Therefore, the interactions between modules should be tested carefully to discover integration errors before the system is delivered. The following section introduces the traditional integration strategies.

- Integration strategies: The traditional integration testing strategies are usually categorized into top-down, bottom-up, big-bang, threads, and critical modules integration.
  - Top-down integration: The top-down integration strategy is the one in which the integration begins with the module in the highest level, i.e., it starts with the module that is not used by any other module in the system. The other modules are then added progressively to the system. In this way, there is no need for drivers (it simulates the functionality of high level modules), but stubs are needed which mimic functionality of lower level modules. The actual components replace stubs when lower level code becomes available. One of the main advantages of this approach is that it provides early working module of

the system and therefore design errors can be found and corrected at early stage. Figure 4 shows an example of applying this approach. The top-down approach starts by testing the main class, then it tests the integration of the main class with the classes $C1$, $C2$, and $C3$. Then it tests the integration of all classes.

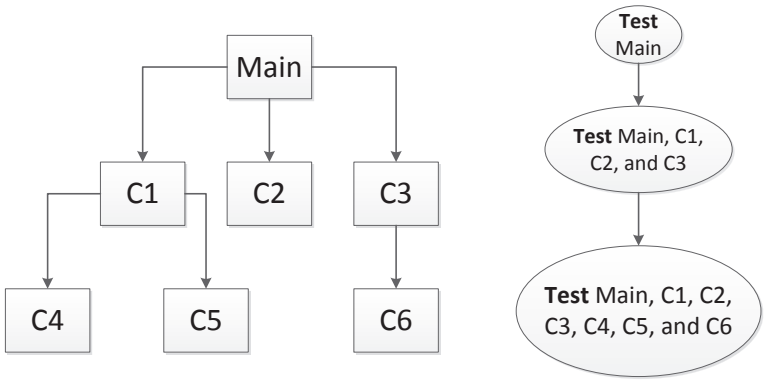


Figure 4: An example of top-down strategy.

– Bottom-up integration: The bottom-up integration strategy is the one in which the integration begins with the lower modules (terminal modules), i.e., it starts with the modules that do not use any other module in the system, and continues by incrementally adding modules that are using already tested modules. This is done repeatedly until all modules are included in the testing. In this way, there is no need for stubs, but drivers are needed. These drivers are replaced with the actual modules when code for other modules gets ready. Figure 5 shows an example of applying this approach. It starts by testing the classes at the lower level (C4, C5, and C6), then it adds the classes in the above level incrementally until all the classes being integrated.

– Sandwich integration: The sandwich integration strategy combines top-down strategy with bottom-up strategy. The system is divided into three layers: 1) A target layer in the middle; 2) A layer above the target; and 3) A layer below the

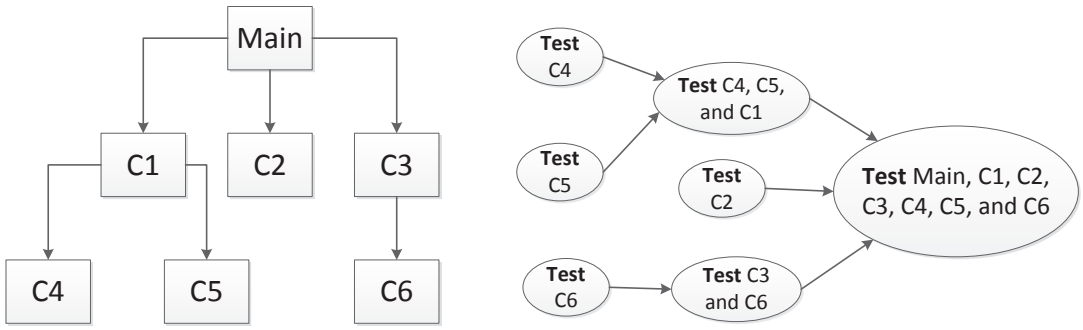


Figure 5: An example of bottom-up strategy.

target. The layers often selected in a way to minimize the number of stubs and drivers needed.

– Big-bang integration: To avoid the construction of drivers and stubs it is possible to follow the big-bang integration order, where all modules are integrated at once. One of the main disadvantages of this approach is that the identification and the removal of faults are much more difficult when dealing with the entire system instead of subsystems. Also, integration testing can only begin when all modules are ready. Figure 6 shows an example of applying this approach.

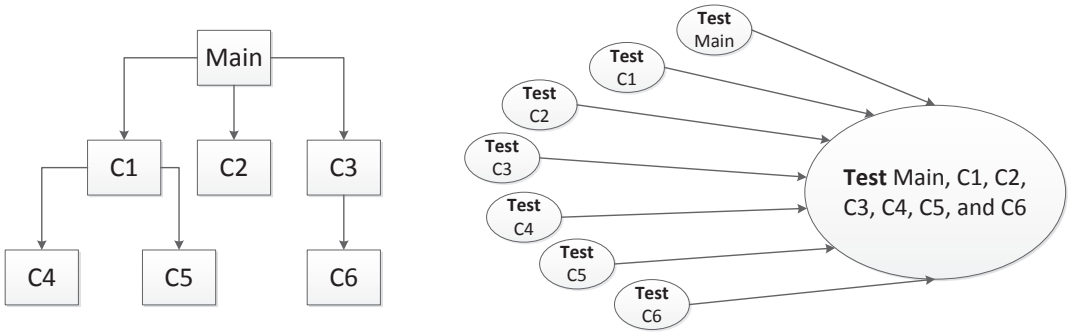


Figure 6: An example of big-bang strategy.

– Threads integration: A thread is a part of many modules which together present a program feature. Integration starts by integrating one thread, then another, until all the modules are integrated.

- Critical modules integration: In the critical modules integration strategy, units are merged according to their criticality level, i.e., most riskiest or complex modules are integrated first. In this approach, risk assessment is necessary as a first step.

Top-down and bottom-up approaches can be used for relatively small systems. A combinations of thread and critical modules integration testing are usually preferred for larger systems. In our work, we are not following any of these strategies. The closest one to our strategy is the critical modules integration. Critical modules integration starts with the most critical modules while our strategy starts with the connections that are more error prone.

It is very important to understand the different types of integration errors. This will help in the subsequent steps such as error seeding. The following section gives a classification for integration errors.

- Integration errors: When integrating software systems, several errors may occur. Leung and White [38] provide categorization of integration errors [53]. The categories are:

  - Interpretation errors: Interpretation errors occur when the dependent module misunderstand either the functionality the dependee module provides or the way the dependee module provides the functionality. Interpretation errors can be categorized as follows.

    * Wrong function errors: A wrong function error occurs when the functionality provided by the dependee module is not the required functionality by the dependent module.
    * Extra function errors: An extra function error happens when the dependee module contains functionality that is not required by the dependent.

    - Missing function errors: A missing function error occurs when there are some inputs from the dependent module to the dependee module which are outside the domain of the dependee module.
  - Miscoded call errors: Miscoded call errors happen when an invocation statement is placed in a wrong position in the dependent module. Miscoded call errors can result in three possible errors:
    - Extra call instruction: It occurs when the invocation statement is placed on a path that should not contain such invocation.
    - Wrong call instruction placement: It happens when the invocation statement is placed in a wrong position on the right path.
    - Missing instruction: It happens when the invocation statement is missing.
  - Interface errors: Interface errors occur when the defined interface between two modules is violated.
  - Global errors: A global error occurs when a global variable is used in a wrong way.

2.2. Related Work

This section presents a literature review for coupling metrics, error-proneness prediction, software dependencies, integration testing approaches, and cost reduction testing techniques. The section is organized as follows. In section 2.2.1, we present a review of existing coupling measures. In section 2.2.2, we present some work related to fault-proneness prediction. Section 2.2.4 presents some major integration testing approaches and Section 2.2.5 presents some related work that aims to reduce the cost of software testing.

2.2.1. Coupling Metrics

Coupling between objects (CBO) and response for a class (RFC) were introduced by Chidamber and Kemerer [18]. According to CBO, two classes are coupled when

methods in one class use methods or fields defined by the other class. RFC is defined as set of methods that can be potentially executed in response to a message received by an object of that class. In other words, RFC counts the number of methods invoked by a class. Li and Henry [40] defined coupling through message passing and coupling through abstract data type. Message passing coupling (MPC) counts the number of messages sent out from a class. Data abstraction coupling (DAC) is a count of the number of fields in a class having another class as its type, whereas DAC' counts the number of classes used as types of fields (e.g., if class c_1 has five fields of type class c_2, $DAC(c_1)$=5 and $DAC'(c_1)$=1). Afferent coupling (Ca) and efferent coupling (Ce), that use the term category (a set of classes that achieve some common goal), were identified by Martin [45]. Ca is the number of classes outside the category that depend upon classes within the category, while Ce is the number of classes inside the category that depend upon classes outside the categories. Lee et al. [37] defined information flow-based coupling (ICP). ICP is a coupling measure that takes polymorphism into consideration. ICP counts the number of methods from a class invoked in another class, weighted by the number of parameters. Two alternative versions, $IH-ICP$ and $NIH-ICP$, count invocations of inherited methods and classes not related through inheritance, respectively. All of these existing coupling metrics are defined for classes. Our work is different from previous research in that it provides a way to capture and analyze the strength of coupling among methods. Our coupling metrics define the coupling at three levels; method level, method-pair level, and class-pair level.

2.2.2. Fault-proneness Prediction

Class fault-proneness can be defined as the number of faults detected in a class. There is much research on building fault-proneness prediction models using different sets of metrics in object-oriented systems [8, 14, 15, 24]. The metrics are used as independent variables and fault-proneness is the dependent variable. In [8], the authors identified and used polymorphism measures to predict fault-prone classes. Their results showed that their

polymorphism measures can be used at early phases of the product life cycle as good predictors of its quality. The results also showed that some of the polymorphism measures may help in ranking and selecting software artifacts according to their level of risk given the amount of coupling due to polymorphism. Briand et al. [14] empirically investigated the relationships between object-oriented design measures and fault-proneness at the class level. They defined fault-proneness as the probability of detecting a fault in a class. They considered a total of 28 coupling measures, 10 cohesion measures, and 11 inheritance measures as the independent variables. Their results showed that coupling induced by method invocations, the rate of change in a class due to specialization, and the depth of a class in its inheritance hierarchy are strongly related to the fault-proneness in a class. Their results also showed that using some of the coupling and inheritance measures can be used to build accurate models which can be used to predict in which classes most of the faults actually lie. Predict fault-prone classes can be used in the unit testing process such that the testers can focus the testing on the faulty classes. On the other hand, identifying fault-prone classes cannot be used effectively in integration testing process because we do not know what the fault-prone connections are. Therefore, we need to identify error-prone connections between methods in order to focus the testing on them.

Zimmermann and Nagappan [72] proposed the use of network analysis on dependency graphs such as closeness measure to identify program parts which are more likely to contain errors. They investigated the correlation between dependencies and defects for binaries in Windows Server 2003. Their experimental results show that network analysis measures can detect 60% of binaries that are considered more critical by developers. They mentioned in their paper that most complexity metrics focus on single components and do not take into consideration the interactions between elements. In our work, we take the interactions between methods in our consideration.

Borner and Paech [10] presented an approach to select the test focus in the integration testing process. They identified the correlations between dependency properties and the number of errors in both the dependent and the independent files in the previous versions of a software system. They used information about the number of errors in dependent and independent files to identify the dependencies that have a higher probability to contain errors. One disadvantage of their method is that it is not applicable for systems that do not have previous versions.

2.2.3. Software Dependencies

Program dependencies is useful for many software engineering activities such as software maintenance [56], software testing [35], debugging [54], and code optimization and parallelization [25].

Sinha and Harrold [61] defined control dependencies in terms of control-flow graphs, paths in graphs, and the post-dominance relation. In addition, they presented two approaches for computing inter-procedural control dependencies: one approach computes precise inter-procedural control dependencies but it is extremely expensive; the second approach achieved a conservative estimate of those dependencies.

Schröter et al. [59] showed that design data such as import dependencies can be used to predict post-release failures. Their experimental study on ECLIPSE showed that 90% of the 5% most failure-prone components, as predicted by their model from design data, produce failures later. Orso et al. [54] presented two approaches for classifying data dependencies in programs that use pointers. The first approach categorizes a data dependence based on the type of definition, the type of use, and the types of paths between the definition and the use. Their technique classifies definitions and uses into three types and it classifies paths between definitions and uses into six types. The second approach classifies data dependencies based on their spans. It measures the extent of a data dependence in a program.

Nagappan and Ball [50] used software dependencies and churn metrics to predict post-release failures. In addition, they investigated the relationship between software dependencies and churn measures and their capability of assessing failure-proneness probabilities at statistically significant levels. Their experiments on Windows Server 2003 showed that there is an increase in the code churn measures with an increase in software dependency ratios. Their results also indicated that software dependencies and churn measures can be used significantly to predict the post-release failures and failure-proneness of the binaries. Zimmermann and Nagappan [73] used dependencies to predict post-release defects. The dependencies include call dependencies, data dependencies, and Windows specific dependencies. Their results on Windows Server 2003 showed that the dependency information can assess the defect-proneness of a system.

2.2.4. Integration Testing Approaches

There are many approaches for integration testing using UML diagrams [1] [26] [3]. An integration testing technique using design descriptions of software component interactions are produced by Abdurazik and offutt [1]. They used formal design descriptions that are taken from collaboration diagrams. They developed static technique that allows test engineers to find problems related to misunderstandings of the part of the detailed designers and programmers. They also developed a dynamic technique that allows test data to be created to assure reliability aspects of the implementation-level objects and interactions among them. An integration testing method using finite state machines is defined by Gallagher et al. [27]. They represented data flow and control flow graphs for the system in a relational database. They derived DU-pairs (define-use) and DU-paths that are used as the source of testing. Software classes are modeled as finite state machines and data flows are defined on the finite state machines. An approach for integration testing that uses information from both UML collaboration diagrams and state charts are described in [3] defined. They used collaboration diagrams and state charts to generate a model.

One important problem in integration testing of object oriented software is to determine the order in which classes are integrated and tested, which is called class integration test order (CITO) problem. When integrating and testing a class that depends on other classes that have not been developed, stubs should be created to simulate these classes. Creating these stubs are very costly and error-prone. A number of methods are proposed in literature to derive an integration and test order to minimize the cost of creating stubs [13]. Some of these approaches aimed to minimizing the number of stubs [29] [16] [31], while other approaches aimed to minimizing the overall stub complexity [2] [9] [69]. Briand et al. [11] presented an approach to devise optimal integration test orders in object-oriented systems. The aim is to minimize the complexity of stubbing during integration testing. Their approach combined use of coupling metrics and genetic algorithms. They used coupling measurements to assess the complexity of stubs and they used genetic algorithms to minimize complex cost functions. In [2], the authors presented an approach to solve the problem of class integration and test order. They added edge weights to represent the cost of creating stubs, and they added node weights which are derived from couplings metrics between the integrated and stubbed classes. They proved that their method reduces the the cost of stubbing. Borner and Paech [9] proposed an approach to determine an optimal integration testing order that considers the test focus and the simulation effort. They selected three heuristic approaches to select test focus and the simulation effort. Their results show that simulated annealing and genetic algorithms can be used to derive integration test orders.

2.2.5. Cost Reduction Testing Techniques

In previous studies, a number of techniques have been proposed to reduce the cost of testing which include test prioritization [22] [23], test selection [28] [12], and test minimization [58] [63]. Test prioritization aims to rank test cases so that test cases that are more effective according to such criteria will be executed first to maximize fault detection.

Test selection aims to identify test cases that are not needed to run on the new version of the software. Test minimization aims to remove redundant test cases based on some criteria in order to reduce the number of tests to run.

Elbaum et al. [22] identified a metric, $APFD_C$, for calculating fault detection rate of prioritized test cases. They also presented some prioritizing test cases techniques using their metric and based on the effects of varying test case cost and fault severity. Briand et al. [12] presented a test selection technique for regression testing based on change analysis in object-oriented designs. They assumed that software designs are represented using Unified Modeling Language (UML). They classified regression test cases into three categories: reusable (it does not need to be rerun to ensure regression testing is safe), retestable (it needs to be rerun for the regression testing to be safe), and obsolete (it cannot be executed on the new version of the system as it is invalid in that context). Their results showed that design changes can have a complex impact on regression test selection and that automation can help avoid human errors. Rothermel et al. [58] compared the costs and benefits of minimizing test suites of different sizes for many programs. Their results showed that the fault detection capabilities of test suites can be severely compromised by minimization. A test suite minimization approach using greedy heuristic algorithm is presented by Tallam and Gupta [63]. They explored the concept analysis framework to develop a better heuristic for test suite minimization. They developed a hierarchical clustering based on the relationship between test cases and testing requirements. Their approach is divided into four phases: (1) apply object reductions; (2) apply attribute reductions; (3)select a test case using owner reduction; and (4) build reduced test suite from the remaining test cases using a greedy heuristic method. Their empirical results showed that their test suite minimization technique can produce a reduction in the size of test suite which is the same size or even smaller than those which had been produced by the traditional greedy approach.

Our approach does not belong to any of these categories because test suites are not available in our case while test prioritization, test selection, and test minimization techniques depend on the availability of test suites. Therefore, our approach can lead to more reduction in time and cost because we ask the developer to write small number of test cases while the other techniques ask the developer to write a complete set of test cases, then these techniques try to select part of the test cases or remove some of them later.

CHAPTER 3. THE PROPOSED APPROACH

In this section, we discuss the proposed approach. Figure 7 provides an overview of the proposed approach. Our approach is divided into five steps. First of all, the dependency extractor extracts the dependencies from the compiled Java code. The result of this step is an XML file that contains the dependencies at method and class levels. After that, metrics extractor extracts the metrics using both the source code and the dependencies. The output of this step is the metrics at different levels of granularity which includes method level metrics, method-pair metrics, and class-pair metrics. Then, the connections between methods are ranked according to a weight which is calculated using combination of metrics defined in the previous step. The rank of the connections indicates which connections should be focused on during the testing process. Next, test focus selector selects the error-prone connections as a test focus and predicts the number of test cases needed to test each connection based on the weights of the connections produced in the previous step and given the initial number of test cases needed. The last step is to generate test cases manually to test the required application. The following sections explain these steps in detail.

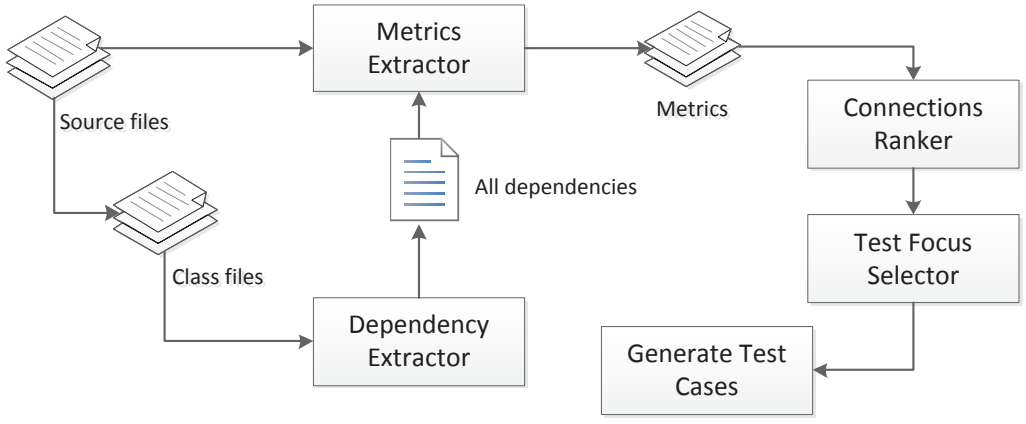


Figure 7: An overview of the proposed approach.

3.1. System Representation

We first define a representation for a software system.

A software system S is an object-oriented system. S has a set of classes $C = \{c_1, c_2, \cdots, c_n\}$. The number of classes in the system is $n = |C|$. A class has a set of methods. For each class $c \in C, M(c) = \{m_1, m_2, \cdots, m_t\}$ are the set of methods in c, where $t = |M(c)|$ is the number of methods in a class c. The set of all methods in the system S is denoted by $M(S)$.

3.2. Dependency Extractor

The dependency extractor step extracts dependencies from Java class files. It detects three levels of dependencies: 1) class to class; 2) feature to class; and 3) feature to feature. The term feature indicates class attributes, constructors, or methods. We use the Dependency Finder tool [66] to extract the dependencies. The Dependency finder tool is widely used to compute dependencies in the literature [19, 41, 60, 68, 21]. Dependency Finder is also free and open source. We create the dependencies for three Java systems manually and then we compare it with the output created by the Dependency Finder tool. Both sets of data provided consistent results. Dependency Finder uses particular classes to parse .class files. It also includes tools that looking at the contents of these files. For example, ClassReader is used to put the class in a .class file in human-readable form. With the -xml switch, it outputs the structure to an XML file. Dependency Finder creates dependency graphs based on the information available in Java class files. A dependency graph contains nodes for software systems connected together using two types of relationships namely composition and dependency. Packages contain classes and classes contain features. These kinds of relationships are called composition relationships. A feature node is connected to its class through a composition and a class is connected to its package through a composition. In our work, we do not consider composition relationships. The second type of relationships is dependency. A class depends on other classes, a feature depends on other

features, and a feature depends on other classes. In our work, we consider dependency relationships on feature level. Figure 8 shows a toy system that has four classes and Figure 9 shows the dependencies extracted by the dependency finder tool. As we can see in Figure 9, ClassA.example() method depends on ClassB class, ClassB.getName() method, and ClassB.x attribute. ClassB class depends on ParentClass class and ParentClass depends on Interface class.

```
public class ClassA {
    public void example(ClassB b){
        String name = b.getName()+b.x;
        System.out.println(name);
    }
}

public class ClassB extends ParentClass{
    int x = 5;
    public String getName(){
        return "ClassB";
    }
    public String getType(){
        return "Child";
    }
}

public interface Interface {
    public String getName();
    public String getType();
}

public class ParentClass implements Interface{
    public String getName(){
        return "ParentClass";
    }
    public String getType(){
        return "Parent";
    }

}
```

Figure 8: Toy system.

3.3. Metrics Extractor

The aim of this step is to identify set of metrics and to extract those metrics automatically from both the dependencies produced in the previous step and the Java source code. This section describes the software metrics that we use in our work. We define the metrics on method, method-pair, and class-pair.

```
<?xml version="1.0" encoding="utf-8" ?>

<dependencies>
            <name>ClassA</name>
            <feature confirmed="yes">
                <name>ClassA.example(ClassB)</name>
                <outbound type="class" confirmed="yes">ClassB</outbound>
                <outbound type="feature" confirmed="yes">ClassB.getName()</outbound>
                <outbound type="feature" confirmed="yes">ClassB.x</outbound>
            </feature>
        </class>
            <name>ClassB</name>
            <outbound type="class" confirmed="yes">ParentClass</outbound>
            <inbound type="feature" confirmed="yes">ClassA.example(ClassB)</inbound>
            <feature confirmed="yes">
                <name>ClassB.getName()</name>
                <inbound type="feature" confirmed="yes">ClassA.example(ClassB)</inbound>
            </feature>
            <feature confirmed="yes">
                <name>ClassB.x</name>
                <inbound type="feature" confirmed="yes">ClassA.example(ClassB)</inbound>
            </feature>
        </class>
        <class confirmed="yes">
            <name>Interface</name>
            <inbound type="class" confirmed="yes">ParentClass</inbound>
        </class>
        <class confirmed="yes">
            <name>ParentClass</name>
            <outbound type="class" confirmed="yes">Interface</outbound>
            <inbound type="class" confirmed="yes">ClassB</inbound>
        </class>
    </package>
</dependencies>
```

Figure 9: Dependencies of the toy system.

3.3.1. Method Level Metrics

We define metrics on individual methods within a class. For method m_i in class c_i, most of these metrics calculate the number of classes, methods, and fields that have a dependency with method m_i. Figure 10 shows a simple Java example that will be used to explain the method level metrics. The Java example contains two classes: MO class and RO class. MO class contains two methods: getMin method and getMax method. GetMin method returns the minimum value of any three numbers while getMax method returns the maximum value of any three numbers. RO class contains the main method. The main method creates an object from MO class. Figure 11 shows the coupling dependency graph for the Java fragment of code. In Figure 11, the RO.main() method depends on MO.magicNumber attribute, MO.getMin method, MO.getMax method, and MO.MO constructor. In Figure 10, RO.main method calls the implicit constructor for MO class.

The metrics that are defined on individual methods within a class are as follows.

1. Inbound Method Dependencies (IMD): Methods in other classes that depend on method m_i. For example, $IMD(\text{MO.getMax}()) = 1$.

2. Outbound Method Dependencies (OMD): Methods in other classes that method m_i depends on. For example, $OMD(\text{RO.main}()) = 3$.

3. Outbound Field Dependencies (OFD): Fields in other classes that method m_i depends on. For example, $OFD(\text{RO.main}()) = 1$.

4. Outbound Class Dependencies (OCD): Classes that method m_i depends on. For example, $OCD(\text{RO.main}()) = 1$.

5. Local Variables $(LVAR)$: Number of local variables use by method m_i.

6. $NOCMP$: Number of complex input parameters in method m_i. The input parameter is complex if it is not a primitive type. For example, in Figure 12, we pass classA as a parameter to method1.

7. Maximum Nesting Depth (MND): The maximum depth of nesting in method m_i. This metric represents the maximum nesting level of control constructs (if, for, while, and switch) in the method. We use Understand tool [1] to compute this metric. For example, in Figure 13, $MND(methodA) = 3$

3.3.2. Method Pair Metrics

We define the following metrics on the method pair (m_i, m_j) where m_i is a dependent and m_j is a dependee, $m_i \in c_i$, $m_j \in c_j$ where $c_i \neq c_j$.

[1] http://www.scitools.com/

1. Inbound Common Method Dependencies ($ICMm_im_j$): Number of common methods that depend on both m_i and m_j. In Figure 14, $ICMm_1m_2 = 2$ (m_3 and m_4 depend on both m_1 and m_2).

2. Outbound Common Method Dependencies ($OCMm_im_j$): Number of common methods that both m_i and m_j depends on. In Figure 15, $OCMm_1m_2 = 1$ (Both m_1 and m_2 depend on m_3.

3.4. Connections Ranker

In this step, We use combination of metrics defined in the previous step to rank the connections between methods. The combination of metrics will be used to examine several hypothesis regarding the correlation between these metrics and error discovery rate. The rank of the connections specifies the connections that should be focused on during the testing process.

For method-pair (m_i,m_j), the weight for the connection between m_i and m_j is calculated as follows:

$$weight(m_i, m_j) = (weight(m_i) + weight(m_j)) \times (ICMm_im_j + OCMm_im_j + 1) \quad (2)$$

where $weight(m_i)$ is calculated as follows:

$$weight(m_i|c_k, c_l) = \frac{IC_{m_i} \times (IMDm_i + OMDm_i + OFDm_i)^2}{\sum_{y \in M(c_k,c_l)} IC_y \times (IMDy + OMDy + OFDy)^2} \quad (3)$$

where $M(c_k, c_l)$ is the set of methods in both class c_k and class c_l. IC_{m_i} is the internal complexity of method m_i. It can be measured as follows:

$$IC_{m_i} = MNDm_i + NOCMPm_i + LVARm_i \quad (4)$$

3.5. Test Focus Selector

The Test focus selector step predicts the number of test cases needed to test each connection based on the weights of the connections produced in the previous step and given the initial minimum number of test cases needed. We would like to start with a small initial number of test cases. In our work, we assume the initial number of test cases needed to test a system S to be 0.10% of the number of interactions. After that, the number of test cases can be adjusted depending on the error discovery rate. For example, if the initial number of test cases to test a system was 50 and the error discovery rate was 60%, then we generate and run 0.10% more test cases in each iteration until we reach 80% of error discovery rate. The method-pair weight is computed using the equation in the previous section. The class-pair weight is computed as the summation of all method-pair weights that belong to the two classes. If the class-pair weight is zero, we specify one test case to test the class-pair connection. Figure 16 explains the testing process used in our approach. We start by creating w test cases where w is the initial number of test cases given by the approach. We then run the test cases against the seeded versions of the applications and we compute the error discovery rate. We stop if we achieve 80% error discovery rate. Otherwise, we create more test cases (10% of the interactions in each iteration) until the 80% is achieved.

3.6. Generate Test Cases

In this step, test cases is created manually to test the required application. For evaluating the testing process, both error seeding technique [47, 51] and mutation testing are used. The test case generation step compares the original program with the seeded program. If the test cases are enable to differentiate between the original program and the seeded program, the seeded program is said to be killed; otherwise, it is still alive.

3.7. Tool Implementation

We build a **S**oftware **M**etrics for **I**ntegration **T**esting (SMIT) tool to calculate the metrics automatically. SMIT computes the dependency and complexity metrics at three levels of granularity:

- Method level
- Method-pair level
- Class-pair level

The tool is developed using R language version 2.15.0 [65]. Binary versions of this language are available for several platforms including Windows, Unix and MacOS. It is not only free but also an open source. R provides a wide variety of statistical and graphical techniques. It includes an effective data handling and storage facilities, a suite of operators to perform calculations on matrices, a large collection of tools for data analysis. R also provides powerful functions to deal with regular expressions. R can be extended very easily by the use of packages. There are many packages that are available from the R distribution and from the CRAN family of Internet sites.

Figure 17 shows a high level description of SMIT tool. SMIT tool uses the Dependency Finder tool to extract dependencies from compiled Java code. SMIT directly invokes the Dependency Finder tool in the source code. The input for this step is the directory that contains the compiled files (.class files). SMIT tool starts by saving the names of the ".class" files in the working directory. The output of this step is a file in XML format which contains all of the dependencies. Figure 18 shows an example of the dependencies for a method in the Monopoly application. It shows both the inbound and the outbound dependencies for the method. The Dependency Finder tool also computes some software metrics such as number of parameters for the method (PARAM), number of code lines in the method (SLOC), and number of local variables use by the method (LVAR).

Then, SMIT extracts all of the call graphs and saves the results in Call-Graphs Matrix (CGM). We only consider calls between methods that belong to different classes. The CGM matrix is a square binary $t \times t$ matrix, where t represents the number of methods in the system. The matrix indicates the direct method invocation interactions. The value of CGM[i,j] is defined as follows:

$$CGM[i,j] = \begin{cases} 1 & \text{if the ith method invokes the jth method} \\ 0 & \text{otherwise} \end{cases}$$

Where $1 \leq i \leq t$ and $1 \leq j \leq t$. Rows of CGM matrix represent the callers (dependents) where columns represent the callees (dependees). We exclude calls between methods in the same class.

After extracting all of the call graphs, SMIT computes the method level metrics namely NOCMP, IMD, OMD, and OFD. The NOCMP metric represents the number of complex input parameters in a method where input parameter is considered complex if it is not a primitive type (e.g., if it is of type class, array, or hashmap). Then, SMIT computes method-pair metrics and computes a weight for each connection as discussed in the connections ranker Section. After that, SMIT computes a weight for each class-pair. A class-pair weight is computed as the summation of all method-pair weights that belong to the two classes. Finally, SMIT predicts the number of test cases needed to test each connection as explained in the test focus selector Section.

SMIT implementation program contains the following functions:

- classFiles(): It returns a list that contains the names of all class files (the files that have the extension ".class") in the working directory.

- extractDep(): This function extracts all of the dependencies for the system under test using the DependencyFinder and it stores the the output in an XML file.

- callGraphs(): It extracts the call graphs for all methods in the system and it stores the results in a matrix.
- inboundMethodCalls(m_i): It returns all methods that depend on method m_i.
- outboundMethodCalls(m_i): It returns all methods that method m_i depends on.
- outboundFeildDependencies(m_i): It returns all fields that method m_i depends on.
- lvarMetric(): It calculates the number of local variables used by a method.
- nocmpMetric(): It calculates the number of complex input parameters in a method.
- mndMetric(): It calculates the value of the MND metric for a method .
- icmMetric(): It calculates the value of the ICM metric for a method-pair.
- ocmMetric(): It calculates the value of the OCM metric for a method-pair.
- outboundMDep(): This function extracts the outbound method dependencies for a method.
- inboundMDep(): This function extracts the inbound method dependencies for a method.
- weightmi(): This function calculates the weight for a method.
- weightmimj(): This function calculates the weight for a method-pair.
- classPairMetrics(): It computes the values of all class-pair metrics.

SMIT is provided with a command-line interface (CLI). Figure 19 shows an example of running SMIT from the command line. It invokes the Rscript command which is followed by the name of the program to be run (D:/javaSystems/smit.R) and then followed by an argument that specifies the working directory.

The outputs of our tool are four files in CSV format, method level metrics file, method-pair level metrics file, class-pair level metrics file and a final report file. Figure 20 shows the output of SMIT and Figure 21 shows a screen capture for part of the final report for the PureMVC application.

3.8. Toy Example

This section illustrates the proposed approach using a simple toy example. Figure 22 shows three classes and the dependencies between methods that belong to different classes. For example, a directed arrow between m_1 and m_5 means that method m_1 depends on method m_5. SMIT tool starts by computing the method-level metrics automatically from both source code and byte code. Then, SMIT determines the method-pair interactions such that the two methods should belong to different classes (i.e., we are not interested in dependencies between methods in the same class). SMIT also calculates the method-pair metrics. After that, the weight for each method pair is computed using Equation (2) and the weight for each method is calculated using Equation (3). Figure 22 shows the weight of each connection using toy numbers. For example, $weight(m_2, m_6) = 0.81$. SMIT computes the the initial number of test cases which equals to $10\% \times$ No. of connections in the system.

For the toy example in Figure 22, we assume that the initial number of test cases is equal to 6. SMIT then computes the weight for each class pair as shown in Figure 23. The class-pair weight is computed as the summation of all method-pair weights that belong to the two classes. In Figure 22, $weight(Class1, Class2) = 1.1$ which equals to the summation of the weights of the three method-pair ($m1 - m5$, $m2 - m6$, and $m3 - m7$).

Table 1: The number of test cases needed to test class pairs.

Class-pair	Weight	Normalized Weight	# of test cases
Class1 , Class2	1.1	0.453	$0.453 \times 6 = \|2.718\| = 3$
Class1 , Class3	0.41	0.169	$0.169 \times 6 = \|1.014\| = 1$
Class2 , Class3	0.92	0.379	$0.379 \times 6 = \|2.274\| = 2$

After that, SMIT computes the initial number of test cases needed to test each class-pair as shown in Table 1. For example, the predicted number of test cases needed to test class pair (class 1, class 2) is equal 3 and it is computed by multiplying the normalized weight of the class-pair by the initial number of test cases and rounding the result to the nearest integer. Finally, SMIT computes the initial number of test cases needed to test each method-pair as shown in Table 2. For example, the predicted number of test cases needed to test the method pair (m_2, m_6) is equal 2 and it is computed by multiplying the normalized weight of the method-pair (0.736) by the initial number of test cases needed to test the class-pair (3) and rounding the result to the nearest integer.

Table 2: The number of test cases needed to test method pairs.

Method-pair	Weight	Normalized Weight	# of test cases
m_1, m_5	0.07	0.063	$0.063 \times 3 = \|0.189\| = 0$
m_2, m_6	0.81	0.736	$0.736 \times 3 = \|2.208\| = 2$
m_3, m_7	0.22	0.2	$0.2 \times 3 = \|0.6\| = 1$
m_4, m_{10}	0.41	0.41	1
m_8, m_{11}	0.73	0.793	$0.793 \times 2 = \|1.586\| = 2$
m_9, m_{12}	0.19	0.206	$0.206 \times 2 = \|0.412\| = 0$

```
public class MO
{
   public int magicNumber = 5000;
   public double getMin( double x, double y, double z )
   {
      double minimum = x;
      if ( y < minimum )
         minimum = y;
      if ( z < minimum )
         minimum = z;
      return minimum;
   } // end method getMin

   public double getMax( double x, double y, double z )
   {
      double maximum = x;
      if ( y > maximum )
         maximum = y;
      if ( z > maximum )
         maximum = z;
      return maximum;
   } // end method getMax
} // end class MO


public class RO
{
   public double a = 5;
   public double b = 3;
   public double c = 1;

   public void main()
   {
      MO mywork = new MO();
      double w1 = mywork.getMin( a, b, c );
      double w2 = mywork.getMax( a, b, c );
      int m = mywork.magicNumber;
      System.out.println(m);
   } // end main
} // end class RO
```

Figure 10: Simple Java example that contains two classes MO and RO.

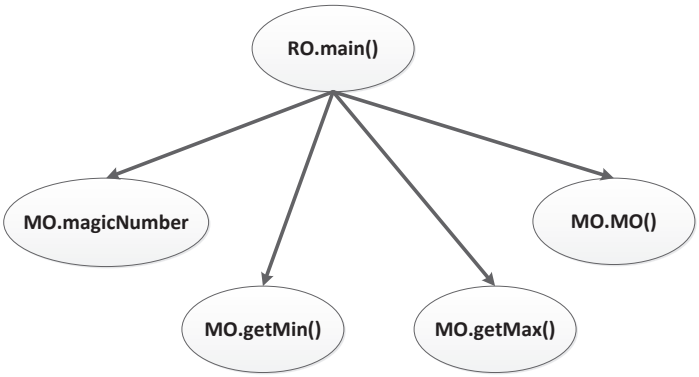


Figure 11: The coupling dependency graph for the Java example.

```
class classA
{
   int number;
   string name;
} // end class
```

```
public  void method1(classA w)
 {
    w.number = 300;
    w.name = "Mark";
 } // end method
```

Figure 12: An example of complex input parameter.

```
public  void methodA()
 {
        if ( ... )
                if ( ... )

        for ( ... )
                for ( ... )
                        for ( ... )
 } // end method
```

Figure 13: An example of maximum nesting depth.

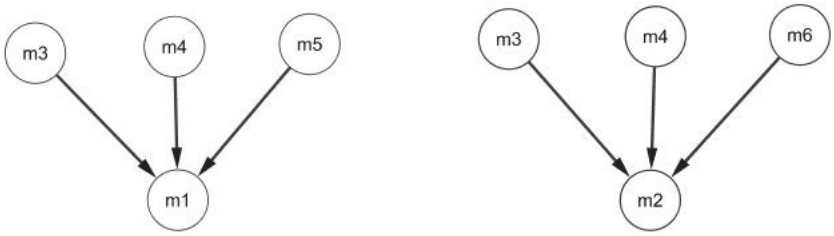


Figure 14: An example of computing the ICM metric ($ICMm_1m_2 = 2$).

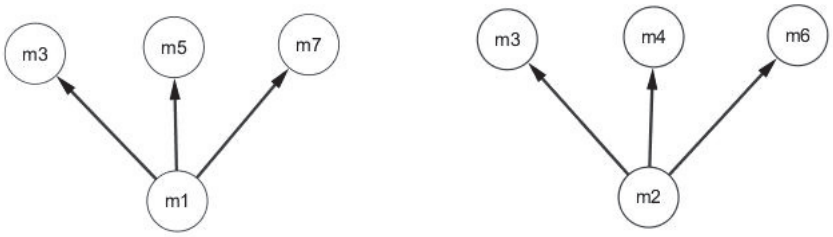


Figure 15: An example of computing the OCM metric ($OCMm_1m_2 = 1$).

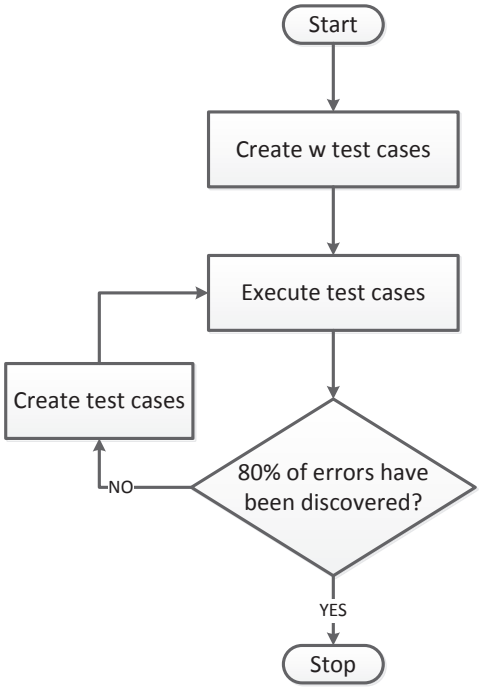


Figure 16: Our testing approach.

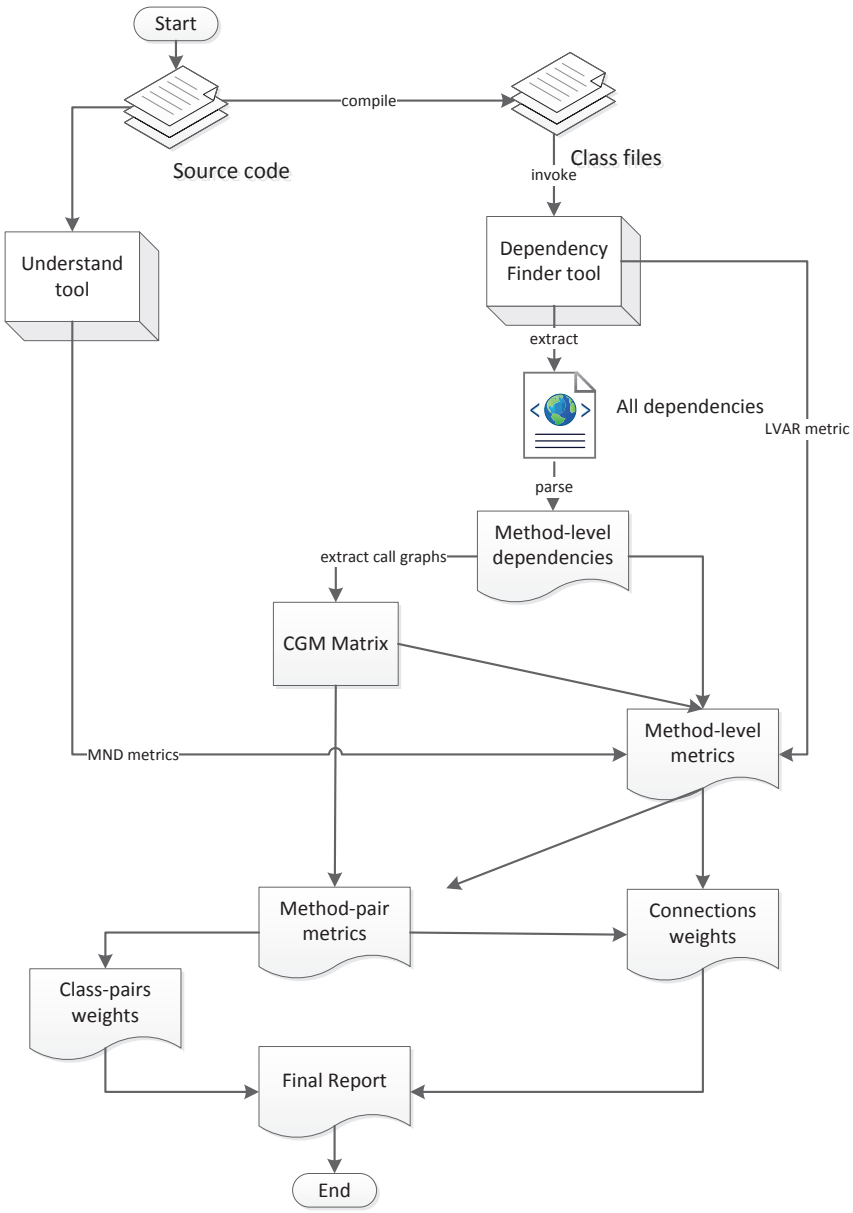


Figure 17: High level description of SMIT tool.

```
<?xml version="1.0" encoding="utf-8" ?>

<dependencies>
    <package confirmed="yes">
        <name>edu.ncsu.monopoly</name>
        <class confirmed="yes">
            <name>edu.ncsu.monopoly.GameMaster</name>
            <feature confirmed="yes">
                <name>edu.ncsu.monopoly.GameMaster.completeTrade(edu.ncsu.monopoly.TradeDeal)</name>
                <outbound type="feature" confirmed="yes">edu.ncsu.monopoly.GameBoard.queryCell(java.lang.String)</outbound>
                <outbound type="feature" confirmed="yes">edu.ncsu.monopoly.GameMaster.gameBoard</outbound>
                <outbound type="feature" confirmed="yes">edu.ncsu.monopoly.GameMaster.getCurrentPlayer()</outbound>
                <outbound type="feature" confirmed="yes">edu.ncsu.monopoly.GameMaster.getPlayer(int)</outbound>
                <outbound type="feature" confirmed="yes">edu.ncsu.monopoly.Player.buyProperty(edu.ncsu.monopoly.Cell, int)</outbound>
                <outbound type="feature" confirmed="yes">edu.ncsu.monopoly.Player.sellProperty(edu.ncsu.monopoly.Cell, int)</outbound>
                <outbound type="feature" confirmed="yes">edu.ncsu.monopoly.TradeDeal.getAmount()</outbound>
                <outbound type="feature" confirmed="yes">edu.ncsu.monopoly.TradeDeal.getPlayerIndex()</outbound>
                <outbound type="feature" confirmed="yes">edu.ncsu.monopoly.TradeDeal.getPropertyName()</outbound>
                <inbound type="feature" confirmed="yes">edu.ncsu.monopoly.GameMaster.btnTradeClicked()</inbound>
            </feature>
        </class>
    </package>
</dependencies>
```

Figure 18: The dependencies for completeTrade method in the Monopoly application.

Figure 19: Run SMIT from command line.

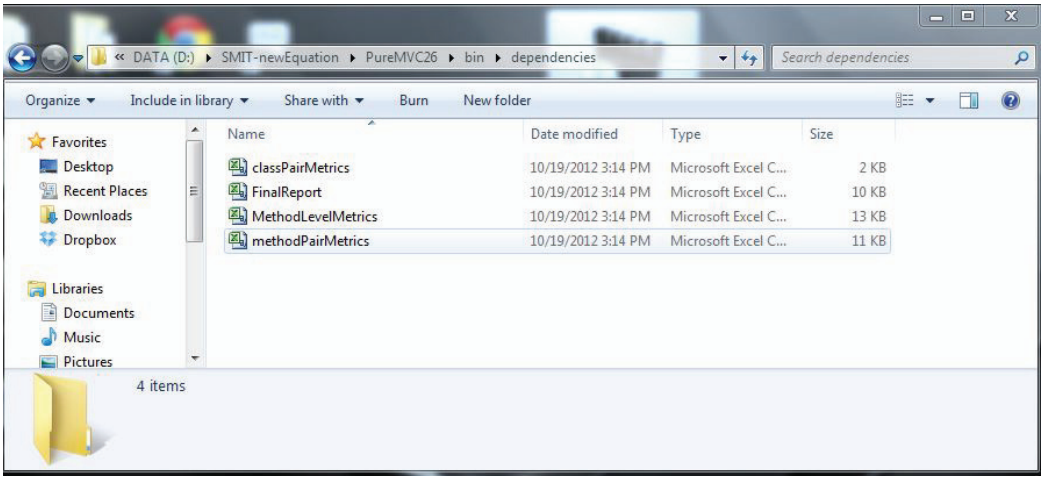
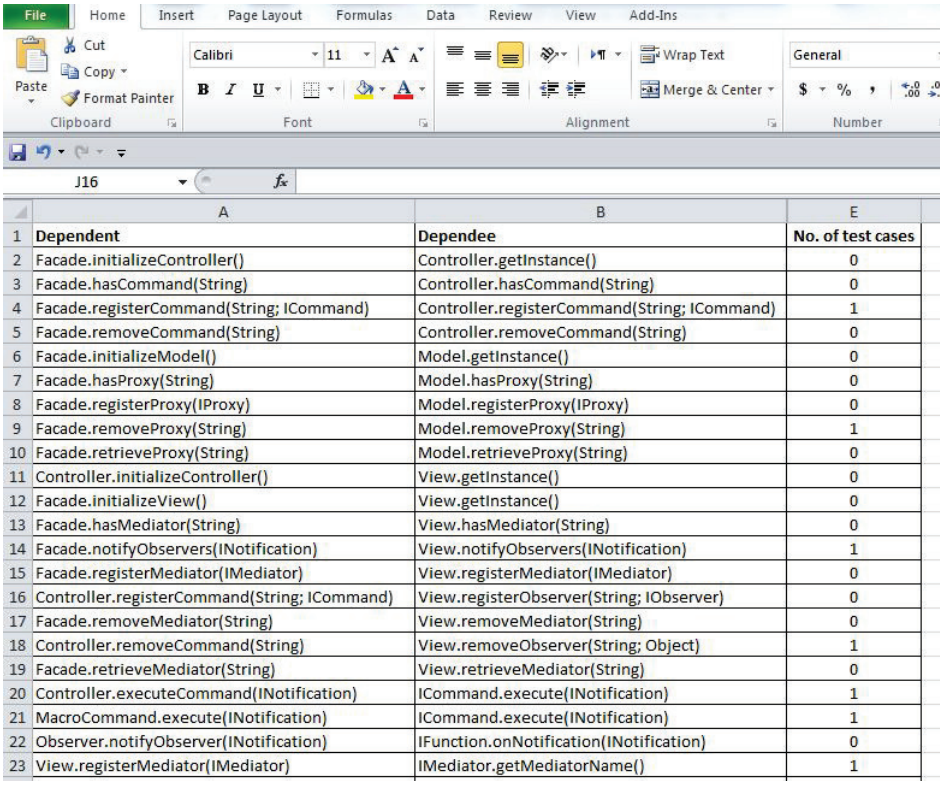


Figure 20: A screen capture for SMIT output.



	A	B	E
1	**Dependent**	**Dependee**	**No. of test cases**
2	Facade.initializeController()	Controller.getInstance()	0
3	Facade.hasCommand(String)	Controller.hasCommand(String)	0
4	Facade.registerCommand(String; ICommand)	Controller.registerCommand(String; ICommand)	1
5	Facade.removeCommand(String)	Controller.removeCommand(String)	0
6	Facade.initializeModel()	Model.getInstance()	0
7	Facade.hasProxy(String)	Model.hasProxy(String)	0
8	Facade.registerProxy(IProxy)	Model.registerProxy(IProxy)	0
9	Facade.removeProxy(String)	Model.removeProxy(String)	1
10	Facade.retrieveProxy(String)	Model.retrieveProxy(String)	0
11	Controller.initializeController()	View.getInstance()	0
12	Facade.initializeView()	View.getInstance()	0
13	Facade.hasMediator(String)	View.hasMediator(String)	0
14	Facade.notifyObservers(INotification)	View.notifyObservers(INotification)	1
15	Facade.registerMediator(IMediator)	View.registerMediator(IMediator)	0
16	Controller.registerCommand(String; ICommand)	View.registerObserver(String; IObserver)	0
17	Facade.removeMediator(String)	View.removeMediator(String)	0
18	Controller.removeCommand(String)	View.removeObserver(String; Object)	1
19	Facade.retrieveMediator(String)	View.retrieveMediator(String)	0
20	Controller.executeCommand(INotification)	ICommand.execute(INotification)	1
21	MacroCommand.execute(INotification)	ICommand.execute(INotification)	1
22	Observer.notifyObserver(INotification)	IFunction.onNotification(INotification)	0
23	View.registerMediator(IMediator)	IMediator.getMediatorName()	1

Figure 21: A screen capture for part of the final Report output for PureMVC.

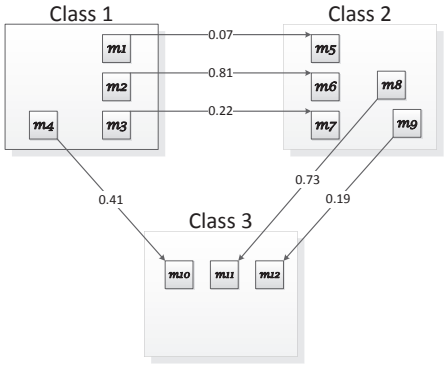


Figure 22: A toy example of classes and the dependencies between methods.

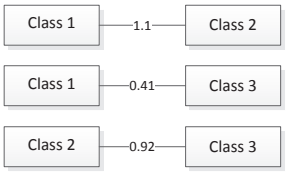


Figure 23: Class-pairs for the toy system and their weights.

CHAPTER 4. EXPERIMENTAL EVALUATION

In order to evaluate the proposed approach, we select open-source applications implemented in Java. Table 3 shows a summary of the selected applications. The selected applications vary in size and domain and can be downloaded freely from the Internet. In this chapter, we:

- describe the Java systems that we use in our evaluation
- present the results of the proposed approach
- discuss the results

Table 3: A summary of the selected applications.

Project	# classes	# methods	Source
Monopoly	57	336	http://realsearchgroup.com/rose/
PureMVC	22	139	http://puremvc.org/
Cinema	10	106	http://alarcos.esi.uclm.es
ApacheCli	20	207	http://commons.apache.org/cli/
Pacman	25	208	http://code.google.com/p/stq-jpacman/
ApacheValidator	59	660	http://commons.apache.org/validator/
JTopas	63	753	http://sir.unl.edu

4.1. Selected Systems under Test

We select seven application in order to evaluate the proposed approach. We choose these seven application to represent lots of domains. The two games applications (Monopoly and Pacman) represent applications where systems have to interact a lot to satisfy the logic rules of the underlying strategy of the game logic. The libraries and frameworks are commonly used in Java where we usually strive for reusability in dependent applications. We choose three libraries (ApacheCLI, ApacheValidator, and JTopas) to represent this perspective. Since Java web-applications are widely used nowadays, we choose PureMVC which implements the famous web design pattern Model-View-Controller (MVC). We

choose one business information system application (Cinema). A brief description of the applications appears below.

4.1.1. Monopoly System

The Monopoly application presents a Monopoly-like computer game. Monopoly provides many features that appear in the Monopoly board game. Many players play in turns. A player moves based on the dice roll (two dices). When the user reaches the end of the board, he/she cycles around. The system implements many rules of the Monopoly game. For example, when a player passes or lands on the GO cell, the bank gives the player 200 dollars. Figure 24 shows the class diagram of the Monopoly system.

4.1.2. PureMVC

PureMVC is a light weight framework for creating applications based on the classic Model, View and Controller concept. There are two versions of the PureMVC framework: Standard and MultiCore. We use the standard Version that provides a methodology for separating the coding interests according to the MVC concept. The application layers are represented by three Singletons (a design pattern that limits the instantiation of a class to one object). The MVC Singletons manage Proxies, Mediators and Commands. Another Singleton, the Faade, provides a single interface for communications through the application. Figure 25 shows the class diagram of the PureMVC system.

4.1.3. Cinema Management System

The Cinema application is an information management system. It is a movie theater system that manages tickets booking, seats assignments, movie times, and movie locations. This system is general enough to handle different types of theater halls such as VIP hall and regular hall. Figure 26 shows the class diagram of the Cinema system.

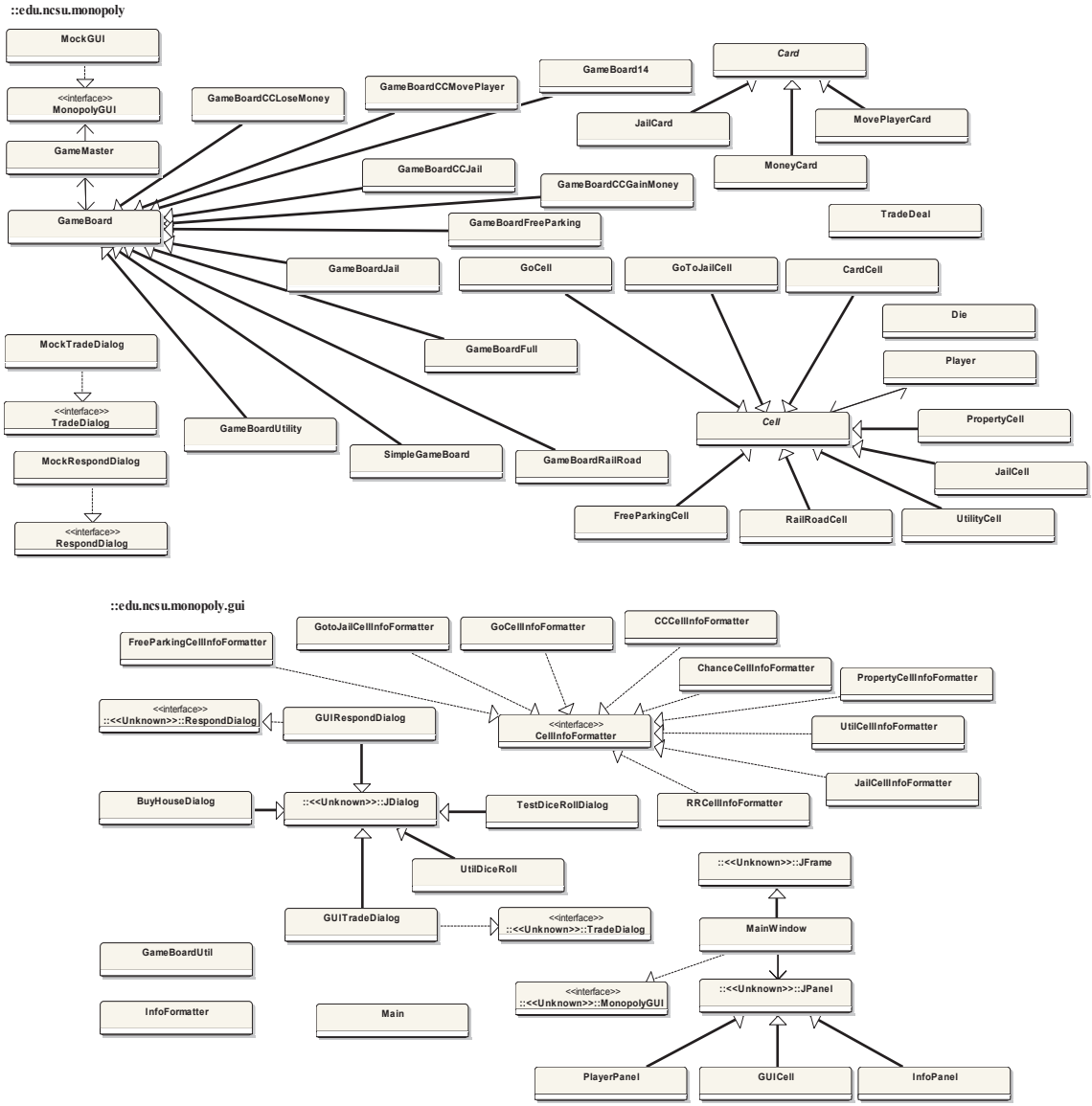


Figure 24: The class diagram of Monopoly.

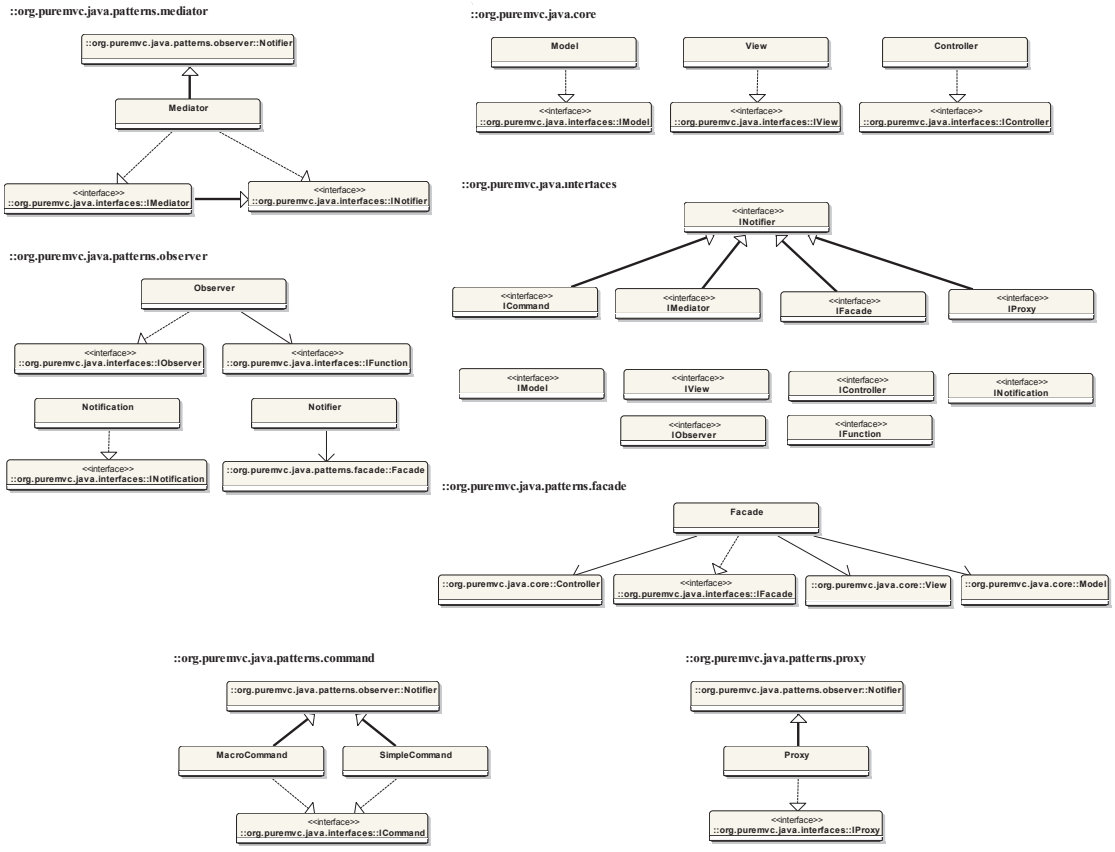


Figure 25: The class diagram of PureMVC.

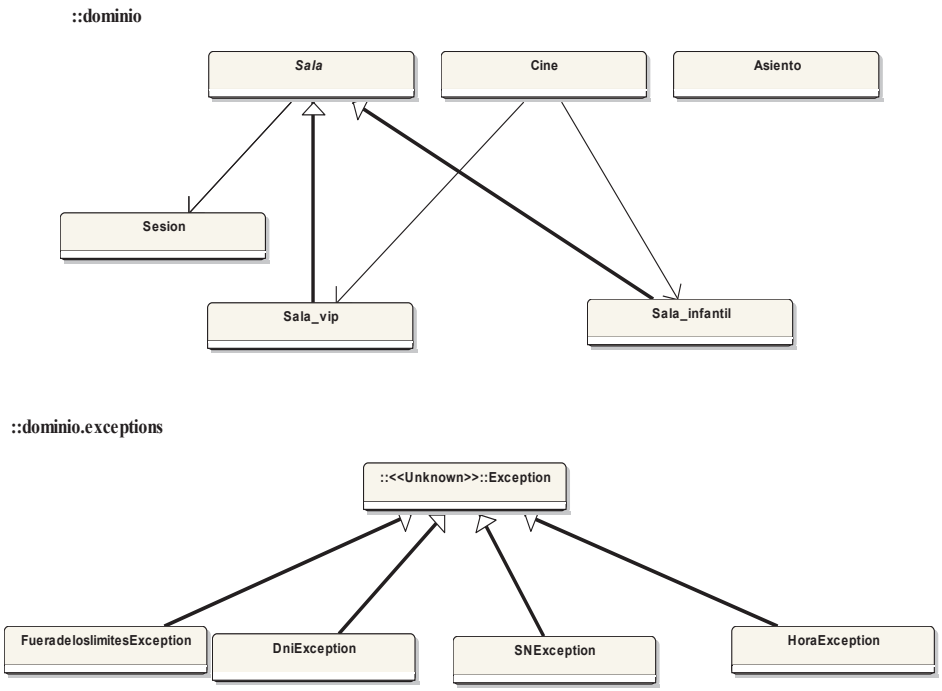


Figure 26: The class diagram of Cinema.

4.1.4. ApacheCli

The ApacheCli is a library that provides an API for parsing command line options passed to programs. The library also can print help messages describing the available options for a command line tool. For example, a boolean option is represented on a command line by the presence of the option, i.e. the option value is true if the option is found, otherwise the value is false. Figure 27 shows the class diagram of the ApacheCli library.

4.1.5. Pacman System

The Pacman application simulates the arcade Pacman game. In this game, the player controls Pac-Man through a maze, eating the dots. Pac-Man is taken to the next stage when all dots are eaten. The Pacman system contains two packages namely controller and model. An example of a class in this system is the Board class. The Board class maintains

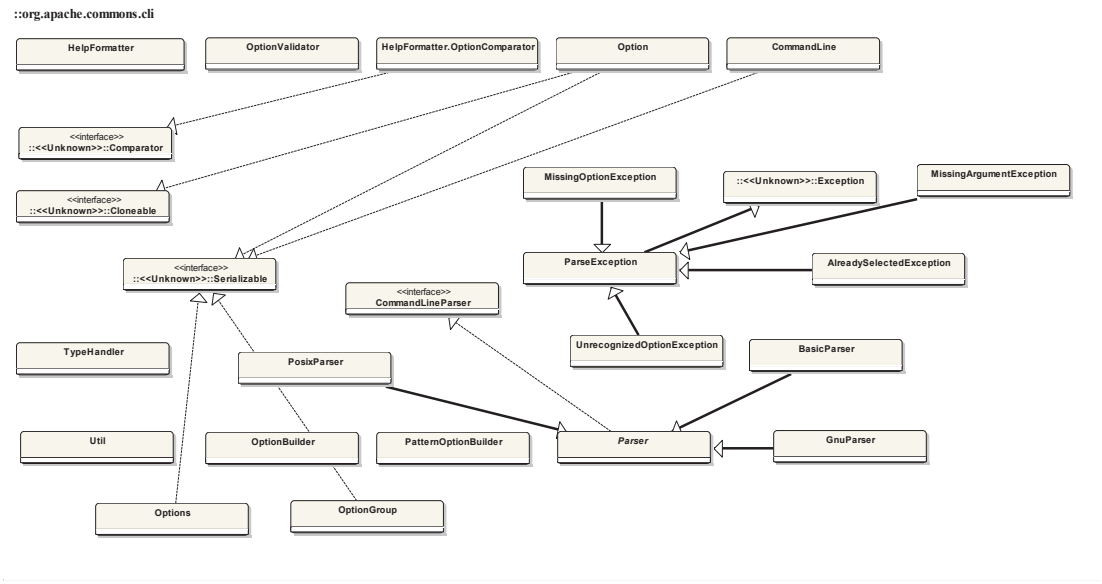


Figure 27: The class diagram of the ApacheCLI.

a rectangular board of cells where guests can move around on the board, and keep track of their position on the board. Figure 28 shows the class diagram of the Pacman system.

4.1.6. ApacheValidator

A major problem when receiving electronic data is verifying the integrity of the data. This task becomes more complicated because different sets of validation rules need to be applied to the same set of data. The ApacheValidator library tries to address this issue and speed development and maintenance of validation rules. The ApacheValidator is a library which provides validation for JavaBeans based on an XML file. This library also provides standard validation routines and functions. It also provides reusable ”primitive” validation methods. Figure 29 shows part of the class diagram of the ApacheValidator library.

4.1.7. JTopas

JTopas is used for parsing of arbitrary text data. These data can come from different sources such as HTML, XML or RTF stream, source code of various programming languages. JTopas classes provides many characteristics such as pattern matching and whitespace handling. Figure 30 shows the class diagram of the JTopas library.

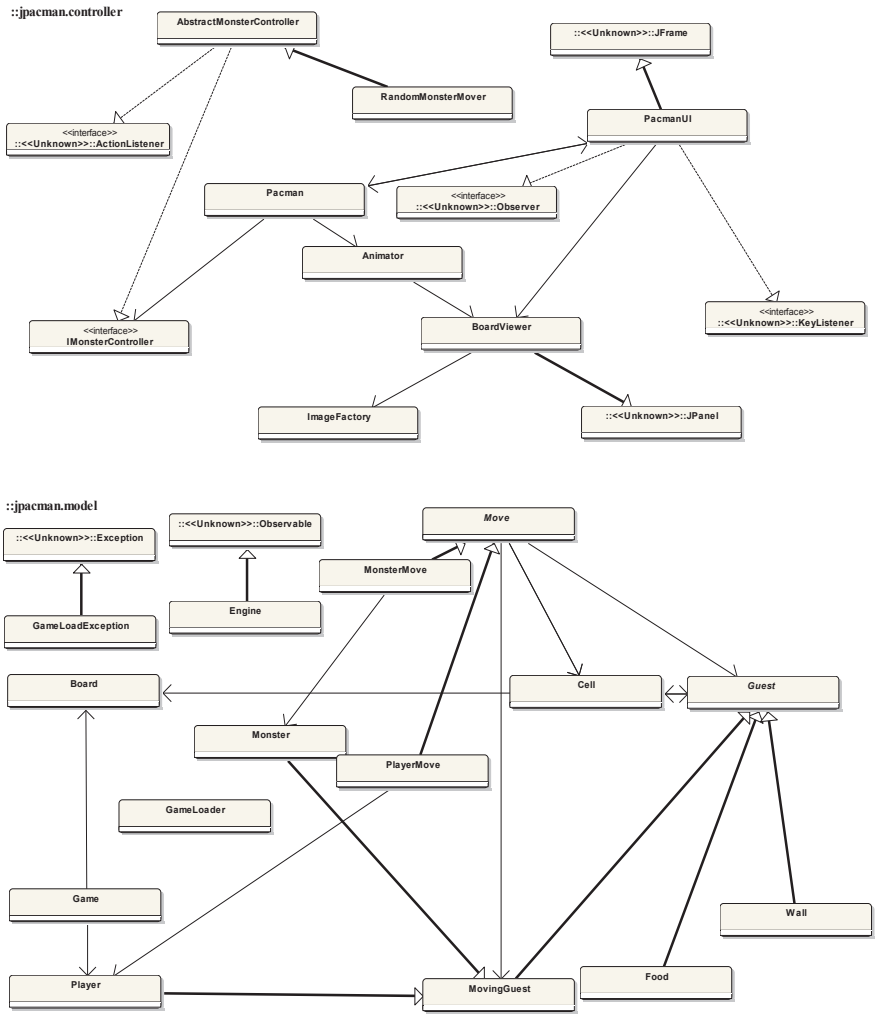


Figure 28: The class diagram of Pacman.

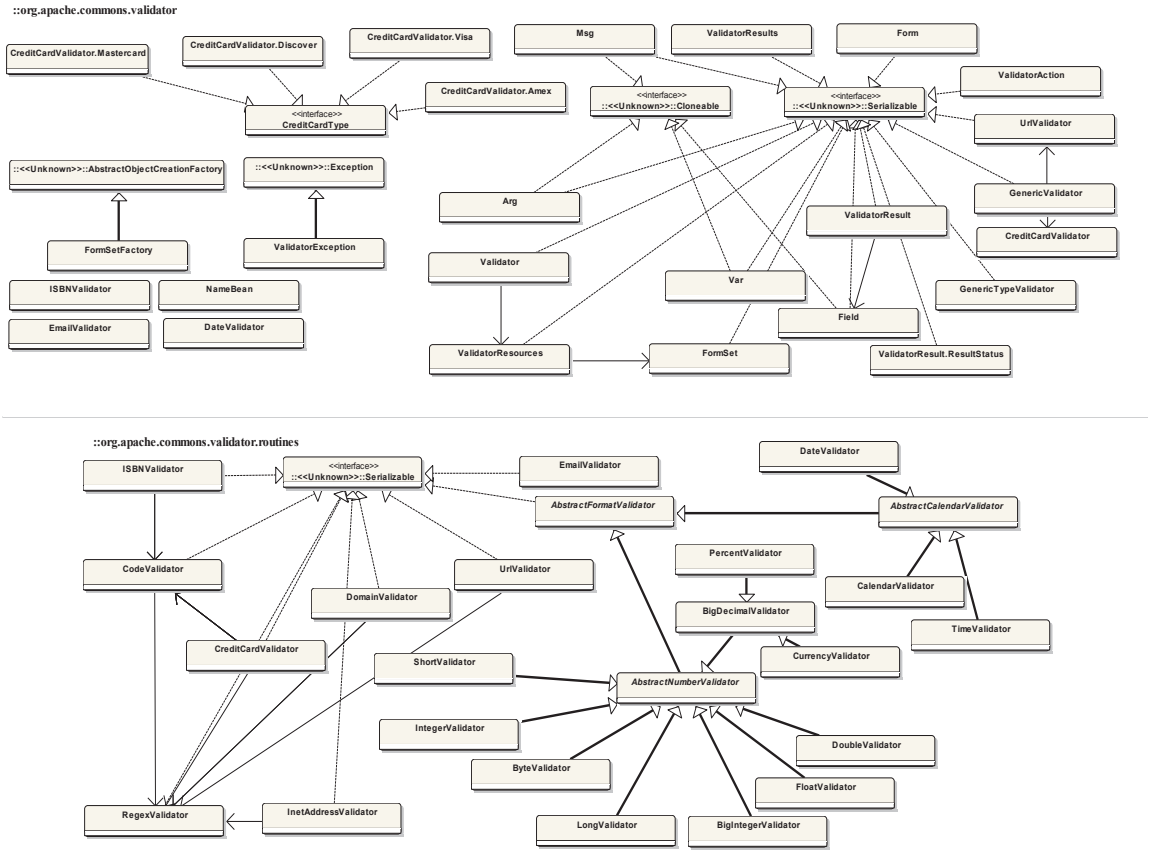


Figure 29: Part of the class diagram of ApacheValidator.

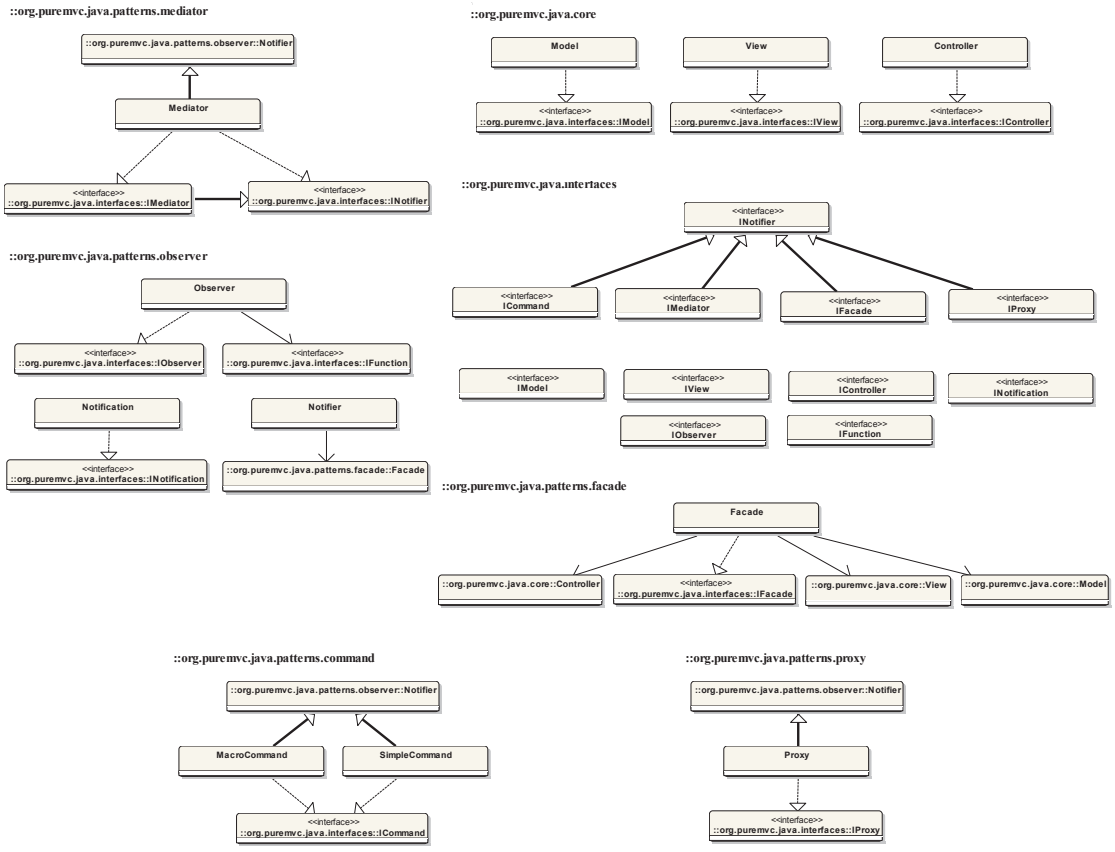


Figure 30: The class diagram of JTopas.

4.2. JUnit Testing Framework

As mentioned in Chapter 3, SMIT tool predicts the number of test cases needed to test each connection. We develop the test cases needed to test each system using JUnit testing framework[1]. The JUnit framework is an open-source testing framework. JUnit is usually used for developing unit tests where each single method is tested in isolation. In integration testing, objects interact with each other in order to perform a task. Moreover, Objects in medium and large size applications are very complex and they depend on external objects to perform their tasks. For example, a method may need to access a database to perform some tasks. Therefore, methods should be tested together and external objects should be available in some way to simplify the testing process. A common technique for developing integration test cases using JUnit is to create mock objects (mocks) that are used only during running the test cases. A mock object, which is presented by Tim Mackinnon et al. [44], is used to mimic a real-world object during testing.

Mocks are used to replace complex objects (e.g., databases, files, and internet connection) that are needed by a method under test. One mock object is created for each real object. Then, we can call a mock object in the test case. Mocks do not implement any business logic and they are just dump objects driven by the tests. In other words, they are empty skeletons that provide a mechanism to simulate the behavior of the faked class [4].

For example, in the Monopoly application, a mock object (mockGUI) is created to simulate the Graphical User Interface (GUI) of the game. For each test suite that needs to interact with the GUI, we provide the mock in the setup method of that test suite (gameMaster.setGUI(new MockGUI())). Then, an object of that mock is created inside the method in which the interaction with the GUI is needed (MonopolyGUI gui = gameMaster.getGUI()).

[1] http://www.junit.org/

4.3. Experiments

In order to evaluate the proposed approach, we use both error seeding and mutation analysis techniques. Section 4.3.1 presents the evaluation using error seeding and Section 4.3.4 presents the evaluation using mutation testing.

4.3.1. Error Seeding Testing

We gave error seeders a list that contains the most common integration errors as categorized by Leung and White [38] and discussed by Orso [53]. We asked the error seeders to inject different types of integration errors based on both the given integration errors category and their experience. In order to get accurate results, applications are given to three different third parties for error seeding and all results are included. The error seeders have been asked to do the seeding independently to make the process as credible as possible. Two types of error seeding experiments are used as follows:

- A number of seeded (faulty) programs are created for each application. Each seeded program contains one error [32, 39]. Then, test cases are running against both the original program and the seeded one. We say that the test cases detect the error if they distinguish between the original program and the seeded one. Six Java applications are seeded by third party namely Monopoly, PureMVC, Cinema, ApacheCli, Pacman, and ApacheValidator. In our work, error seeders are programmers with at least three years of programming experience in Java.

- A combination of errors are injected into one version of the program to see the effect of combining seeded errors in one faulty program on the effectiveness of our proposed approach. This approach contains two variations as follows:

  - Three faulty programs are created for each application by third party. The programs are Pacman and Cinema. Each seeded program contains five errors.

– One faulty program is created for both PureMVC and JTopas. All integration errors are injected in one faulty version. The number of injected faults is 15.

We run the minimum number of test cases for each system on both the original source code of the system and the faulty versions of the system under test. We know the number of inserted errors by the third party but we donot know the location of these errors. We check that all test cases pass when they run against the original source code to make sure that the test case detects the injected error when it fails while running against the faulty version.

4.3.2. Mutation Testing

We also applied mutation testing in order to further investigate the effectiveness of our proposed approach. Previous work found that mutation testing is a reliable way of assessing the fault-finding effectiveness of test cases and the generated mutants are similar to real faults [5, 6]. We choose inter-class level mutation operators. Inter-class level testing is usually applied when two or more classes are tested together to find integration faults [43]. Table 31 shows the mutation operator that we use in our work [43]. The set contains 24 mutation operators. Each mutation operator is related to one of the six groups namely access control, inheritance, polymorphism, overloading, Java-specific features, and common programming mistakes. The first four groups are common to all object-oriented programming languages. Java-specific features group is exclusive for Java programming language while the last group depends on common programming mistakes in object-oriented languages. Mutants are usually created using an automated mutation system. In our work, mutation operators are automatically generated using muJava tool [1]. MuJava tool is widely used to perform mutation analysis [71, 46]. After creating mutation operators, test cases are running against both the original program and the faulty programs. We say that the mutant is killed if test cases differentiate the output of the original program from the mutant programs; otherwise the mutant is still alive.

[1] http://cs.gmu.edu/ offutt/mujava/

Language Feature	Operator	Description
Access Control	AMC	Access modifier change
Inheritance	IHD	Hiding variable deletion
	IHI	Hiding variable insertion
	IOD	Overriding method deletion
	IOP	overriding method calling position change
	IOR	Overriding method rename
	ISK	*super* keyword deletion
	IPC	Explicit call of a parent's constructor deletion
Polymorphism	PNC	*new* method call with child class type
	PMD	Instance variable declaration with parent class type
	PPD	Parameter variable declaration with child class type
	PRV	Reference assignment with other comparable type
Overloading	OMR	Overloading method contents change
	OMD	Overloading method deletion
	OAO	Argument order change
	OAN	Argument number change
Java-Specific Features	JTD	*this* keyword deletion
	JSC	*static* modifier change
	JID	Member variable initialization deletion
	JDC	Java-supported default constructor creation
Common Programming Mistakes	EOA	Reference assignment and content assignment replacement
	EOC	Reference comparison and content comparison replacement
	EAM	Accessor method change
	EMM	Modifier method change

Figure 31: Mutation Operators for Inter-Class Testing.

4.3.3. Results of Error Seeding and Mutation

In this Section, we show the results of applying both error seeding and mutation testing on the selected Java systems. For error seeding, the error detection rate is calculated by dividing the number of detected seeded errors by the total number of seeded errors. For mutation testing, the mutation score is calculated by dividing the number of killed mutants by the total number of mutants.

Table 4: Error seeding results of the PureMVC application.

Source	# of seeded errors	Detected	Not Detected	Error detection rate
Third party A	19	16	3	84.21%
Third party B	10	8	2	80.00%
Third party C	15	13	2	86.67%

Table 4 shows the results of applying error seeding on the PureMVC application. For the PureMVC application, 19 integration errors are inserted by third-party A and 16 of them

are detected. 10 integration errors are inserted by third-party B and 8 of them are detected. 15 integration errors are inserted by third-party C and 13 of them are detected. Table 5 shows the results of applying mutation testing on the PureMVC application. The number of injected mutants is 51 and all of them are killed. Table 6 shows the results of applying error seeding on the Cinema application. For the Cinema application, 20 integration errors are inserted by third-party A and 17 of them are detected. 15 integration errors are inserted by third-party B and C and 12 of them are detected. Table 7 shows the results of applying mutation testing on the Cinema application. The number of injected mutants is 116 and all of them are killed.

Table 5: Mutation testing results of the PureMVC application.

Application	Class	Live	Killed	Total	Mutation score
PureMVC	Facade	0	10	10	100.00%
	Mediator	0	5	5	100.00%
	Notification	0	19	19	100.00%
	Notifier	0	11	11	100.00%
	Proxy	0	6	6	100.00%
Total		0	51	51	100.00%

Table 6: Error seeding results of the Cinema application.

Source	# of seeded errors	Detected	Not Detected	Error detection rate
Third party A	20	17	3	85.00%
Third party B	15	12	3	80.00%
Third party C	15	12	3	80.00%

Table 7: Mutation testing results of the Cinema application.

Application	Class	Live	Killed	Total	Mutation score
Cinema	Asiento	0	6	6	100.00%
	Cine	0	94	94	100.00%
	Sesion	0	16	16	100.00%
Total		0	116	116	100.00%

Table 8 shows the results of applying error seeding on the ApacheCLI application. For the ApacheCli application, 22 integration errors are inserted by third-party A and 19 of them are detected. 15 integration errors are inserted by third-party B and 13 of them are detected. 15 integration errors are inserted by third-party C and 12 of them are detected. The number of injected mutants is 313 and all of them are killed.

Table 8: Error seeding results of the ApacheCLI application.

Source	# of seeded errors	Detected	Not Detected	Error detection rate
Third party A	22	19	3	86.36%
Third party B	15	13	2	86.67%
Third party C	15	12	3	80.00%

Table 10 shows the results of applying error seeding on the Pacman application. For the Pacman application, 22 integration errors are inserted by third-part A and 18 of them are detected. 15 integration errors are inserted by third-part B and 12 of them are detected. 15 integration errors are inserted by third-part C and 13 of them are detected.

Table 9: Mutation testing results of the ApacheCLI application.

Application	Class	Live	Killed	Total	Mutation score
ApacheCLI	CommandLine	0	37	37	100.00%
	AlreadySelectedException	0	7	7	100.00%
	HelpFormatter	0	124	124	100.00%
	MissingArgumentException	0	6	6	100.00%
	MissingOptionException	0	1	1	100.00%
	Option	0	40	40	100.00%
	OptionBuilder	0	25	25	100.00%
	OptionGroup	0	39	39	100.00%
	Options	0	27	27	100.00%
	ParseException	0	1	1	100.00%
	PosixParser	0	4	4	100.00%
	TypeHandler	0	1	1	100.00%
	UnrecognizedPotionException	0	1	1	100.00%
Total		0	313	313	100.00%

Table 10: Error seeding results of the Pacman application.

Source	# of seeded errors	Detected	Not Detected	Error detection rate
Third party A	22	18	4	81.82%
Third party B	15	12	3	80.00%
Third party C	15	13	2	86.67%

Table 11: Error seeding results of the ApacheValidator application.

Source	# of seeded errors	Detected	Not Detected	Error detection rate
Third party A	24	21	3	87.50%
Third party B	15	13	2	86.67%
Third party C	15	13	2	86.67%

Table 11 shows the results of applying error seeding on the ApacheValidator application. For the ApacheValidator application, 24 integration errors are inserted by third-party A and 21 of them are detected in the first iteration. 15 integration errors are inserted by third-party B and 8 of them are detected in the first iteration. Therefore, a second iteration is performed to achieve at least 80% error detection rate. 13 errors out of 15 are detected in the second iteration.

Table 12: Error seeding results of the Monopoly application.

Source	# of seeded errors	Detected	Not Detected	Error detection rate
Third party A	21	19	2	90.48%
Third party B	15	13	2	86.67%
Third party C	15	14	1	93.33%

Table 12 shows the results of applying error seeding on the Monopoly application. For the Monopoly application, 21 integration errors are inserted by the third-party A and 19 of them are detected. 15 integration errors are inserted by the third-party B and 13 of them are detected. 15 integration errors are inserted by the third-party C and 14 of them are detected. Table 13 shows the results of applying mutation testing on the Monopoly application. The number of injected mutants is 888 and all of them are killed.

We choose the JTopas application from Software-artifact Infrastructure Repository (SIR) at University of Nebraska-lincoln [1]. The JTopas application contains 63 classes, 753 methods, and 461 connections. We consider version 3 of the application where 16 seeded errors are available. We run SMIT tool on the JTopas application. SMIT suggests writing 112 test cases. We develop the test cases using JUnit framework and we run the test cases against the faulty version of the application. For the Jtpoas application,13 errors are detected out of 16. The error detection rate is 81.25%.

Table 13: Mutation testing results of the Monopoly application.

Application	Class	Live	Killed	Total	Mutation score
Monopoly	CardCell	0	1	1	100.00%
	FreeParkingCell	0	1	1	100.00%
	GameBoard	0	9	9	100.00%
	GameBoard14	0	131	131	100.00%
	GameBoardCCGainMoney	0	21	21	100.00%
	GameBoardCCJail	0	21	21	100.00%
	GameBoardCCLoseMoney	0	21	21	100.00%
	GameBoardCCMovePlayer	0	21	21	100.00%
	GameBoardFreeParking	0	1	1	100.00%
	GameBoardFull	0	241	241	100.00%
	GameBoardJail	0	51	51	100.00%
	GameBoardRailRoad	0	41	41	100.00%
	GameBoardUtility	0	41	41	100.00%
	GameMaster	0	177	177	100.00%
	GoToJailCell	0	1	1	100.00%
	JailCard	0	2	2	100.00%
	JailCell	0	2	2	100.00%
	MockTradeDialog	0	2	2	100.00%
	MoneyCard	0	6	6	100.00%
	MovePlayerCard	0	3	3	100.00%
	CellInfoFormatterTest	0	24	24	100.00%
	PropertyCell	0	10	10	100.00%
	RailRoadCell	0	4	4	100.00%
	SimpleGameBoard	0	51	51	100.00%
	TradeDeal	0	3	3	100.00%
	UtilityCell	0	2	2	100.00%
Total		0	888	888	100.00%

[1] http://sir.unl.edu

It is worth pointing out that all of the selected systems achieve a detection rate higher than 80% after the first iteration except for the ApacheValidator application seeded by third-party B which achieves a detection rate higher than 80% after the second iteration.

Figure 32 shows the error detection rate for the applications under test where A represents the programs seeded by third party A, B represents the programs seeded by third party B, and C represents the programs seeded by third party C. Table 14 shows the number of test cases developed to test each system. It also shows the percentage of connections that are covered by the developed test cases. For example, in the Monopoly application, we write 45 test cases to test 45 connections out of 449 connections and we only cover 10.02% of the connections while detecting 90.48% of integration errors. The Monopoly application achieves the highest reduction of the number of tested connections (10.02%) while the PureMVC application achieves the lowest reduction (44.44%). For the ApacheValidator, 72 test cases are developed for the first iteration. The error detection rate for the system seeded by third-party B is 53.33%. Thus, a second iteration is performed by adding 11 more test cases as recommended by SMIT.

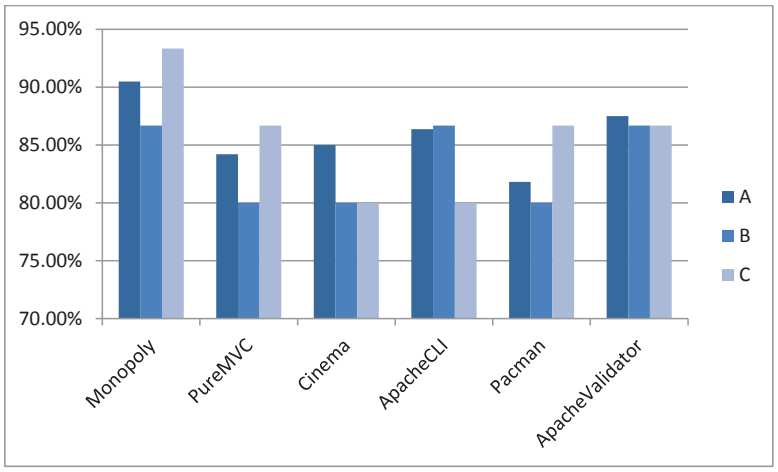


Figure 32: Error detection rate for the selected applications.

Table 14: Number of test cases created for each application.

Project	# of connections	# of test cases	Covered connections
Monopoly	449	45	10.02%
PureMVC	54	24	44.44%
Cinema	97	15	15.46%
ApcheCli	196	43	21.93%
Pacman	176	46	26.13%
ApacheValidator	275	72	26.18%
JTpoas	461	112	24.30%

4.3.4. Comparison with Related Work

Several approaches are found in the literature for defect prediction. These approaches predict the probability that a file will have at least one error. Other approaches predict the exact number of errors that may be found in a file where a file contains many classes. Most of these approaches use complexity metrics as independent variables to predict the faulty files. Zimmerman and Nagappan [72] mentioned that a main disadvantage of most complexity metrics is that they only work on single files and they do not take the interactions between different files in their considerations. On the same hand, these approaches can be used for reducing the cost of unit testing by focusing the testing process on faulty files. These approaches cannot be used for integration testing because they do not predict the important interactions between files. In our work, we predict error-prone interactions and we predict the number of test cases needed to test each one. A similar approach to ours is a research by Borner and Paech [10]. In their work they presented an approach to select the test focus in the integration test process. They identified correlations between dependency properties and the number of errors in both the dependent and the independent files in the previous versions of the system under test. They divided the test focus into four groups: 1) Not Test Focus, 2) Test Focus Dependent file, 3) Test Focus Independent File, and 4) Test Focus Both Files. A dependency is assigned to the first group if it does not have any error-prone property where a property is error prone if it correlates with the number of

errors in the dependent or independent file. A dependency is assigned to the second group if it has at least one property that correlates with the number of errors in the dependent file. A dependency is assigned to the third group if it has at least one property that correlates with the number of errors in the independent file while a dependency is assigned to the last group if it has at least one property that correlates with the number of errors in both files. The main differences between our approach and Borner and Paech approach are:

- Their approach just works for systems that have previous versions while our approach does not need previous versions of the system under test.

- Their approach predicts the error-prone dependencies while our approach not only predicts the error-prone dependencies but also predicts the number of test cases needed to test each dependency. In addition, we rank dependencies by giving a weight for each dependency in which a dependency with a higher weight is assigned more test cases than a dependency with a lower weight.

- They identify the correlations between the dependency properties and the number of errors in the dependent and the independent file. In our work, we do not identify the correlations between our metrics and the number of errors in files because we are working on the method level and information about number of errors at the method level is not available. In our view, identifying the correlations with the number of errors in files is not an accurate measure because errors belong to different classes inside the file and we cannot tell in which class the errors reside.

Previous integration testing approaches assume that all classes are not yet developed when testing is started. Therefore, stubs and drivers are needed to simulate the functionalities of the classes that are not been developed yet. The focus of these approaches is to minimize the cost of testing by minimizing the number of stubs [16] or by minimizing the overall stub complexity [2]. They achieve cost reduction by devising integration test

orders. In our work, we assume that all classes of the system under test are available when the testing process is performed. Therefore, stubs and drivers are not needed in our case. In addition, our focus is to reduce cost of integration testing by using small number of test cases while detecting at least 80% of integration errors.

4.3.5. Comparison with the Base Line Approach

In this section, we are going to compare our proposed approach with a base line approach. In our work, a base line approach is an approach in which all method-pair connections should be tested. We assume that every connection needs only one test case. We also assume that the base line approach will achieve 100% error detection rate because writing integration test cases for all of the connections can be very time consuming. We conduct two comparisons with the baseline approach. The first comparison is performed by measuring the savings that can be obtained by our proposed approach. We measure the percentage of test cases reduction using the following formula [58]:

$$Savings = \frac{|T| - |T_{smit}|}{|T|} * 100 \tag{5}$$

Where T is the number of test cases in the base line approach and T_{smit} is the number of test cases given by SMIT. The formula assumes that all test cases have uniform costs. Table 15 measures the percentage of savings. It is clear from Table 15 that the minimum percentage of savings is obtained for the PureMVC application (55.56) while the maximum percentage of savings is obtained for the Monopoly application (89.98).

The second comparison is performed by computing a score which takes both error detection rate and number of developed test cases in consideration. The score is computed as follows:

$$Score = \frac{\text{Error detection rate}}{\text{Number of test cases}} \tag{6}$$

Table 15: The percentage of savings.

Application	Savings
Monopoly	89.98
PureMVC	55.56
Cinema	84.54
ApacheCli	78.06
Pacman	73.86
ApaValidator	73.81
JTopas	75.70

Table 16 shows the results of comparing our approach with the base line approach. The results indicate that our proposed approach achieves a higher score than the base line approach for all of the selected applications. We conclude that the proposed approach outperforms the baseline approach for all of the applications.

Table 16: The results of comparing the proposed approach with the baseline approach.

Application	Our Approach			The baseline Approach		
	# of test cases	Detection score	Score	# of test cases	Detection score	Score
Monopoly	45	90.48%	2.01	449	100.00%	0.22
PureMVC	24	84.21%	3.51	54	100.00%	1.85
Cinema	15	85.00%	5.67	97	100.00%	1.03
ApacheCli	43	86.36%	2.01	196	100.00%	0.51
Pacman	46	80.00%	1.74	176	100.00%	0.57
ApacheValidator	72	87.50%	1.22	275	100.00%	0.36
JTopas	112	81.25%	0.73	461	100.00%	0.22

4.4. Discussion

As mentioned in the previous Section, we use both error seeding and mutation testing techniques in order to evaluate the effectiveness of the proposed approach. We will start by discussing the results of applying error seeding technique by three different third-parties on six Java applications and JTpoas application which is seeded by SIR.

4.4.1. Applications Seeded by Third-party A

For the Monopoly system, 21 integration errors are seeded by a third party and 19 of them are detected by our developed test cases (45 test cases). The seeded errors are

distributed as follows: 9 wrong function errors are injected and 8 of them are detected, 3 extra function errors are injected and all of them are detected, 7 missing instructions are injected and all of them are detected, 2 extra call instructions are injected and one of them is detected using the developed test cases. The Monopoly system contains 57 classes and 449 connections where only 10.02% of the connections are covered by the developed test cases while achieving 90.48% error detection rate. The results indicate that most of the integration errors are exist in the top ranked 10% of the connections. This also proves that our approach can predict effectively the important connections. In other words, the connections that have higher weights are more important than the connections that have lower weights.

For the PureMVC framework, 19 integration errors are injected, 16 of them are detected by the developed test cases (24 test cases). The seeded errors are distributed as follows: 8 wrong function errors are injected and 7 of them are detected, 2 extra function errors are injected and one of them is detected, 8 missing instructions are injected and 7 of them are detected, 1 extra call instruction is injected and it is detected using the developed test cases. PureMVC contains 22 classes and 54 connections where 44.44% of the connections are covered by the developed test cases while achieving 84.21% error detection rate. The results indicate that the PureMVC framework gives little reduction of the number of covered connections (it covers 44.44% of the connections). One reason that PureMVC covers more than 40% of the connections is that the number of connections between classes is small (it contains 22 classes and 54 connections). Therefore, if we cover only 10% of the connections, most of the class-pair connections will not be tested. Also, in our approach, we specify at least one test case to test class-pair connections. Therefore, we write test cases that cover most of the connections if the classes have few connections between them. For the Cinema system, 20 integration errors are injected, 17 of them are detected by the developed test cases (15 test cases). The seeded errors are distributed as

follows: 8 wrong function errors are injected and 7 of them are detected, 3 extra function errors are injected and all of them are detected, 6 missing instructions are injected and 5 of them are detected, 3 extra call instruction are injected and two of them are detected using the developed test cases. The Cinema system contains 10 classes and 97 connections where only 15.46% of the connections are covered by the developed test cases while achieving 85.00% error detection rate. The results indicate that 85% of errors exist in the top 15% of connections. The Cinema system achieves the second highest reduction after the Monopoly system.

For ApacheCLI, 22 integration errors are injected, 19 of them are detected by the developed test cases (43 test cases). The seeded errors are distributed as follows: 7 wrong function errors are injected and 6 of them are detected, 3 extra function errors are injected and two of them are detected, 8 missing instructions are injected and 7 of them are detected, 4 extra call instruction are injected and all of them are detected using the developed test cases. ApacheCLI contains 20 classes and 196 connections where 21.93% of the connections are covered by the developed test cases while achieving 86.36% error detection rate. The results indicate that 86.36% of errors exist in the top 22% of connections.

For Pacman, 22 integration errors are injected, 18 of them are detected by the developed test cases (46 test cases). The seeded errors are distributed as follows: 8 wrong function errors are injected and 6 of them are detected, 2 extra function errors are injected and one of them are detected, 7 missing instructions are injected and all of them are detected, 5 extra call instruction are injected and 4 of them are detected using the developed test cases. Pacman contains 25 classes and 176 connections where 26.13% of the connections are covered by the developed test cases while achieving 81.82% error detection rate in the first iteration of the proposed approach. The approach starts with an initial number of test cases that equals to 18 (10% of the connections). Then, the approach adds one test case to cover the class-pair connections that have not been covered in the 10% of connections (i.e.,

the approach assigns at least one test case to cover each class-pair connection). The results indicate that 81.82% of errors exist in the top 27% of connections. The Pacman system achieves the lowest error detection rate.

For ApacheValidator, 24 integration errors are injected, 21 of them are detected by the developed test cases (72 test cases). The seeded errors are distributed as follows: 11 wrong function errors are injected and all of them are detected, 4 extra function errors are injected and two of them are detected, 5 missing instructions are injected and all of them are detected, 4 extra call instruction are injected and 3 of them are detected using the developed test cases. ApacheValidator contains 59 classes and 275 connections where 26.18% of the connections are covered by the developed test cases while achieving 87.50% error detection rate. The ApacheValidator library is the largest system in terms of the number of classes in our experimental study and it's detection rate exceeds 80% in the first iteration.

4.4.2. Applications Seeded by Third-party B

For the Monopoly system, 15 integration errors are seeded by a third party and 13 of them are detected by our developed test cases. The seeded errors are distributed as follows: 10 interpretation errors are injected and 9 of them are detected, 5 miscoded call errors are injected and 4 of them are detected. For PureMVC, 10 integration errors are seeded by a third party and 8 of them are detected by our developed test cases. The seeded errors are distributed as follows: 6 interpretation errors are injected and all of them are detected, 4 miscoded call errors are injected and 2 of them are detected. For Cinema, 15 integration errors are seeded by a third party and 12 of them are detected by our developed test cases. The seeded errors are distributed as follows: 6 interpretation errors are injected and 5 of them are detected, 4 miscoded call errors are injected and all of them are detected, and 5 interface errors and 3 of them are detected. For ApacheCLI, 15 integration errors are seeded by a third party and 13 of them are detected by our developed test cases. The seeded errors are distributed as follows: 7 interpretation errors are injected and 5 of them are detected,

6 miscoded call errors are injected and all of them are detected, and 2 interface errors and 1 of them is detected. For Pacman, 15 integration errors are seeded by a third party and 12 of them are detected by our developed test cases. The seeded errors are distributed as follows: 6 interpretation errors are injected and 4 of them are detected, 4 miscoded call errors are injected and all of them are detected, and 5 interface errors and 4 of them are detected. For ApacheValidator, 15 integration errors are seeded by a third party and 13 of them are detected by our developed test cases. The seeded errors are distributed as follows: 9 interpretation errors are injected and 8 of them are detected, 2 miscoded call errors are injected and 1 of them is detected, and 4 interface errors and 4 of them are detected.

4.4.3. Applications Seeded by Third-party C

For the Monopoly system, 15 integration errors are seeded by a third party and 14 of them are detected by our developed test cases. The seeded errors are distributed as follows: 2 interpretation errors are injected and all of them are detected, 8 miscoded call errors are injected and 7 of them are detected, and 5 interface errors and all of them are detected. For PureMVC, 15 integration errors are seeded by a third party and 13 of them are detected by our developed test cases. The seeded errors are distributed as follows: 1 interpretation error is injected and it is detected, 13 miscoded call errors are injected and 12 of them are detected, and 1 interface errors and it is not detected. For Cinema, 15 integration errors are seeded by a third party and 12 of them are detected by our developed test cases. The seeded errors are distributed as follows: 3 interpretation errors are injected and 1 of them is detected, 8 miscoded call errors are injected and all of them are detected, and 4 interface errors and 3 of them are detected.

For ApacheCLI, 15 integration errors are seeded by a third party and 12 of them are detected by our developed test cases. The seeded errors are distributed as follows: 7 interpretation errors are injected and 6 of them are detected, 6 miscoded call errors are injected and 4 of them are detected, and 2 interface errors and all of them are detected.

For Pacman, 15 integration errors are seeded by a third party and 13 of them are detected by our developed test cases. The seeded errors are distributed as follows: 7 interpretation errors are injected and all of them are detected, 4 miscoded call errors are injected and 3 of them are detected, and 3 interface errors and 2 of them is detected. For ApacheValidator, 15 integration errors are seeded by a third party and 13 of them are detected by our developed test cases. The seeded errors are distributed as follows: 5 interpretation errors are injected and all of them are detected, 7 miscoded call errors are injected and 5 of them are detected, and 3 interface errors and all of them are detected.

We also conduct an experiment where combination of errors are injected into one version of the program to see the effect of combining seeded errors in one faulty program on the effectiveness of our proposed approach. We select JTopas which contains 461 connections. The number of seeded errors is 16. For the Jtpoas application,13 errors are detected out of 16. The error detection rate is 81.25% and we cover only 24.30% of the connections. The results of JTopas indicates two main findings: 1) The effectiveness of the proposed approach since we use another source of seeding errors other than the third party; and 2) The proposed approach works well even when we combine all of the errors in one version of the source code.

4.4.4. Mutation Testing

The second approach that we use to evaluate our approach is mutation testing. We make the following observations based on the experimental results of mutation testing:

- For Monopoly, 888 inter-class mutations are injected and all of them are killed by the developed test cases.
- For Cinema, 116 inter-class mutations are injected and all of them are killed by the developed test cases.
- For ApacheCLI, 313 mutations are injected and all of them are killed.

- For PureMVC, 51 inter-class mutations are injected and all of them are killed by the developed test cases.

The effectiveness of the proposed approach is confirmed by using error seeding and mutation testing. The results of error seeding show that the developed test cases based on SMIT detect at least 80% of integration errors. The mutation testing is performed using mutation operators. The mutation operators focus on the integration aspects of Java to support inter-class level testing [42]. The results of using mutation testing show that all of the mutants are killed which serve as another evidence of the effectiveness of our proposed approach. Therefore, our approach is effective in detecting most of the integration errors by testing the highly ranked connections. The experimental results show that the highly ranked connections contain most of the integration errors. It also shows SMIT reduces the number of test cases needed for integration testing.

4.4.5. Threats to Validity

There are many reasons which limit the generality of the results of the proposed approach. First, all of the considered systems are Java systems. Second, all of the selected systems are open-source systems that may not represent all domains. Third, the selected systems are not representative in terms of the number and sizes of classes. Therefore, large-scale assessment is needed taking into account software systems from diverse domains, implemented in different programming languages and environments in order to get more general results.

CHAPTER 5. CONCLUSION AND FUTURE WORK

In this work, we proposed an approach to select the test focus in integration testing. The goal is to reduce cost and time of integration testing through testing part of the connections while still detecting at least 80% of integration errors. Our proposed approach is divided into five steps. The first step is to extract the dependencies from the compiled Java code. The dependencies will be used to extract the dependency metrics. The second step is to extract the metrics automatically using both the source code and the dependencies from the previous step. The output of this step is the metrics at different levels of granularity which include method level metrics, method-pair metrics, and class-pair metrics. The third step is to calculate a weight for each method-pair connection using combination of metrics defined in the previous step. The fourth step is to predict the number of test cases needed to test each method-pair connection based on the weights of the connections produced in the previous step given the initial minimum number of test cases. The number of test cases can be increased depending on the error discovery rate. The last step is to generate test cases manually to test the designated application.

Some of the metrics used in this work are defined and selected to cover different types of dependencies. We defined three method level dependency metrics namely Inbound Method Dependencies (IMD), Outbound Method Dependencies (OMD), and Outbound Field Dependencies (OFD). We defined two method-pair level dependency metrics namely Inbound Common Method Dependencies (ICM) and Outbound Common Method Dependencies (OCM). The other metrics are selected to cover the internal complexity of a method. In our work, the internal complexity represented by three metrics namely Local Variables (LVAR), Number of complex input parameters (NOCMP), and Maximum Nesting Depth (MND).

We built SMIT tool using R language to calculate the metrics automatically and to implement the proposed approach. The outputs of SMIT are four files in CSV format,

method metrics, method-pair metrics, class-pair, and a final report. The final report specifies the number of test cases needed to test each connection.

We conducted experiments on several Java systems taken from different domains which include two games systems, three Java libraries, one business application, and one web application. To assess the effectiveness of our proposed approach, we used both error seeding and mutation testing as follows:

- Manual integration errors were injected into the source code of the applications by three third-parties to make sure that we get accurate results and solid conclusions.
- Automatic inter-class mutants were inserted into the source code by MuJava tool.

The effectiveness of the developed test cases based on SMIT recommendation was evaluated using the following measures:

- Detection rate: The number of detected seeded errors divided by the number of all seeded errors.
- Mutation score: The number of killed mutants divided by the number of all mutants.
- Savings: The percentage of test cases reduction.
- Score: The error detection rate divided by the number of developed test cases.
- Covered connections: The number of connections that we developed test cases for divided by the number of all connections.

Our experimental evaluation using error seeding technique shows that the developed test cases achieved error detection rate higher than or equal to 80.00% for all selected systems in the first iteration except the ApacheValidator system which achieved an error detection rate higher than 80% after the second iteration. Moreover, the results showed

that the PureMVC framework gave the lowest reduction of the number of covered connections (44.44%) while the Monopoly system achieved the highest reduction (it covered only 10.02% of the connections). Therefore, the experimental results showed that our proposed approach is effective in selecting the test focus in integration testing. The small number of developed test cases detected at least 80.00% of integration errors in all selected applications. The proposed approach reduced the number of test cases needed by covering only part of the connections. In addition, the results showed that at least 80% of integration errors typically exist in the highly ranked connections, i.e., the highly ranked connections have a higher probability to contain integration errors. Our experimental evaluation using mutation testing shows that the developed test cases based on the proposed approach kill all of the inter-class mutants which give another evidence on the effectiveness of our proposed approach.

We compared our approach with the baseline approach. The comparison was performed by calculating both the percentage of test cases reduction and the error detection rate divided by the number of developed test cases. The results indicated that the proposed approach outperformed the baseline approach for all applications. Therefore, our goal of reducing time and cost of integration testing is achieved. One significant advantage of our proposed approach is that almost all steps of our approach can be performed automatically.

In future, we want to select the test focus for integration testing using both method level metrics and integration errors history of previous versions of the system under test. Information about errors history can be obtained using bug tracking systems. All of the dependency metrics for source code can be extracted automatically using SMIT tool. We are planning to use previous versions of the system under test to identify the metrics that correlate with the number of integration errors in the source code. The method level metrics that have a high correlation with the number of integration errors will be used to select the test focus of the new version of the system.

We are also planning to use our method level metrics to select the test focus for unit testing. Our goal is to give a weight for each method in the system under test using combination of dependency metrics and internal complexity metrics, and then we focus the testing process on the highly ranked methods, i.e., methods that have higher weights. We also want to predict the number of test cases needed to test each method in the system.

Future directions also include using textual coupling as another source of dependencies. Textual coupling can be computed using the similarity between method-pairs. Each method can be represented as a document and then information retrieval techniques can be used to compute similarities between methods. We would like to investigate the effect of using hybrid dependency metrics (our previous dependency metrics and the textual coupling) on error detection rate.

In our work, we defined dependencies on method level. A finer grain level of dependencies may improve the results. Therefore, we want to investigate the effect of defining dependencies on statement level on the error detection rate. We are also planning to define dependency metrics on the feature level. Different functionalities of a system can be implemented as features. A feature contains many methods scattered over a system. Feature level dependency metrics can be used to measure impact analysis where some changes made to one feature usually have accidental results for other features resulting in incorrect system behavior.

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APPENDIX. SMIT SOURCE CODE

```
#################################################################
##############  Author: Shadi Bani Ta'an  ######################
#####################     2012     ##############################
#!/usr/bin/env Rscript
args <- commandArgs(TRUE)
directory = args[1]

setwd("D:/SMIT-newEquation")
source("Allfunctions.R")
di = list.dirs(directory)
files = classFiles(di) # It saves the names of the ".class" files.

classFiles = function(di){
cfiles = list()
cfileso = list()
for (dd in 1:length(di)){
  package1 = list.files(path = di[dd], pattern = ".class",
  all.files = FALSE, full.names = TRUE, recursive = FALSE,
  ignore.case = FALSE, include.dirs = FALSE)
  cfiles = append(cfiles,package1) #.class files
  cfileso = append(cfileso,package2)
} # end for
return (cfiles)
} # end function

extractDep # invokes the dependency finder tool
extractDep = function(){
# path of the Dependency Finder
depf = "C:/DependencyFinder-1.2.1-beta4/bin"
outputf = "met"
```

```
x = ""
for(i in 1:length(cfiles)){
  # x contains all of the .class files
  x = paste(x," ",cfiles[[i]],sep= "")
}
#The following command extracts all dependencies from
# the compiled files and save the output in xml
command1=paste(depf,"/DependencyExtractor-xml ",x," -out ",
directory,"/dependencies/alldependencies.xml",sep="")
eee = paste(directory,"/dependencies",sep="")
dir.create(eee) # save the XML output in this folder
system(command1)
}

command2 = paste(depf,"/OOMetrics -csv ", x," -methods -out ",
directory,"/dependencies/",outputf,sep="")
system (command2)
methodD = paste(directory,"/dependencies/",outputf,
"_methods.csv",sep="")
metT = read.csv(methodD, header = TRUE, sep = ",",
blank.lines.skip = TRUE)
newM = metT[3:dim(metT)[1],] #the data starts from row3
cc11 = list()
bbc = strsplit(as.character(newM[1,1]),"\\.")
if (length(bbc[[1]]) > 3){

 for (h in 1:dim(newM)[1]){ #iterate over methods
  o = newM[h,1]
  oo = strsplit(as.character(o),"\\(")[[1]][1]
  bb = strsplit(oo,"\\.")
  thec = bb[[1]][1]
```

```
   for (hh in 3:length(bb[[1]])-1){
    thec = paste(thec,".",bb[[1]][hh],sep="")
   }# end for hh
   cc11 = append(cc11,thec)
  } # end for h
  cc11 = unique(cc11)
} #end if
############
myM = lvarMetric(newM)
lvarMetric = function(newM){
myM = newM[,c(1,6)] # methodName, Local Variables
return (myM)
}
rn = as.matrix(newM[,1])
row.names(newM) = rn
mmm = matrix(0,length(rn),length(rn)) # CGM Matrix
row.names(mmm) = rn
colnames(mmm) = rn

CList = list() # save classes names in CList
for (ss in 1:length(cfiles)){
  #m1 calls omethod and they are in different classes
  CList = append(CList,strsplit(cfiles[[ss]],"\\.")[[1]][1])
}

# Extract Call Graphs
# We only consider calls between methods in different classes
n1 = paste(directory,"/dependencies/method",sep="")
#create folder to save dependencies for each method
dir.create(n1)
for (j in 1:length(rn)){
m1 = rn[j]  # example
```

```
if ( substr(m1,nchar(m1),nchar(m1)) != ")") {
next
}
m2 = strsplit(m1,"\\(")[[1]][1]

command3 = paste(depf,"/DependencyReporter -xml -out ",
directory,"/dependencies/method/M-",m2,".xml -f2f ",
directory,"/dependencies/alldependencies.xml
-feature-scope-includes /",m2,"/",sep="")
system (command3)
} #end for j

mmm = callGraphs(rn)
callGraphs = function(rn){
for (i in 1:length(rn)){
m1 = rn[i]
moriginal1 = rn[i]
if ( substr(m1,nchar(m1),nchar(m1)) != ")") {
next
}
m2 = strsplit(m1,"\\(")[[1]][1]
name = paste(directory ,"/dependencies/method/M-",
m2,".xml",sep="")
aaa1 = strsplit(m1,"\\(")[[1]]
ana11 = gsub(".",":", aaa1[2], fixed=TRUE)
m1 = paste(aaa1[1],"(",ana11,sep="")
moutbound = readLines(name)
ou = ""
oumm = ""
ou =grep("<outbound",moutbound,value=TRUE)
oumm =grep(")",ou,value=TRUE)
if (length(oumm) > 0) {
```

```
  for (j in 1:length(oumm)){ # all outbound dependencies
   tex = oumm[j]
   p1 = strsplit(tex,">")
   omethod = strsplit(p1[[1]][2],"<")[[1]][1]
   if (omethod %in% rn){
     strc = strsplit(omethod,"\\.")
     className = strsplit(omethod,"\\.")[[1]][length(strc[[1]])-1]
     strcm = strsplit(m1,"\\.")
     className2 = strsplit(m1,"\\.")[[1]][length(strcm[[1]])-1]
     if (className != className2) {
       mmm[moriginal1,omethod] = 1
     } # end if
   } # end if
  } # end for j
} #end if
} # end for i
return (mmm)
}
#Read the Maximim nesting depth metric
msd = paste(directory,"/MaximumNesting.csv",sep="")
msdM = read.csv(msd, header = TRUE, sep = ",",
blank.lines.skip = TRUE)
#Calculate Method-level metrics ####
fn = paste(directory,"/dependencies/MethodLevelMetricsF.csv"
,sep="")
file.remove(fn)
cat(file=fn," ", "LVAR","NOCMP","MND","IMD","OMD","OFD",
"OCD",sep=",","\n",append=TRUE)

for (i in 1:dim(rn)[1]) {
  methodi = rn[i]
  methodpp = rn[i]
```

```
if ( substr(methodi,nchar(methodi),nchar(methodi)) != ")")
{
  next
}
if (length(cc11) > 0){
      cfile = cc11
}
NOCMP = nocmpMetric(methodi,cfile)
methodi = strsplit(methodi,"\\(")[[1]][1]
imc = inboundMethodCalls(methodi)
omc = outboundMethodCalls(methodi)
ofc = outboundFeildDependencies(methodi)
IMD = length(imc)
OMD = length(omc)
OFD = length(ofc)
cc = list()
if (length(omc) > 0) {
  for (ii in 1:length(omc)){
    p = strsplit(omc[[ii]],"\\.")
    cc = append(cc,p[[1]][1])
  }
}
OCD = length(unique(cc))
le = length(which(msdM[,2] == methodi))
NDepth = mndMetric(methodi)
methodpp = gsub(",",";", methodpp, fixed=TRUE)
aaa = strsplit(methodpp,"\\(")[[1]]
ana = gsub(".",":", aaa[2], fixed=TRUE)
newmethod = paste(aaa[1],"(",ana,sep="")
cat(file=fn,newmethod,as.character(myM[i,2]),
NOCMP,NDepth,IMD,OMD,OFD,OCD,sep=",",
"\n",append=TRUE)
```

```
} # end for i
mndMetric = function(methodi){
  NDepth = msdM[which(msdM[,2]== methodi),3]
  return (NDepth)
}
# No. of methods in the application
nom = dim(read.csv(fn, header = TRUE, sep = ",",
blank.lines.skip = TRUE))[1]

# Extract Method Pair Metrics
mmCalls = which(mmm[,] == 1, arr.ind = TRUE)
name = paste(directory ,"/dependencies/methodPairMetrics
.csv",sep="")
name1 = paste(directory ,
"/dependencies/methodPairMetricsNONZERO.csv",sep="")
file.remove(name)
file.remove(name1)
cat(file = name,"Caller","Callee","OCM","ICM",
"Weight(mi)","Weight(mj)","Weight(mimj)",
"caller class","callee class","class-pair",
sep=",","\n",append=TRUE)
cat(file = name1,"Caller","Callee","OCM","ICM",
sep=",","\n",append=TRUE)
cpl = list() #contains the class-pairs
for (y in 1:dim(mmCalls)[1]){
  me11 = rn[mmCalls[y,][1]]
  aaa = strsplit(me11,"\\(")[[1]]
  ana = gsub(".",":", aaa[2], fixed=TRUE)
  me11 = paste(aaa[1],"(",ana,sep="")
  me1 = strsplit(me11,"\\(")[[1]][1]
  me22 = rn[mmCalls[y,][2]]
  aaa1 = strsplit(me22,"\\(")[[1]]
```

```
   ana1 = gsub(".",":", aaa1[2], fixed=TRUE)
   me22 = paste(aaa1[1],"(",ana1,sep="")
   me2 = strsplit(me22,"\\(")[[1]][1]
   OCM1 = outboundMethodCalls(me1)
   ICM1 = inboundMethodCalls(me1)
   OCM2 = outboundMethodCalls(me2)
   ICM2 = inboundMethodCalls(me2)
   OCM = OcmMetric(OCM1,OCM2)
   ICM = icmMetric(ICM1,ICM2)
   me11 = gsub(",",";", me11, fixed=TRUE)
   me22 = gsub(",",";", me22, fixed=TRUE)
#CALCULATE THE WEIGHT OF EACH CONNECTION
mlmetrics = read.csv(fn, header = TRUE,
sep = ",",blank.lines.skip = TRUE)
row.names(mlmetrics) = mlmetrics[,1]
ICcaller = mlmetrics[me11,2] +
mlmetrics[me11,3] + mlmetrics[me11,4]
ICcallee = mlmetrics[me22,2] +
mlmetrics[me22,3] + mlmetrics[me22,4]
wCaller = ICcaller * ((mlmetrics[me11,5]
 + mlmetrics[me11,6] +
mlmetrics[me11,7])^2) #numerator
wCallee = ICcallee * ((mlmetrics[me22,5]
 + mlmetrics[me22,6] +
mlmetrics[me22,7])^2) #numerator

c.m = as.matrix(mlmetrics[,1])
nom = dim(as.matrix(c.m))[1] # No. of methods
cmM = matrix(0,nom,2)
for (p in 1:nom){
 nest = length(strsplit(as.character(c.m[p]),"\\.")[[1]])
 cmM[p,1] = strsplit(as.character(c.m[p]),"\\.")[[1]][nest-1]
```

```
 cmM[p,2] = c.m[p] #method name
}
loan =  length(strsplit(me11,"\\.")[[1]])
loan1 =  length(strsplit(me22,"\\.")[[1]])
#methods in the caller class
micaller = as.matrix(cmM[which(cmM[,1] ==
strsplit(me11,"\\.")[[1]][loan-1]),2])
#methods in the caller class
micallee = as.matrix(cmM[which(cmM[,1] ==
strsplit(me22,"\\.")[[1]][loan1-1]),2])
sum = 0
for (k in 1:dim(micaller)[1]){
 mi = micaller[k]
 weightmi = (mlmetrics[mi,2] + mlmetrics[mi,3]
 + mlmetrics[mi,4]) * ((mlmetrics[mi,5] +
 mlmetrics[mi,6] + mlmetrics[mi,7])^2)
 sum = sum + weightmi
}
sum2 = 0
for (kk in 1:dim(micallee)[1]){
 me = micallee[kk]
 weightme = (mlmetrics[me,2] + mlmetrics[me,3]
 + mlmetrics[me,4]) *
 ((mlmetrics[me,5] + mlmetrics[me,6] +
 mlmetrics[me,7])^2)
 sum2 = sum2 + weightme
}
sumAll = sum + sum2
if (sumAll == 0){
 weightmiAll = 0
 weightmjAll = 0
} else{
```

```
 weightmiAll = wCaller/sumAll
 weightmjAll = wCallee/sumAll
}

weightmimj = (weightmiAll + weightmjAll)*(ICM + OCM + 1)

callerc = strsplit(me11,"\\.")[[1]][loan-1]
calleec = strsplit(me22,"\\.")[[1]][loan1-1]
if (callerc !=calleec) {
        cat(file = name,me11,me22,OCM,ICM,weightmiAll,
        weightmjAll, weightmimj,callerc,calleec,sep=",",
        "\n",append=TRUE)
}
  if (OCM > 0 || ICM > 0 ){
  cat(file = name1,me11,me22,OCM,ICM,sep=",",
  "\n",append=TRUE)
  }
}

# Class Pair
cpmname = paste(directory ,"/dependencies/
classPairMetrics.csv",sep="")
file.remove(cpmname)
cat(file=cpmname,"Class-Class","weight",
sep=",","\n",append=TRUE)
mpm = read.csv(name) # read method pair metrics
twoclasses = matrix(0,dim(mpm)[1],3) #save class pairs
for (w in 1:dim(mpm)[1]){ #
 cindx = length(strsplit(as.character(mpm[w,1]),
 "\\.")[[1]]) - 1
 twoclasses[w,1] = strsplit(as.character(mpm[w,1]),
 "\\.")[[1]][cindx]
```

```
 cindx1 = length(strsplit(as.character(mpm[w,2]),
 "\\.")[[1]]) - 1
 twoclasses[w,2] = strsplit(as.character(mpm[w,2]),
 "\\.")[[1]][cindx1]
 if (twoclasses[w,1] < twoclasses[w,2]){
   twoclasses[w,3] = paste(twoclasses[w,1],
   twoclasses[w,2],sep="-")
 } else
{
twoclasses[w,3] = paste(twoclasses[w,2],
twoclasses[w,1],sep="-")
}
} #end for w
cps = unique(twoclasses[,3])
cpma = matrix(0,length(cps),4)
for (yy in 1:length(cps)){
  ccCalls = which(twoclasses[,3] == cps[yy], arr.ind = TRUE)
  ccss = sum(mpm[ccCalls,7])#finds the summation of weights
  cat(file=cpmname,cps[yy],ccss,sep=",","\n",append=TRUE)
  cpma[yy,1] = cps[yy]
  cpma[yy,2] = ccss
}
# 10% of interactions
nom11  =  round((dim(mpm)[1] * 0.10),digits = 0)
cpma[,3] = as.numeric(cpma[,2]) /
sum(as.numeric(cpma[,2])) # normalized class-pair weight
cpma[,4] = round((as.numeric(cpma[,3]) * nom11 ),digits = 0)
# we assign one test case for the class pair that assigned zero
# test cases to ensure that at least one test case is assigned
# to test class pair connections
cpma[which(cpma[,4]==0,arr.ind = TRUE),4] = 1
ddd = c("class-pair","weight","Norm. weight","No. of test cases")
```

```
write.table(as.data.frame(cpma),file=cpmname,col.names=ddd,
sep=",",row.names=FALSE)
mptestc = matrix(0,dim(mpm)[1],5)
mptestc = mpm[,c(1,2,7)]
for (g in 1:dim(cpma)[1]){
  q = cpma[g]
  mptestc[which(twoclasses[,3]==q),4]= mpm[which(twoclasses[,3]
  ==q),7]/ sum(mpm[which(twoclasses[,3] ==q),7])
  mptestc[which(twoclasses[,3]==q),5]=round((as.numeric(cpma[
  which(cpma[,1]==q),4]))* mptestc[which(twoclasses[,3]==q),4]
  ,digits=0)
        nocases = (as.numeric(cpma[which(cpma[,1]== q),4]))
  if ( nocases < 3){
     mptestc[which(mptestc[,4] == max(mptestc[which(twoclasses
        [,3]==q),4])),5] = 1
  }
} # end for
dd = c("Dependent","Dependee","Weight","Norm. weight",
"No. of test cases")
final = paste(directory ,"/dependencies/FinalReport.csv",
sep="")
file.remove(final)
write.table(as.data.frame(mptestc),file=final,col.names=dd,
sep=",",row.names=FALSE)

outboundMethodCalls = function(m){
m1 = m
methodsList = list()
name = paste(directory ,"/dependencies/method/M-",m1,
".xml",sep="")
moutbound = readLines(name)
ou = ""
```

```
oumm = ""
# we just take the outbound dependencies
ou =grep("<outbound",moutbound,value=TRUE)
oumm =grep(")",ou,value=TRUE)
if (length(oumm) > 0) {
  for (j in 1:length(oumm)){ # all outbound dependencies
   tex = oumm[j]
   p1 = strsplit(tex,">")
   omethod = strsplit(p1[[1]][2],"<")[[1]][1] #m1 calls omethod
   # we want to exclude calls between methods in the same class
     className = strsplit(omethod,"\\.")[[1]][1]
     className2 = strsplit(m1,"\\.")[[1]][1]
         #the methods belong to different classes
     if (className != className2) {
       methodsList = append(methodsList,omethod)
     } # end if
  } # end for j
} #end if
return (methodsList)
} # end function

inboundMethodCalls = function(m){
m1 = m
methodsList = list()
name = paste(directory ,"/dependencies/method/M-",m1,
".xml",sep="")
moutbound = readLines(name)
ou = ""
oumm = ""
ou =grep("<inbound",moutbound,value=TRUE)
oumm =grep(")",ou,value=TRUE)
if (length(oumm) > 0) {
```

```
  for (j in 1:length(oumm)){ # all outbound dependencies
   tex = oumm[j]
   p1 = strsplit(tex,">")
   omethod = strsplit(p1[[1]][2],"<")[[1]][1] #m1 calls omethod
   # we want to exclude calls between methods in the same class
     className = strsplit(omethod,"\\.")[[1]][1]
     className2 = strsplit(m1,"\\.")[[1]][1]
         #the methods belong to different classes
     if (className != className2) {
       methodsList = append(methodsList,omethod)
     } # end if
  } # end for j
} #end if
return (methodsList)
} # end function

outboundFeildDependencies = function(m){
m1 = m
fieldsList = list()
name = paste(directory ,"/dependencies/method/M-",m1,
".xml",sep="")
moutbound = readLines(name)
ou = ""
oumm = ""
# we just take the outbound dependencies
ou =grep("<outbound",moutbound,value=TRUE)
# Indices for the method dependencies
oumm =grep(")",ou,value=FALSE)
oo = as.matrix(ou)
oumm = oo[-oumm,1]
if (length(oumm) > 0) {
  for (j in 1:length(oumm)){ # all outbound dependencies
```

```
    tex = oumm[j]
    p1 = strsplit(tex,">")
    ofield = strsplit(p1[[1]][2],"<")[[1]][1] #m1 calls omethod
    # we want to exclude calls between methods in the same class
      className = strsplit(ofield,"\\.")[[1]][1]
      className2 = strsplit(m1,"\\.")[[1]][1]
      if (className != className2) {
        fieldsList = append(fieldsList,ofield)
      } # end if
  } # end for j
} #end if
return (fieldsList)
} # end function

icmMetric = function(ICM1,ICM2){
ICM = length(intersect(ICM1,ICM2))
return (ICM)
}
OcmMetric = function(OCM1,OCM2){
OCM = length(intersect(OCM1,OCM2))
return (OCM)
}
# Computer No. of complex parameters
nocmpMetric = function(m,cl){
NOCMP = 0
m = strsplit(m,"\\(")
para = substr(m[[1]][2],1,(nchar(m[[1]][2])-1))
p = strsplit(para,",")
if (length(p[[1]]) > 0) {
  for (ww in 1:length(p[[1]])){
    pa = p[[1]][ww]
    pa = gsub(" ","", pa, fixed=TRUE)
```

```
    if (pa %in% cl) {
      NOCMP = NOCMP + 1
    }
  } # end for
} # end if
return (NOCMP)
} # end function
```