RUMBA: Runtime Monitoring and Behavioral Analysis Framework for Java Software Systems

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

A goal of runtime monitoring is to observe software execution to determine whether it complies with its intended behavior. Monitoring allows one to analyze and recover from detected faults, providing prevention activities against catastrophic failure. Although runtime monitoring has been in use for so many years, there is renewed interest in its application largely because of the increasing complexity and ubiquitous nature of software systems.

To address such a demand for runtime monitoring and behavioral analysis of software systems, we present RUMBA framework. It utilizes a synergy between static and dynamic analyses to evaluate whether a program behavior complies with specified properties during its execution. The framework is comprised of three steps, namely: i) *Extracting Architecture* where reverse engineering techniques are used to extract two meta-models of a Java system by utilizing UML-compliant and graph representations of the system model, ii) *Seeding Objectives* in which information required for filtering runtime events is obtained based on properties that are defined in OCL (Object Constraint Language) as specifications for the behavioral analysis, and iii) *Runtime Monitoring and Analysis* where behavior of the system is monitored according to the output of the previous stages, and then is analyzed based on the objective properties. The first and the second stages are static while the third one is dynamic.

A prototype of our framework has been developed in Java programming language. We have performed a set of empirical studies on the proposed framework to assess the techniques introduced in this thesis. We have also evaluated the efficiency of the RUMBA framework in terms of processor and memory utilization for the case study applications.

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Chapter 1

Introduction

Software systems play an important role in our economy, government, and military. This requires a constant need to understand a program's behavior by exploring its correctness during the runtime. Traditional methods, testing and verification [8], are not enough to guarantee that the current execution of a running system is correct. There are possibilities to introduce errors into an implementation of the design that has been verified. Testing may scale well and check implementation directly, but it is mostly informal and it does not guarantee completeness. Verification is formal and may guarantee completeness, but it does not scale well and deals mostly with design instead of implementation. An approach of continuously monitoring and checking a running system with respect to particular specifications is required to use for filling the gap between these two approaches.

Runtime software monitoring has been used for profiling, performance analysis, software optimization as well as software fault-detection, diagnosis, and recovery. Software fault detection provides evidence whether a program behavior complies with specified properties during program execution. Following the standard [55], software *failure* is a deviation between the observed and the required behavior of a software system. A *fault*

occurs during the execution of software and results in an incorrect state that may or may not lead to a *failure*. An *error* is a mistake made by a human that leads to a *fault* that may result in a *failure*. Many tools have been proposed for runtime monitoring to detect, diagnose, and recover from software faults [6, 22, 31, 37, 47, 52]. There are various definitions for runtime software-fault monitors in the literature. The definition most in agreement with the interpretation considered in this thesis is "*A monitor is a system that observes the behavior of a target program and determines if it is consistent with a given specification*" [20]. A monitor takes an executing software system and a specification of software properties. It checks that the execution meets the properties, i.e., that the properties hold for the given execution. In this regard, the monitor requires an understanding of the target system regarding the information which is going to be observed.

Program understanding has been increasingly used in software engineering tasks such as auditing programs for security vulnerabilities and finding errors in general. Such tools often require much more sophisticated analysis than those traditionally used in compiler optimizations. Generally, to understand a program, three actions can be taken [18]: reading documentation, reading source code, and running the program (e.g., watching execution, getting trace data, examining dynamic storage, etc.). Documentation can be excellent or it can be misleading. Studying the dynamic behavior of an executing program can be very useful and can dramatically improve understanding by revealing program characteristics which cannot be assimilated from reading the source code alone. However, the source code is usually the primary source of information. There are three approaches that can be taken into account for the program understanding:

- **Static Analysis** examines program code and reasons over all possible behaviors that might arise at runtime. Compiler optimizations [15, 62] are standard static analysis. Typically, static analysis is *sound* and *conservative* [27]. *Soundness* guar-

antees that the analysis result is an accurate description of the program's behavior, no matter on what inputs or in which environment the program is run. *Conservatism* means reporting weaker properties than may actually be true. The weak properties are guaranteed to be true, preserving soundness, however may not be strong enough to be useful. Static analysis usually uses an abstracted model of a program state. On one hand, such an abstraction may cause loosing some information. On the other hand, it provides a model which is compact and straightforward for manipulation.

- **Dynamic Analysis** operates by executing a program and observing the executions. Standard dynamic analysis includes *testing* and *profiling* [59]. Dynamic analysis is precise because no approximation or abstraction need to be done [27]. In other words, the analysis can examine the actual and exact runtime behavior of a program. Dynamic analysis can be as fast as program execution. Some dynamic analyses run quite fast, but in general, obtaining accurate results entails a great deal of computation, especially when large programs are analyzed. The disadvantage of dynamic analysis is that its results may not be applicable for future executions. There is no guarantee that the test suite, over which the program is run, can cover all possible program executions.

- **Hybrid Analysis** is the combination of the two approaches that can be applied to a single problem, producing results that are useful in different contexts. It sacrifices a small amount of the soundness of static analysis and a small amount of the accuracy of dynamic analysis. Static analysis is typically used for proofs of correctness, type safety, or other properties. Dynamic analysis demonstrates the presence (not the absence) of errors and increases confidence in a system. In this way, new techniques are obtained whose properties are better-suited for particular

usage than either static or dynamic solely. The hybrid analysis replaces the (large) gap between static and dynamic analyses with a continuum. Users would select a particular analysis fitted to their needs. In principle, they would turn the knob between soundness and accuracy. For instance, hybrid analyses are used for program verification.

Most of the research works provide mechanisms utilizing only the static analysis to know where to collect the required information in a target program for runtime monitoring. Moreover, most of them use instrumentation and modification of the target program which aggregates low-level monitoring information with the program code directly and increases monitoring overhead. In this context, our goal is to develop a framework utilizing a synergy between static and dynamic analyses without any modifications on the source code of a target system.

1.1 Problem Description

A runtime state of a program uniquely identifies an execution trace in the system. The execution trace of a target program P is a sequence of program states which belongs to a set of state space S_P. The state space S_P is discrete and hence finite or countably infinite. Monitoring is considered with actual transitions between states, not only the possible ones. A monitor takes an execution trace and a *property* and checks whether the execution trace meets the property. In other words, the property is verified while the target system is executing. A *property* is defined according to the *objective* of the user who intends to run the monitoring process on the target program. The *objective* is considered as the intention to detect faults in the system or to keep track of specific resources of the system. A *property* often has the form $\mu \rightarrow \alpha$, where μ is some condition on S_P, and it identifies those states of S_P in which α must hold. The set of such states is denoted

by $S_{\alpha|\mu}$ where $S_{\alpha|\mu} \subset S_P$. In any state $s \in S_P$, if μ is true, then α must also be true, which indicates that $s \in S_{\alpha|\mu}$. If α evaluates to be false for s, then s is a state the current execution has reached ($s \notin S_{\alpha|\mu}$). This is a point where the defined property is violated while the system runs in its environment. Such a violation is reported by the monitoring system. Furthermore, a monitoring system may extend this capability by diagnosing faults using the obtained information about the target program. As an example, if the objective of the monitoring is to detect faults, a property can be defined accordingly in which a violation means a fault. As soon as a fault is detected, the user will be provided with appropriate information. Such an information will aid her/him in understanding the cause of the fault to assist the system in recovering. The recovery can be done by directing the system to a correct state (forward recovery) or by reverting to a state known to be correct (backward recovery) [75]. At the time being, our work focuses only on monitors that are used to detect violations or report about specific behaviors of different resources of a system. In this way, monitoring of evolving systems to unprecedented levels can help us to observe and possibly orchestrate their continuous evolution in a complex and changing environment [57].

1.2 Thesis Contributions

The major contribution of the thesis is to address the problem of runtime monitoring and behavioral analysis of Java software systems. Our framework proposes a semi-automated process which receives the Java source code of a target program. During the execution of the program, the framework reports whether there is any violation in the behavior of the program with respect to the specifications of certain properties. Specifically, the major contributions of the proposed framework are as follows:

- The framework utilizes a synergy between static and dynamic analyses to do the

runtime monitoring and analysis.

- By using the hybrid analysis, the source code of a target system is not modified during the processes of the framework.
- Two models of a target system are created using reverse engineering techniques through the static analysis.
- The objectives of runtime monitoring and analysis are specified utilizing Object Constraint Language (OCL) [65, 69]. They are actually the properties defined on the behavior of the system which are described as OCL rules.
- By using the capabilities of Java Platform Debug Architecture (JPDA) [39], we have implemented a monitoring technique that finds the locations of the required attributes for the analysis process.

1.3 Thesis Organization

The rest of the thesis is organized as follows:

- Chapter 2 presents a survey on the related works. It describes four elements of the runtime monitoring techniques, mostly focusing on two of them which are main concerns of this thesis: the *specification language* and the *runtime monitor*. A review of the state of the art in runtime monitoring is also presented followed by putting this thesis in the context.
- Chapter 3 proposes a runtime monitoring framework which utilizes a synergy between static and dynamic analyses. The framework is composed of three major stages: *Architecture Recovery*, *Seeding Objectives*, and *Runtime Monitoring and Analysis*. The first and the second stages are static while the third one is dynamic.

- Chapter 4 discusses reverse engineering techniques used within the first stage of the framework, *Architecture Recovery*. Two models are built for an existing object-oriented software system in this stage: a UML-compliant model, called *class model* and a graph-based model, called *SAIG model*.

- Chapter 5 discusses the processes within the second stage of the framework, *Seeding Objectives*. In this stage, OCL-based safety properties are identified and then added to the *class model* of the system. A pattern of required events is also generated to reduce and filter event traces during the runtime monitoring.

- Chapter 6 describes the processes within the third stage of the framework, *Runtime Monitoring and Analysis*. The runtime event traces of the system are generated while no instrumentation is performed on the source code of the system. Afterwards, the processing of the generated traces is carried out with respect to the OCL based properties identified in the previous stage.

- Chapter 7 shows the application of the proposed framework on two open source Java software systems. The prototype of the framework is described as well. Case studies will be explained and the efficiency of the framework will be discussed.

- Chapter 8 presents the contributions of the thesis, and explains the potential future research directions.

Chapter 2

Related Works

Runtime monitoring helps users of a system to detect specific anomalies which may exist in the way that the system behaves in its environment. Delgado et al. [20] presented a thorough survey of the current literature on runtime monitoring and identified a wide spectrum of tools that have monitoring capabilities. We use this reference as our main source for reviewing the major directions of runtime monitoring in literature which are also related to the proposed framework in this thesis.

Figure 2.1 is adopted from [20] which depicts a taxonomy of runtime monitoring systems. As the figure shows, there are four major elements used for classifying the state of the art in monitoring approaches and techniques. The first three of them are the most common elements of monitoring systems: the *Specification Language* used to define properties as the relations within and among runtime states of a target system, the *Runtime Monitor* that overseas the execution of a target program, and the *Event Handler* that captures and communicates monitoring results. In addition to these three elements, the fourth one considers the *Operational Issues* which mostly deal with the external environment rather than the monitor itself.

In this chapter, we focus on the two elements which are main concerns of the thesis: the *specification language* and the *runtime monitor*. While these two categories are explained in more detail in the rest of this chapter, we summarize for the other two categories here.

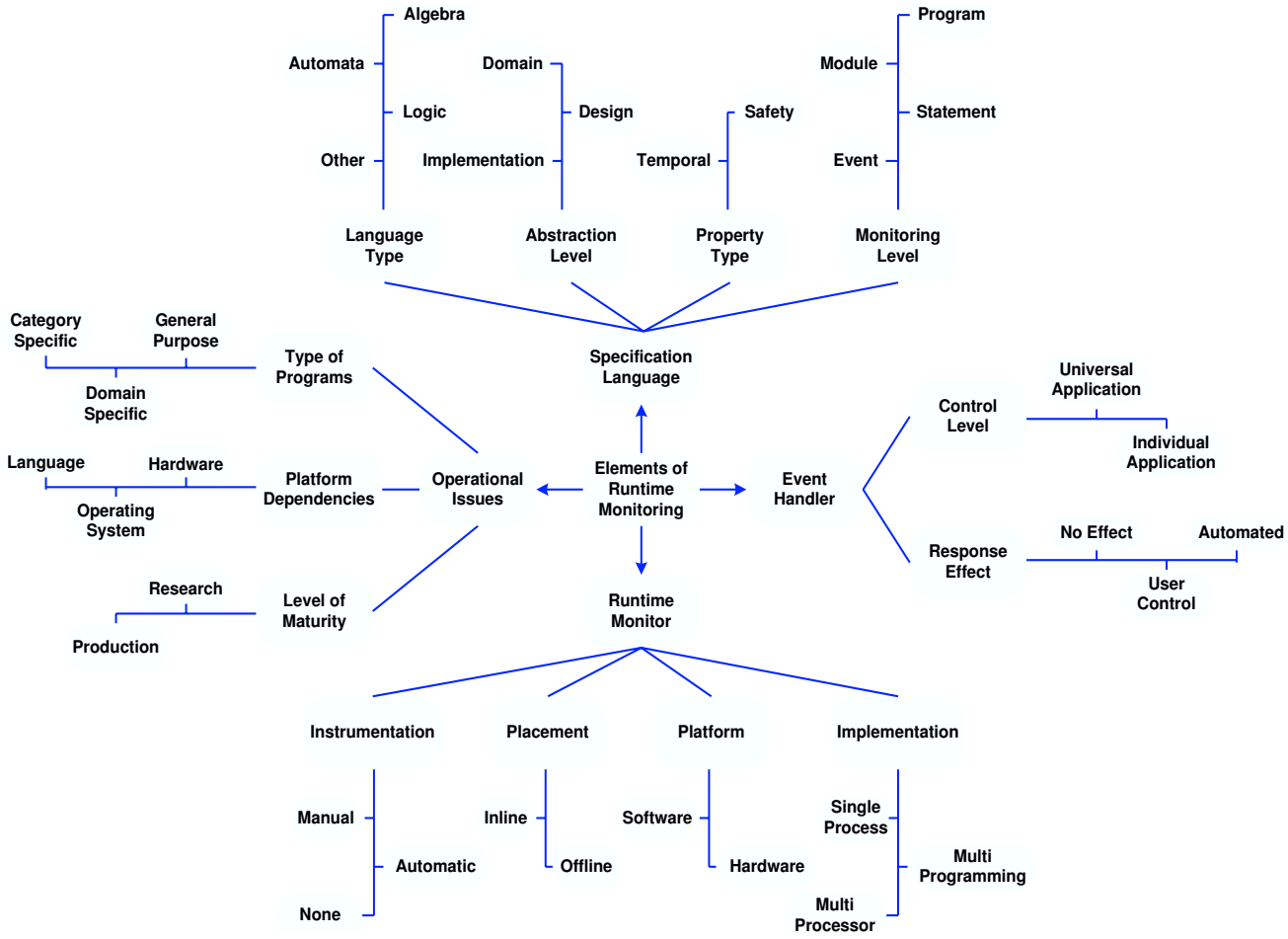


Figure 2.1: Runtime Monitoring Taxonomy

The event handler refers to how the monitor reacts to a violation of a specification in a particular state. Response actions can alter the application state space, report application behavior, or start up another process. At the *control-level* category, monitors that react universally to a violation are separated from those that permit the user to individ-

ually specify the actions of the monitor or the target program. *Response effect* reflects the extent to which the monitor's response to a violation can affect program behavior. According to this category, a monitor may i) have no effect on the behavior of a target program, ii) use the user's interactions, or iii) be an automated system.

On the other hand, the operational issues consider a monitoring system from three points of view: i) the *type of programs* targeted by the monitoring system, ii) *platform dependencies*, and iii) the *level of maturity* of the system. A target program may be general-purpose, domain-specific, or category-specific. Platform dependencies capture restrictions on monitoring systems. Some monitors can only operate on certain hardware, operating systems, or programs written in a specific language. Level of maturity identifies the purpose of the development of the monitoring systems which can be research prototypes or tools available for public.

The rest of the chapter addresses the first two categories of the taxonomy and the state of the art in this field. Section 2.1 describes the specification language while Section 2.2 discuses issues about the runtime monitor. In Section 2.3, we review the state of the art in software systems monitoring. Finally, Section 2.4 summarizes the material presented in this chapter.

2.1 Specification Language

A specification language in a monitoring system is classified based on: i) the *language type* that is used to define the monitored properties, ii) the *abstraction level* of the specification, iii) the *property type*, and iv) the *monitoring level*. More details about each of these four directions in the specification language are as follow:

- **Language Type** may be *algebra*, *automata*, *logic*, or *other*. Another orthogonal category (*other*) denotes that the specification language is a functional, object-

oriented, or imperative language or it is an extension of the source language.

- **Abstraction Level** determines how the language provides support for specifying properties. It can be at *domain*, *design*, or *implementation* levels. At the domain level, a language expresses properties in a particular domain or supports capture of knowledge about a specific problem domain. At the design level, the specification concerns software design at a level that is independent of implementation. A language that supports specification of properties about the implementation of a program is classified in the implementation level.

- **Property Type** may be *safety* or *temporal*. A safety property expresses that something (bad) never occurs. The temporal category includes properties related to progress and bounded liveness as well as timing properties.

- **Monitoring Level** determines the level at which a property can be evaluated within a program. It can be at *program-level*, *module-level*, *statement-level*, or *event-level*. At the program-level, properties are specified on threads or on relations between threads. At the module-level, properties are specified on functions, procedures, methods, or components, such as abstract data types or classes. Properties are specified for a particular statement at the statement-level specifications. Event-level specifications define properties based on a state change or sequence of state changes.

2.2 Runtime Monitor

A monitor observes and analyzes the states of a system. The monitor checks correctness by comparing an observed state of the system with an expected state of the system. There are various approaches for implementing monitors. Instrumentation, placement,

platform, and implementation are among the implementation strategies for a monitor, which are elaborated furthers as follows:

- **Instrumentation** refers to the points in a target program at which execution of monitoring code will be initiated. It can be *manual*, *automatic*, or *none*. In the *manual* one, instrumentation of the target program is performed manually at the source code level, byte code level, or any level of the intermediate code. In the *automatic instrumentation*, points of instrumentation are detected automatically, which can be achieved through *dynamic* analysis, *static* analysis, or a combination of both. In the third category, it is not required to consider any physical point in the program to run a monitoring code and hence no instrumentation is required.

- **Placement** refers to where the monitoring code executes. It can be *inline* in which the monitoring code is embedded in the target code (including calls to subroutines). On the other hand, the monitoring can be performed *offline*, meaning that the monitor executes as a separate thread or process, possibly on a separate machine. The monitor is classified as *asynchronous offline* in two ways: i) the application can continue to execute without waiting for the analyzer to complete, or ii) the monitor uses an execution trace that is analyzed after execution. If the application must wait until the check is complete, the monitor is classified as *synchronous offline*.

- **Platform** differentiates monitors as *software* or *hardware* ones. A *software* monitor uses code to observe and analyze the values of monitored variables. A *hardware* monitor may be a microprocessor attached to a system with connectors or a hardware device connected to the buses of the target system that allows it to detect events of interest or collect relevant data.

- **Implementation** refers to the way a monitor can execute which can be *single process*, *multiprogramming*, or *multiprocessor*. In the single process, the monitor executes in the same process as the target program. In the multiprogramming way, the monitor and the target program execute as separate processes or threads on the same processor. The monitor and the target program execute on different processors in the multiprocessor case.

2.3 State of the Art in Software Systems Monitoring

In this section, we review the state-of-the-art about existing monitoring systems from the specification language and the monitor points of view. Afterwards, we compare specific features of our framework with what are contributed by other systems.

- **Alamo** (A Lightweight Architecture for Monitoring) [41, 42] has been developed for C and Icon programs. The Icon programming language is used to specify assertions as the safety properties for monitoring. The Alamo monitoring architecture utilizes CCI, a Configurable C Instrumentation tool [72], as a preprocessor. It uses parse trees to identify monitoring points and inserts events into the source code of a target program. There is an Execution Monitor (EM) which executes the Target Program (TP). Then the control is returned to the EM with information in the form of an event report. The EM can query the TP for additional information, such as the values of program variables and keywords.

- **Annalyzer** [53, 54] uses ANNA (ANNotated Ada), an extension of Ada, to specify properties as annotations. The annotations are converted into code that checks the properties at runtime. The Annalyzer compares the runtime behavior of an application with properties that are specified at different levels of abstraction (package,

subprogram, data structures, or statement level). A monitor is used to pinpoint and analyze errors by using a *two-dimensional pinpointing* approach in which the Annalyzer initially finds errors using properties specified at a higher level of abstraction. Finally, an event handler notifies the user when a violation occurs.

- **BEE++** [10] is an object-oriented application framework for the dynamic analysis of distributed programs written in C or C++. It views the execution of a distributed program as a stream of events. The monitor, referred as an event interpreter, supports specification of high-level events from low-level events by way of inheritance. A sensor provides a placeholder for an event that is either user-defined or predefined by BEE++. When a sensor is encountered, or triggered, runtime data is loaded into the event and it is sent off to each analysis tool that has bound itself to that sensor. The insertion of sensors in the application is the task of the programmer.

- **DynaMICs** (Dynamic Monitoring with Integrity Constraints) [31, 32] is a tool that supports the elicitation of properties from domain experts, designers, and developers as well as their application to monitoring. Properties, expressed in logic, capture relations on objects modeled by the application, design limitations, and implementation assumptions. These properties are specified as event-condition-action, where the event defines the trigger for the check, the condition specifies the check, and the action defines the response to a violation. The approach automatically inserts constraint-checking and knowledge-generating codes by analysis of a program's path expression. The control-flow graph of the program's intermediate code generates the path expression. Monitoring code automatically generated from specifications triggers the execution of monitoring code by another process or processor [71].

- **Edit Automata** [52] analyzes the space of security policies that can be enforced by monitoring and modifying programs at run time. Program monitors in this system,

called edit automata, are abstract machines that examine the sequence of application program actions and transform the sequence when it deviates from a specified policy. It uses the general term *security automaton* to refer to any automaton that is used to model a program monitor. Edit automata has a set of transformational powers which: i) may terminate the application, thereby truncating the program action stream, ii) may suppress undesired or dangerous actions without necessarily terminating the program, and iii) may insert additional actions into the event stream.

- **Falcon** [35] provides online monitoring and steering of large-scale parallel programs. A monitoring specification consists of low-level sensor specification constructs and higher-level view specification constructs. Using a semi IDL (Interface Description Language) language, programmers define: i) the application-specific sensors and probes for capturing the program and performance behaviors during runtime, and ii) the program attributes that direct steering. Probes update program attributes asynchronously to the program's execution. Actuators may also execute additional functions to ensure that modifications of program state do not violate program correctness criteria. Monitoring is accomplished through the use of runtime libraries for information capture, collection, filtering, and analysis.

- **Jass** (Java with assertions) [6] is a general-purpose monitoring approach that is implemented for sequential, concurrent, and reactive systems written in Java. A precomplier translates annotations to programs written in Java into pure Java code. Compliance with the specified annotations is dynamically tested during runtime. Trace assertions, based on the process algebra CSP (Communicating Sequential Process), describe the observable behavior of a class and they are used to monitor the correct invocation of a method as well as the order and timing of method

invocations. The generated code will check that the trace of the current program execution is included in the traces of the main process; otherwise, a trace exception is thrown that can trigger a user-defined rescue block.

- **JassDA** (Jass with Debug Architecture) [9] is the later version of Jass. JassDA has been also designed to provide a trace assertion facility, but in contrast to Jass, trace assertions are not precompiled into the source code but are checked at runtime via the Java Platform Debug Architecture (JPDA) [39].

- **JPaX** (Java PathExplorer) [6, 37] is a general-purpose monitoring approach for sequential and concurrent Java programs. This technique facilitates logic-based monitoring and error pattern analysis. Formal requirement specifications are written in a linear temporal logic [68] or in the algebraic specification language Maude [16, 17]. JPaX instruments Java byte code to transmit a stream of relevant events to the observation module that performs two kinds of analysis: i) logic-based monitoring that checks events against high-level requirements specifications, and ii) error pattern analysis that searches for low-level programming errors. Maude's rewriting engineMaude [16, 17] is used to compare the execution trace to the specifications. Error pattern runtime analysis explores an execution trace to detect potential errors, including data races and deadlocks, even if these errors do not explicitly occur in the trace.

- **JRTM** (Java Runtime Timing-Constraint Monitor) [61] targets timing properties of distributed, real-time systems written in Java. The timing properties express assertions that specify the occurrences of different events in a language based on Real Time Logic (RTL). Java programmers insert the event triggering method calls in their Java programs where event instances occur. JRTM can detect some property violations statically through constraint graphs. Whenever an event is triggered at

runtime, the application sends a message to the monitor reporting the occurrence time of the event instance and the event name. The monitor keeps these event occurrence messages in a sorted queue with the earliest event message at the head of the queue. The constraints are checked for violation and synchronization is enforced.

- **Mac** (Monitoring and Checking) [45, 46, 47, 48, 49, 70] provides a framework for runtime monitoring of real-time systems written in Java. Requirement specifications are written in MEDL (Meta Event Definition Language). MEDL allows the user to define auxiliary variables which store values. Such values are used to identify events and conditions as well as guarded statements that assign them to auxiliary variables for encoding information on past states. A monitoring script, written by the user in PEDL (Primitive Event Definition Language), is used to monitor objects and methods. PEDL can look at local and global variables and can detect alias variable names. A filter maintains a table that contains names of monitored variables and addresses of the corresponding objects. It acts as an observer which communicates the information that is to be checked by the runtime monitor. Monitoring points are inserted automatically since the monitoring script specifies which information needs to be extracted, not where in the code extraction should occur. Static analysis is used to determine monitoring points and dynamic analysis is used to reduce monitoring overhead without evaluating new program state.

- **PMMS** (Program Monitoring and Measuring System) [51] is an approach that automatically collects information about the execution characteristics of a program. The user can specify objects and relations at the program, event, or statement-level. PMMS accepts the original program and properties given in a formal specification language. It installs instrumentation code in the program, determines what data must be collected, and inserts code to collect and process that data. The imple-

mentation uses temporal dependency among events to filter out irrelevant data at runtime and uses a main memory active database to facilitate the collection, computation, and access to results. PMMS handles events by installing code that reacts whenever relevant events occur.

- **RAC** (Runtime Assertion Checker for the Java Modeling Language) [11, 13] assists in the generation of test oracles and identifies errors during testing of Java programs. Programmers write pre and post conditions for class methods using a side-effect-free subset of the Java Modeling Language. It is also possible to check class-level post-state assertions such as invariants. These annotations are translated into Java code embedded in the source code. When violations of pre or post-conditions occur, exceptions are thrown.

- **ReqMon** (Requirements Monitor for executing software) [66, 67] provides a framework and tool for monitoring requirements at runtime. The high-level requirements are translated into a Unified Modeling Language (UML) design model from which a Java program is generated. ReqMon generates a Promela model [38] from the program source code and a monitored program event log from instrumented compiled Java classes. The model is checked using Spin [38] to determine if the current execution is on a path that can lead to a requirement failure. ReqMon has been applied to distributed web services. ReqMon automates the translation of monitor specifications into a monitor implementation. Templates for monitor specifications are specialized through the selection of appropriate parameters. At runtime, the monitors track web service traffic at the transport protocol, routers, and gateways. Integrative monitors combine information from individual monitors, and alerts are reported.

- **Sentry** [14] is a monitoring approach designed for sequential and concurrent C programs. The *Sentry* is an observer that is implemented as a separate process to concurrently monitor the execution of a target program and issue a warning if it does not behave correctly with respect to a given set of properties. The properties are specified in a propositional calculus that is extended to include integer arithmetic operators and relations using C syntax. Universal and existential quantifiers are permitted, as well as summation over a fully instantiated subrange. Annotations are written within specially formatted comments in the places where the properties should be evaluated. The original source file with the annotations is replaced by calls to macros. Properties observed by the global sentry are invariants that are maintained throughout the entire program execution. The local sentry checks properties at a particular point in the execution process and runs in parallel with the source program. The source program sends its variables to the sentry as it executes. The global sentry continuously observes and evaluates the global properties of the source program, waiting until a process writes new state information. The sentry then reads new variables from their buffers, preserving mutual exclusion with the processes, and enables the checking of any property involving those variables. After the sentry has read the available state information from all processes, it checks the enabled properties. Detected violations are reported by sending a signal to the program, and the program initiates a user-defined recovery action based on the type of fault.

- **Temporal Rover** [21] is a specification-based verification tool that uses Linear-Time Temporal Logic (LTL) and Metric Temporal Logic (MTL), allowing the user to specify future time temporal formulae as well as lower and upper bounds, and ranges for relative-time and real-time properties. In Temporal Rover, the user de-

termines the point at which a property should be checked and inserts an annotation of the property. The Temporal Rover parser converts an annotated program into an identical program with the properties implemented in the source code. During application execution, the generated code validates the executing program against the formal specifications. Temporal Rover takes a Java, C, C++, Verilog, or VHDL source code program as input and it enables customizable actions for the program domain.

- **TPTP** (Test and Performance Tools Platform) [73] is an open source project of the Eclipse foundation. TPTP is divided into four projects. One of them is the monitoring tools project that addresses the monitoring and logging phases of an application lifecycle. The monitoring tools project provides frameworks for building monitoring tools by extending the TPTP platform for collecting, analyzing, aggregating, and visualizing data that can be captured in the log and statistical models. The framework has the capability of collecting and analyzing system and application resources. It provides statistical agents to monitor and collect Windows and Linux systems, JBoss and JOnAS application server JMX data, Apache HTTP server status data, and MySQL database table and variable data. It is also able to instrument Java applications so they can be monitored. The log analysis tools can correlate disparate logs from multiple points across an environment. It also includes tools for monitoring application servers and system performance, such as CPU and memory utilization.

Runtime monitoring requires an understanding of the target system regarding the information which is going to be monitored. Several works address this problem through static analysis. DynaMICs [31] automatically inserts monitoring-related information to a target program by analysis of the program's path expression. Such a path expression is

generated from the control-flow graph of the intermediate code of the program through static analysis. Jass [6] has a precompiler to translate the monitoring information into Java code and insert it to the target program source code. The resulted compliance with the specified information is tested during the runtime. To the best of our knowledge, Mac [47] is the only system that uses the benefits of combined static and dynamic analyses. In this system, static analysis is used to determine monitoring points and dynamic analysis is used to reduce monitoring overhead by not evaluating new program state. Our work also addresses this issue using a synergy between static and dynamic analyses.

Programming analysis techniques are useful for runtime monitoring to know what to collect and where to locate the required information in a target program. However, there is still required to know how such information can be collected from the target program. Generally, runtime monitoring approaches track the execution of a target program by generating and processing execution events. Such a task is usually performed by modifying the target program at the source code level prior to the compilation [6, 22, 31, 52] or at the intermediate code level before running the program [37, 47]. This is called instrumentation of the target program which aggregates low-level monitoring information with the program code directly. New techniques are needed to reduce the monitoring overhead resulted from the instrumentation and modification of different levels of a target program. To the best of our knowledge, the JassDA [9] framework is the only monitoring system that generates monitoring events at runtime without any modifications to the target program. JassDA has become our motivation to address this issue in runtime monitoring by utilizing reverse engineering techniques and the capabilities of JPDA [39] so that the source code would not be modified. Following chapters will elaborate further on our approach and its contributions.

2.4 Summary

This chapter presents a survey of related works. A taxonomy of runtime monitoring systems, based on four elements, has been presented in this chapter. The first three of them are the most common elements of monitoring systems: *Specification Language*, *Runtime Monitor*, and *Event Handler*. In addition to these three elements, the fourth one considers the *Operational Issues* rather than the monitor itself. The main goal of the chapter is to provide a background knowledge of the existing and ongoing projects related to this area. Moreover, we review the state of the art in this chapter and compare specific features of our framework with what are contributed by other works.

Chapter 3

A Runtime Monitoring and Behavioral Analysis Framework

Software engineering strives enabling the economic construction of software systems in order to behave correctly and reliably in their environment. In other engineering disciplines, correctness is assured in part by a detailed monitoring of processes. In software, we can address this issue in the behavior of programs by monitoring their execution. Runtime software monitoring has been used for profiling, performance analysis, software optimization as well as software fault-detection, diagnosis, and recovery. Studying the dynamic behavior of an executing program can be very useful and can dramatically improve understanding by revealing program characteristics. Although this can not be assimilated from reading the source code alone, it is usually the primary source of information.

In this thesis, we propose a framework, namely RUMBA, to address the runtime monitoring and the behavioral analysis of Java software systems. RUMBA integrates concepts of reverse engineering and runtime monitoring and it is a synergy between static and dynamic analyses. It confirms whether a program behavior complies with OCL-based

specification of certain properties during its execution. The properties are defined based on the objectives of the user who intends to monitor the execution of a target program.

Runtime monitoring and analysis require certain information about a target system. In our framework, such information is obtained through hybrid analysis in such a way that does not require to modify the source code. Three key features of the RUMBA framework are: i) the theory defined for static analysis part of RUMBA is fully extendable at different granularity levels, for example towards monitoring information about the methods of a system, ii) the source code of a target system is not modified, and iii) the most processes of the framework are automated. Using the help of reverse engineering techniques through static analysis, we can reduce the large size of runtime information in dynamic analysis. We filter the information to what is required for the analysis.

This chapter outlines the proposed framework, while the details are discussed further in subsequent chapters. Section 3.1 presents the architecture of the framework and introduces the different stages of it. The two stages, performing static analysis, are described in Sections 3.2 and 3.3 respectively. Section 3.4 presents the third stage of the framework which performs dynamic analysis. We introduce an example target program in Section 3.5 which will be used further in subsequent chapters to understand the details of each process included in the framework. Finally, Section 3.6 summarizes the chapter.

3.1 The RUMBA Framework

The RUMBA framework is comprised of three stages namely: i) *Architecture Recovery*, ii) *Seeding Objectives*, and iii) *Runtime Monitoring and Analysis*. The first and the second stages are static while the third one is dynamic. Figure 3.1 illustrates the architecture of the framework.

As depicted in Figure 3.1, the main input of the RUMBA framework, which goes into the first stage, is the source code of the target system. At this time, the framework works for Java based systems. However, the modular architecture of RUMBA allows to replace or equip appropriate components in the future work, in such a way that other OO languages can be supported.

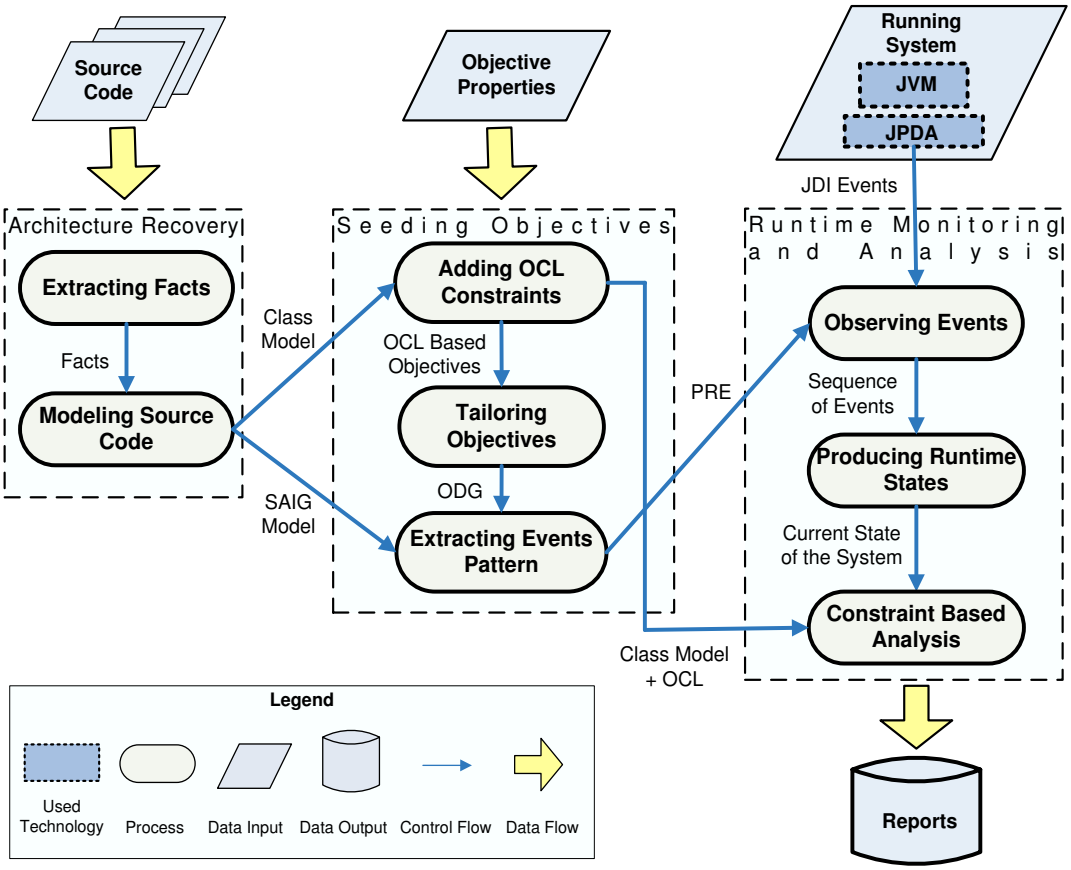


Figure 3.1: The RUMBA Architecture

The input of the second stage is provided based on the assumption that the user of the framework has some information about the domain of the target system. Particular OCL-based constrains are defined according to such information and the objectives of the runtime monitoring and analysis. Such constraints are utilized as the main input

of the stage. The structural models obtained from the first stage are also passed as the inputs of the second one. One of the inputs of the third stage is a structural model of the target system plus the defined objectives in OCL. As another input, a pattern of the required information for runtime monitoring, generated in the second stage, is passed to the third one. The output of RUMBA is actually the output of the last stage which is a list of sucesses/failurs of each constraint per state. The output can be considered as a repository which represents the results of analyzing some particular points of the behavior of the target system during runtime. Further explanations about each stage of the RUMBA framework can be found in the following subsections.

3.2 Architecture Recovery

Software architecture recovery aims at reconstructing views on the architecture as-built. Reverse engineering techniques have claimed to offer great contributions to Architecture recovery from legacy systems through static analysis. In the first step of our framework, such techniques are used to extract a meta-model of the system by utilizing graph representation of the system model.

We have two goals in this stage: i) modelling the structure of the system, and ii) describing the model in two representations: a *UML-compliant model* and a *graph based model*. Indeed, there are two main processes in this stage, *extracting facts* and *modeling source code*, to achieve the two aforementioned goals.

The Java Compiler (JavaCC) [74] is utilized in the "extracting fact" process. JavaCC is one of the most popular parser generators for use with Java applications. Its top-down nature allows it to be used with a wider variety of grammars than other traditional parsing tools. The JavaCC based extractor has been implemented in Java to automatically extract the information from a target system. However, the modular architecture of the

framework enables us to extend the work for future for other types of OO languages.

The "modeling source code" process utilizes graph-based structures, since graphs are very versatile data structures and can be applied for various computer vision problems. They are good for modeling, traversing, and transformation purposes. In our framework, attributed graphs [26] are used to model the system structure. The graph-based structure facilitates the extendibility of the model for future work. Such a graph based model is then traversed in other part of the static analysis. Finally, the graph based artifacts are exported as XML documents and transformed between different stages of the framework. The details of the two processes involved in this stage are elaborated further in Chapter 4.

3.3 Seeding Objectives

The Object Constraint Language (OCL) [65, 69] is a formal notation for analysis and design of OO systems. It is a subset of the industry standard Unified Modeling Language (UML) [1] that allows software developers to write constraints and queries over object models. A constraint can be seen as a restriction on a model or a system. OCL plays an important role in the analysis phase of the software lifecycle as a formal language to express constraints. It can be used for specifying constraints on a model in order to restrict possible system states [34]. Users of UML and other languages can use OCL to specify constraints and other expressions attached to their models.

OCL is an *expression language*. Therefore, an OCL expression is guaranteed to be without side effect; it cannot change anything in the model. This means that the state of the system will never change because of an OCL expression, even though an OCL expression can be used to specify a state change, e.g. in a post-condition. The values for all objects, including all links, will not be changed. Whenever an OCL expression is evaluated, it simply delivers a value. OCL is not a *programming language*, so it is not

possible to write program logic or flow control in OCL. It is not possible to invoke processes or activate non-query operations within OCL. Since OCL is a modeling language in the first place, nothing in it is promised to be directly executable. OCL is a *typed language*, hence each OCL expression has a type. In a correct OCL expression, all types used must be type conformant. For example, it is not possible to compare an Integer with a String. Types within OCL can be in any kind of classifier within UML. As a *modeling language*, all implementation issues are out of scope and cannot be expressed in OCL. Each OCL expression is conceptually atomic and the state of the objects in the system cannot change during the evaluation.

We use OCL in this stage of RUMBA to define particular properties as objectives of the behavioral analysis. We consider an *objective* as a *property* that constrains the permitted actions, and, therefore, the permitted state changes of a system [60]. A specific set of rules can be defined to formalize our expectation about the runtime of a system that actually determine the *objectives* of evaluating the behavior of the system.

The *properties* are particularly useful, as they allow us to create a specific set of rules. Such rules can govern some aspects of the objects of our interest. The objects and some of their attributes are our points of interest, since their changes determine our expectation about the runtime of the system. However, the domain of the available information about these objects is limited to their names and some of their attributes involved in the definition of the OCL rules. We need more information to be able to track them and filter the events during the runtime of a program. For that reason, information required for filtering runtime events is also obtained in this stage.

In summary, we have two main goals in this stage: i) identifying properties as OCL rules on the class model of the target program, and ii) extracting patterns of required events to reduce and filter generated events during monitoring the runtime. There are three main processes in this stage which are explained further in Chapter 5.

3.4 Runtime Monitoring and Analysis

In this stage, the runtime execution of the target system is monitored according to the output of the previous stages. Afterwards, the obtained runtime information is analyzed and verified. The analysis is constraint based and is performed based on the the properties defined in the second stage.

Approaches to runtime monitoring and analysis have to track the execution of a system and therefore have to deal with generating and processing event traces. However, these techniques are mostly applied at the code level (so-called instrumentation). Such an instrumentation can be done either by inserting new source code prior to the compilation or by modifying the target code, e.g. Java byte code, before running the program. Our framework does not modify the source code. We use Java Platform Debug Architecture (JPDA) [39] for monitoring purpose to generate event traces. JPDA is a multi-tiered debugging architecture contained first within Sun Microsystem Java 2 SDK version 1.4.0. It consists of a Java Virtual Machine Debug Interface (JVMDI), and a Java Debug Interface (JDI), as well as a protocol, Java Debug Wire Protocol (JDWP). We have used the JDI, which defines and requests information at the user code level, in order to implement our monitoring component

On the other hand, a back-end analysis component carries out the processing of the generated traces with respect to the properties. We have used an open source tool called USE (UML-based Specification Environment) developed in Bremen University [3]. We have adopted some parts of the source code of USE to be incorporated into our framework as a part of the design and the implementation of the analysis component.

Totally, there are three processes included in this stage. Two of them are responsible for monitoring the execution traces of a target program. They specify the traces of the runtime states of the program. The third process is responsible for OCL-based constraint

analysis on the generated states coming from the other two. These three processes are elaborated further in Chapter 6.

3.5 An Example: Trading System

This section introduces a *Trading* system as an example to understand the details of each process included in the framework. Sample artifacts generated from different stages of the framework are elaborated on this simple example in subsequent chapters.

Consider a trading system with two major classes, namely *Stock* and *Trader*. In this system, some traders instantiated from the *Trader* subscribe in a stock instantiated from the *Stock*. The stock has some items to sell and provides traders with information about each item, including its price, whenever it is ready for market. Each trader decides whether she/he wants to buy the item or not, based on her/his trading policy. If yes, she/he lets the stock know about her/his decision so that nobody else can buy that item.

We study a transaction based property in this system in subsequent chapters. Such a property may be violated due to the interference caused by making access to critical sections mutually exclusive [60]. It means that at least two traders are able to buy the same item with the stock at the same time. Since there is no support to handle transactional issues in our example system, there are states during the runtime where at least two traders have bought the same item. This is a behavior that is unwanted and unexpected from the user's point of view. According to the definition of an objective, there must be something that constrains the permitted actions of this system. It is a constraint that must be defined to check whether the system respects the transactional access. We define such a constraint as the objective for the behavioral analysis. Indeed, we monitor the runtime of the system to detect the points at which there is a violation in the behavior of the system with the specified objective.

3.6 Summary

In this chapter, we have outlined the proposed framework which utilizes hybrid analysis to confirm whether a program behavior complies with specified properties during its execution. The framework is comprised of three stages: i) *Architecture Recovery*, ii) *Seeding Objectives*, and iii) *Runtime Monitoring and Analysis*. There are some processes included in each stage of the framework which have been briefly explained in the chapter. The role of each stage of the framework has been addressed in this chapter. In the subsequent chapters, we will elaborate further on the processes involved in each stage. We will describe how each process works with respect to its input(s) coming from other processes and the output(s) which will be generated.

Chapter 4

Architecture Recovery

The ability to recover up-to-date architectural information from existing software artifacts is a key to have effective software maintenance, reengineering and reuse. This information is beneficial to the engineer who is trying to understand a software system. An architecture recovery system extracts *facts* from a system implementation, then combines these facts into higher level of abstractions (for example, modules and subsystems). The extracted facts may be in many forms. Researchers have extracted information about function calls, data accesses, and file operations to help reconstruct views of an architecture [28, 29, 33, 44, 56, 58, 63].

In contrast to several monitoring systems that need to do some modifications at the source code or byte code levels [6, 22, 37, 47, 52] of their target system through the instrumentation, we do not require any instrumentation. For achieving such a goal, our framework needs some structural information about the target system. This information, which is obtained through the architecture recovery in the static analysis, helps our monitor to track the location of required information during the runtime.

Therefore, the first stage of RUMBA is the architecture recovery stage. We have two

goals in this stage: i) modeling the structure of the system that is the target of runtime monitoring, and ii) describing the model in two representations: a *UML-compliant model* and a *graph based model*. To achieve these goals, as Figure 4.1 illustrates, two main processes are performed in this stage. First, we parse the source code of the target system to extract facts from its implementation. Then, we model the facts into the forms which will be useful for the next stages of RUMBA. This chapter describes these two processes: *extracting facts* and *modeling source code*. In Section 4.1, we discuss about the fact extraction process in more details. We explain the source code modeling process in Section 4.2 including details and examples about two generated models during the process. Finally, Section 4.3 summarizes the chapter.

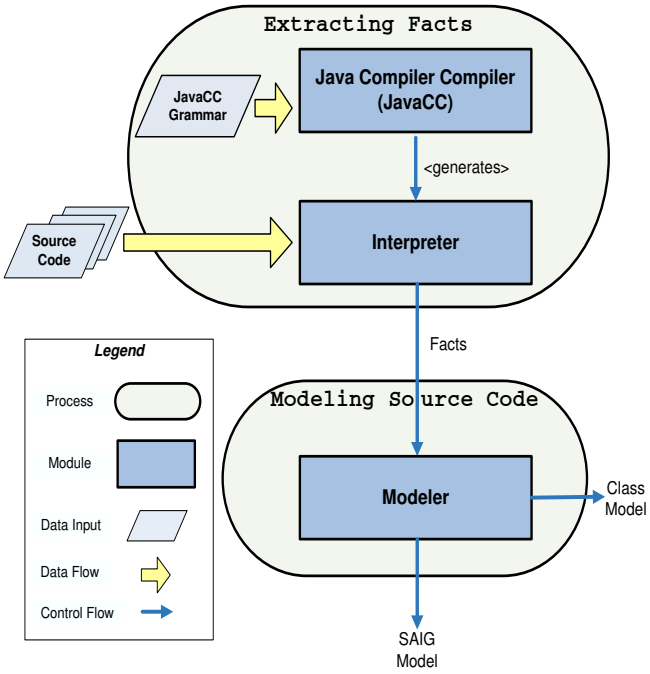


Figure 4.1: Architecture Recovey

4.1 Extracting Facts

The fact extraction is an automated process which extracts facts from the source code of a target system. One group of the facts that we extract from a target system are classes of the system, their attributes, and data type of each attribute. The following terminology can formulate our desired notation for these facts:

Terminology 4.1 *Consider set of all languages in the world as L and set of all data types of these languages as T_L. An object-oriented software system S is implemented in a language l, where $l \in L$. We denote any class type and class attribute of the language l with c_t and c_a classifiers respectively. T_l is the set of all data types of l where $T_l \subset T_L$. For example, $T_{Java} = \{int, short, long, double, float, boolean, byte, char, string\}$.*

The other group of facts extracted from the system is a set of relations. Our interested relations can be classified in three forms: i) a class has a relationship with the attribute that it owns, ii) an attribute has a relation with its data type, and iii) a class may have a relation with another class. For the third one, we consider the *association relationship* according to the UML 2.0 specification [1]. UML specifies that the association between two classes represents the ability of an instance of the first class to send a message to an instance of the second one. This is typically implemented with a pointer or reference instance variable, a method parameter, or a creation of a local variable. We formalize the three types of relations as follows:

Definition 4.1 *A set of relations R over the system S in the language l is defined on a set D, where $D = \{c_t, c_a\} \cup T_l$.*

Considering t_i is a data type of language l where $t_i \in T_l$ and $i \in \{1, ..., |T_l|\}$, R includes:

- ***has-attr**: the attribute ownership of a class. It is denoted as c_t **has-attr** c_a*

- *`has-type`: the relation between a data type and an attribute defined over that type. It is denoted as* c_a `has-type` t_l

- *`depends-on`: the association relation between any two class entities of* S*. It is denoted as* c_t `depends-on` c_t

Extracting facts can be facilitated with the help of reverse engineering techniques and tools. Source code parsers have been used for several years. The best known of them are *Yacc* [76] and *Lex* [50] from the Unix domain or their GNU version, *Bison* [7] and *Flex* [30]. Lex is a lexical analyzer generator and Yacc is a parser generator. In combination, they can be used as the front end of a language translator. Lex program recognizes regular expressions and yacc generates parsers that accept a large class of context-free grammars [19]. Our automated fact extraction process uses JavaCC [74] to extract required facts. JavaCC is one of the most popular parser generators for use with Java applications. It generates top-down, recursive descent parsers. The top-down nature of JavaCC allows it to be used with a wider variety of grammars than other traditional tools, such as Yacc and Lex. Another difference between JavaCC and Yacc/Lex is that JavaCC contains all parsing information in one file. The convention is to name this file with a .jj extension.

Our target systems are limited to the Java based systems in the current version of the RUMBA framework. Therefore, our automated fact extraction process uses JavaCC and extracts required facts from a Java based system. However, as mentioned before, the modular architecture of RUMBA makes it possible to extend the work for future and work with other types of OO languages.

In a nutshell, the target Java program is parsed in the first process of the architecture recovery to extract information about its classes (and the packages which contains them), attributes, data types, and relations as described earlier. These facts are essential for

representing the system as two models in the next process of the architecture recovery stage.

4.2 Modeling Source Code

The source code modeling process forms the extracted facts from the previous process into two models: a *UML-compliant model* and a *graph based model* of the system structure. The following sections elaborate further on these two models.

4.2.1 The Class Model

The UML-compliant model is used later for the analysis part of the RUMBA framework. The specification of this model is based on the USE specification [3]. USE (UML-Based Specification Environment) is a tool for the specification of information systems. We have adopted some parts of the source code of this tool to be incorporated into RUMBA as the analysis component which will be discussed further in later chapters. The USE specification language is based on UML and OCL. It contains a textual description of a model using features found in UML class diagrams (classes, relations, etc).

From now on, we call the UML-compliant model as *Class Model* of the system. Expressions written in the Object Constraint Language (OCL) are used to specify additional integrity constraints on the class model. This model is generated automatically during the modeling process. Later, the OCL based rules are added to it as the objectives of the runtime analysis. For each snapshot of the runtime traces of the system, the OCL constraints are automatically checked on this model.

The class model has three major sections:

- **Classes Section** lists the classes of the system. Each subsection includes name of a class and its attributes names followed by the data type of each attribute.

- **Associations Section** lists the association relations which exist among the classes. Each subsection specifies a name to an association and contains the name of two involved classes and the degree in which they depend on each other.

- **Constraints Section** lists the OCL based constraints on the class model. This section is not generated during the modeling process. It is later added to the class model in subsequent stages of the framework.

```
model Trading


-- classes
class Trader
attributes
    name: String
    itemID: Integer
    basePrice: Integer
    tradePrice: Integer
end

class Stock
attributes
    name: String
    item: Integer
    currentPrice: Integer
end


-- associations
association depend_1 between
  Trader[0..*]
  Stock[1]
end


-- constraints
    -- will be added later in
    -- subsequent stages
```

Figure 4.2: A Class Model Example - The Trading System

As an example, the class model resulted from the source code modeling process on our

example trading system is depicted in Figure 4.2 in USE specification.

4.2.2 The $SAIG$ Model

The source code modeling process also generates another model of the system automatically. This model is graph based and is called $SAIG$ (Schema Attributed Instance Graph) of the system. This graph is our extension to the attributed graphs [26]. We export the $SAIG$ as XML documents that can be easily queried and traversed in subsequent stages. Before going into more details, formal definitions of the attributed graphs and related concepts need to be given.

Definition 4.2 *An **Attributed Graph** is a directed graph $AG(V, E)$ in which:*

- $V = V_m \cup V_d$ *that* V_m *and* V_d *are called **main** and **data** nodes respectively*
- $E = E_l \cup E_a$ *that* E_l *and* E_a *are called **link** and **attribute** edges respectively such that:*
  - $\star$ $E_l = \{(u, v) \mid u, v \in V_m\}$
  - $\star$ $E_a = \{(u, v) \mid (u \in V_m) \wedge (v \in V_d)\}$

Attributed graphs can be categorized at two levels:

- ***Abstract Level*** for modelling a schema or class diagram which is called Attributed Abstract Graph (AAG)
- ***Instance Level*** for modelling an individual system structure which is called Attributed Instance Graph (AIG)

Definition 4.3 *An **Attributed Abstract Graph** $AAG = \langle AG, T_L \rangle$ is an AG over the set of data types T_L such that: $V_d \subseteq T_L$.*

The AAG is in generic format. We can define such a graph in a less abstract way for a specific langauge l. The resulted graph is called *Schema Attributed Abstract Graph*. It is *abstract*, since no individual system is still considered in this representation. In other words, there is no mapping through any morphism functions(s) that can instantiate the graph for representing an individual system.

Definition 4.4 *A **Schema Attributed Abstract Graph** of a language l, namely $SAAG(V, E)$, is an $AAG = \langle AG, T_l \rangle$ where the following characteristics are hold:*

- $V_m = \{c_t, c_a\}$
- $V_d = T_l$
- $E_l = \{(c_t, v) \mid [(c_t \ \texttt{depends-on}\ v) \ \textit{iff}\ (v = c_t)] \vee [(c_t \ \texttt{has-attr}\ v) \ \textit{iff}\ (v = c_a)]\}$
- $E_a = \{(c_a, t) \mid (t \in T_l) \wedge (c_a \ \texttt{has-type}\ t)\}$

As mentioned before, $SAAG$ in actually an AAG, but in a less abstract form over a specific language l. The graph, which is obtained based on the AAG through two morphism functions, is called *Attributed Instance Graph (AIG)*. In other words, AIG is instantiated from AAG to model an individual system.

Definition 4.5 *An **Attributed Instance Graph** $AIG = \langle AG, \mu_V, \mu_E \rangle$ over AAG is an AG (over the same T_L as AAG) equipped with a pair of morphism functions $\mu_V : V^{AG} \rightarrow V^{AAG}$ and $\mu_E : E^{AG} \rightarrow E^{AAG}$.*

We need the $SAAG$ and AIG to define our primary graph which is called *Schema Attributed Instance Graph (SAIG)*. This graph is instantiated in the least abstraction level

than the previous ones and is instantiated from $SAAG$. It is used for modeling the structure of an individual system S implemented in a specific language l. The formal definition of $SAIG$ is as follows:

Definition 4.6 *A **Schema Attributed Instance Graph** of the system S, namely $SAIG(V, E)$, is defined over the $SAAG$ where S is implemented in the same language l. The $SAIG(V, E)$ is an $AIG = \langle AG, \mu_V, \mu_E \rangle$, where:*

- *V_m is the set of all classes or the attributes of the classes*
- *$V_d \subseteq {V_d}^{SAAG}$*
- *$E_l \subseteq {E_l}^{SAAG}$*
- *$E_a \subseteq {E_a}^{SAAG}$*
- *We know that for an AG(V, E), $V = V_m \cup V_d$ and $E = E_l \cup E_a$. While any $SAIG$ is considered as AG, morphism functions μ_V and μ_E can be defined as follows:*
  - $\star$ $\forall\ v \in V$:
    - $\diamond$ *if $v \in V_m$ and v is a class of the system S, then $\mu_V(v) = c_t$ where $c_t \in V^{SAAG}$*
    - $\diamond$ *if $v \in V_m$ and v is a class attribute of the system S, then $\mu_V(v) = c_a$ where $c_a \in V^{SAAG}$*
    - $\diamond$ *if $v \in V_d$, then $\mu_V(v) = v$ where $V_d \subseteq {V_d}^{SAAG}$ and $v \in V^{SAAG}$*
  - $\star$ $\forall\ e \in E : \mu_E(e) = e$ *where $E \subseteq E^{SAAG}$ and $e \in E^{SAAG}$*

We export the $SAIG$ of the target system as an XML document to be used as the input for other process of RUMBA. The XML schema for this graph is depicted in Figure 4.3. The XML schema shows that three types of information are captured in the $SAIG$:

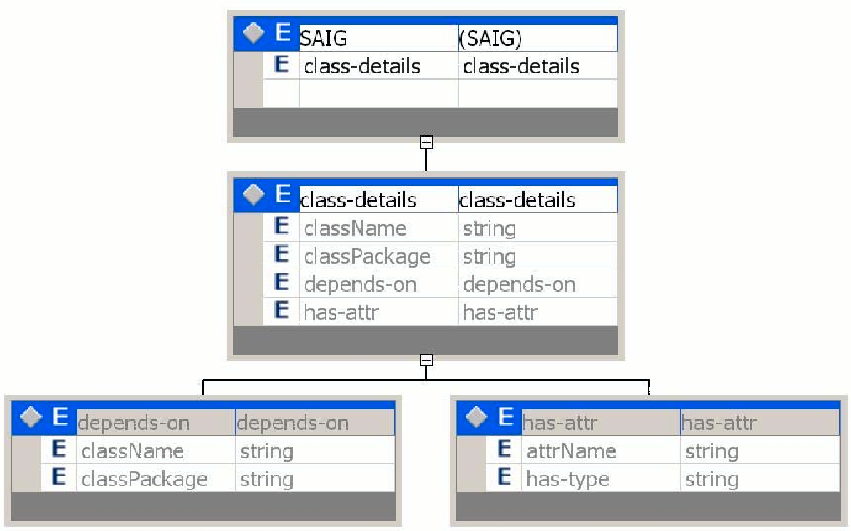


Figure 4.3: XML Schema for the SAIG Model

- **Class Details Field** , namely *class-details*, records the name of each class of the given system and the package in which the class is located. They are denoted by *className* and *classPackage* respectively in the schema. There are also some other fields contained by this one which are explained in below.
- **Dependency Field** , namely *depends-on*, is contained by the *class-details* field. It records all classes of the system with which the corresponding class has association relation followed by the package in which they are located. The name and package of such classes are denoted by *className* and *classPackage* respectively.
- **Attribute Ownership Field** , namely *has-attr*, is contained by *class-details* field. It records all the attributes of the corresponding class followed by the type of that attribute. The name and the type of such attribute are denoted by *attrName* and *has-type* respectively.

An example of the *SAIG* model resulted from the modeling process is depicted in Figure 4.4. This *SAIG* corresponds to our example *Trading* system.

```
<SAIG>
    <class-details>
        <className>Trader</className>
        <classPackage>org.atrade</classPackage>
        <depends-on>
            <className>Stock</className>
            <classPackage>org.atrade</classPackage>
        </depends-on>
        <has-attr>
            <attrName>name</attrName>
            <has-type>String</has-type>
        </has-attr>
        <has-attr>
            <attrName>itemID</attrName>
            <has-type>int</has-type>
        </has-attr>
        <has-attr>
            <attrName>basePrice</attrName>
            <has-type>int</has-type>
        </has-attr>
        <has-attr>
            <attrName>tradePrice</attrName>
            <has-type>int</has-type>
        </has-attr>
    </class-details>
    <class-details>
        <className>Stock</className>
        <classPackage>org.atrade</classPackage>
        <has-attr>
            <attrName>name</attrName>
            <has-type>String</has-type>
         </has-attr>
        <has-attr>
            <attrName>item</attrName>
            <has-type>int</has-type>
        </has-attr>
        <has-attr>
            <attrName>currentPrice</attrName>
            <has-type>int</has-type>
        </has-attr>
    </class-details>
</SAIG>
```

Figure 4.4: A SAIG Model Example - The Trading System

It is worth mentioning that, by modeling the *SAIG* of a system, we are actually able to keep track of the location (package) of each class of the system. We also record the location (class) of the attributes of each object in the system. This information is useful since our objective constraints are constructed based upon the attributes of the runtime objects of the system and their dependencies. We can not track the location of those attributes unless we instrument specific parts of the code. However, using the *SAIG* that records the structural information of the system, we can avoid such an instrumentation. More details about the benefits of *SAIG* and the algorithm through which we map our objectives over this model are further discussed in Chapter 5.

4.3 Summary

We have discussed the fact extraction and source code modeling processes which are contained in the architecture recovery stage of the RUMBA framework. The first process automatically extracts facts from the source code of a target system in the forms of classes, their attributes, data type of each attribute, and some relations (attributes ownership of classes, relation of an attribute with its corresponding data type, and association relations among classes). The modeling process automatically generates two models from the extracted facts: a UML-compliant model, called the *class model*, and a graph based model of the system structure, called the *SAIG model*. Next stage of the framework will use these two models for different purposes which will be explained further in the next chapter.

Chapter 5

Seeding Objectives

In this stage of the RUMBA framework, there are two models available from the previous stage. The first one, the *class model* is updated by adding the OCL constraints to it. The second one, the *SAIG model*, is not modified but is used to track the locations of those attributes which are involved in the OCL constraints. Based on this tracking, a pattern of all required attributes for runtime monitoring is generated. This pattern is called *Pattern of Required Events* (*PRE*).

Therefore, we have two goals in this stage: i) identifying objective properties as OCL rules on the class model of the system, and ii) extracting pattern of required events to reduce and filter generated events during monitoring the runtime. To address these goals, three main processes are performed in this stage as shown in Figure 5.1. First, we identify some OCL-based constraints as specifications for the behavioral analysis and add them to the class model of the system. Then, a dependency graph, namely *Objective Dependency Graph (ODG)*, is obtained from tailoring the OCL-based properties. Finally, a pattern of required events for runtime monitoring is generated by traversing through the *SAIG* model of the system based on the *ODG*.

The three aforementioned processes of this stage are described through Sections 5.1, 5.2, and 5.3 respectively. Afterwards, Section 5.4 summarizes the chapter.

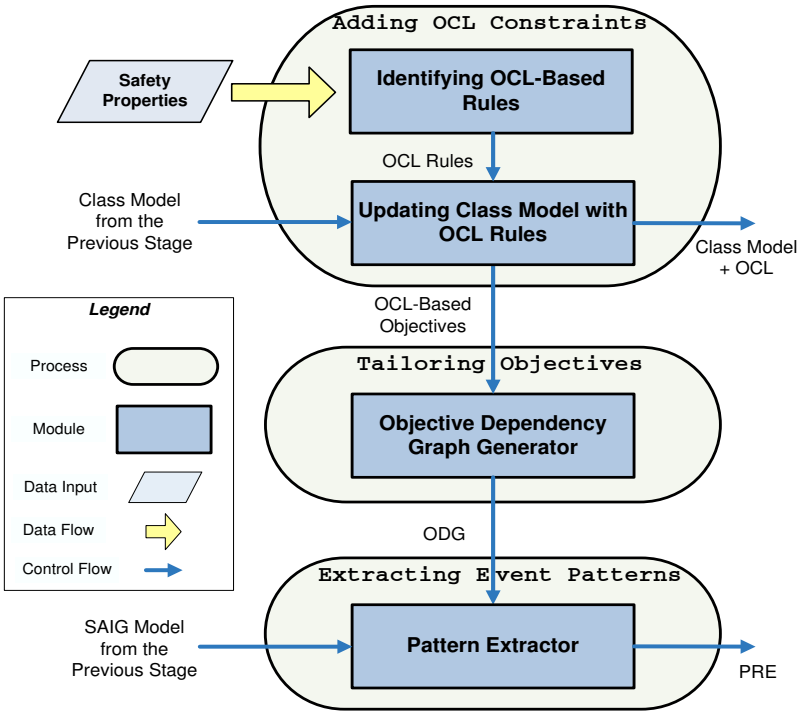


Figure 5.1: Seeding Objectives

5.1 Adding OCL Constraints

At this stage, the objectives of the behavioral analysis are specified. They are certain properties on the behavior of the system which are described as OCL rules and added to the class model. This process is performed manually. User has to have some knowledge about the domain of the target system. Based on this information, the behavioral expectation of the system will be defined as OCL rules. Such rules are defined on the class model of the system based on its class objects and their attributes.

We use an example to explain the usage of OCL in identifying the properties. Back

to our example *Trading* system from the previous chapters, we know from our knowledge about the system that there are some traders subscribed in a stock. These traders are in trade with the stock on some items offered by the stock. What happens if at a particular time, two traders trade the same item with the stock? This means that, there are states during the runtime where at least two traders have bought the same item due to a transactional problem. This is a behavior that is unwanted and unexpected from the user point of view. The reason for such a transactional problem is the interference caused by making access to critical sections mutually exclusive [60]. In other words, according to the definition of an objective, there must be something that constrains the permitted actions of this system. It is a constraint that must be defined to check whether the system respects the transactional access or not. We define such an objective using OCL as follows:

Whatever we write as OCL constraints will be checked on the sequence of states coming from the runtime monitoring of the system. Anytime a new item is traded, the monitor will generate the corresponding state trace for that change. Therefore, we check if there exists any two traders which have the same itemID. It means that, they have bought same item from the stock which is not allowed according to our expectation from the behavior of the system. Such a constraint in OCL will be as shown in below:

context Trader **inv** Transaction:

Trader.**allInstances** → **forAll** (t_1, t_2: Trader | (t_1 <> t_2)

implies ($t_1.itemID$ <> $t_2.itemID$)

The constraint indicates that for every two traders in the system, they are not allowed to buy the same item. However, this constraint has a problem. When at the first time it becomes false, it will stay false for the rest of the states. We have to include timing

in this rule. Here, our clocking system helps to keep track of the latest changes in the traders' attributes. The variable *myClock* is a time stamp which we can add to each class object during the monitoring process. When the status of an object changes, i.e. the value of any of its attributes is updated, this time stamp will be updated (increased by one) and assigned to the recent change of that object. When such a change is specified as the current state of the system, the *myClock* time stamp has the greatest value among time stamps of other states. It means that this state shows the recent change to the corresponding object.

Therefore, the *Transaction* objective will check the $itemID$ value of the last updated trader object with all the previous traders in the system. In this way, *myClock* of such a trader must be greater than all other traders. Moreover, its $itemID$ attribute must be different from all other traders in the system. Otherwise, such a trader has bought an item which is the same as at least one of the other traders in the system, and that is a conflict with our objective. Therefore, the above OCL rule is corrected and added to the class model of the trading system. The updated class model of the trading system resulted from this process is depicted in Figure 5.2 in USE specification. Generally, after identifying OCL constraints, we add them to the class model of the system generated from the architecture recovery stage of RUMBA.

5.2 Tailoring Objectives

The OCL-based objective, identified in the previous process, are checked at this point to extract class objects and attributes on which they depend. The extracted information is represented in a simple dependency graph called the Objective Dependency Graph (ODG). We export the ODG of the target system as an XML document to be used as the input for other processes of RUMBA. This graph records the names of classes and

```
model Trading


-- classes
class Trader
attributes
     name: String
     itemID: Integer
     basePrice: Integer
     tradePrice: Integer
     myClock: Integer
end

class Stock
attributes
     name: String
     item: Integer
     currentPrice: Integer
     myClock: Integer
end


-- associations
association depend_1 between
  Trader[0..*]
  Stock[1]
end


-- constraints
context Trader
  inv Transaction:
    Trader.allInstances->exists (
       t1: Trader | (
          Trader.allInstances->
          forAll(t2 : Trader |
          (t1 <> t2) implies (
             (t1.myClock > t2.myClock)
              and
             (t1.itemID <> t2.itemID)
          ))
       )
    )
```

Figure 5.2: The Class Model of the Example Trading System with the Added OCL Constraint

attributes of the system that particular properties depend on. The XML schema for this graph is depicted in Figure 5.3. The XML schema shows that three types of information are recorded in the *ODG*:

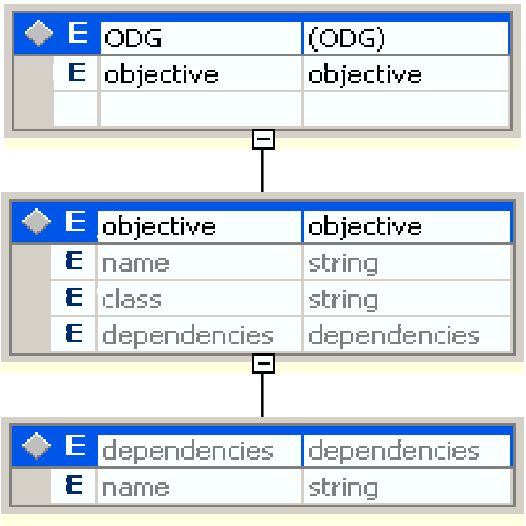


Figure 5.3: XML Schema for the Objective Dependency Graph (ODG)

- **Objective Field** , namely *objective*, records the name of each objective (OCL-based property) added to the class model of the system. The name of this objective is denoted by *name* in the schema. There are also some other fields contained by this one which are explained in below.

- **Class Field** , namely *class*, is contained by the *objective* field. It records the name of the class of the system on whose context the corresponding objective is defined.

- **Dependencies Field** , namely *dependencies*, is contained by the *objective* field. It records names of attributes of the context class on which the corresponding objective depends.

An example of the *ODG* resulted from the tailoring process is depicted in Figure 5.4. This *ODG* corresponds to our example *Trading* system. As shown in the figure, the so-added *myClock* attribute of *Trader* is not recorded in this graph. Because, it is not the actual attribute of this class. Our framework add this attribute to all the classes in the class model of the target system. It also keeps track of the value of *myClock* for all the runtime objects of the classes recorded in ODG (here the *Trader*). Therefore, there is no need to record this attribute which will be monitored by default during the runtime.

```
<ODG>
  <objective>
        <name>Transaction</name>
        <class>Trader</class>
        <dependencies>
            <name>itemID</name>
        </dependencies>
  </objective>
</ODG>
</SAIG>
```

Figure 5.4: An Example of ODG - The Trading System

The only information recorded in the *ODG* is name based information. We need to have more information about the *location* and *type* of its entities in the structure of the system to be able to track their locations and values during the runtime. In this regard, we have formed this graph in the same format as the *SAIG*, because in the next process, *PRE* will be obtained as a result of traversing these two graphs.

5.3 Extracting Event Patterns

Once the *ODG* is constructed, a model of required attributes for dynamic analysis is available. It is still required to populate the model on the structure of the system to construct another model called the *Pattern of Required Events (PRE)*. The static analysis

creates the PRE while it is utilized by dynamic analysis. It helps to filter generated event traces during monitoring the runtime and reduce them to what is needed by the analysis component.

Before presenting the algorithm through which the PRE is generated, we need to give a formal definition for *Adjacency Function* of a directed graph. This concept is used in the algorithm.

Definition 5.1 *An **Adjacency Function** of a directed graph $G(V, E)$, namely $Adj^G : V \rightarrow P(V)$, returns the set of out-edge nodes for each node of G where $P(V)$ or 2^V, namely power set of V, is the set of all subsets of V.*

Algorithm 5.1: Extracting Event Patterns

```
1  Input: SAIG , Adj^SAIG, and ODG of an OO system S
2  Output: PRE to monitor the behavior of S
3  PRE ← ∅
4  foreach v ∈ V^SAIG do
5      flag2VisitingNode(v) ← false
6  while (∃u ∈ V_m^SAIG) & (∼ flag2VisitingNode(u)) do
7      traverse(u)
8   Procedure traverse(v)
   begin
9      flag2VisitingNode(v) ← true
10     if v ∈ V^ODG then
11         foreach v' ∈ Adj^SAIG(v) do
12             if ∼ flag2VisitingNode(v') then
13                 if v' ∈ V_d^SAIG then
14                     PRE ← PRE ∪ {(v, v')}
15                     flag2VisitingNode(v') ← true
16                 else
17                     if v' ∈ V^ODG then
18                         PRE ← PRE ∪ {(v, v')}
19                         traverse(v')
20                     else
21                         flag2VisitingNode(v') ← true
   end
```

Algorithm 5.1 describes the process through which PRE is generated from traversing the $SAIG$ and the ODG. In this algorithm, $SAIG$ is traversed in depth-first order based on the ODG to build the attributes of the PRE. For each common node v between the ODG and the $SAIG$ (line 10), any out-edge neighbor (v') of v in the $SAIG$, that has not been traversed yet (lines 12), will be considered for further traverse. If v' is a *data* node, its relation with v (including the two nodes) is added to the PRE (line14) in order to record the information about the data type of v. If v' is a *main* node included by the ODG, its information is added to the PRE (lines 16 to 18). Also, v' is traversed further (line 19) to obtain its dependencies information. Because, according to the ODG, the definitions of some objectives depend on the entity (class type or class attribute) corresponding to this node. Finally, if v', as a *main* node, is not included by the ODG (line 20), there is no need to traverse it to obtain more details. Therefore, the $flag2VisitingNode$ for this node is set as true. The PRE is exported as an XML document to be used as the input for the runtime monitoring component. The XML schema for this graph is depicted in Figure 5.5.

The XML schema shows that two types of information are captured in the PRE:

- **Class Information Field** , namely *className*, records the information about each class of the system which is point of our interest for monitoring. The name of such a class and the package in which it is located are denoted by *name* and *package* respectively in the schema. There is also a *classAttr* field contained by this one which is explained in below.

- **Class Attribute Field** , namely *classAttr*, is contained by the *className* field. It records those attributes of the corresponding class which are points of interest for monitoring. The name and the type of such attributes are denoted by *name* and *type* respectively.

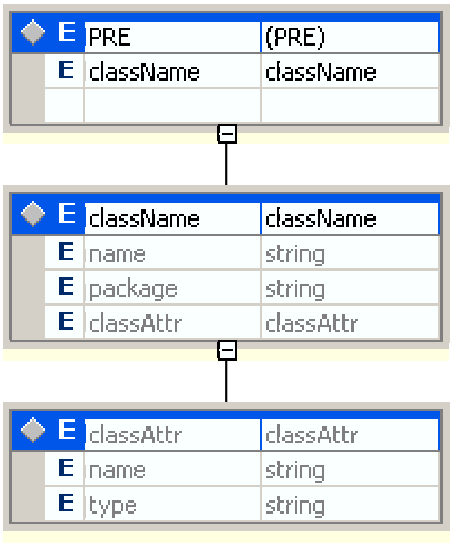


Figure 5.5: XML Schema for the Pattern of Required Events (PRE)

An example of the *PRE* resulted from applying Algorithm 5.1 on our example *SAIG* and *ODG* from the trading system is depicted in Figure 5.6. According to the PRE, during the runtime, we need to monitor any object instantiated from the *Trader* class located in the *org.atrade* package. We also need to monitor any changes in the value of the *ietmID* attribute of this class with the type *integer*.

```
<PRE>
    <className>
        <name>Trader</name>
        <package>org.atrade</package>
        <classAttr>
            <name>itemID</name>
            <type>int</type>
        </classAttr>
    </className>
</PRE>
```

Figure 5.6: An Example of PRE - The Trading System

5.4 Summary

We have discussed about the three main processes involved in the second stage of the RUMBA framework, *Seeding Objectives*. First, objectives are defined in OCL (Object Constraint Language) as specifications for the behavioral analysis. They are added to the class model of the system. Second, the identified OCL-based properties are tailored to extract their dependencies to the classes and attributes of the target system. The resulted artifact is the ODG of the properties. Third, information required for filtering runtime events is obtained. This process is done by traversing through the $SAIG$ of the system based on the obtained ODG from the previous process. Next stage of the RUMBA will use the PRE and the class model to respectively do the monitoring and the analysis on the behavior of the target system based upon them.

Chapter 6

Runtime Monitoring and Analysis

There is renewed interest in the field of dynamic software fault-monitoring largely because software systems are becoming more difficult to verify due to increases in size and complexity. Runtime monitoring is a lightweight formal technique that checks only the current execution of a target program against the specification. It does not consider the possible transitions of the runtime states, however only the actual transitions are counted into the account. Many tools have been proposed for runtime monitoring with the purpose of detecting, diagnosing, and recovering from software faults. However, most of them address this issue by modifying their target program utilizing the instrumentation techniques.

In this stage of RUMBA, as depicted in Figure 6.1, the runtime monitoring and analysis of the behavior of a target system is performed dynamically while no modification of the target program is required. There are three processes in this stage. Two of them, *Observing Events* and *Producing Runtime States*, are responsible for monitoring. Afterwards, the third one, *Constraint Based Analysis*, carries out the processing of the generated traces with respect to the objective properties identified in the previous stage.

The monitoring technique and the two processes responsible for monitoring are described in Section 6.1. In Section 6.2, we discuss about the process of constraint based analysis. Finally, Section 6.3 summarizes the chapter.

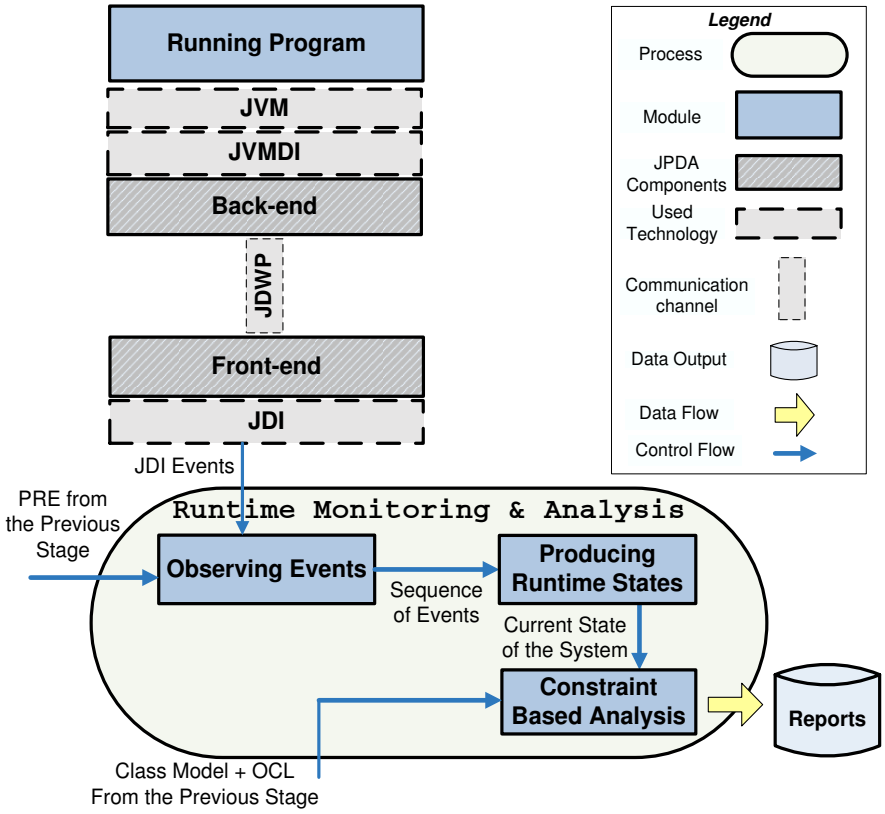


Figure 6.1: The Structure of the Runtime Monitoring

6.1 Monitoring Process

To avoid any modifications in a target program for the runtime monitoring, it is desirable to monitor a program by listening to the runtime events of the program dynamically. One way is to invoke a system from another program and listen to all the event traces during the runtime. In such a case, the target program is being debugged by a part of

the monitor. We also need a means of filtering traces and events so that only required properties would be monitored. Required properties and attributes can be constructed statically, and events which match with those properties will be chosen during the runtime.

JPDA (Java Platform Debugging Architecture) [39] is a multi-tiered debugging architecture deployed first within Sun Microsystems Java 2 SDK 1.4.0. It consists of two interfaces (JVMDI and JDI), a protocol (JDWP), and two software components which tie them together (back-end and front-end). Figure 6.1 illustrates how we utilize JPDA for monitoring a target Java system. As shown in the figure, JVMDI (Java Virtual Machine Debug Interface) comes between the JVM and the back-end program. It describes the requests to the JVM for information (e.g., current stack frame), actions (e.g., setting a breakpoint), and notification (e.g., when a breakpoint has been hit). The JDWP (Java Debug Wired Protocol) defines the format of information and requests transferred between the target program and the front-end, which implements JDI (Java Debug Interface). The back-end receives JDWP packets from the front-end, and executes the commands received over the JDWP. Results are returned back to the front-end via JDWP.

The JDI provides a pure Java programming language interface to access and control the state of a virtual machine. It is implemented by the front-end while a debugger-like application (IDE, debugger, tracer, monitoring tool like in our case, and so on) is the client. The JDI defines information and requests at the user code level. It provides introspective access to a running virtual machine's state, class, array, interface, primitive types, and instances of those types. It also provides explicit control over a virtual machine's execution.

Utilizing JDI capabilities, two processes, *Observing Events* and *Producing Runtime States*, are responsible for runtime monitoring. The runtime event traces of a target system are generated within these processes while no instrumentation is performed on the source code of the system.

6.1.1 Observing Events

This process is a Java based program that has been implemented using the JDI specifications. It invokes the main class of a target Java program that has been passed to it. This process helps us to generate a trace of the program's execution by listening to the VM (Virtual Machine) events and making access to its dynamic information.

An event is considered as an occurrence in the target VM that is of interest to this process. The event can be in different types. When a specific type of event occurs, an instance of *Event* as a component of an event set is enqueued in the virtual machine's event queue. Our interested types of events which are captured by this process using the JDI capabilities are as follows:

- **VM Start Event :** It notifies about the initialization of the target VM. This event is received before the main thread is started and before any application code has been executed.

- **Step Event :** It notifies about completing a step in the target VM. The step event is generated immediately before the code at its location is executed; thus, if the step is entering a new method the location of the event is the first instruction of the method. When a step leaves a method, the location of the event will be the first instruction after the call in the calling method.

- **Method Entry Event :** It notifies about a method invocation in the target VM. This event occurs after entering into the invoked method and before executing any code. Method entry events are generated for both native and non-native methods.

- **Method Exit Event :** It notifies about a method return in the target VM. This event is generated after all code in the method has executed, but the location of this event is the last executed location in the method. Method exit events are generated

for both native and non-native methods. Method exit events are not generated if the method terminates with a thrown exception.

- **Class Preparation Event :** It notifies about a *class preparation* in the target VM. Class preparation involves creating the attributes (class variables and constants) for a class or interface and initializing such attributes to the standard default values. This does not require the execution of any Java code; explicit initializers for attributes are executed as part of initialization, not preparation. Class prepare events are not generated for primitive classes (for example, java.lang.Integer.TYPE).

- **Field Modification Event :** It notifies about the modification of a class attribute in the target VM.

For the time being, we do not do any action upon receiving method entry and exit events. The current version of the RUMBA framework monitors the values of attributes and the local variables of primitive types. The reason is that the state of a program is ultimately contained in the attributes and variables of primitive types. As a future direction, the theory of the SAIG model can be extended to define and model a method as an entity of a target system. In such a case, specific actions can be done regarding monitoring the method invocations and exits and also analyzing the behavior of the system based on the methods behavior.

When a new event arrives, it will be checked to determine its type. It will be then dispatched to the corresponding handler to perform certain procedures based on its contents. The PRE from the previous stage is utilized by this process to filter monitored event traces. Therefore, only those event traces, which match with the specifications of the PRE, are passed to the next process. As an example on our *Trading* system, the information included by the PRE, depicted in Figure 5.6, directs this process of RUMBA to read the contents of any *Class Preparation Event* regarding loading a new *Trader* class

object. The *itemID* attribute of this class object will be monitored to check whether its value changes during the runtime. If it changes, a *Field Modification Event* will be triggered for this attribute. The recent updated value will be obtained based on the contents of such an event to create a snapshot of the system state according to the recent change.

6.1.2 Producing Runtime States

This process receives the runtime information from the previous process. It will form the information as a sequence of system states for the analysis component. As mentioned before, the analysis component uses part of the USE tool [3] to perform constraint based analysis on the class model of the system. The set of data which are analyzed over this model are the sequence of runtime states of the system. Therefore, in this process, the sequence of generated traces is formed in the USE specification format which is acceptable by the analysis component. Each event represents a state of the system at the time that it was extracted from the running program. To specify the events information into the USE format, some commands are used. Three types of commands that we use are as follows:

- `create` command specifies a new created object of the system. The content of a class preparation event contains the name of the new object and its class type. The format of the *create* command is as follows:

  - ◇ !*create* [*objectname*] : [*classname*]

  For example, when a new object of the *Trader* class is created and loaded into the *Trading* system, the state that shows this change in the system would be as follows:

  - ◇ !*create* $trader1 : Trader$

- `insert` command specifies that there is an association dependency between two class objects of the system. The format of the *insert* command is as follows:

  - ◇ !*insert* ([*first object name*], [*second object name*]) *into* [*dependency name*]

  The dependency name is according to the static model of the system (class model) from the architecture recovery stage of the framework. As an example, when a new trader object is created during the runtime, it subscribes in a stock. This dependency is shown as follows:

  - ◇ !*insert* (*trader*1, *mainstock*) *into dependency*1

- `set` command specifies the changes to the value of the class attributes. The format of the *set* command is as follows:

  - ◇ !*set* [*object name*].[*attribute name*] := [*value*]

  value has to match with the data type of the attribute according to the static information (from PRE). As an example, the state indicating a change in the *itemID* of a trader object is specified as follows:

  - ◇ !*set trader*1.*itemdID* := 10

In a nutshell, a sequence of system states are generated in this process and specified in the USE format using the aforementioned commands. The sequence is given to the analysis process to perform constraint based analysis on the class model of the target system.

6.2 Constraint Based Analysis

This process performs OCL-based constraint analysis on the generated states from the monitoring part. Part of the USE tool has been used in this stage of RUMBA. The two

main components of this tool are an animator for simulating UML models and an OCL interpreter for constraint checking. We have incorporated the later one into the RUMBA framework to perform the analysis process. System states are snapshots of a running system which are fed to the analysis process. We get the real data coming from the monitoring component to make the snapshots of the running system.

During the running time of the RUMBA framework, the analysis process runs with the specifications in terms of the class model with the OCL-based objectives. Hence, the first part of the specifications contains a textual description (classes, associations, attributes, and constraints) as the class model of the system. The second part is represented through OCL constraints added to the class model, which can be evaluated and appraised during the analysis.

The analysis process starts with an empty system state where no objects and association links exist. Once the class model has been loaded to the process, we need to create objects and initialize the attributes. The next step consists of establishing the associations between objects. The monitoring component provides this information for the analysis part in terms of the snapshots of the system states defined using the aforementioned commands set from the previous process.

Each time a change occurs in the system, the monitor generates a new snapshot of the system state and gives it to the analysis part. An automatic checking of the specified rules will be carried out on the new generated state. For example, when a new object is introduced, it is checked whether it fulfils the specification of the model and the constraints. The analysis is constraint based as the OCL rules are evaluated on the states. Either a constraint fails or succeeds for a system state, there will be a report for it as the result of the analysis on that state.

Part of the reports of the constraint based analysis during the runtime monitoring of the *Trading* system is depicted in Figure 6.2. Suppose that there are 4 traders instantiated

in our trading system to trade with a stock. There are 100 items (distinguished by their item number) available for sale in the stock.

```
-----------------------------------------
State: !create trader57 : Trader
State: !set trader57.myClock := 0
Checking Objective Transaction: OK.
-----------------------------------------
State: !create trader58 : Trader
State: !set trader58.myClock := 1
Checking Objective Transaction: OK.
-----------------------------------------
State: !create trader59 : Trader
State: !set trader59.myClock := 2
Checking Objective Transaction: OK.
-----------------------------------------
State: !create trader60 : Trader
State: !set trader60.myClock := 3
Checking Objective Transaction: OK.
-----------------------------------------
                    .
                    .
                    .
-----------------------------------------
State: !set trader58.itemID := 11
State: !set trader58.myClock := 18
Checking Objective Transaction: OK.
-----------------------------------------
State: !set trader59.itemID := 11
State: !set trader59.myClock := 19
Checking Objective Transaction: FAILED.
-----------------------------------------
```

```
-----------------------------------------
State: !set trader58.itemID := 12
State: !set trader58.myClock := 20
Checking Objective Transaction: OK.
-----------------------------------------
State: !set trader60.itemID := 12
State: !set trader60.myClock := 21
Checking Objective Transaction: FAILED.
-----------------------------------------
                    .
                    .
                    .
-----------------------------------------
State: !set trader58.itemID := 30
State: !set trader58.myClock := 61
Checking Objective Transaction: OK.
-----------------------------------------
State: !set trader57.itemID := 30
State: !set trader57.myClock := 62
Checking Objective Transaction: FAILED.
-----------------------------------------
State: !set trader59.itemID := 30
State: !set trader59.myClock := 63
Checking Objective Transaction: FAILED.
-----------------------------------------
                    .
                    .
                    .
```

Figure 6.2: An Example Result of the Constraint Based Analysis for the Trading System

As mentioned before, as an objective of monitoring, we want to check whether there are any two traders which buy the same items from the stock. Such an objective has been defined as an OCL constraint, namely *Transaction*, in Sections 5.1. As Figure 6.2 illustrates, at the beginning (point with time stamps 0, 1, 2, and 3) the four trading objects are created and checked against the specification. The result at these points is OK for the *Transaction* objective. A little bit later, at point 18 where *trader58* buys item number 11, the objective is still reported as OK, since no body has bought this item so far. However, at point 19, *trader59* results in a conflict with the *Transaction*

objective because of buying the same item as trader58. A similar scenario happens for *trader58* and *trader60* at points 20 and 21 because of buying the same item (number 12). Furthermore, there are reports of conflicts at points 62 and 63, because *trader57* and *trader59* have bought the same item as *trader58* at the corresponding points of time.

6.3 Summary

In this chapter, we have discussed about the three main processes involved in the third stage of the RUMBA framework, *Runtime Monitoring and Analysis*. Two of them, *Observing Events* and *Producing Runtime States*, are responsible for monitoring. Using the JDI capabilities (included in JPDA), the main class of a target Java system is invoked so that the system starts running while the monitor is making access to its dynamic information. The runtime event traces of the system are generated within these processes while no instrumentation is performed on the source code of the system. Afterwards, the third process of this stage, *Constraint Based Analysis*, carries out the processing of the generated traces with respect to the OCL based objectives identified in the previous stage. If a constraint fails for a system state, there will be a report for that indicating the state and the specific property corresponding to the constraint. We will show the effectiveness of RUMBA in this regard by applying the aforementioned three stages on two open source Java software systems in the next chapter. We will also evaluate the efficiency of our framework on the two systems in terms of processor and memory utilization.

Chapter 7

Experimental Studies

In this chapter, we perform a set of empirical studies on the proposed RUMBA framework to assess the techniques introduced in this thesis. The proposed framework has been implemented in a prototype that aims to assess the behavior of a given Java software system with respect to particular specifications. We have applied the preliminary version of RUMBA on a small Java based trading system in our previous work [4]. At that time, we checked two properties; a transaction-based property and a boundary-based one.

At the time being, that RUMBA has been fully developed as a semi-automated process, we have applied it on two open source Java software systems. One of them is a resource management system, namely Rapla, while the other one is a GUI framework for technical and structured graphics, namely JHotDraw. The purpose of the empirical study in this chapter is to test the effectiveness of the proposed RUMBA framework. We also evaluate the efficiency of our runtime monitoring technique in this chapter.

We outline the implementation of the prototype for the RUMBA framework in Section 7.1. We empirically evaluate the usefulness and the correctness of the framework on two Java based case study systems in Sections 7.2 and 7.3. Section 7.2 includes informa-

tion about a resource management case study system, Rapla, while Section 7.3 discusses about a GUI based case study application, JHotDraw. In Section 7.4, we evaluate the efficiency of our framework on the two case studies in terms of processor and memory utilization. Finally, we summarize this chapter in Section 7.5.

7.1 A Prototype for RUMBA

A prototype has been developed in Java programming language on the Windows XP platform to implement the RUMBA framework in a semi-automated manner. The prototype provides functionality for: i) recovering the required structural information of a target system, ii) modeling the structural information utilizing graph theory concepts, iii) defining the objectives of the behavioral analysis in OCL specifications, iv) extracting and modeling the required information for runtime monitoring based on the structural information and OCL specifications, v) monitoring the runtime of the system with respect to the model of the required information, and vi) evaluating the system behavior at runtime with respect to the predefined objectives.

The prototype consists of two Java based applications. These applications construct the automated parts of the framework. There is still required to manually define the OCL based objectives and create the ODG based on them. The ODG is represented as an XML document ready to be used as an input for one of the applications. The two applications are as follows:

- The first application has been developed in Eclipse 3.1 [24] using JDK 1.5.0 and JavaCC plugin [40]. It receives the source code of a Java based system and performs the first stage of RUMBA fully automated. Two structural models of the system, *class model* and $SAIG$ *model*, are generated by this application. The class model is in the format of USE and therefore it is generated as a ".use" document. The $SAIG$

model is an XML document containing the graph representation of the *SAIG*.

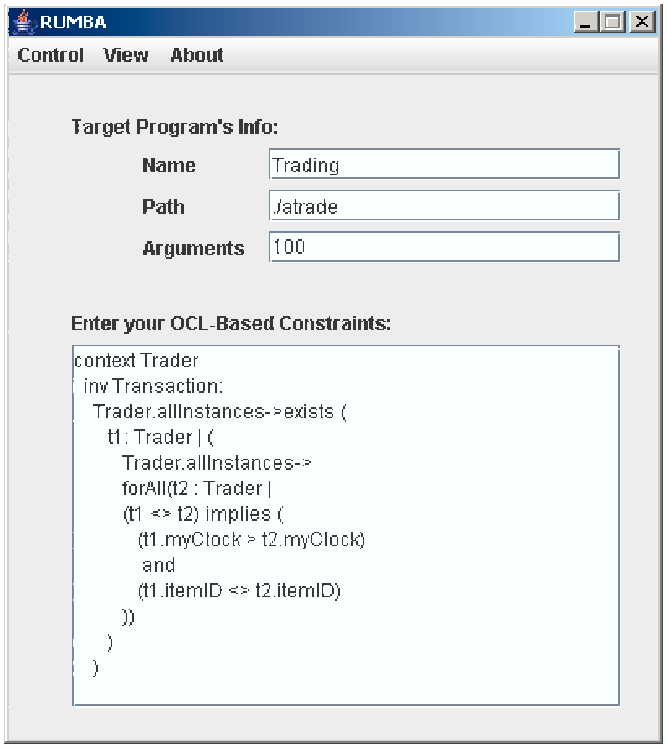


Figure 7.1: A Snapshot of the RUMBA in NetBeans

- The second application has been developed in NetBeans 5.0 [64] environment using JDK 1.5.0 and JPDA [39] capabilities. A snapshot of its GUI is depicted in Figure 7.1. This application receives four inputs: iii) the name of the *class model* of the target Java based system, ii) the classpath of the system, iii) the required input arguments for running the target system, if there exists any, and iv) the OCL-based specifications of the objectives. Moreover, the application receives the "saig.xml" and "odg.xml" from the classpath as the *SAIG* and *ODG* models respectively. There are five initialization tasks performed as soon as the application runs: i) the *ODG* and *SAIG* models are imported from their corresponding XML documents to

appropriate dynamic data structures, ii) the PRE is generated based on the $SAIG$ and ODG using the algorithm presented in Chapter 5, iii) the OCL interpreter of the USE tool is invoked in a separate thread (as the analysis process) by giving the *class model* of the system to it, iv) a buffer is created for the communication of the monitoring process and analysis process, and v) the main class of the target system is invoked by passing the appropriate arguments to it. Afterwards, the target program starts running in the same way as it runs as a stand-alone application. However, in this way, it is being monitored by the monitoring process of our application. Each time an interesting change (according to the PRE) occurs in the system, the monitor generates a new snapshot of the system state and gives it to the analyzer via the communication buffer. An automatic checking of the specified rules will be carried out on the new state.

It is worth mentioning that, the analysis process runs online with the monitor in the above scenario. It is also possible to run it in an offline manner. In other words, instead of transferring the sequence of generated traces to the communication buffer, they will be stored in a repository during the monitoring process. The *class model* and the repository of the traces can be given to the analyzer in a later time so that the OCL based checking would be done on the traces.

7.2 Case Study: Rapla

Rapla [2] is a resource management system, written in Java. It has been developed at the University of Bonn in Germany. Rapla allows coordination between the lectures and the administration. It offers multiple ways to view the available resources and schedule the events. A snapshot of the Rapla GUI is depicted in Figure 7.1. Rapla started as a simple room booking software, but in the last five years it evolved into a configurable framework

for event and resource-management.

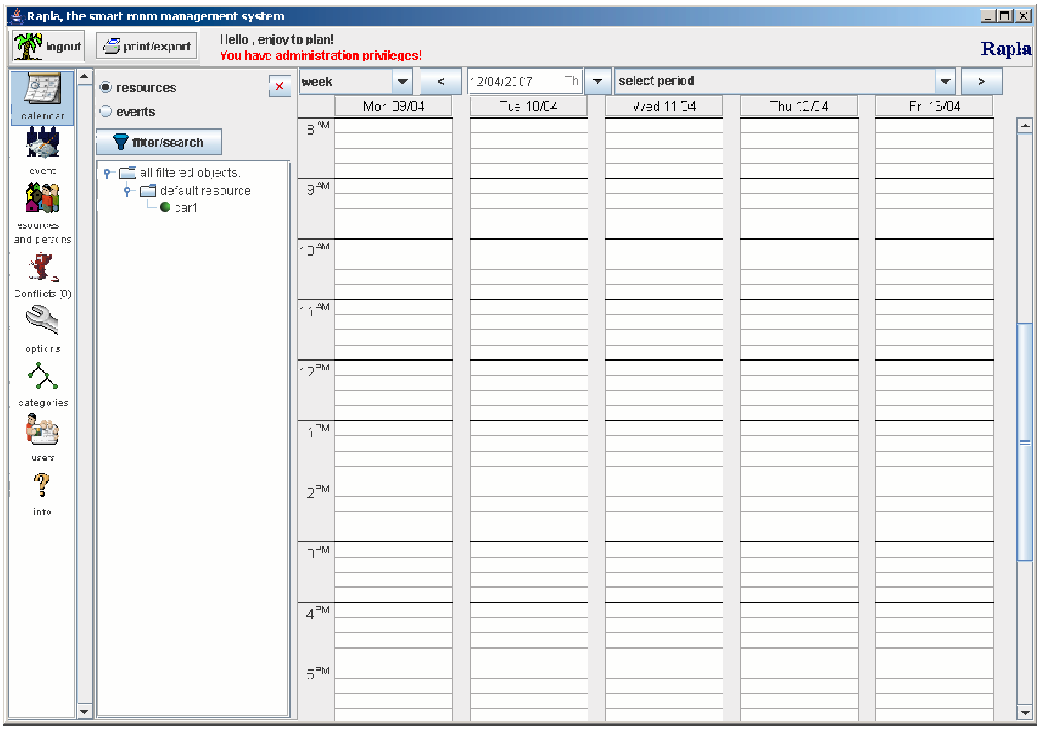


Figure 7.2: A Snapshot of the Rapla System

In this section, we apply the processes of RUMBA on Rapla to empirically evaluate the usefulness of the framework. The version we worked on is 0.12.4 that has 65K lines of code. It consists of 438 Java source files that defines 467 classes and 101 interfaces distributed in 43 packages.

7.2.1 Rapla: Architecture Recovery

To extract the class model and the *SAIG* model, we applied the architecture recovery of the framework on Rapla. As mentioned before, this stage of the framework has been developed in Eclipse 3.1 using JavaCC 1.5. This Java based application which includes

our parser and modeler, has been run to build the system architectural models that are represented by the class and *SAIG* models.

As mentioned before, the class model has been represented in USE format while we exported the *SAIG* model as an XML document. The information in *SAIG* is included by the predefined XML tags. Just to present a view of the Rapla's *SAIG* model, a small part of its XML document is depicted in Figure 7.3.

```
.
.
.
<class-details>
    <className>PeriodImpl</className>
    <classPackage>org.rapla.entities.impl</classPackage>
    <depends-on>
        <className>Calendar</className>
    </depends-on>
    <has-attr>
        <attrName>serialVersionUID</attrName>
        <has-type>long</has-type>
    </has-attr>
    <has-attr>
        <attrName>name</attrName>
        <has-type>String</has-type>
    </has-attr>
        .
        .
        .
</class-details>
        .
        .
        .
```

Figure 7.3: Part of the *SAIG* Model of Rapla

7.2.2 Rapla: Seeding Objectives

In the second stage, Rapla 0.12.4 was manipulated to find out if there is any conceptual anomaly in the system that can be used as a basis to check the validity of RUMBA. We found that there is a conceptual anomaly in the way that a period of time is created in the system. A period of time can be defined and added to the system by assigning a start time and an end time to it, plus assigning a name to the period. However, it is possible to define more than one period with the same name. Hence, whenever an

event is scheduled for a period of time, there is an ambiguity in the periods selection. Because, there is a list of various periods available for scheduling, possibly with the same name. In this regard, we defined an OCL-based objective, so-called *NameConflict*, on the context of "Period" class of Rapla. This objective defines a property on a class, namely "PeriodImpl", which implements a period in the system. This objective and its corresponding *ODG* are depicted in Figure 7.4.

```
context PeriodImpl
  inv NameConflict:
    PeriodImpl.allInstances->exists (
       p1:PeriodImpl | (
          PeriodImpl.allInstances->
          forAll(p2 : PeriodImpl |
          (p1 <> p2) implies (
             (p1.myClock > p2.myClock)
              and
             (p1.name <> p2.name)
          ))
       )
    )
```

(a) The OCL Constraint

```
<objective>
<name>NameConflict</name>
    <class>PeriodImpl</class>
        <dependencies>
            <name>name</name>
        </dependencies>
</objective>
```

(b) The Corresponding ODG

Figure 7.4: An Example of an OCL-Based Objective and the Corresponding *ODG* for Rapla

The *NameConflict* objective will check any period, p_1, recently created and added to the system and will compare it with other periods in the system. If the assigned name to p_1 is same as the name of any other period object in the system, like p_2, the *NameConflict*

will be reported as *Failed* for this recent state. Otherwise, it will be reported as *OK*. After the *ODG* is constructed, *Pattern Extractor*, another Java based application, utilizes algorithm 5.1, as discussed in Section 5.3, to generate the Pattern of Required Events (*PRE*) based on the *SAIG* and the *ODG*. A part of *PRE*, corresponding to the required information for the predefined OCL-based objective, is depicted in Figure 7.5. According to the *PRE*, during the runtime, we need to monitor any object instantiated from the *PeriodImpl* class located in the *org.rapla.entities.imple* package. We also need to monitor any changes in the value of the *name* attribute of this class with the type String.

```
<classInfo>
    <name>PeriodImpl</name>
    <package>org.rapla.entities.impl</package>
    <classAttr>
        <name>name</name>
        <type>String</type>
    </classAttr>
</classInfo>
```

Figure 7.5: Part of the *PRE* Corresponding to the Example Objective for Rapla

7.2.3 Rapla: Runtime Monitoring and Analysis

Finally, we give the produced *PRE* and the path of Rapla source code to the monitoring component. As mentioned before, this component has been developed within a Java program in NetBeans 5.0 using JPDA 5.0 [39]. It invokes the main class of the Rapla and generates event traces from the system based on the *PRE*. Any event regarding the creation of an instance of the *PeriodImpl* class and any event about updating the value of the *name* attribute of this class object, creates a snapshot of the system state. Produced states are given to the next process which performs the constraint based analysis on them. Part of the reports of the constraint based analysis during the runtime monitoring of Rapla is depicted in Figure 7.6.

```
-------------------------------------------
  State: !create periodimpl1786 : PeriodImpl
  State: !set periodimpl1786.name := 'p24'
  State: !set periodimpl1786.myClock := 481
  Checking Objective NameConflict: OK.
-------------------------------------------
  State: !create periodimpl1794 : PeriodImpl
  State: !set periodimpl1794.name := 'p24'
  State: !set periodimpl1794.myClock := 490
  Checking Objective NameConflict: FAILED.
-------------------------------------------
  State: !create periodimpl1805 : PeriodImpl
  State: !set periodimpl1805.name := 'p25'
  State: !set periodimpl1805.myClock := 492
  Checking Objective NameConflict: OK.
-------------------------------------------
```

Figure 7.6: Part of the Result of the Constraint Based Analysis for Rapla

As Figure 7.6 illustrates, at the point with a time stamp of 481, a new period object is created, namely p_{24}. It does not cause any conflict, since there is no period in the system with name p_{24}. However, at the point of time with the time stamp 490, *NameConflict* raises a *failure*, because the new created period object has the same name as the previous one. Furthermore, at the point with the time stamp 492, the current state is reported as an OK state with respect to the *NameConflict* objective. Because, no period with the name p_{25} exists in the system, and it does not cause any conflict.

7.3 Case Study: JHotDraw

JHotDraw [43] is a Java GUI framework for technical and structured graphics. It defines a basic skeleton for a GUI-based editor with tools in a tool palette, different views, user-defined graphical figures, and support for saving, loading, and printing drawings. The framework can be customized using inheritance and combining components. Besides the main drawing window, JHotDraw offers little support for different kinds of windows, such as text editors. With some knowledge of JHotDraw's structure, it can be extended to

include missing functionalities.

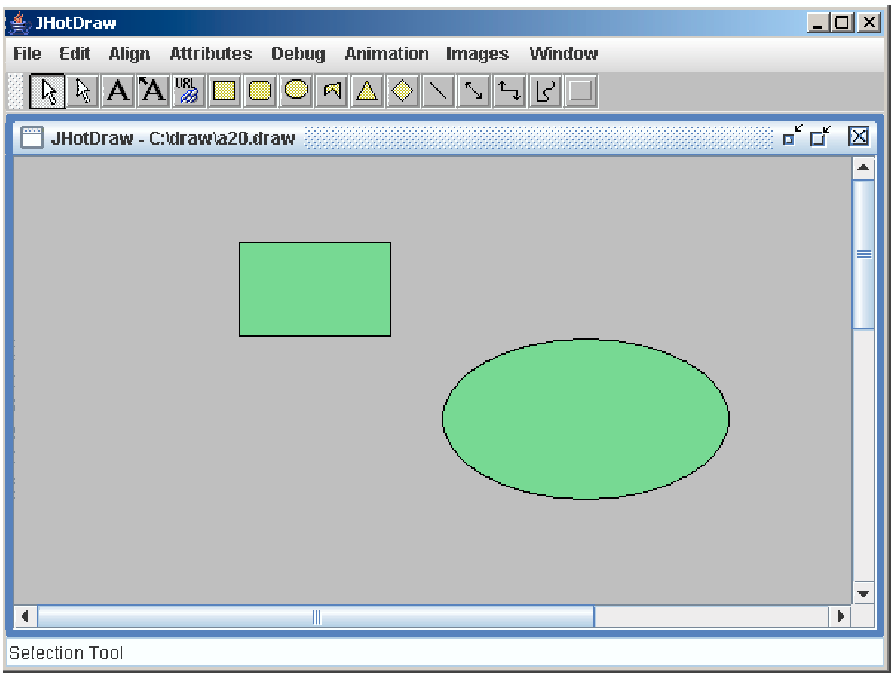


Figure 7.7: A Snapshot of the JHotDraw System

In this section, we apply the processes of RUMBA on JHotDraw to empirically evaluate the correctness of the framework. The version we worked on is 5.3 that has 14K lines of code. It consists of 195 Java source files that defines 208 classes and 33 interfaces distributed in 11 packages. We consider a sample application included in this version, namely *Java Draw Application*. A snapshot of its GUI is depicted in Figure 7.7. This application represents various standard tools and figures provided with JHotDraw. We monitor the behavior of this application in our experiment.

7.3.1 JHotDraw: Architecture Recovery

Similar to what we did for the previous case study application, our Java based parser and modeler have been run on the source code of JHotDraw to build the system architectural

models in the architecture recovery stage. The results are the class model and the *SAIG* model of JHotDraw. Just to present a view of the *SAIG* model of JHotDraw, a small part of its XML document is depicted in Figure 7.8.

```
.
.
.
<class-details>
    <className>DrawApplication</className>
    <classPackage>CH.ifa.draw.application</classPackage>
    <depends-on>
        <className>Tool</className>
          .
          .
          .
    </depends-on>
    <has-attr>
        <attrName>fTool</attrName>
        <has-type>Tool</has-type>
    </has-attr>
    <has-attr>
        <attrName>loadName</attrName>
        <has-type>String</has-type>
    </has-attr>
          .
          .
          .
</class-details>
          .
          .
          .
```

Figure 7.8: Part of the *SAIG* Model of JHotDraw

7.3.2 JHotDraw: Seeding Objectives

In the second stage, *Java Draw Application* in JHotDraw 5.3 was manipulated to find out if there is any interesting point for dynamically monitoring the application. We realized that there is a class in the system, namely *DrawApplication*, that is responsible for storing or loading the graphic files into or from the memory. We intended to monitor the behavior of the application regarding the file transactions through this class and its attributes. It is worth mentioning that such an objective works not only for this specific application but also for many other domains. For example, a system administrator may

use such an objective for a daily control on the transactions of different resources of a system to find out the resources (in this case, files) which are more often used. Such resources may obtain higher severity for administration and back-up services than others with less demands.

```
context DrawApplication
  inv ActivityReport:
    DrawApplication.allInstances->exists (
       d1: DrawApplication |
         (DrawApplication.allInstances->forAll (
            d2: DrawApplication |
              (d1 <> d2) implies (d1.myClock > d2.myClock)
            )
         ) and
         (DrawApplication.allInstances->select (
           d3: DrawApplication |
             d3.loadName = d1.loadName)->size() >
             (DrawApplication.allInstances->size()/3)
         )
      )
```

(a) The OCL Constraint

```
<objective>
<name>NameConflict</name>
    <class>PeriodImpl</class>
        <dependencies>
            <name>name</name>
        </dependencies>
</objective>
```

(b) The Corresponding ODG

Figure 7.9: An Example of an OCL-Based Objective and the Corresponding *ODG* for JHotDraw

The *ActivityReport* OCL constraint is defined at this stage to address the aforementioned objective. It is defined on the context of "DrawApplication" class of *Java Draw Application*. This objective and its corresponding *ODG* are depicted in Figure 7.9. It evaluates the access rate of different graphic files during an execution of the system. At each point of a time that a file is accessed, the *ActivityReport* is checked to find out whether the demands for the specific file have been more than a particular percentage of the whole accesses in the system so far. As an example, Figure 7.9 illustrates the OCL-based definition of the *ActivityReport* objective considering the accessing threshold as 33%. In other words, the *ActivityReport* objective will check any recent demand for a file regarding the number of times that the specific file has been accessed so far including the recent one. If this number is more than 33% of the whole file accesses in the system, the result of

check will be reported as *OK*. Otherwise, it will be reported as *Failed*, meaning that the demands for the file have been ignorable so far (according to the 33% policy).

```
<classInfo>
    <name>DrawApplication</name>
    <package>CH.ifa.draw.application</package>
    <classAttr>
        <name>loadName</name>
        <type>String</type>
    </classAttr>
</classInfo>
```

Figure 7.10: Part of the PRE Corresponding to the Example Objective for JHotDraw

After the ODG is constructed, the *Pattern Extractor* of RUMBA, utilizes algorithm 5.1, as discussed in Section 5.3, to generate the Pattern of Required Events (PRE) based on the $SAIG$ and the ODG. A part of PRE, corresponding to the required information for the *ActivityReport* objective, is depicted in Figure 7.10. According to the PRE, during the runtime, we need to monitor any object instantiated from the *DrawApplication* class located in the *CH.ifa.draw.application* package. We also need to monitor any changes in the value of the *loadName* attribute of this class with the type *String* that records the name of any accessed file.

7.3.3 JHotDraw: Runtime Monitoring and Analysis

Similar to what we did for Rapla, we give the produced PRE and the path of JHotDraw source code to the monitoring component. It invokes the main class of the *Java Draw Application* in JHotDraw and generates event traces from the system based on the PRE. Any event regarding the creation of an instance of the *DrawApplication* class and any event about updating the value of the *loadName* attribute of this class object, creates a snapshot of the system state. Because, the name of each graphic file is recorded by *loadName* in *DrawApplication* class. Produced states are given to the next process which

performs the constraint based analysis on them. Part of the reports of the constraint based analysis during the runtime monitoring of *Java Draw Application* is depicted in Figure 7.11.

```
-----------------------------------------------------
State: !create drawapplication579 : DrawApplication
State: !set drawapplication579.loadName := 'a01.draw'
State: !set drawapplication579.myClock := 0
Checking Objective ActivityReport: OK.
-----------------------------------------------------
State: !create drawapplication1752 : DrawApplication
State: !set drawapplication1752.loadName := 'a02.draw'
State: !set drawapplication1752.myClock := 1
Checking Objective ActivityReport: OK.
-----------------------------------------------------
State: !create drawapplication2440 : DrawApplication
State: !set drawapplication2440.loadName := 'a01.draw'
State: !set drawapplication2440.myClock := 2
Checking Objective ActivityReport: OK.
-----------------------------------------------------
State: !create drawapplication1841 : DrawApplication
State: !set drawapplication1841.loadName := 'd21.draw'
State: !set drawapplication1841.myClock := 3
Checking Objective ActivityReport: FAILED.
-----------------------------------------------------
```

```
-----------------------------------------------------
State: !create drawapplication2090 : DrawApplication
State: !set drawapplication2090.loadName := 'w5.draw'
State: !set drawapplication2090.myClock := 4
Checking Objective ActivityReport: FAILED.
-----------------------------------------------------
State: !create drawapplication1845 : DrawApplication
State: !set drawapplication1845.loadName := 'a01.draw'
State: !set drawapplication1845.myClock := 5
Checking Objective ActivityReport: OK.
-----------------------------------------------------
State: !create drawapplication1388 : DrawApplication
State: !set drawapplication1388.loadName := 'a02.draw'
State: !set drawapplication1388.myClock := 6
Checking Objective ActivityReport: FAILED.
-----------------------------------------------------
.
.
.
.
```

Figure 7.11: Part of the Result of the Constraint Based Analysis for JHotDraw

As Figure 7.11 illustrates, at the points with the time stamps of 0, 2, and 5, the *ActivityReport* reports *OK*, meaning that file "a01.draw" is detected as a highly accessed file so far. Because the number of accesses to this file is correspondingly 1 out of 1, 2 out of 3, and 3 out of 6 at the mentioned points of time. It is obvious that for all of them, the access number is more than 33% (the policy of the objective). On the other hand, for file "a02.draw", the report is *OK* at time 1 because it has been accessed once out of 2 times up to that point. However, the *ActivityReport* reports *Failed* at time 6 for the same file, since it has been accessed 2 times out of 7 which is less than 33%. If an administrator has access to such an information as a result of a daily monitoring of the target system, she/he can detect high demanding files and provide appropriate action on them accordingly.

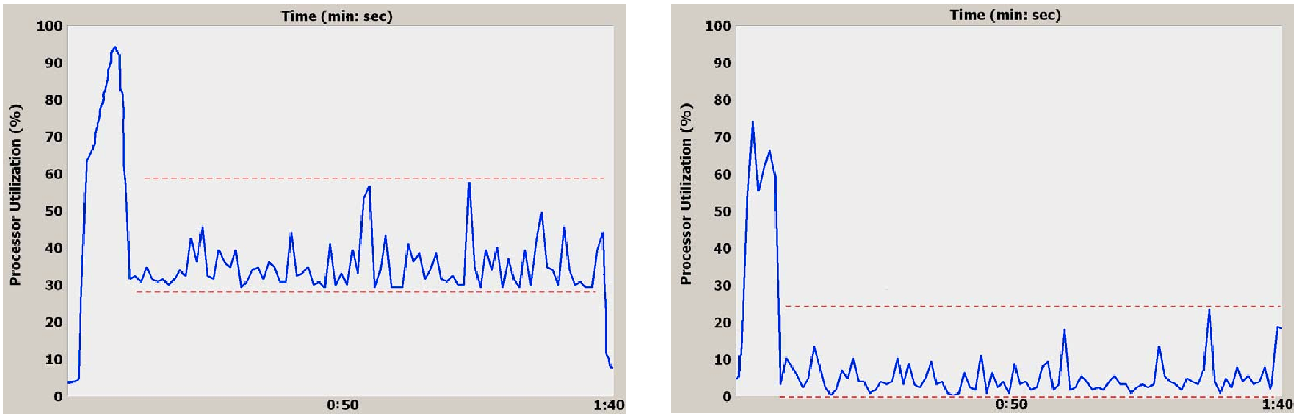
7.4 Evaluation

The monitoring process of the RUMBA framework invokes the main class of the target program and listens to all event traces during the runtime. Therefore, the evaluation criteria need to address performance. We study this issue in terms of *processor utilization* and *memory consumption* in the system. The evaluation was carried on a Windows desktop with Intel Pentium IV CPU 3.4GHz, with 2GB memory.

7.4.1 Processor Utilization

The processor utilization indicates to what extent the CPU of a computer is occupied with the process of a running application. We compare the processor utilization while the case study applications are running in two different scenarios: i) without monitoring, ii) with monitoring. Figure 7.12 illustrates the processor utilization for Rapla in the two scenarios. For both, we consider a period of 100 seconds monitoring of the system with the same set of interactions during this period. After that time, we stop the monitoring to show a snapshot of changes from the beginning to the end of a monitoring process. A longer period does not change the performance results, because as the systems passes its initialization loads after the first few seconds, it gets stable for the rest of the time. We further elaborate on this issues in the rest of this chapter.

The first graph of Figure 7.12 illustrates the percentage of CPU utilization for the execution period of Rapla with our monitoring framework. On the other hand, in the second graph, the same trend is shown but for the regular execution of the Rapla without monitoring. It is obvious that there is almost a constant increase in CPU utilization, about 30%, in the first graph against the second one. The reason behind such an increase is that our monitoring technique hooks into the JVM and listens to all event traces during the runtime. Hence, no matter what the running application would be, there is an expense

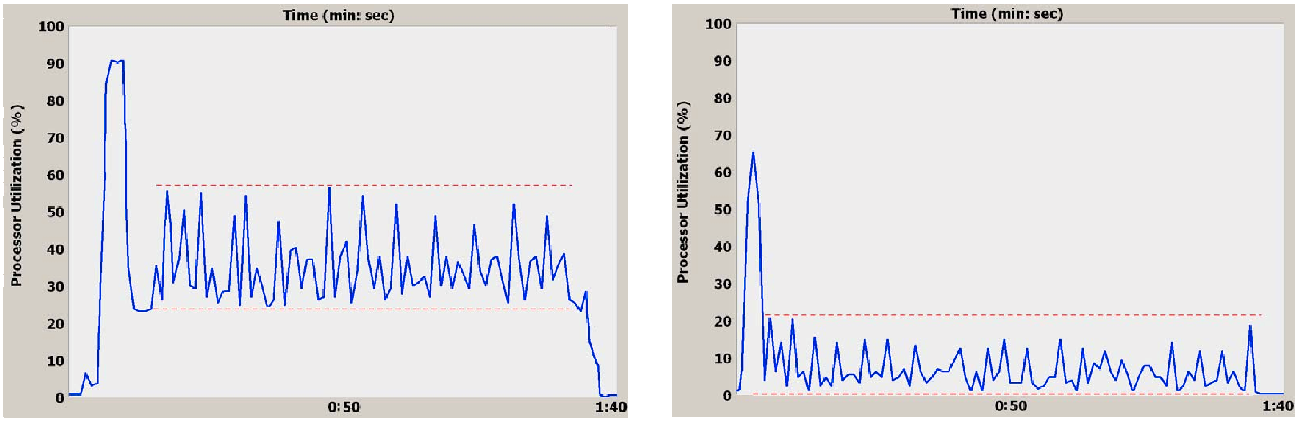


(a) With Monitoring **(b) Without Monitoring**

Figure 7.12: Processor Utilization for Rapla

for such a hooking. This increase is about 24% for JHotDraw application according to the corresponding graphs in Figure 7.13. We believe in a decrease in this expense for our future case study applications which will be from different domains. Because, both of the current applications are heavily user interactive systems. In such systems, there are too many events generated because of the interaction of a user with the system GUI. Therefore, our monitor collects such events at the first glance, but they will be ignored after the monitor finds them unnecessary for the analysis.

In addition to the above expense, there is another one which we call it *processing load* resulted from our monitoring. Back to Figure 7.12 for Rapla, there are a bunch of ripples in both graphs. There are actually the major processing periods of the running system. The peaks are mainly because of an access to the IO, a major computation load, and etc. We can compare the maximum length of these ripples in both graphs. It can be computed based on the distance of the two dashed lines in each graph. The distance is about 30% and 25% for graphs a and b from Figure 7.12 respectively. We find this 5% increase in graph a in comparison to graph b reasonable and because of the processing



(a) With Monitoring **(b) Without Monitoring**

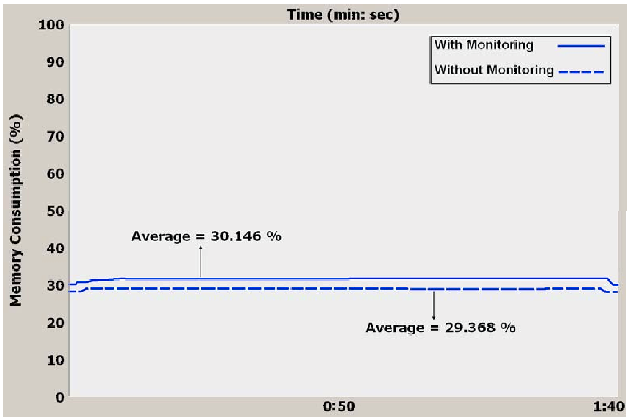
Figure 7.13: Processor Utilization for JHotDraw

load of our monitoring and analysis processes. The *PRE* is utilized by the monitor to filter the event traces. Those event traces, which match with the specifications of the *PRE*, are passed to the analysis process. Moreover, the analysis needs to be done on the passed data. The maximum length of the ripples for JHotDraw is about 31% and 23% for graphs *a* and *b* respectively in Figure 7.13. Thus, the processing load for JHotDraw is 8%. Our justification for a more load increase in JHotDraw than Rapla is that the type of property that we monitor and analyze in JHotDraw is different from the one in Rapla. For JHhotDraw, we monitor the IO accesses to the graphic resources and do the analysis based on the changes in such resources.

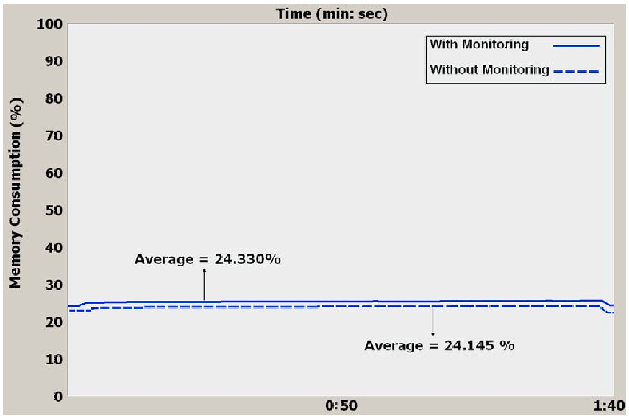
It is worth mentioning that in both systems, there is a considerable amount of CPU utilization at the beginning of the execution period. This is reasonable, since any application requires a specific amount of initialization load when it starts running. However, this amount is higher for both systems in case that they are running under the monitoring framework. This is also reasonable, because at the beginning, our monitor needs to do some extra initialization works which obviously require utilizing more CPU power.

7.4.2 Memory Consumption

To evaluate our framework in terms of memory consumption, we study the increase in memory usage while the case study applications are running under monitoring in contrast to the situation where no monitoring is done. Figure 7.14 illustrates the memory consumption in our computer while Rapla and JHotDraw were running in the two scenarios. Similar to processor utilization evaluation process, we consider a period of 100 seconds monitoring of the system with the same set of interactions during this period.



(a) Rapla



(b) JHotDraw

Figure 7.14: Memory Consumption

In average, during a regular execution of Rapla, 29.368% of memory is in use, while it is 30.146% under monitoring. For JHotDraw, in average 24.145% memory is in use during a regular execution while it is 24.330% when the application is monitored. It is obvious that the difference of memory usage for both applications in the two scenarios is not significant. The reason is that our monitoring technique does not consider any unnecessary event. As soon as an event does not match with the PRE specification, it will be ignored and the memory for such an event will be deallocated.

7.5 Summary

In this chapter, we have outlined the implementation of the prototype for the RUMBA framework. Afterwards, we explained about two case studies application used for evaluating the effectiveness of our framework in runtime monitoring and behavioral analysis. In both case studies, the specified properties have been monitored and the objective changes have been reported correctly according to our expectation from the behavior of the systems. We have also evaluated the efficiency of the RUMBA framework in terms of processor and memory utilization for the two case study applications. We found that there is a constant load in processor utilization, specially due to the nature of the monitoring technique. There has been also a processing load for both applications due to our monitoring and analysis processes. In both case studies, we found that the increase of memory usage for monitoring is not significant.

Chapter 8

Conclusion and Future Directions

In this chapter, we summarize the findings of the thesis and outline future research directions that may arise from this research. In Section 8.1, we present the contributions of the thesis, and in Section 8.2, we discuss some potential future work to be extended from this research. Finally, we make some concluding remarks of the work in Section 8.3.

8.1 Contributions

The major contribution of the framework proposed in this thesis is that, it addresses the problem of runtime monitoring and behavioral analysis of Java software systems. Specifically, the principle contributions of this thesis were stated in Chapter 1. Based on the material already presented, we discuss them in more details as follows:

- The framework utilizes a synergy between static and dynamic analyses to do the runtime monitoring and analysis. By utilizing a synergy between these two approaches, our framework obtains an understanding of the target system to find out where to locate and monitor the required information in the system. Such a hybrid

technique reduces the monitoring overhead that could be resulted from the instrumentation and modification of different levels of a target program. Because, the information obtained from the static analysis helps the technique used in dynamic analysis to consider only those VM (Virtual Machine) events which contain the required information.

- Two models of a target system are created using reverse engineering techniques in the static analysis. There is a UML-compliant model, *class model*, which is used later by the analysis part of the framework. The specification for the constraint-based analysis is added to this model. There is also a graph based model, *SAIG model*, generated from the target system which is exported as XML documents and transformed between different stages of the framework. We can not track the location of runtime objects and attributes unless we instrument specific parts of the code. By using the *SAIG* that records the structural information of the system, we can avoid such an instrumentation
- Object Constraint Language (OCL) is utilized to specify the objectives of the behavioral analysis in our framework. They are certain properties on the behavior of the system which can be described as OCL rules. These OCL rules are without side effect since the OCL is an expression language. We add them to the specific locations in the class model, and they cannot change anything in the model. This means that the state of the system will never change because of an OCL expression. All values for all objects, including all links, will not change. Whenever an OCL expression is evaluated, it simply delivers a value.
- By using the capabilities of Java Platform Debug Architecture (JPDA) [39], we have implemented a monitoring technique that finds the locations of the required attributes according to the *PRE* (Pattern of Required Events) model. It invokes

the main class of a target Java program that has been passed to it. It generates a trace of the program's execution by listening to the VM events and making access to its dynamic information.

- We have adopted an OCL based analysis environment to our system, called USE [3]. This tool has an OCL interpreter for constraint checking. We have incorporated the COL interpreter of USE into the RUMBA framework to perform the analysis process. It helps us to do a constraint based analysis on the class model of the target system based on the generated event traces from the monitoring part of our framework. Either a constraint fails or succeeds for a system state, there will be a report for it as the result of the analysis on that state.

8.2 Future Work

Our current research focuses mostly on the automated monitoring and tracking of the dynamic information at runtime based on the extracted static information. We believe that some potential extensions can be made on some aspects of the RUMBA framework. The framework can be extended to:

- Work as a fully automated process.
- Provide various domains of objectives for monitoring.
- Provide appropriate actions regarding the monitored behaviors.

Such future directions are listed in more details in this section.

8.2.1 Automatic Generation of Monitoring Scenarios

As mentioned before, the objectives of the behavioral analysis in RUMBA are defined and specified manually. User has to have some knowledge about the domain of the target sys-

tem. Based on this information, the behavioral expectation of the system will be defined as OCL rules. This approach is applicable for specific types of monitoring like the one we did for Rapla and JHotDraw application. In such cases, the user is interested in monitoring particular objects and resources of a system. Hence, she/he defines the objectives as specific OCL rules in the context of those objects and resources. However, when the intention of the monitoring is to check the behavioral correctness of a system in general, it is less expensive and more reliable to do it automatically. In other words, objective scenarios can be constructed automatically from system requirements. In this regard, *Automatic Test Case Generation* techniques [25] may be useful to extend the RUMBA's capabilities by generating the specifications (monitoring objectives) automatically.

8.2.2 Various Objective Domains

The current version of RUMBA can define specific types of objectives and is able to monitor corresponding properties. They are mostly invariants, properties that check values and boundaries of variables, and properties that generally deal with resource changes. Such types of properties are classified as *safety properties* according to [20]. There is also another type of property so-called *temporal*. It includes properties such as progress and bounded liveness as well as timing properties. However, this category is not a disjoint set with safety. For example, deadlock-freeness could be classified as a safety property indicating that a system can never be in a situation in which no progress is possible.

Various types of properties can be studied to expand the domain of monitoring objectives as future extensions to RUMBA. However, this depends on expressiveness of OCL that how much it is able to define different types of properties. One way to find out more about this issue is to apply RUMBA on other open source systems, possibly from different domains. Such a broad domain can help us to provide a concrete evaluation from comparing the obtained results from various case studies.

8.2.3 Steering and Diagnosis

The intent of program steering can be illustrated with the following quote from [5]: "*Scientists not only want to analyze data that results from super-computations, they also want to interpret what is happening to the data during super-computations. Researchers want to steer calculations in close-to-real-time; they want to be able to change parameters, resolution or representation, and see the effects . They want to drive the scientific discovery process; they want to interact with their data.*"

In [36], the authors refer to the above statement and define program steering as the capacity to control the execution of long-running, resource-intensive programs. Such execution control includes modifying program state, managing data output, starting and stalling program execution, altering resource allocations, etc . Dynamic program steering consists of two separable tasks: i) monitoring program or system state (monitoring), and then ii) enacting program changes made in response to observed state changes (steering).

Steering can be considered as the process of predicting the occurrence of violations and preventing them by controlling a system execution [23, 70]. It can also be considered as the process of correcting the execution of a target program when requirements are violated [12]. What we consider as a possible future extension to RUMBA is the second type of steering, where a monitoring tool can assure correctness during program execution. To do so, specific handlers are required to not only report errors or throw exceptions, but also execute appropriate actions, e.g. resetting states or rebooting the system.

At the time being, the analysis component of RUMBA detects if there is any conflict with a property or reports about specific changes in the behavior of resources of a system. It can be extended to diagnose/control the reported conflicts/specific changes (forward recovery) or revert the system to a state known to be correct (backward recovery) [75]. It is obvious that such a recovery may not be feasible for all types of conflicts. This is an

important issue which needs further study to categorize specific types of properties based on which the execution of a target system can be monitored and steered if necessary.

8.3 Conclusion

In this thesis, we have presented the RUMBA framework which addresses the demand of runtime monitoring and behavioral analysis for Java software systems. We discuss how RUMBA can facilitate the process of program comprehension from the behavioral point of view. It utilizes a synergy between static and dynamic analyses to confirm whether a program behavior complies with specified properties.

Three key features of the RUMBA framework are: i) the theory defined for static analysis part of RUMBA is fully extendable at different granularity levels, for example towards monitoring information about the methods of a system, ii) the source code of a target system is not modified, and iii) the most processes of the framework are automated. Using the help of reverse engineering techniques through static analysis (generating the Pattern of Required Events (PRE)), we have reduced the large size of runtime information in dynamic analysis. We have filtered the information to what is required for the analysis.

We have evaluated the effectiveness of RUMBA on two open source applications. The reports of the objectives along the runtime states have been according to our expectation from the behavior of the applications. The efficiency of the framework has been studied in terms of processor and memory utilization. We have found that there is a constant load in processor utilization, specially due to the nature of the monitoring technique. There has been also a processing load for both applications due to our monitoring and analysis processes. In both case studies, we have found that the increase of memory usage for monitoring is not significant. As a future work, RUMBA can be applied on more case studies from various domains to check different types of objectives on such systems.

Bibliography

[1] *UML 2.0 Superstructure Specification.* Object Management Group, Framingham, Massachusetts, USA, 2004.

[2] A resource management system (Rapla), 2007. http://rapla.sourceforge.net/.

[3] A UML-Based Specification Environment (USE), 2007. http://www.db.informatik.uni-bremen.de/projects/USE/.

[4] A. Ashkan and L. Tahvildari. A hybrid analysis framework to evaluate runtime behavior of OO systems. In *Proceedings of the* 2^{nd} *International Workshop on Program Comprehension through Dynamic Analysis*, pages 1–5, 2006.

[5] M. D. Brown B. H. McCormick, T. A. DeFanti. Visualization in scientific computing. *ACM SIGGRAPH Computer Graphics*, 21(6):entire issue, 1987.

[6] D. Bartetzko, C. Fischer, M. Moller, and H. Wehrheim. Jass-Java with assertions. *Electronic Notes in Theoretical Computer Science*, 55(2):1–15, 2001.

[7] Bison, the YACC-compatible parser generator, 2007. http://dinosaur.compilertools.net/#bison.

[8] J. S. Bradbury, J. R. Cordy, and J. Dingel. An empirical framework for comparing effectiveness of testing and property-based formal analysis. In *Proceedings of the*

ACM SIGPLAN-SIGSOFT Workshop on Program Analysis For Software Tools and Engineering, pages 2–5, 2005.

[9] M. Brorkens and M. Moller. JassDA trace assertions, runtime checking the dynamic of Java programs. In *Proceedings of the International Conference on Testing of Communicating Systems*, pages 39–48, 2002.

[10] B. Bruegge, T. Gottschalk, and B. Luo. A framework for dynamic program analyzers. In *Proceedings of the* 8^{th} *Annual Conference on Object-Oriented Programming Systems, Languages, and Applications*, pages 65–82, 1993.

[11] L. Burdy, Y. Cheon, D. Cok, M. D. Ernst, J. Kiniry, G. T. Leavens, K. Ru. M. Leino, and E. Poll. An overview of JML tools and applications. *Software Tools for Technology Transfer*, 7(3):212–232, 2005.

[12] F. Chen and G. Rosu. Java-MOP: A monitoring oriented programming environment for java. In *Proceedings of the* 11^{th} *International Conference on Tools and Algorithms for the Construction and Analysis of Systems*, pages 546–550, 2005.

[13] Y. Cheon. A runtime assertion checker for the Java modeling language. Technical Report 03-09, Department of Computer Science, Iowa State University, 2003.

[14] S. Chodrow and M. Gouda. Implementation of the Sentry system. *Software Practice and Experience*, 25(4):373–387, 1995.

[15] A. G. M. Cilio and H. Corporaal. Global program optimization: register allocation of static scalar objects. In *Proceedings of* 5^{th} *Annual Conference of the Advanced School for Computing and Imaging*, pages 52–57, 1999.

[16] M. Clavel, F. Duran, S. Eker, P. Lincoln, N. Marti-Oliet, J. Meseguer, and J. Que-

sada. Using Maude. In *Proceedings of the* 3^{rd} *International Conferenece on Fundamental Approaches to Software Engineering*, pages 371–374, 2000.

[17] M. Clavel, S. Eker, P. Lincoln, and J. Meseguer. Principles of Maude. *Electronic Notes in Theoretical Computer Science*, 4(1):65–89, 1996.

[18] T. A. Corbi. Program understanding: challenge for the 1990s. *IBM Systems Journal*, 18(2):294–306, 1989.

[19] J. Dassow. On contextual grammar forms. *International Journal of Computer Mathematics*, 17(1):37–52, 1985.

[20] N. Delgado, A. Q. Gates, and S. Roach. A taxonomy and catalog of runtime software-fault monitoring tools. *IEEE Transactions on Software Engineering*, 30(2):859–872, 2004.

[21] D. Drusinsky. The Temporal Rover and the ATG Rover. In *Proceedings of the* 7^{th} *International SPIN Workshop*, pages 323–330, 2000.

[22] D. Drusinsky. Monitoring temporal rules combined with time series. In *Proceedings of Computer Aided Verification Conference*, pages 114–117, 2003.

[23] A. Easwaran, S. Kannan, and O. Sokolsky. Steering of discrete event systems: control theory approach. *Electronic Notes in Theoretical Computer Science*, 144(4):21–39, 2006.

[24] Eclipse - An open development platform, 2007. http://www.eclipse.org/.

[25] J. Edvardsson. A survey on automatic test data generation. In *Proceedings of the* 2^{nd} *Conference on Computer Science and Engineering in Linkping*, pages 21–28, 1999.

[26] H. Ehrig, U. Prange, and G. Taentzer. Fundamental theory for typed attributed graph transformation. In *Proceedings of the* 2^{nd} *International Conference on Graph Transformation*, pages 161–177, 2004.

[27] M. D. Ernst. Static and dynamic analysis: synergy and duality. In *Proceedings of the ICSE Workshop on Dynamic Analysis*, pages 24–27, 2003.

[28] R. Ferenc, I. Siket, and T. Gyimothy. Extracting facts from open source software. In *Proceedings of the* 20^{th} *IEEE International Conferenece on Software Maintenance*, pages 60–69, 2004.

[29] P. J. Finnigan, R. C. Holt, I. Kalas, S. Kerr, K. Kontogiannis, H. A. Müller, J. Mylopoulos, S. G. Perelgut, M. Stanley, and K. Wong. The software bookshelf. *IBM Systems Journal*, 36(4):564–593, 1997.

[30] Flex, a fast scanner generator, 2007. http://dinosaur.compilertools.net/#flex.

[31] A. Q. Gates, S. Roach, O. Mondragon, and N. Delgado. DynaMICs: comprehensive support for runtime monitoring. *Electronic Notes in Theoretical Computer Science*, 55(2):1–17, 2001.

[32] A. Q. Gates and P. Teller. An integrated design of a dynamic software-fault monitoring system. *Integrated Design and Process Science*, 14(3):63–78, 2000.

[33] J. Girard and R. Koschke. Finding components in a hierarchy of modules: a step towards architectural understanding. In *Proceedings of the* 13^{th} *International Conference on Software Maintenance*, pages 58–65, 1997.

[34] M. Gogolla and M. Richters. On constraints and queries in UML. In *Proceedings of the UML Workshop*, pages 109–121, 1997.

[35] W. Gu, G. Eisenhauer, E. Kraemer, K. Schwan, J. Stasko, and J. Vetter. Falcon: onine monitoring and steering of large-scale parallel programs. Technical Report GIT-CC-94-21, College of Computing, Georgia Institute of Technology, 1994.

[36] W. Gu, J. Vetter, and K. Schwan. An annotated bibliography of interactive program steering. *ACM SIGPLAN Notices*, 29(9):140–148, 1994.

[37] Klaus Havelund and Grigore Rosu. Monitoring Java programs with Java PathExplorer. *Electronic Notes in Theoretical Computer Science*, 55(2):97–114, 2001.

[38] G. J. Holzmann. The model checker Spin. *IEEE Transactions on Software Engineering*, 23(5):279–295, 1997.

[39] Java Platform Debugger Architecture (JPDA), 2007. http://java.sun.com/products/jpda/.

[40] JavaCC Eclipse plug-in for Eclipse 3.1 - 3.2, 2007. http://eclipse-javacc.sourceforge.net/.

[41] C. L. Jeffery. Program monitoring and visualization: An exploratory approach. *Springer-Verlag*, 1999.

[42] C. L. Jeffery, K. Templer W. Zhou, and M. Brazell. A lightweight architecture for program execution monitoring. In *Proceedings of the ACM SIGPLAN/SIGSOFT Workshop Program Analysis for Software Tools and Engineering*, pages 67–74, 1998.

[43] JHotDraw as open source project, 2007. http://www.jhotdraw.org/.

[44] R. Kazman and S. J. Carriere. View extraction and view fusion in architectural understanding. In *Proceedings of the* 5^{th} *International Conference on Software Reuse*, pages 290–299, 1998.

[45] M. Kim and M. Viswanathan. MaC: A framework for runtime correctness assurance of realime systems. Technical Report MS-CIS-98-37, Deptartment of Computer and Information Sciences, University of Pennsylvania, 1998.

[46] M. Kim and M. Viswanathan. Formally specified monitoring of temporal properties. In *Proceedings of the European Confernece on Realtime Systems*, pages 114–122, 1999.

[47] M. Kim, M. Viswanathan, S. Kannan, I. Lee, and O. V. Sokolsky. Java-MaC: A runtime assurance approach for Java programs. *Journal of Formal Methods in System Design*, 24(2):129–155, 2004.

[48] I. Lee and H. Ben-Abdallah. A monitoring and checking framework for runtime correctness assurance. In *Proceedings of the Korea-U.S. Technical Conference on Strategic Technologies*, 1998.

[49] I. Lee and M. Kim. Runtime assurance based on formal specifications. In *Proceedings of the International Conference on Parallel and Distributed Processing Techniques and Applications*, pages 279–287, 1999.

[50] Lex, A lexical analyzer generator, 2007. http://dinosaur.compilertools.net/#lex.

[51] Y. Liao and D. Cohen. A specificational approach to high level program monitoring and measuring. *IEEE Transactions on Software Engineering*, 18(11):969–978, 1992.

[52] J. Ligatti, L. Bauer, and D. Walker. Edit Automata: enforcement mechanisms for runtime security policies. *International Journal of Information Security*, 4(1-2):2–16, 2005.

[53] D. Luckham and F. W. Von Henke. An overview of Anna specification language for Ada. *IEEE Software*, 2(2):9–23, 1985.

[54] D. Luckham, S. Sankar, and S. Takahashi. Two-dimensional pinpointing: debugging with formal specifications. *IEEE Software*, 8(1):74–84, 1991.

[55] M. R. Lyu. *Handbook of Software Reliability Engineering.* IEEE Computer Society Press and McGraw-Hill, 1996.

[56] S. Mancoridis, B. Mitchell, Y. Chen, and E. R. Gansner. Bunch: A clustering tool for the recovery and maintenance of software system structures. In *Proceedings of the* 15^{th} *International Conference on Software Maintenance*, pages 50–62, 1999.

[57] H. A. Müller. Bits of history, challenges for the future and autonomic computing technology. In *Proceedings of the* 13^{th} *IEEE Working Conference on Reverse Engineering*, pages 9–18, 2006.

[58] H. A. Müller, M. A. Orgun, Scott R. Tilley, and James S. Uhl. A reverse engineering approach to subsystem structure identification. *Journal of Software Maintenance: Research and Practice*, 5(4):181–204, 1993.

[59] A. M. Memon. Employing user profiles to test a new version of a GUI component in its context of use. *Software Quality Journal*, 14(4):359–377, 2006.

[60] J. Misra. A logic for concurrent programming: Safety. *Journal of Computer and Software Engineering*, 3(2):239–272, 1995.

[61] A. Mok and G. Liu. Efficient runtime monitoring of timing constraints. In *Proceedings of the* 3^{rd} *IEEE Realtime Technology and Applications Symposium*, pages 252–262, 1997.

[62] R. Morgan. *Building an Optimizing Compiler.* Butterworth-Heinemann, Boston, Massachusetts, 1998.

[63] G. C. Murphy, D. Notkin, and Kevin Sullivan. Software refexion models: bridging the gap between source and high-level models. In *Proceedings of the* 3^{rd} *ACM SIGSOFT Symposium on the Foundations of Software Engineering*, pages 18–28, 1995.

[64] NetBeans IDE, 2007. http://www.netbeans.org/.

[65] OCL Center, 2007. http://www.klasse.nl/ocl/.

[66] W.N. Robinson. Monitoring software requirements using instrumented code. In *Proceedings of the Hawaii International Conference on System Sciences*, pages 276–287, 2002.

[67] W.N. Robinson. Monitoring web service requirements. In *Proceedings of the* 12^{th} *IEEE International Conference on Requirements Engineering*, pages 65–74, 2003.

[68] G. Rosu and K. Havelund. Synthesizing dynamic programming algorithms from linear temporal logic formulae. Technical Report TR 01-15, RIACS, 2001.

[69] Bernd B. Schmid, T. Clark, and J. Warmer. *Object Modeling With the OCL: the Rationale Behind the Object Constraint Language*. Springer, 2002.

[70] O. Sokolsky, S. Kannan, and M. Viswanathan. Steering of realtime systems based on monitoring and checking. In *Proceedings of the* 5^{th} *International Workshop on Object-Oriented Realtime Dependable Systems*, pages 11–18, 1999.

[71] P. Teller, M. Maxwell, and A. Q. Gates. Towards the design of a snoopy coprocessor for dynamic software-fault detection. In *Proceedings of the* 18^{th} *IEEE International Performance, Computing, and Commuunication Conference*, pages 310–317, 1999.

[72] K. Templer and C. Jeffery. A configurable automatic instrumentation tool for ANSI C. In *Proceedings of the* 13^{th} *IEEE International Conference on Automated Software Engineering*, pages 249–258, 1998.

[73] The Eclipse Test and Performance Tools Platform (TPTP) Project, 2007. http://www.eclipse.org/tptp/.

[74] The Java parser generator, 2007. https://javacc.dev.java.net.

[75] J. M. Voas. Building software recovery assertions from a fault injection-based propagation analysis. In *Proceedings of the* 21^{st} *International Computer Software and Applications Conference*, pages 505–510, 1997.

[76] Yacc, Yet another compiler-compiler, 2007. http://dinosaur.compilertools.net/#yacc.