MINING BEHAVIORAL SPECIFICATIONS OF DISTRIBUTED SYSTEMS

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Mining Behavioral Specifications of Distributed Systems

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DECLARATION

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis. This thesis has also not been submitted for any degree in any university previously.

[illegible]

Sandeep Kumar

24 August 2012

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Summary

Software specifications provide explicit and high-level descriptions of a program ensuring a clear and consistent understanding of expected behavior. The importance of specifications and their neglect in real life software engineering processes have motivated research into automated techniques to recover specifications after software has been implemented and tested. A relatively recent, yet promising direction in this research is that of dynamic specification mining in which specifications of various types are *mined* from traces collected during actual executions of a software system.

Current specification mining methods are largely limited to the analysis of sequential interactions between software components. This dissertation presents problems and methodologies in an attempt to advance the application of specification mining in two directions. First, it proposes methodologies and algorithms for mining specifications that account for concurrency and asynchronicity of processes in a distributed system. These methods are then coupled with a process class abstraction technique to produce simpler and more accurate specifications. Together, these methods make it possible to perform mining on execution traces for a larger class of systems and produce models that can be expressed in the visual format of sequence diagrams or Message Sequence Charts that have been popular ways of representing and picturing distributed system behavior and telecommunication protocols.

The second advancement proposed in this thesis is towards better comprehension of evolving software. It discusses an approach to elicit behavioral changes of a program at the specification level by directly mining program traces from two versions. As formal specifications need not be manually created, such a method can be frequently used on successive versions of evolving software by those who have limited familiarity with the actual program. Mined difference specifications can be used to comprehend changes in evolving software and to automatically adapt existing specifications of earlier versions to changes in the system implementation.

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Chapter 1

Introduction

Technological developments in the field of computer networks have resulted in a widespread adoption of distributed computing models. Distributed systems contain several autonomous processes that collaborate through message passing to perform the desired computational tasks. While most of these systems are designed to hide such collaboration and communication from end users, the protocol of communication is an important consideration in their design and development. Specifications of interaction protocols are a common way to communicate the intended behavior of processes in such systems and they act as standards using which implementations can be verified. This dissertation discusses a set of methodologies to automate the process of creating and maintaining specifications of interaction protocols for distributed systems. This chapter will discuss the nature of distributed software specifications and their importance (Section 1.1) and introduce the approach of specification mining (Section 1.2). In Sections 1.3 and 1.4 the thesis statement, research problems and main contributions made in this research will be presented.

1.1 Distributed System Specifications

Software specifications can take both a static (or architectural) view as well as a dynamic (or behavioral) view of systems. The architectural view depicts how the processes or components in the system are interconnected. The behavioral view describes how the state of the system or of its components (and therefore their response to inputs) changes over time. Both these aspects are important for comprehending software systems. However, as the separation of components in distributed systems and connections between them are explicit, we have focussed our research on behavioral specifications of distributed systems.

For each use-case scenario, processes in a distributed system interact through a pre-defined pattern of message exchanges. For example, when a person sends an email, his or her email application communicates with a server application residing at a remote machine in a precise manner to ensure accurate delivery. If the client applications of the sender and recipient as well as their server applications are considered to be processes of a distributed system, then the sequence of messages exchanged by these applications describe one *execution scenario* or simply scenario of that system. Execution scenarios can be abstract and refer only to the type of messages exchanged and not their actual payload. Traditionally, distributed systems have been specified by describing important execution scenarios. For example, the SMTP protocol [11] specifies the order of commands and acknowledgements exchanged between an email client and server to successfully send an email. Such descriptions of interactions between two or more components are important to understanding distributed system behavior.

Message Sequence Charts (MSCs) are visual formalisms used to specify execution scenarios [6]. They are also part of UML standards in the form of sequence diagrams. While MSCs and sequence diagrams are intended to precisely prescribe the nature of interactions, they are also descriptive and directly provide a visual image of how processes interact. As scenarios involve multiple processes, they carry a ‘broad picture’ of the system as opposed to the narrow view provided by the specifications of individual components. The MSC formalism has been used to specify various telecommunication protocols and embedded systems [2, 7]. However, for a large number of distributed systems, the protocol of interaction is specified in informal and vague terms. In open source systems, specifications often have to be parsed from source code comments, bug repositories, changelogs and release notes. In brief, the following factors justify our research into scenario based specifications:

- Scenario based specification languages are visual and informal in nature.
- Scenario based specifications such as MSCs and sequence diagrams provide a broad perspective that is not easily provided by specifications of individual processes.
- Formal specifications (and in many cases informal ones) are not documented and readily available for a large number of real life distributed systems.

In Chapter 2, we shall formally define the specification language that is used to represent scenarios in this thesis.

1.2 Specification Mining

Specification mining [17] is a program analysis method to automatically infer the specification of a program based on examples of correct usage. Here, ’usage’ refers to the manner in which a program or its exposed methods are invoked. For example, the correct usage of resources such as a file or network connection follows an acceptable invocation sequence: acquisition, access and then release. Similarly to use individual methods correctly, the parameters passed to it should meet the necessary preconditions. These are the implicit rules, followed by most programs but not explicitly stated, that mining techniques attempt to uncover. The mining of various specification formats such as automata [17, 53, 60], and temporal rules [86, 55] has been studied. In general, specification mining techniques employ data mining or machine learning on execution traces to generate models that are useful in program verification. These techniques work under the assumption that by observing sufficient executions of a good software implementation, inferences regarding the specification (or expected behavior) of the software can be made.

There have been both dynamic and static approaches for specification mining. These techniques are discussed in detail in Chapter 8. Broadly, dynamic specification mining techniques rely on actual executions of programs. In contrast, static approaches look to extract the specification by reasoning on the control flow of a subject program or of other 'client' programs that invoke the subject. Static specification mining can be performed if program source code is available. However, to obtain precise specifications, expensive analysis may have to be performed to eliminate infeasible paths. This obstacle is more overwhelming in the distributed case, where feasible scenarios (the number of processes and how they will interact) have to inferred based on the a static view provided by the program source code executed by each process.

Dynamic approaches are chosen to recover behavioral specifications for distributed systems as they provide the following advantages:

- A dynamic approach is capable of basing inferences upon actual global interactions whereas static approaches have to speculate upon what the actual interactions are likely to be.

- Dynamic approaches witness the global synchronization patterns during the execution of the distributed system.

- A potential user of dynamic analysis tools can determine the set of test inputs thereby controlling the use case scenarios to be analyzed. By doing so, the user can first study behavior under the most common use case scenarios and subsequently expand upon this knowledge through additional testing and trace generation.
- Dynamic approaches can infer behavioral specifications even in cases where the program source code is not available.

This thesis is a result of research that attempts to advance the state of the art in dynamic specification mining techniques. The thesis statement, research problems and contributions are described in following sections.

1.3 Thesis Statement

The thesis of this research is as follows:

"Directed and domain specific dynamic analysis of distributed system behavior can synthesize and maintain accurate high-level scenario based specifications thereby enhancing the comprehension of distributed system behavior as well as the evolution of these systems over program versions".

1.4 The Research Problem and Contributions

The chief focus of this dissertation is the problem of automated discovery of global behavioral specifications for distributed systems. The discovery process is directed in that it seeks to represent the behavior of systems in a specific language. The methods are also tailored to the distributed domain as they take in to account and exploit the prior knowledge about the set of processes the system is composed of and the behavioral similarities, if any, that exist between those processes. Characteristics such as concurrency and scalability that should be common to most distributed systems pose the following research problems:

1. **Concurrency and Asynchronicity:** The processes in a distributed system are usually required to honour only a weak set of ordering constraints in order to achieve high levels of concurrency and therefore the best utilization of resources. However, the distributed system as a whole can function as desired only when certain global ordering rules are obeyed by its processes. An important problem in mining specifications is to describe these essential constraints and how they achieve global state transitions.

2. **Parameterized Systems:** As specification mining observes interactions between a configuration of active processes executing in a real distributed system, it is susceptible to inferring properties that are peculiar to that particular configuration. However, most distributed systems need not stick to a single configuration and may contain a varying number of constituent processes. A good specification of distributed systems, should not be particular to a specific configuration, but rather like distributed system implementations themselves, are a parameterized definition of generic behavior that can be instantiated in multiple ways.

3. **Evolution:** Like most other software systems, distributed systems evolve due to reasons such as the addition of new features or resolution of bugs. Some of these changes impact the scenario based specification of the system. Changes to a single component may have intended or unintended consequences to the global specification. To comprehend the evolution of systems, it is important to understand the changes in global behaviors. Most existing specification mining techniques have sought to mine specifications for a single version, suggesting that change comprehension should be achieved by

visually comparing multiple mined specifications or employing model matching techniques. Such comparisons are particularly difficult between models that describe a collection of possible execution scenarios involving several parties.

4. **Human Assistance:** As mining processes produce specifications that are at best an approximation of the actual behavior, mined specifications end up having to be verified and corrected through user inputs. However, when mining is repeated in subsequent versions of an evolving program these corrections are not remembered. Ideally, an automated process should be able to remember and maintain these corrections, while at the same time update the specification with crucial changes to the behavior of the program.

To address limitations of existing methods and solve the problems listed above, we propose a specification mining framework that takes, as input, execution traces from the subject program(s) and produces scenario based specifications in a high-level version of the MSC specification language called Message Sequence Graphs (MSG). Figure 1.1 provides an overview of the proposed research including mining and evaluation. The mined specifications are evaluated by comparison against benchmark specifications of the subjects.

At a conceptual level, this research makes the following contributions:

- A fundamental shift from analyzing and inferring specifications of the behavior of individual processes to inferring scenario-based specifications of global behaviors.

- The inference of an abstract state-based model of distributed systems that specifies a collection of valid behaviors based on traces collected by executing a test suite that provides good coverage of global behaviors.

- The inference of class-level specifications for more accurate specification of parameterized systems.
- The analysis of execution traces from different program versions, using specification mining as a means, to identify important differences between those versions.

More specifically, the technical contributions of this dissertation are as follows:

- A technique to summarize multiple execution scenarios involving two or more processes as a single high-level MSC specification.
- A techniques for inferring class-level specifications which specify constrained symbolic interactions between various system processes.
- A technique to mine difference specifications based on the MSC language. The difference specification highlights changes between program versions.
- A technique to update existing specifications to reflect changes in software implementation.
- Mechanisms to evaluate the quality of mining by measuring the accuracy of mined results.

Many of the techniques and results presented in this dissertation also appear in conference proceedings [46, 45, 47].

1.5 Outline

Chapter 2 describes the basic language of mined specifications and some concepts utilized in the paper. In Chapter 3 the desired patterns to be mined are formally defined and the mining algorithm for high-level scenario based specifications is introduced. Chapter 4 discusses specification techniques for describing class level

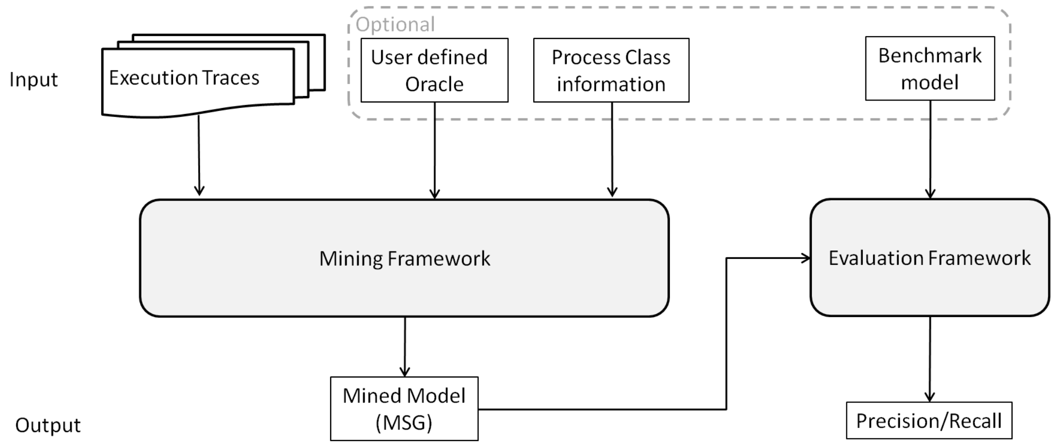


Figure 1.1: Overview of proposed mining and evaluation frameworks

behavior in distributed systems and proposes mining techniques to discover such specifications. In Chapter 5, a procedure for directly mining difference specifications is presented, and in Chapter 6 this technique is extended to update existing specifications to reflect the inferred differences. Chapter 8 compares the research to other work in specification mining. Chapter 9 looks at possible extensions to the proposed work. The concluding remarks can be found in Chapter 10.

Chapter 2

Background

This chapter provides a brief background on the scope of systems and specifications that this dissertation shall be concerned with. The basic characteristics of software systems of interest are described and a formal definition of the language used to represent their specifications are also provided. Section 2.8 contains a brief discussion on possible methods of collecting execution traces for analyses of such systems.

2.1 Distributed System Characteristics

Distributed systems are usually composed of several physically separate computers connected by a network. In a general sense, the distributed computing model includes any system containing separate autonomous processes that communicate by message passing. These logically separate entities have been referred to as components or nodes of the distributed system. In the modeling of distributed systems that is used here, each logical node is viewed as containing exactly one process that is capable of executing external actions/events such as send or receive of messages to or from other nodes. The following are some physical and logical characteristics of distributed systems [50]. They:

- Include an arbitrary number of system and user processes (Multiplicity of general-purpose resource components).
- Have modular architecture, consisting of varying number of processing elements.
- Have mechanisms for processes to communicate via message passing.
- Contain dynamic interprocess cooperation and runtime management.
- Accommodate interprocess message transit delays.

This research caters to distributed systems that possess such characteristics, while making the following assumptions:

- Each process in the system can be uniquely identified.
- The following information regarding interprocess communication can be recorded:
  - The identity of the process participating in the action.
  - The identity of the counterpart to or from which it sends or receives the message.
  - A (possibly abstract) representation of the message being exchanged.
- In the case of asynchronous message passing, two events, one at the time of dispatch and another at the time of receipt can be recorded.
- For every event denoting the send/dispatch of a message its corresponding receipt can be recorded.

We believe that these assumptions are valid in a large class of distributed systems. Many systems, in which processes communicate over a reliable transport layer such as TCP, satisfy a stronger restriction that messages are delivered in the order they are sent and that every message that is sent is also received.

As other classes of systems such as embedded systems and object oriented systems comply with these assumptions, our techniques can in general be extended to derive similar specifications for such systems.

2.2 Modelling and Specifying Distributed Systems

As distributed systems typically bring together several processes that may be programmed by different individuals and based on varying interests, there has been considerable interest in ensuring compatibility and safe inter-operation. This has led to several ways to precisely specify and verify communication patterns. The semantics of distributed programming and specification languages are typically formalized using concurrency models such as Petri nets, Automata, Mazurkiewicz traces or process calculi such as π-calculus. Some of the specification methods used for distributed systems are as follows:

- **Communicating Finite State Machines (CFSM):** CFSMs is an early method developed to model distributed system protocols [27]. Protocols are specified by defining how processes can send or receive messages over FIFO channels. The CFSM model is important as it specifies how individual processes should be implemented. These models have been used as an intermediate model to realize scenario based specifications like Message Sequence Charts (MSC) [24]. However it is challenging to mentally translate design intentions which are typically based on a global view of the system into a protocol specification using CFSMs. It is similarly challenging to comprehend intended behaviors based on individual automata without a global context.

- **Session Types:** Session types are a type theoretic approach of specifying the valid manners of interaction or "conversations" between two processes. Session types allow the specification of how individual processes may respond to messages that it receives. This has been extended to multi-party session types to specify global behavior in distributed systems [42]. Session types potentially form a powerful component of programming languages targeted for programming client-server systems and web services.

- **Language of Temporal Ordering Specification (LOTOS):** LOTOS is a language for formally specifying distributed system behavior and structure by combining process algebra and abstract data types [25]. Systems are specified in LOTOS as processes whose behaviors are defined using expressions. Process interaction is modelled through the concept of gates by which other processes can observe certain (external) actions of a process. LOTOS also permits an architectural specification and allows the definition of a hierarchy of processes and sub-processes.

- **Live Sequence Charts (LSC):** LSCs are a scenario based specification that can be used to define global system properties with the ability to differentiate between necessary and optional behavior [32]. This enables the specification of important global temporal properties in the form of a scenario based specification. LSCs were proposed as an extension to Message Sequence Charts and shall be discussed in Chapter 8 as one of the alternatives for inferring distributed system specifications.

Message Sequence Charts (MSCs) are distinct from these approaches as they have a visual syntax that is naturally suited for expressing behaviors of multiple processes. While some of the other techniques like communicating automata have better expressive power [39], MSCs and sequence diagrams have found a greater interest and popularity outside the research community. The formal semantics of the MSC language is defined in [76] using a process algebra approach. In subsequent sections we shall describe the basic syntax of MSCs and its partial order semantics.

2.3 Message Sequence Charts

Message Sequence Charts (MSCs), a recommendation from the International Telecommunication Union - Telecommunications Standardization Sector (ITU-T) [6], have traditionally played an important role in software development and been incorporated into modelling languages such as ROOM [26], SDL [12] and UML [83]. MSCs describe scenarios by depicting the interaction between different components (objects) of a system, as well as the interaction of components of reactive systems with their environment. Over the years, the MSC standard has been expanded to include several features. This dissertation shall consider a basic version of MSCs along with a few non-standard variations that shall be introduced and detailed in subsequent chapters.

2.3.1 MSC Syntax

The basic MSC syntax consists of a set of vertical lines-each denoting a process or a system component, internal events representing intraprocess execution and annotated uni-directional arrows denoting inter processes communication. Figure 2.1 shows a simple MSC with two processes; m_1 and m_2 are messages sent from p to q.

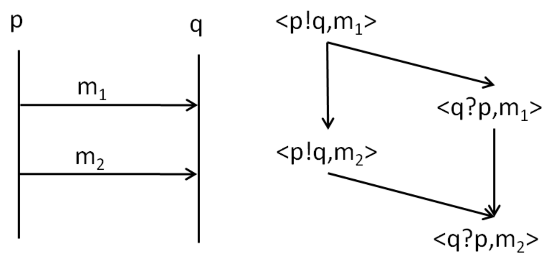


Figure 2.1: A schematic MSC and its partial order.

2.3.2 MSC Semantics

Semantically, an MSC denotes a set of events (message send, message receive and internal events corresponding to computation) and prescribes a partial order over these events. This partial order is the transitive closure of (a) the total order of the events in each process[1] and (b) the ordering imposed by the send-receive of each message.[2]. It is also understood that arrows depicting the inter process communication is either a horizontal line or one that is slanting downwards. The events are described using the following notation. A send of message m from process p to process q is denoted as $\langle p!q, m\rangle$. The receipt by process q of a message m sent by process p is denoted as $\langle q?p, m\rangle$.

Consider the chart in Figure 2.1. The total order for process p is $\langle p!q, m_1\rangle \leq \langle p!q, m_2\rangle$ where $e1 \leq e2$ denotes that event $e1$ "happens-before" event $e2$. Similarly for process q we have $\langle q?p, m_1\rangle \leq \langle q?p, m_2\rangle$. For the messages we have $\langle p!q, m_1\rangle \leq \langle q?p, m_1\rangle$ and $\langle p!q, m_2\rangle \leq \langle q?p, m_2\rangle$. The transitive closure of these four ordering relations defines the partial order of the chart. Note that it is *not* a total order since from the transitive closure one cannot infer that $\langle p!q, m_2\rangle \leq \langle q?p, m_1\rangle$ or $\langle q?p, m_1\rangle \leq \langle p!q, m_2\rangle$. Thus, in this example chart, the send of m_2 and the receive of m_1 can occur in any order. The partial order suggested by the MSC in this example is also shown in Figure 2.1.

The vertical lines representing the independent processes or threads whose

[1]Time flows from top to bottom in each process.
[2]The send event of a message must happen before its receive event.

interactions are captured are also referred to as *lifelines*. MSCs can be formally defined as follows.

Definition 2.3.1 (MSC) *An MSC M can be viewed as a partially ordered set of events $M = (L, \{E_l\}_{l \in L}, \leq, \gamma, \Sigma)$, where L is the set of lifelines in m, E_l is the set of events in which lifeline l takes part in M. Σ is the alphabet of send and receive event labels* [1] *and $\gamma : \{E_l\}_{l \in L} \to \Sigma$ is a function assigning each send or receive event a label. $\leq$ is the partial order over the occurrences of events in $\{E_l\}_{l \in L}$ such that*

- *$\leq_l$ is the linear ordering of events in E_l, which are ordered top-down along the lifeline l,*
- *$\leq_{sm}$ is an ordering on message send/receive events in $\{E_l\}_{l \in L}$. If $\gamma(e_s) = \langle p!q, m \rangle$ and the corresponding receive event is $e_r, with \gamma(e_r) = \langle q?p, m \rangle$, we have $e_s \leq_{sm} e_r$.*
- *$\leq$ is the transitive closure of $\leq_L = \bigcup_{l \in L} \leq_l$ and $\leq_{sm}$, that is, $\leq = (\leq_L \bigcup \leq_{sm})^\star$*

Concatenation of MSGs can be defined in two different manners. For a concatenation of two MSCs say $M_1 \circ M_2$, all events in M_1 must happen before any event in M_2. In other words, it is as if the participating processes synchronize or hand-shake at the end of an MSC. In MSC literature, it is popularly known as *synchronous concatenation.* On the other hand, *asynchronous concatenation* performs the concatenation at the level of lifelines (or processes). Thus, for a concatenation of two MSCs, say $M_1 \circ M_2$, any participating process (say Interface) must finish all *its* events in M_1 prior to executing any event in M_2. For the rest of this dissertation the latter definition of concatenation shall be used.

[1] Internal events are ignored for simplicity

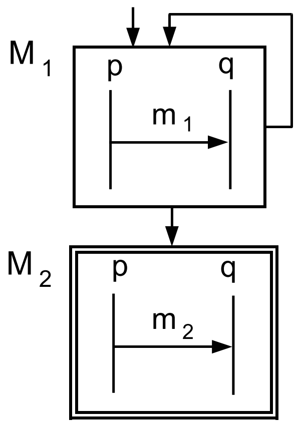


Figure 2.2: A schematic Message Sequence Graph

2.4 Message Sequence Graphs

An MSC as defined above is suited to specify a single execution scenario. A complete specification of a system would therefore require multiple MSCs. A large number of MSCs will be required to describe most non-trivial systems. For this reason, MSC standards include High Level Message Sequence Charts (HMSCs) that make it easy to define and visualize large collections of MSCs. HMSCs are hierarchical graphs that have as nodes either a basic MSC or a lower level HMSC chart. Mining exercises are limited to a simpler yet semantically equivalent representation of *Message Sequence Graphs* [62].

Formally an MSC-graph or MSG is a directed graph $(V, E, V_s, V_f, \lambda)$, in which V is the set of vertices, E a set of edges, V_s a set of entry vertices, V_f a set of accepting vertices and λ a labelling function that assigns an MSC to every vertex.

Figure 2.2 shows a simple MSG specification containing two basic MSCs M_1 and M_2 which are vertices of the graph represented using rectangular boxes. The entry vertices are represented by incoming arrows that do not have a source vertex. The accepting vertices are represented using double-lined boxes. The transitions in the MSG are described using arrows from one vertex to another.

2.4.1 MSG Semantics

An MSG specifies a system by defining the precise set of scenarios it may execute. Each scenario is represented as an MSC. Formally, an MSG specifies a (possibly infinite) set $\mathcal{M} = \{\ldots, M_i, \ldots\}$ of MSCs such that, $M_i \in \mathcal{M}$ **iff** there exists a path in the MSG of the form $(v_1, v_2 \ldots v_n)$, where $v_1 \in V_s \wedge v_n \in V_f$,
and
$M_i = \lambda(v_1) \circ \lambda(v_2) \ldots \lambda(v_n)$.

The MSG in example in Figure 2.2 specifies the infinite set of scenarios of the form: $\{M_1 \circ M_2, M_1 \circ M_1 \circ M_2, M_1 \circ M_1 \circ M_1 \circ M_2, \ldots\}$.

2.5 Symbolic Message Sequence Charts

Symbolic Message Sequence Charts (SMSCs) are class level specifications that adopt the basic syntax of MSCs and introduce the concept of *process classes* [79]. Like MSCs, SMSCs contain vertical lifelines and horizontal arrows depicting communication. Different from MSCs, lifelines in an SMSC may describe a collection behaviorally similar processes called *process classes*. Moreover, SMSCs define *guards* against events (send events – from which message arrows originate and the corresponding receive event where arrows terminate) on lifelines process classes.

Semantically, an SMSC prescribes a partial order $\leq$ over the events from across lifelines. This partial order is a combination of the total ordering of events within each lifeline (denoted by $\leq_{\tilde{p}}$) and the ordering of send and receive counterparts (denoted by $\leq_{sm}$). Formally: $\leq \, \equiv \, \left((\bigcup_{\tilde{p} \in \mathcal{P}} \leq_{\tilde{p}}) \bigcup \leq_{sm} \right)^{\star}$. Where, $\mathcal{P}$ is the set of process classes in the system. An event in a lifeline is referred to as a symbolic event of the form $(\langle \tilde{p} \oplus \tilde{q}, m \rangle, \mathcal{Q}.g)$ where,

- $\tilde{p}, \tilde{q}$ are the communicating process classes
- $\oplus \in \{!, ?\}$ differentiates between send and receive

- $\mathfrak{Q}$ is one of $\exists, \exists_k, \forall, \forall_k$ – a universal or existential quantifier.
- g is a predicate on the state of a concrete process of process class $\tilde{p}$.

The concept of process classes and the semantic interpretation of quantifiers and predicates in guards are further expanded in Chapter 4.

2.6 Symbolic Message Sequence Graphs

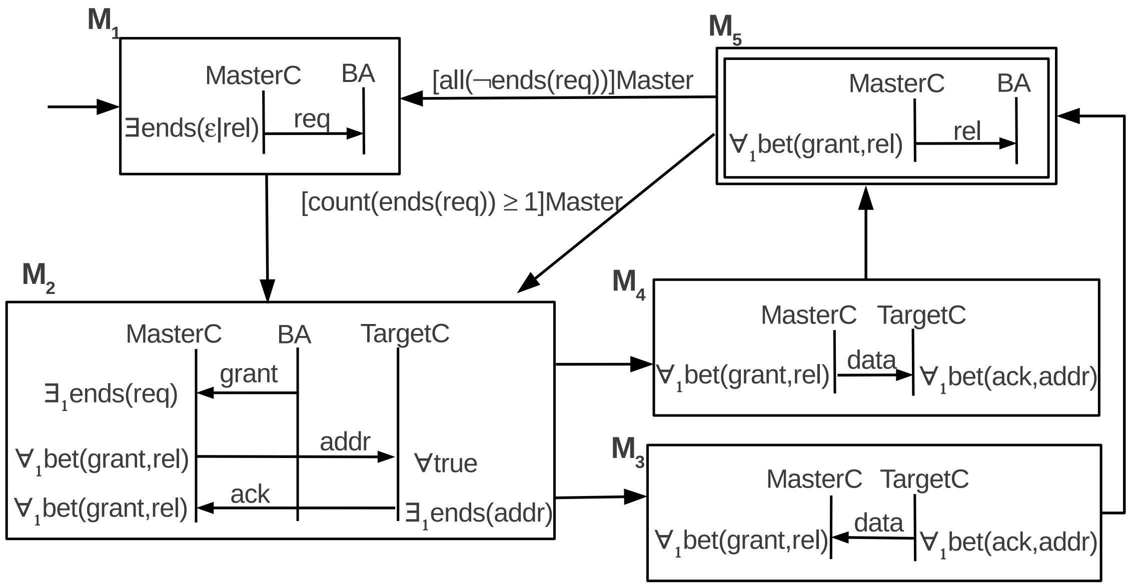
A Symbolic Message Sequence Graphs (SMSG) is a high-level SMSC, which represents a collection of SMSCs in graph form. It is a directed graph with *basic SMSCs* as its vertices. Every path in the SMSG prescribes a valid scenario, which is specified by "concatenating" basic SMSCs located at vertices along the path. A *concatenation* of two basic MSCs M_1 and M_2 yields a bigger SMSC in which events from each process class $\tilde{p}$ in M_1 have to occur before the occurrence of any event of the same process class $\tilde{p}$ in M_2. The nature of such concatenation is 'asynchronous' because no ordering between events from across distinct process classes is explicitly enforced as a result of concatenation.

Furthermore, a process class constraint can be attached to an edge in an SMSG to assert the condition of (the state of) the process class for the source SMSC to be concatenated to the target SMSC.

2.7 Example of SMSG Specification

Figure 2.3 shows an example of an SMSG specification of a bus arbitration protocol. In such a system, there is a single centralized bus arbiter (BA), one or more master devices and several slave or target devices. This specification contains five basic SMSCs. M_1 denotes the request phase when control of bus is requested. In M_2, the bus arbiter grants access to a single master, which then places the address

(a) Mined Symbolic Message Sequence Graph:



(b) Regular Expressions:

ends($\epsilon|rel$): $h \in L\Big(\big(\Sigma^\star\langle \text{MasterC}\,!\,\text{BA}, \text{rel}\rangle\big)^\star\Big)$

ends(req): $h \in L\Big(\Sigma^\star\langle \text{MasterC}\,!\,\text{BA}, \text{req}\rangle\Big)$

ends(addr): $h \in L\Big(\Sigma^\star\langle \text{TargetC}\,?\,\text{MasterC}, \text{addr}\rangle\Big)$

bet(grant,rel):

$h \in L\Big(\Sigma^\star\langle \text{MasterC}\,?\,\text{BA}, \text{grant}\rangle\big(\Sigma - \langle \text{MasterC}\,!\,\text{BA}, \text{rel}\rangle\big)^\star\Big)$

bet(ack,addr):

$h \in L\Big(\Sigma^\star\langle \text{TargetC}\,!\,\text{MasterC}, \text{ack}\rangle\big(\Sigma - \langle \text{TargetC}\,!\,\text{MasterC}, \text{addr}\rangle\big)^\star\Big)$

Explanation: Predicate ends(X) refers to the scenarios when the last event to be executed is X; similarly, predicate bet(X, Y) refers to scenarios in which the event Y has not occurred after the last execution of event X.

Figure 2.3: Class-level specification of centralized bus arbitration protocol

of the target device on the bus. Only the matching device responds. M_3 and M_4 represent the data phase where the read from or write to the device take place. The master device faithfully relinquishes control of bus at the end of data transfer as in M_5.

The symbolic events in this specification have guards whose predicates are of the form $bet(X, Y)$ or $ends(X)$, where X and Y range over action labels, m. These are predicates over the execution history h of either MasterC or TargetC. Figure 2.3(b) regards these predicates as tests that determine if an execution history

h, treated as a sentence, belongs to the language of a regular expression. The SMSC M_1 contains an event at the $MasterC$ process class with guard $\exists\, ends\,(\epsilon \,|\, rel)$. The guard ensures that either the master device is making a request for the first time, or it has released control over its previous request. Consider the SMSC M_2 in Figure 2.3, the $addr$ message is received by process class $TargetC$ having a guard $\forall true$. Here the predicate $g = true$ ensures that every concrete process belonging to class $TargetC$ will receive the address placed by master. The guard $\forall_1 ends(grant)$ implies that exactly one master device has been granted control, and that device sends address. The guard $\exists_1 ends(addr)$ accepts any selection in which exactly one of the processes that receive the address responds with ack. The SMSG has two edges with process class constraints. One of them is $count(ends(req)) \geq 1$. It refers to the scenario when there are one or more master devices whose requests for bus have not been granted. The other constraint is $all(\neg ends(req))$. This refers to the complementary scenario when there is no process still waiting to be granted control to the bus. Together, these two constraints ensure that after M_5, M_2 is executed if there are more requests to be processed and M_1 is executed only after all requests have been processed.

2.8 Trace Collection

As discussed in Section 2.1, certain assumptions have been made regarding the nature of systems that can be analyzed using the proposed approaches. Many of the assumptions are made to ensure that system interactions can be observed and duly recorded. Traces used for subsequent analyses are obtained by executing instrumented distributed systems. Traces are sequences of events recording the dispatch or receipt of messages by the processes of a distributed system. In most distributed systems that communicate over TCP/IP, processes can be uniquely identified using the combination of IP and port addresses. Connection mechanisms such as sockets also provide information regarding the port and IP address of the other party in the connection. An advantage in distributed systems is that traces can be collected without any instrumentation of the application, but rather by capture and filter of its communication packets. This ability of converting captured packet logs into scenarios has been available as part of visualization and debugging tools [13, 1]. Our techniques can be applied to any input data set that can be represented as multiple scenarios (in formats such as sequence diagrams or message sequence charts).

Message labels can be obtained by inspecting the messages exchanged between processes. The message may have to be abstracted to obtain small and meaningful specifications. In our analyses, we assume such assistance can be provided to select the level of abstraction at which messages should be represented. For example, in our experiments, messages in the form of XML packets are represented by certain attributes extracted from those packets. In evaluating our technique on mining program evolution, we shall use example subjects that are object oriented programs rather than real distributed systems. In some of these examples the objects represent behavior of processes in distributed or embedded systems. In such systems the instrumentation framework ensures that interactions between objects in the form of method invocations are recorded in the trace file.

Specific tracing mechanisms used in experiments shall be discussed along with case studies and experiments performed to evaluate the proposed mining methods in subsequent chapters.

Chapter 3

Mining Message Sequence Graphs

As described in Chapter 2, Sequence diagrams and Message Sequence Charts (MSCs) are commonly used to express specifications of distributed systems. Message Sequence Graphs (MSGs) are used to represent a collection of MSCs to allow for choice and iteration. Using MSGs, a large collection of system behavior can be represented in a concise manner. This chapter describes a technique to construct an MSG specification from execution traces and its implementation as a framework called *MSGMiner*.

Consider a hypotheitcal banking system containing three processes, a user client, an internet portal and a back-end database. Figure 3.3(a) shows three sample traces collected from executions of such a system. Figure 3.3(b) shows

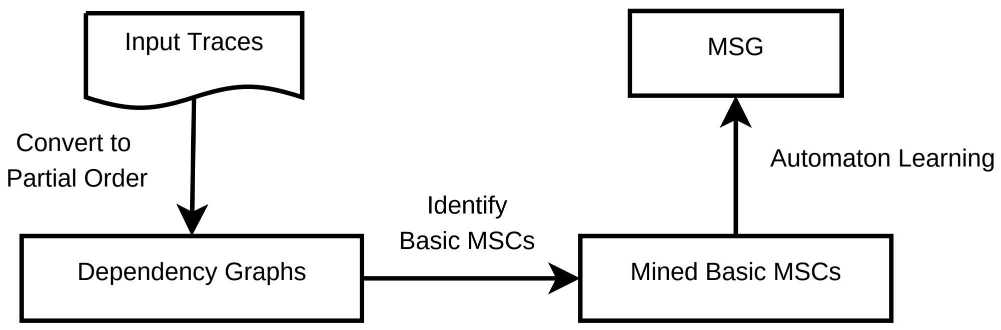


Figure 3.1: Stages in the proposed mining framework.

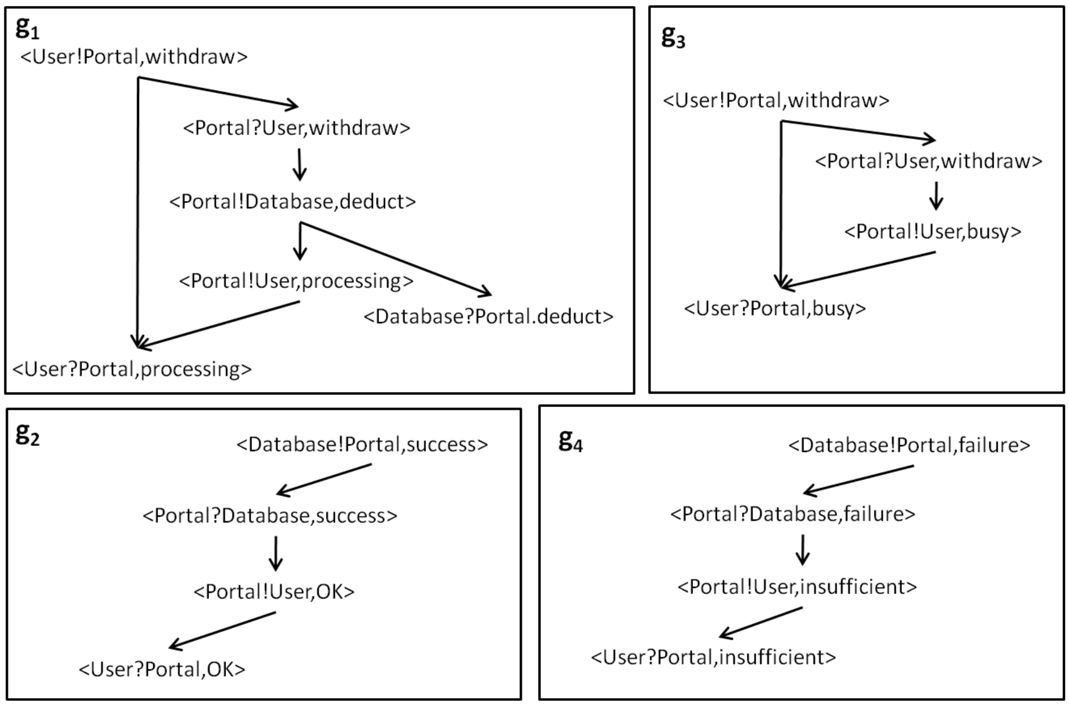


Figure 3.2: Dependency graphs for MSCs in Figure 3.3

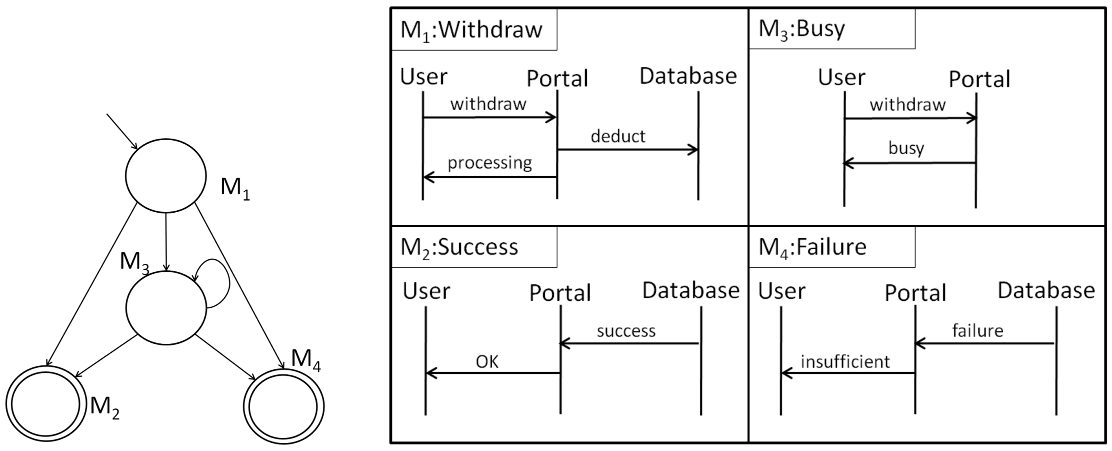
what an MSG mined from traces would appear like. The MSC indicates that the actions described in M_1 where a withdrawal is initiated, the system faces three global choices. The database may return with a success or a failure. Additionally, the user may make an additional withdrawal request before the processing is complete. The MSG shows that the system may iterate over multiple requests from the user before the inital request is fully processed.

The mined MSG is not an exact representation of the set of traces but instead a generalized model of the system suggesting additional scenarios inferred based on the input sample of scenarios. This model describes events within basic MSCs, provide the precise partial order among them and uses the graphical format of MSG to represent the collection of scenarios that are inferred to be valid.

Figure 3.1 describes the transformations performed by *MSGMiner* to construct an MSG. Each execution trace is converted to a partial order (or dependency graph) by (i) considering the individual control flows across different processes and

Trace t_1	Trace t_2	Trace t_3
User!Portal,withdraw	User!Portal,withdraw	User!Portal,withdraw
Portal?User,withdraw	Portal?User,withdraw	Portal?User,withdraw
Portal!Database,deduct	Portal!Database,deduct	Portal!Database,deduct
Portal!User,processing	Database?Portal,deduct	Database?Portal,deduct
Database?Portal,deduct	Portal!User,processing	Portal!User,processing
User?Portal,processing	User?Portal,processing	Database!Portal,failure
User!Portal,withdraw	Database!Portal,success	User?Portal,processing
Portal?User,withdraw	Portal?Database,success	Portal?Database,failure
Portal!User,busy	Portal!User,OK	Portal!User,insufficient
User?Portal,busy	User?Portal,OK	User?Portal,insufficient
Database!Portal,success		
Portal?Database,success		
Portal!User,OK		
User?Portal,OK		

(a) Sample execution traces (inputs to our MSGMiner)



(b) Mined MSG (output from our MSGMiner)

Figure 3.3: Banking System Example

(ii) marking the dependencies between a send event and its corresponding receive. These dependency graphs are then analyzed to find recurring portions — which then appear as the basic MSCs in the mined model. The basic MSCs constitute the nodes of the mined MSG model. These nodes are then connected up using automata learning techniques. The approach used thus involves a combination of automata learning and mining of partial orders.

The main challenge in this process lies in the task of discovering snippets of concurrent behavior from traces and specifying them using MSCs. MSCs are represented using data structures called dependency graphs that fully capture the partial order relationship among events in the MSC. Furthermore, we introduce a novel idea of *maximal connected dependency graph* (MCD) for a given trace set to capture basic MSCs that can be used as the building blocks for constructing an MSG. The entire mining process is thus divided into three stages, which are elaborated in following sections.

1. *Trace processing (Convert to Partial Order)*: At this stage each trace is transformed into a corresponding dependency graph.

2. *MSC mining (Identify Basic MSCs)* : In this phase, basic MSCs (in MCD representation) are identified from dependency graphs, and each dependency graph is transformed into a chain of MSCs.

3. *MSG construction (Automaton Learning)* : The chains of MSCs are merged into a single MSG specification at this final stage.

3.1 Dependency Graphs

Traces are collected by instrumenting and executing a system implementation with various inputs. In a distributed system the trace points are chosen to be at program locations where processes send or receive messages. A trace event is either a send or receive message of the form $\langle p\ !\ q, m\rangle$ or $\langle q\ ?\ p, m\rangle$ respectively, where m is the message being exchanged between a sender named p and a receiver named q. Furthermore every event must contain a time stamp to determine the global ordering of events.

For presentation clarity, it is assumed that traces are strings of events, which are drawn from a trace alphabet Σ. The collected traces record some linear temporal order in which events occur during the execution of the system. Our first task is to eliminate temporal ordering of events from different lifelines, when they are not explicitly imposed through message passing. With this, we will have converted the total ordering of events implied by the traces into a partial ordering that captures concurrent behavior.

Recall from 2.3.1 that an MSC $M = (L, \{E_l\}_{l\in L}, \leq, \gamma, \Sigma)$ prescribes the partial ordering $\leq$ among a set of events. $\leq$ was defined to be a transitive closure of the union of an ordering relationship between events within each lifeline ($\leq_l$) and the ordering of send and receive events of a message ($\leq_{sm}$). It is observed that only the ordering imposed by $\leq_l$ and $\leq_{sm}$ are sufficient to specify a scenario, and define a dependency graph to capture its behavior. Specifically, a dependency graph is a graph data structure $g = (L, \{V_l\}_{l\in L}, R, \gamma', \Sigma)$ where:

- each $v_i \in V_l$ corresponds to an event $e_i \in E_l$,
- there is a directed edge $v_1 R v_2$ iff for their corresponding events e_1 and e_2, $(e_1, e_2) \in (\cup_{l\in L} \leq_l) \cup \leq_{sm}$
- $\gamma'(v_i) = \gamma(e_i)$ for every event e_i and its corresponding vertex v_i in the dependence graph.

(V, R, γ) is used as a shorter representation for dependency graphs whenever the lifelines and event alphabet is not relevant to the analysis. Note that dependency graphs are a graphical representation that is equivalent to the concept of Mazurkiewicz traces in trace theory [33]. Figure 3.2 shows the corresponding dependency graphs g_1 and g_2, for basic MSCs M_1 and M_2 respectively.

Some of the properties of dependence graphs used by the mining algorithm are as follows.

Definition 3.1.1 (Equivalence $\equiv$) *If dependence graph* $g_1 = (V_1, R_1, \gamma_1)$ *and graph* $g_2 = (V_2, R_2, \gamma_2)$*,* $g_1 \equiv g_2$ *iff there exists a bijection* $f : V_1 \to V_2$ *such that,*

$\forall v_1 \in V_1(\gamma_1(v_1) = \gamma_2(f(v_1)))$ *and*

$\forall v_1, v_2 \in V_1 (v_1 R_1 v_2 \Leftrightarrow f(v_1) R_2 f(v_2))$.

Definition 3.1.2 (Concatenation $\circ$) *For two graphs,* $g_1 = (L_1, \{V_{1l}\}_{l \in L_1}, R_1, \gamma_1, \Sigma)$ *and* $g_2 = (L_2, \{V_{2l}\}_{l \in L_2}, R_2, \gamma_2, \Sigma)$ *the concatenation* $g_1 \circ g_2 = (L, \{V_l\}_{l \in L}, R, \gamma, \Sigma)$ *such that*

$$L = L_1 \cup L_2$$

$$V_l = \begin{cases} V_{1l} \cup V_{2l} & \textit{if } l \in L_1 \cap L_2 \\ V_{1l} & \textit{if } l \in L_1 - L_2 \\ V_{2l} & \textit{if } l \in L_2 - L_1 \end{cases}$$

$$\gamma = \gamma_1 \cup \gamma_2$$

$$R = R_1 \cup R_2 \cup R_L \cup R_{sr}$$

The concatenated graph contains the following new sets of edges:

1. R_L*: This enforces the ordering that for a lifeline* l*, the events in* V_{1l} *occur before those in* V_{2l}*. Let function* $first(V_{il})$ *return vertex* $v \in V_{il}$ *such that* $\forall v' \in V_{il}, v R_i v'$*. Similarly let* $last(V_{il})$ *return the last event in lifeline* l*.*

   $R_L = \{(last(V_{1l}), first(V_{2l})) | \forall l \in L_1 \cap L_2\}$

2. *R_{sr}: This pairs an unmatched send event in g_1 with an unmatched receive event in g_2. Since a graph may contain repetitions of the same send/receive event, ambiguity is resolved by defining a function $\varphi_l : V_l \to \mathbb{N}_0$ to differentiate between identical events within the same lifeline. For a vertex $v \in V_l$,*

   $\varphi_l(v) = |\{v' | v' \in V_l \wedge (v', v) \in (R_L \cup R_1 \cup R_2)^+ \wedge \gamma(v') = \gamma(v)\}|$.

   $R_{sr} = \{(v_p, v_q) | v_p \in V_{1p} \wedge v_q \in V_{2q} \wedge \exists \langle p!q, m\rangle, \langle q?p, m\rangle \in \Sigma : \gamma(v_p) = \langle p!q, m\rangle \wedge \gamma(v_q) = \langle q?p, m\rangle \wedge \varphi_p(v_p) = \varphi_q(v_q)\}$

Figure 3.4 shows the result of concatenation of dependency graphs g_1, g_3 and g_2 of Figure 3.2. The dotted lines show newly added edges.

Definition 3.1.3 (Sub-Graph) *A sub-graph relationship among dependency graphs is as follows: $g' \subseteq g$ if and only if there exist graphs x and y such that $g \equiv (x \circ g') \circ y$.*

Definition 3.1.4 (Prefix and Suffix) *A subgraph $g' \subseteq g$ is a prefix of g iff for some graph y, $g \equiv g' \circ y$. Similarly g' is a suffix iff for some graph x, $g \equiv x \circ g'$.*

Our definition of sub-graph for dependency graphs is stricter than and not to be confused with the definition commonly used in graph theory. In Figure 3.4, g_x, g_y and g_z are sub-graphs of the concatenated dependency graph. The sub-graph g_x is a prefix and g_z a suffix.

Definition 3.1.5 (Frequency) *The frequency of sub-graph g' in dependency graph g is n, if there exist dependency graphs $g_0, g_1, \ldots g_n$ such that $g \equiv ((((g_0 \circ g') \circ g_1) \circ g') \ldots) \circ g_n$ and $g' \nsubseteq g_0, g_1 \ldots g_n$ for some $n \geq 0$. Note that $g_0, g_1 \ldots g_n$ may be empty.*

Informally, the frequency of a sub-graph g' in g is the number of distinct occurrences of the g' in g. Figure 3.4 also shows the frequency of g_x, g_y and g_z in $(g_1 \circ g_3) \circ g_2$.

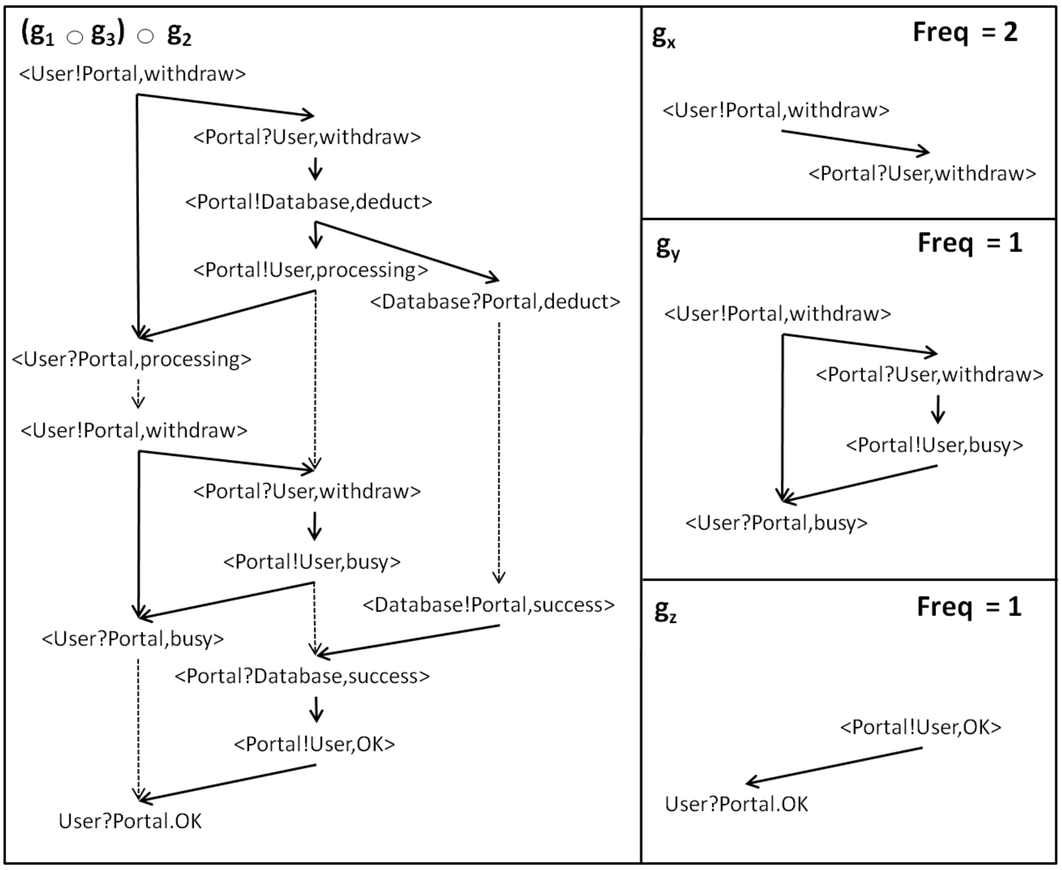


Figure 3.4: Concatenated graph $(g_1 \circ g_3) \circ g_2$, and some of its sub-graphs

A function $dgraph(t)$ is defined, that accepts a trace t as parameter and constructs a dependency graph. The dependency graph is constructed by creating a unique vertex for each occurrence of an event. After this, edges are added to link up events within a lifeline into a chain. Subsequently, the send and receive events are linked up starting from the bottom of the trace. For example the last occurrence of event $\langle q?p, m\rangle$ is linked to the last occurrence of event $\langle p!q, m\rangle$ and so on. The resulting dependency graph captures the "happened before" relationship between events as defined by Lamport [48]. Algorithm 1 details how the dependency graph is constructed from trace.

For construction of dependency graphs from traces, two assumptions have to be made about the system:

1. No messages are lost in the message channels.

2. The message communication occurs through FIFO channels.

Function *dgraph*, by its design has the property that given a trace t, for any of its suffixes t_s, $dgraph(t_s)$ is a suffix of $dgraph(t)$. For example if trace $t = (\langle p!q, m\rangle$, $\langle p!q, m\rangle$, $\langle q?p, m\rangle$, $\langle q?p, m\rangle$), then $dgraph(t)$ is a dependency graph (V, R, γ), having

$V = \{v_1^{\langle p!q,m\rangle}, v_2^{\langle p!q,m\rangle}, v_3^{\langle q?p,m\rangle}, v_4^{\langle q?p,m\rangle} \}$

$R = \{ (v_1, v_2), (v_3, v_4), (v_1, v_3), (v_2, v_4) \}$.

If instead of the full trace t one of its suffixes, say $t_s = (\langle p!q, m\rangle$, $\langle p?q, m\rangle$, $\langle p?q, m\rangle)$ is supplied, $dgraph(t_s)$ would contain,

$V = \{v_1^{\langle p!q,m\rangle}, v_2^{\langle q?p,m\rangle}, v_3^{\langle q?p,m\rangle}\}$

$R = \{ (v_2, v_3), (v_1, v_3)\}$.

Algorithm 1 $dgraph(t = (e_1, e_2 \ldots e_n))$

```
let $L \leftarrow V \leftarrow R \leftarrow \gamma \leftarrow \Sigma \leftarrow \emptyset$
/*Create Vertices */
for $i \leftarrow 1 \ldots n$ do
  if $e_i$ is a send event then
    $p!q, m \leftarrow e_i$
  else
    $p?q, m \leftarrow e_i$
  end if
  create new vertex $v_i$
  $\Sigma \leftarrow \Sigma \cup e_i$; $V \leftarrow V \cup v_i$
  if $p \notin L$ then
    $L \leftarrow L \cup \{p\}$
    /*$t_p$ stores projection of trace $t$ on to process $p$*/
    $t_p \leftarrow ()$
  end if
  $t_p.append(v_i)$; $\gamma \leftarrow \gamma \cup (v_i, e_i)$
end for
/*Add ordering within lifelines to $R$ */
for all $l \in L$ do
  let $(v_1, v_2 ... v_m) \leftarrow t_l$
  for $i \leftarrow 1 \ldots m - 1$ do
    $R \leftarrow R \cup (v_i, v_{i+1})$
  end for
end for
/* Add send receive pairs to $R$ */
for all $p, q \in L \wedge p \neq q$ do
  let $i \leftarrow |t_p|$; $j \leftarrow |t_q|$
  while $j > 0$ do
    if $t_q[j]$ is a receive event then
      let $q?p, m \leftarrow \gamma(t_q[j])$
      while $i > 0 \wedge \gamma(t_p[i]) \neq p!q, m$ do
        $i \leftarrow i - 1$
      end while
      if $i > 0$ then
        $R \leftarrow R \cup (t_p[i], t_q[j])$
      end if
    end if
    $j \leftarrow j - 1$
  end while
end for
return $(L, V, R, \gamma, \Sigma)$
```

3.2 MSC Mining

Using the function *dgraph*, the available trace set $T = \{t_1, t_2, \ldots t_n\}$ is converted to a set of dependency graphs $G = \{g_1, g_2, \ldots g_n\}$, where each dependency graph $g_i \in G$ corresponds to a scenario of system execution. Our next step is to identify basic sections within these graphs, that recur at several places within the same graph or across the graphs in G. Intuitively, these fundamental blocks are likely to capture the basic MSCs in an MSG describing the system. There are many possible ways to break down a graph into fundamental blocks. Our method aims to discover MSCs which are as big as possible and yet recurring frequently enough in the input execution traces (or their corresponding dependency graphs). Therefore, the notion of *Maximal Connected Dependency Graphs* (MCDs) to signify MSCs is introduced. Formally,

Definition 3.2.1 (MCD) *For a given trace set* $T = \{t_1, t_2, \ldots t_n\}$, $g_{mcd} = (V, R, \gamma)$ *is an MCD iff*

1. *There is a trace* $t \in T$ *such that* $g_{mcd} \subseteq \text{dgraph(t)}$.
2. *The total frequency of the MCD - freq*(g_{mcd}) *with respect to the trace set* T *is equal to the frequency of all its proper sub-graphs.*[1]
3. *For every distinct* $v_1, v_2 \in V$, $(v_1, v_2) \in (R \cup R^{-1})^*$.
4. *There is no graph* g' *that satisfies conditions 1-3 such that* $g_{mcd} \subset g'$.

Criterion 2 guarantees that no part of an MCD (and thus its corresponding MSC) appears in some context in which the rest of the MCD does not also appear. Criterion 4 enforces the maximality of MSCs. Criterion 3 requires that events in

[1]Given a trace set $T = \{t_1, t_2, \ldots t_n\}$, *freq*$(g)$ is the sum of the frequency of g in dgraph(t_1), dgraph(t_2), .. dgraph(t_n).

MCDs be connected with each other. This additional constraint is introduced to simplify the mining task.

An exhaustive search for graph structures that meet the conditions specified above could turn out to be expensive. Instead, a graph structure termed *event tail* is identified for each event, and then successively merged to arrive at dependency graphs that will satisfy the frequency, connectedness and maximality criteria of MCDs. Event tails and the method of merging graphs are described in the following sub-sections.

3.2.1 Event Tail

For an event $e \in \Sigma$, when given a trace set $T \subseteq \Sigma^*$, its tail, $tail[e]$, is the largest dependency graph that contains a single minimal vertex (which is a vertex in the graph without any associated incident edges) labelled e and satisfies conditions 1-3 of definition 3.2.1. Apart from the minimal vertex, it therefore contains all events that immediately follows every occurrence of e in a consistent partial order.

Algorithm 3 outputs an associative array - *tail*, that maps every event in Σ to its tail. For an event e and trace set T, T_e is the set of trace suffixes that start with e. T_e can be easily derived from a suffix tree[82] constructed from the trace set. From T_e we obtain a collection of suffix graphs, by identifying $dgraph(t_s)$ for every $t_s \in T_e$. In such a graph, let v_e be the vertex corresponding to the first occurrence of event e. All vertices v in the graph for which $(v_e, v) \notin R^*$ are removed as they do not belong to the tail. After this, the function *getCommonPrefix* is invoked to identify the largest prefix common to all suffix graphs in the collection for event e. This common prefix is the desired event tail $tail[e]$.

Operationally, function *getCommonPrefix* identifies the largest common prefix in a pair of dependency graphs g_1 and g_2 through a simultaneous breadth-first traversal over these two graphs. During the traversal, vertices and edges are gradually added to the largest common prefix g. A vertex v with label e is added to g if and only if 1) there are vertices v_1 in g_1 and v_2 in g_2 having a common label e, and 2) v_1 and v_2 have identical incident edges and all vertices from which there are edges incident to v_1, v_2 have already been added to g. In addition, *getCommonPrefix* ensures that all events added to the common graph have identical frequencies. All these operations ensure that conditions 1,2 and 3 of definition 3.2.1 are satisfied. Moreover, since the event tail is the maximal graph common to all suffixes with v_e as its minimal vertex, it has been ensured that 1) $tail[e]$ contains at least one vertex v_e, and 2) $tail[e]$ cannot be extended without violating conditions 1,2 or 3. Algorithm 2 presents the details of *getCommonPrefix*.

Algorithm 2 getCommonPrefix((V_1, R_1, γ_1), (V_2, R_2, γ_2))

Input: Two dependency graphs — (V_1, R_1, γ_1), (V_2, R_2, γ_2)
Output: The largest common prefix of the input dependency graphs — (V, R, γ).

```
1: let $v_1^s \in V_1$ s.t. $\forall v \in V_1 \Rightarrow (v_1^s, v) \in R_1^*$
2: let $v_2^s \in V_2$ s.t. $\forall v \in V_2 \Rightarrow (v_2^s, v) \in R_2^*$
3: Initialise $(V, R, \gamma), V \leftarrow R \leftarrow \gamma \leftarrow \emptyset$
4: queue$_1$.add([$v_1^s$]); queue$_2$.add([$v_2^s$])
5: while queue$_1 \neq \emptyset \wedge$ queue$_2 \neq \emptyset$ do
6:   $v_1 \leftarrow$ queue$_1$.remove(); $v_2 \leftarrow$ queue$_2$.remove()
7:   if $\forall v_1' \in V_1, (v_1', v_1) \in R_1 \Rightarrow v_1' \in V \wedge$
     freq($\gamma_1(v_1)$) = freq($\gamma_1(v_1^s)$) $\wedge \forall v \in V_1, \gamma_1(v) \neq \gamma_1(v_1)$ then
8:     $V \leftarrow V \cup \{v_1\}$, $\gamma \leftarrow \gamma \cup \{(v_1, \gamma_1(v_1))\}$
9:     $R \leftarrow R \cup \{(v_1', v_1) | (v_1', v_1) \in R_1\}$
10:    for all $v_1'', v_2''$ s.t. $(v_1, v_1'') \in V_1$, $(v_2, v_2'') \in V_2$ and $\gamma_1(v_1'') = \gamma_2(v_2'')$ do
11:      queue$_1$.add($v_1''$); queue$_2$.add($v_2''$);
12:    end for
13:  end if
14: end while
15: return $(V, R, \gamma)$
```

Figure 3.5 shows event tails derived from two sample traces from the banking system.

Algorithm 3 Find Event Tails

```
Input: $T$ - The trace set, $\Sigma$ - set of events appearing in $T$.
Output: $tail[e]$ that maps every event $e \in \Sigma$ to its tail.
 1: for all $e \in \Sigma$ do
 2:    Find $T_e$: the set of all suffixes(of traces in $T$) starting with $e$
 3:    let $T_e = \{t_{s_1}, t_{s_2}, \ldots t_{s_{n_e}}\}$
 4:    $tail[e] \leftarrow \emptyset$
 5:    for $i = 1 \ldots n_e$ do
 6:       $(V, R, \gamma) \leftarrow dgraph(t_{s_i})$
 7:       let $v_e$ be the vertex corresponding to event e
 8:       for all $v \in V$ s.t. $(v_e, v) \notin R^*$ do
 9:          $V \leftarrow V - \{v\}$
10:       end for
11:       if $tail[e] = \emptyset$ then
12:          $tail[e] \leftarrow (V, R, \gamma)$
13:       else
14:          $tail[e] \leftarrow getCommonPrefix(tail[e] , (V, R, \gamma))$
15:       end if
16:    end for
17: end for
```

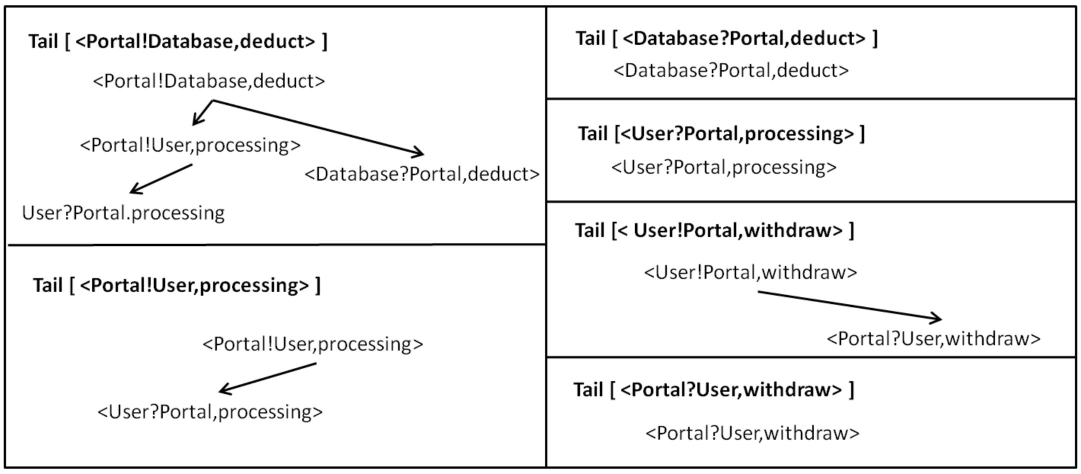


Figure 3.5: Sample traces and event tails for some events

3.2.2 Combining Event tails

Algorithm 4 uses the mapping from events to tails ($tail[e]$) to derive a mapping from events to MCDs - $MCD[e]$. The algorithm starts with $g_1 = tail[e]$. We know that tail e cannot be extended at the end as it is already maximal. Hence we attempt to grow g_1 by prefixing it with other graphs. For every event e' we verify if $tail[e']$ can be merged into g_1. Let $tail[e']$ be the graph g_2. Without loss of generality we can express the two tails as,

$g_1 \equiv g_1^{\text{pref}} \circ g^{\text{comm}}$ and

$g_2 \equiv (g_2^{\text{pref}} \circ g^{\text{comm}}) \circ g_2^{\text{suff}}$

where g^{comm} is the largest possible such graph. If g^{comm} is empty, we do not perform any merging. If g^{comm} is not empty, we obtain $g_2^{\text{pref}} \circ g_1$ as the merged graph. To satisfy the frequency criterion, we chose to accept the merged graph only when $\text{freq}(g_2^{\text{pref}} \circ g_1) = \text{freq}(g_1)$. When more than one prefix of g_2 satisfy the conditions on g_2^{pref}, we select the largest one.

The dependency graph g_1 is an MCD if no more event tails can be merged into it.

Theorem 1 *For every event e, the dependency graph $MCD[e]$ assigned by Algorithm 4 is an MCD.*

Proof: We have established that $tail[e_1]$ satisfies criteria 1-3 of definition 3.2.1. In line 3 of Algorithm 4, we initialize g_1 to $tail[e_1]$. To prove that dependency graph g_1 assigned to event e_1 in line 8 is an MCD, it is sufficient to prove the following:

1. *If g_1 satisfies criteria 1-3 and g_2 is an event tail, then $merge(g_1, g_2)$ also satisfies 1-3.*

   In line 5 of Algorithm 5, we ensure that $\text{freq}(merge(g_1, g_2)) = \text{freq}(g_1)$. Therefore $merge(g_1, g_2)$ must satisfy criterion 1. Since $g^{\text{comm}} \subseteq g_2$ and

g_2 satisfies criterion 2, it follows that $\text{freq}(g_2^{\text{pref}}) = \text{freq}(g^{\text{comm}}) = \text{freq}(g_1)$. $merge(g_1, g_2)$ satisfies criterion 2 as its frequency is equal to the frequency of its sub-parts.

Since g_2 is an event tail, either g_2^{pref} is empty or contains the minimal vertex. In both cases, $g_2^{\text{pref}} \circ g^{\text{comm}}$ is a connected graph. Since g_1 is already a connected graph, $merge(g_1, g_2)$ will remain a connected graph satisfying criterion 3.

2. *If there are no more events $e' \in W$ such that $tail[e']$ can be merged into g_1, then g_1 satisfies criterion 4.*

   If there is graph g_1' such that $g_1 \subsetneq g_1'$ and g_1' satisfies criteria 1-3, then it follows that there is at least one event e in g_1' and not in g_1 for which,

   (a) $g_e \circ g_1$ satisfies criteria 1-3 OR

   (b) $g_1 \circ g_e$ satisfies criteria 1-3.

   Where g_e is a graph containing a single vertex v_e labelled with event e.

   Case a: Assume that $g_1'' \equiv g_e \circ g_1 = (V_1, R_1, \gamma)$ satisfies criteria 1-3.

   Criterion 2 enforces that no two vertices have the same label. Therefore g_1 will not contain a vertex labelled with event e. Consider a graph g_1^{suff} such that, $g_1'' \equiv g_1^{\text{pre}} \circ g_e \circ g_1^{\text{suff}}$ and for every vertex $ving_1^{\text{suff}}$, $v_e R_1^+ v$. Clearly,g_1^{suff} is not empty (g_1'' is a connected graph) and $g_e \circ g_1^{\text{suff}}$ is a prefix of $tail[e]$ ($\text{freq}(g_e \circ g_1^{\text{suff}}) = \text{freq}(g_e)$). For some g^s, we therefore have:

   $g_1 \equiv g_1^{\text{pre}} \circ g_1^{\text{suff}}$

   $tail[e] \equiv (g_e \circ g_1^{\text{suff}}) \circ g^s$

   $\text{freq}(g_e \circ g_1) = \text{freq}(g_1)$

   The implies that $merge(g_1,\ tail[e]) \neq \epsilon$ and contrary to our assumption, g_e should already have been merged into g_1.

Case b: Assume that $g_1'' \equiv g_1 \circ g_e = (V_1, R_1, \gamma)$ satisfies criteria 1-3. Since g_1'' is a connected graph, there is a $v_{e'} \in V_1$ s.t, $v_{e'} \neq v_e$ and $v_{e'} R_1 v_e$. This implies that v_e is part of $tail[e']$. Let g (where $g \subseteq g_1$) be the value of g_1 when $tail[e']$ is merged into g_1. The merged graph will be $g_2^{\text{pref}} \circ g$, for the largest g^{comm}, such that

$g \equiv g^{\text{pref}} \circ g^{\text{comm}}$ and

tail$[e']$= $g_2 \equiv (g_2^{\text{pref}} \circ g^{\text{comm}}) \circ g_2^{\text{suff}}$

If v_e was part of g_2^{pref} or g^{comm} then v_e is already part of the merged graph. If v_e is part of g_2^{suff} it was discarded as it did not satisfy one of conditions 1-3. Both possibilities are contrary to our assumptions about g_1''.

Since we have ruled out the possibilities of a larger graph g_1', g_1 at the end of each iteration of the outer loop is maximal, and hence satisfies criterion 4.

□

Algorithm 4 Combine Event Tails

```
Input: $tail[e]$ for all events $e \in \Sigma$
Output: $MCD[e]$ for all events $e \in \Sigma$
1: for all $e_1 \in \Sigma$ do
2:     $W \leftarrow \Sigma - \{e_1\}$
3:     $g_1 \leftarrow tail[e_1]$
4:     while $\exists e_2 \in W$ s.t. merge($g_1$, $tail[e_2]$) $\neq \epsilon$ do
5:         $g_1 \leftarrow$ merge($g_1$, $tail[e_2]$)
6:         $W \leftarrow W - \{e_2\}$
7:     end while
8:     MCD[$e_1$] $\leftarrow g_1$
9: end for
```

Figure 3.6 shows the set of MCDs that are obtained by merging event tails obtained from traces in Figure 3.5.

Algorithm 5 merge(g_1, g_2)

```
Input: Candidates for merging $g_1$, $g_2$
Output: The merged graph. ($\epsilon$ if merge is not possible).
 1: Let $g^{\text{comm}}$ be the largest suffix of $g_1$ that is a sub-graph of $g_2$.
 2: if ($g^{\text{comm}}$ is empty) then
 3:    return $\epsilon$
 4: else
 5:    Find largest $g_2^{\text{pref}}$ that satisfies:
       $g_2 \equiv (g_2^{\text{pref}} \circ g^{\text{comm}}) \circ g_2^{\text{suff}} \wedge \text{freq}(g_2^{\text{pref}} \circ g_1) = \text{freq}(g_1)$
 6:    if no such $g_2^{\text{pref}}$ is found then
 7:       return $\epsilon$
 8:    else
 9:       return $g_2^{\text{pref}} \circ g_1$
10:    end if
11: end if
```

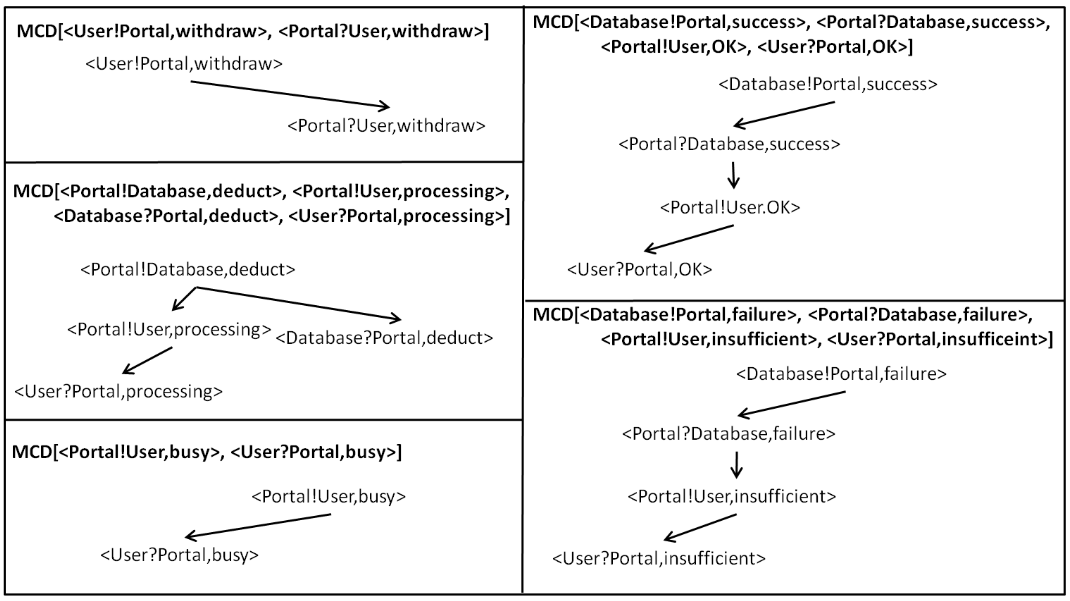

MCD[<User!Portal,withdraw>, <Portal?User,withdraw>]
<User!Portal,withdraw>
<Portal?User,withdraw>
MCD[<Portal!Database,deduct>, <Portal!User,processing>, <Database?Portal,deduct>, <User?Portal,processing>]
<Portal!Database,deduct>
<Portal!User,processing>
<Database?Portal,deduct>
<User?Portal,processing>
MCD[<Portal!User,busy>, <User?Portal,busy>]
<Portal!User,busy>
<User?Portal,busy>
MCD[<Database!Portal,success>, <Portal?Database,success>, <Portal!User,OK>, <User?Portal,OK>]
<Database!Portal,success>
<Portal?Database,success>
<Portal!User.OK>
<User?Portal,OK>
MCD[<Database!Portal,failure>, <Portal?Database,failure>, <Portal!User,insufficient>, <User?Portal,insuffliceint>]
<Database!Portal,failure>
<Portal?Database,failure>
<Portal!User,insufficient>
<User?Portal,insufficient>

Figure 3.6: MCDs obtained by combining tails

3.2.3 Converting trace to sequence of MSCs

Algorithm 4 associates each event with an MCD. Utilizing this association, we transform each trace from the given trace set into a sequence of dependency graphs. In order to achieve this transformation, we group events in a trace based on their associated MCDs. In a trace t, we represent each group of events by a dependency graph g_i and derive a sequence of the form $(g_1, g_2, \ldots g_i \ldots g_m)$ such that $dgraph(t) \equiv (g_1 \circ g_2 \ldots) \circ g_m$. Therefore the ordering of two dependency graphs is constrained by dependency relationships between events from one graph and events from the other.

Certain cases warrant special handling. Firstly, we may have derived two MCDs that share a common sub graph. For example, we may have $MCD[e_1] \equiv g_x \circ g$ and $MCD[e_2] \equiv g \circ g_y$. Since MCDs are maximal, we know that the merged graph $(g_x \circ g) \circ g_y$ must have a lower frequency that its sub graphs. In such scenarios, we will drop the common sub graph g from one of the MCDs. Secondly, two MCDs may not co-exist in a sequence as the dependency relationships constrain each other in a way that they can not be ordered. To resolve such cases, we split one of the MCDs into smaller parts whenever necessary. For example, consider two MCDs

$g_x = (\{v_1, v_2\}, \{(v_1, v_2)\}, \{(v_1, \langle p!q, m\rangle), (v_2, \langle q?p, m\rangle)\})$,

which represents a single message m from p to q, and

$g_y = (\{v_1, v_2\}, \{(v_1, v_2)\}, \{(v_1, \langle q!p, m\rangle), (v_2, \langle p?q, m\rangle)\})$

which represents message m from q to p.

For a trace $t = (\langle p!q, m\rangle, \langle q!p, m\rangle, \langle p?q, m\rangle, \langle q?p, m\rangle)$, it is clear that $g_x \subset dgraph(t)$ and $g_y \subset dgraph(t)$. However, we cannot represent trace t as a sequence of the two MCDs because $dgraph(t) \not\equiv g_x \circ g_y$ and $dgraph(t) \not\equiv g_y \circ g_x$. In such cases we represent t by splitting either g_x or g_y into smaller dependency graphs.

While we have defined MCDs as dependency graphs, we do not require them to correspond to 'complete MSCs'; *ie.*, there may exist a send event in an MCD which does not contain the matching receive event and vice versa. In order to guarantee that all vertices of an MSG denote complete MSCs, we concatenate successive partial graphs in a post-processing step to ensure that each dependency graph in the final sequence of MSCs will represent a complete MSC. Algorithm 6 performs this transformation. This step effectively relaxes the second criterion for MCDs that each MCD must be as frequent as every event occurring within it. This relaxation is applied only at instances where the MCDs are incomplete MSC specifications.

Algorithm 6 Convert to full MSCs

```
Input: gList - A sequence of dependency graphs
Input: $\psi$ - Input from User
Output: outputList - Corresponding sequence of MSCs
 1: outputList $\leftarrow$ [ ]
 2: temp $\leftarrow$ $gList[0]$
 3: for $i \leftarrow 1 \ldots gList.size()$ do
 4:    if temp has an unmatched send event then
 5:       temp $\leftarrow$ $temp \circ gList[i]$
 6:    else
 7:       outputList.add(temp)
 8:       temp $\leftarrow$ $gList$[i]
 9:    end if
10: end for
11: return outputList
```

At the end of this stage we have defined an alphabet of basic MSCs and produced strings from this alphabet for the construction of MSGs.

3.3 Constructing Message Sequence Graphs

There exists a choice of algorithms to learn a finite state machine (FSM) from a training set of strings [74, 22]. For experiments a variant of the *k-tails algorithm* described in [29] is implemented. A shared prefix tree is initially constructed from the set of MSC strings. The algorithm then identifies a set of nodes that are equivalent. Two nodes are considered equivalent if their *k-futures* match. The k-future of a node is simply the set of all valid paths of length k or less (if the end node is reached) starting from that node. Several possible heuristics have been suggested to match two sets of k-futures. For better precision one could insist on the match being exact. Other methods involve matching two sets of strings if they meet a certain probabilistic threshold. Equivalent nodes are merged to get a more general and compact model. During the merging process loops are introduced to the model. For a prefix tree with n nodes, since every pair of nodes are compared, the algorithm has a worse case execution time of $O(n^2m^k)$, where m is the size of the trace alphabet. For an operation comparing the k-futures of any two nodes, the maximum number of nodes to be compared is never greater than the total number of nodes in the tree. As a result, the algorithm has an execution time not worse than $O(n^3)$ for any value k. Note that n is shorter than the number of events in the initial traces as each frequent co-occurring maximal series of events has been identified and is represented using single nodes.

Once an MSG has been mined from traces using the FSM learner, it is refined through a series of state reduction steps. An FSM learner usually produces a Mealy model state machine which then has to be transformed into a minimal Moore model. In the latter state machine each state corresponds to a basic MSC. The final MSG is a structure-preserving homeomorphic embedding of the Moore model state machine. The general rule for reduction is that if any state s is reachable from one and only one state s' and s is the only state reachable from state s', then the MSC in state s can be concatenated to the MSC in state s'. This concatenation yields new basic MSCs. The reduced directed graph of basic MSCs is the final output. The MSG can be exported as image files for visualization.

3.4 Evaluation

We propose an evaluation technique to validate the mined model against a known correct model. The correct model is used only for evaluation and never part of the mining process. Given correct and mined models, we derive a precision and recall score by performing language comparison. As discussed before, concatenating basic MSCs along any path from a starting vertex to an accepting vertex in the MSG produces an MSC that represents a valid execution scenario. We say that such an MSC is *generated* by the MSG. *Precision* is defined as the number of MSCs generated by the mined model that are accepted by the correct model divided by the total number of MSCs generated by the mined model. Similarly *recall* is the ratio of the number of MSCs from the correct model that are accepted by the mined model to the total number of MSCs generated by the correct model. However, MSGs could generate an infinite number of such MSCs that themselves are of infinite length and it is not possible to enumerate all from one MSG and then verify them on the other. Instead we use only a finite sample from the MSG's language for evaluation. Our sample consists of all accepting paths in the MSG with a finite bound on loops. This bound is enforced by limiting the number of times any vertex is revisited in a path. For the dependency graph g corresponding to each MSC from the generating MSG, we verify if there is a path in the accepting MSG that forms a dependency graph identical to g. This is done by an efficient depth first search in the accepting graph. Due to the exponential nature of the number of paths, exploration of all paths within a loop bound of 3 was found to produce a substantial number of paths. On some specifications, the exploration could not be completed even with such a low bound. The experiments are performed with loop bound 3 whenever possible and bound 2 otherwise.

3.5 Comparing MSGs with Per-process Automata

Past studies have recommended automaton learning algorithms to discover specifications of system protocols in the form of state machines. These approaches have been shown to be successful in learning behavioral protocols for Application Programming Interfaces. In a distributed setting containing concurrently executing processes , automaton learning can not be applied directly to interleaved traces. This is because the mined model will not include all other possible interleavings that are also valid resulting in poor recall. Instead, automaton learning could be used to infer the state machine at each process. This can be done by separating the original traces into traces local to each of the constituent processes. The automaton for each process gives an idea about its interactions with the rest of the system components, thus providing a localized view of the system specification. In contrast, an MSG captures the collective behavioral specification of the system and presents a global view.

We compare the accuracy of our proposed approach with the accuracy of mining this alternative model from the same collection of traces. To do this, we derive a similar precision and recall score of the learnt automata with respect to the same correct MSG specification that was used to score the mined MSG. The algorithm used to learn automata is identical to the method used in the automaton learning phase of MSG mining (Section 3.3). Precision and recall for automata is measured as the ratio of the number of traces (rather than MSCs) generated from one model that is accepted by the other model to the total number of traces generated. We generate random sample of traces from the collection of automata. The parallel composition of the automata, may contain accepting paths that create invalid traces(eg: Receive event may appear before the message is sent). To generate only 'correct' traces we simulate the FIFO message channels between processes. While exploring a path in the composed automaton, if an edge outputting a send event $\langle p!q, m\rangle$ is chosen, the message m placed in the buffer corresponding to the channel $[p \to q]$. An edge outputting a receive event $\langle q?p, m\rangle$ can be explored only if message m can be removed from the front of buffer $[p \to q]$. A path explored in the composed automaton signifies a valid trace only when an accepting state is reached and all the message buffers are empty. We impose a bound on the number of loops as before.

3.6 Case Studies

The *MSGMiner* framework is evaluated through case studies involving real distributed systems. The following distributed systems were studied: (a) "Center TRACON Automation System" [67] an air traffic control system from NASA, (b) a system of server and VOiP clients communicating based on the Session Initiation Protocol (SIP) and (c) a system of Server and Clients that follow the XMPP Instant messaging and Chat protocol. In each of these systems, multiple processes perform asynchronous communication over TCP socket connections. Timestamped traces were collected by inserting instrumentation source code at points where messages are written to or read from a socket. The traces were filtered and the message names abstracted with the help of text processing scripts.

3.6.1 CTAS

CTAS is an Air Traffic Control system from NASA. The CTAS weather control logic specification [68] was one of the case studies recommended by the 3rd International Workshop on Scenarios and State Machines (SCESM04). CTAS is a distributed system having a central Communications Manager (CM) process to which *client* processes connect. The weather control specification details how clients should connect to CM and how a graphical user interface referred to as the weather control panel (WCP) ought to communicate with CM to update weather status. As access to the CTAS system is limited, we procure execution traces by implementing and executing a simulation of this system in Java. Our implementation is based on a formal specification of the system in Promela and high level HMSC that was developed by a fellow researcher. The process classes in this systems are CM, WCP and Client. CM and WCP are singleton classes.

3.6.2 Session Initiation Protocol

SIP is a signalling protocol used to establish, manage and terminate VoIP calls and multimedia sessions in general [10]. SIP clients interact with servers that perform the necessary call routing and function as gateways to the Public Switched Telephone Network(PSTN). We attempt to specify how clients should interact with their proxy server to achieve some of the basic call features. For this, we set up a system having three SIP clients connected to a single server. We use instrumented versions of *KPhone* [5] - a SIP client implementation and the *Opensips* server [8] both of which are available with source code under a GPL license. We execute a set of test cases involving features such as basic call setup, call screening and call forwarding. A set of test cases for each feature are identified and a trace set is prepared by executing them on the system. The system contains two process classes - Server and Client. The specifications were derived for cases involving just a single server.

3.6.3 XMPP

Extensible Message and Presence Protocol is an open Instant Messaging standard originally developed by the Jabber open source community. The core functionality of the protocol is specified in RFCs 3920 and 3921. XMPP is the protocol for exchange of instant chat messages and presence information between various entities in a network that are addressed by unique jabber ID. The clients communicate to the server through structured XML messages. The protocol defines how XML nodes known as stanzas are to be exchanged between various entities. A client connecting to a server is authenticated through TLS or SASL through special XML stanzas. We attempt to discover the client server interaction protocol from a system having two jabber clients that are brokered by a single server. In the specification, the server and client processes are the lifelines and the message arrows represent the XML stanzas. The *Openfire* XMPP server [4] and Jeti [3]/Pidgin [9] client implementations were instrumented and executed for trace collection. For discovering the core specification as an MSG, we only record stanzas used for authentication or those having a *message* or *presence* tag and ignore rest of the message exchanges.

In addition to the core specification, XMPP Standards Foundation (XSF) has standardized several additional chat features. We attempt to mine behavioral specification for the Multi User Chat(MUC) functionality [14]. For this we use a separate set of test cases involving features such as service discovery, multi-party chat and creation and administration chat rooms.

In the XMPP system the process classes are Server and Client. Configurations involving a single server and multiple clients are studied.

The mining framework is evaluated by comparing various specifications against a correct hand derived specification. To evaluate the proposed technique for mining MSGs against techniques that mine FSM based models (per-process automata) we compare both specifications against a specification that is considered to be accurate. The correct specifications are also represented as MSGs. For mining MSG specifications we obtain traces from a pre-defined configuration of the system. The number of processes involved in every execution is fixed and behavioral similarity is avoided. This is done by restricting the system to contain only one process from each process class or by defining different roles for processes from the same process class. The restrictions enforced for trace collection in this evaluation is as follows:

- **CTAS:** The execution traces and correct specifications assume that there is only a single client in the system.
- **SIP:** The test cases involve three clients or SIP user agents labelled as Alice, Bob and Carol whose roles were restricted in the following manner. In all test cases, Alice initiates calls and Bob is the intended recipient. Features such as call screening or forwarding are enabled at the client Bob. Carol is the recipient of diverted calls.
- **XMPP:** The order of client login is the same in all executions. Only the client labelled *Client1* can initiate chat rooms thereby acquiring the role of chatroom administrator.

The subjects were made to execute random test scenarios with these restrictions. It was ensured that all the interactions appearing in the correct specification were also executed in at least one of the test cases. In each case a specification(that reflects allotted client names and roles) was manually derived by the author for quantitative analysis and comparison. In each case, both types of mined models are derived from the same set of input traces and compared against the same correct specification. Table 3.1 tabulates the results from the case studies. It shows the precision, recall and F_1 measure(harmonic mean of precision and recall) of the mined models obtained from the two alternatives (automaton learning and MSG Mining) for each case study. The mining was performed on a JVM running on an Intel duo core CPU with 1GB of available memory. The results from the systems considered for case study suggest that the proposed MSG mining method provides better mining accuracy.

System	No: of events	Mined Automata				Mined MSG			
		Prec	Rec	F_1 Score	Time (s)	Prec	Rec	F_1 Score	Time (s)
SIP	1870	0.50	1	0.67	1.0	0.78	0.87	0.82	3.14
XMPP-Core	3212	0.72	0.44	0.55	8.3	1	0.71	0.83	10.2
XMPP-MUC	5736	1	1	1	22.0	1	1	1	28.7
CTAS	6418	0.95	1	0.97	48.1	1	1	1	45.8

Table 3.1: Table comparing accuracy of mining for MSG and Automata specifications

The MSG mined from the traces collected from the CTAS system is shown in Figure 3.7.

Our mining on the CTAS system succeeds in identifying the states of the system that are mentioned in the informal requirements documents [68]. The narrative in sub-sections of the document matches neatly with the visual representation provided by the basic MSCs.

3.7 Extensions

The semantics of MSCs as per definition 2.3.1 accounts for only a basic subset of the standardized MSC syntax. The framework described in this chapter discovers specifications in this restricted language. The following sections describe how some of these restrictions in the specification language can be removed through minor modifications to the mining framework.

3.8 Parallel Composition in MSCs

In Definition 2.3.1, it is assumed that events within a lifeline follow a strict total order. In specifying certain systems, it may be simpler to prescribe partial order on events even if they belong to the same lifeline. For example, a process may

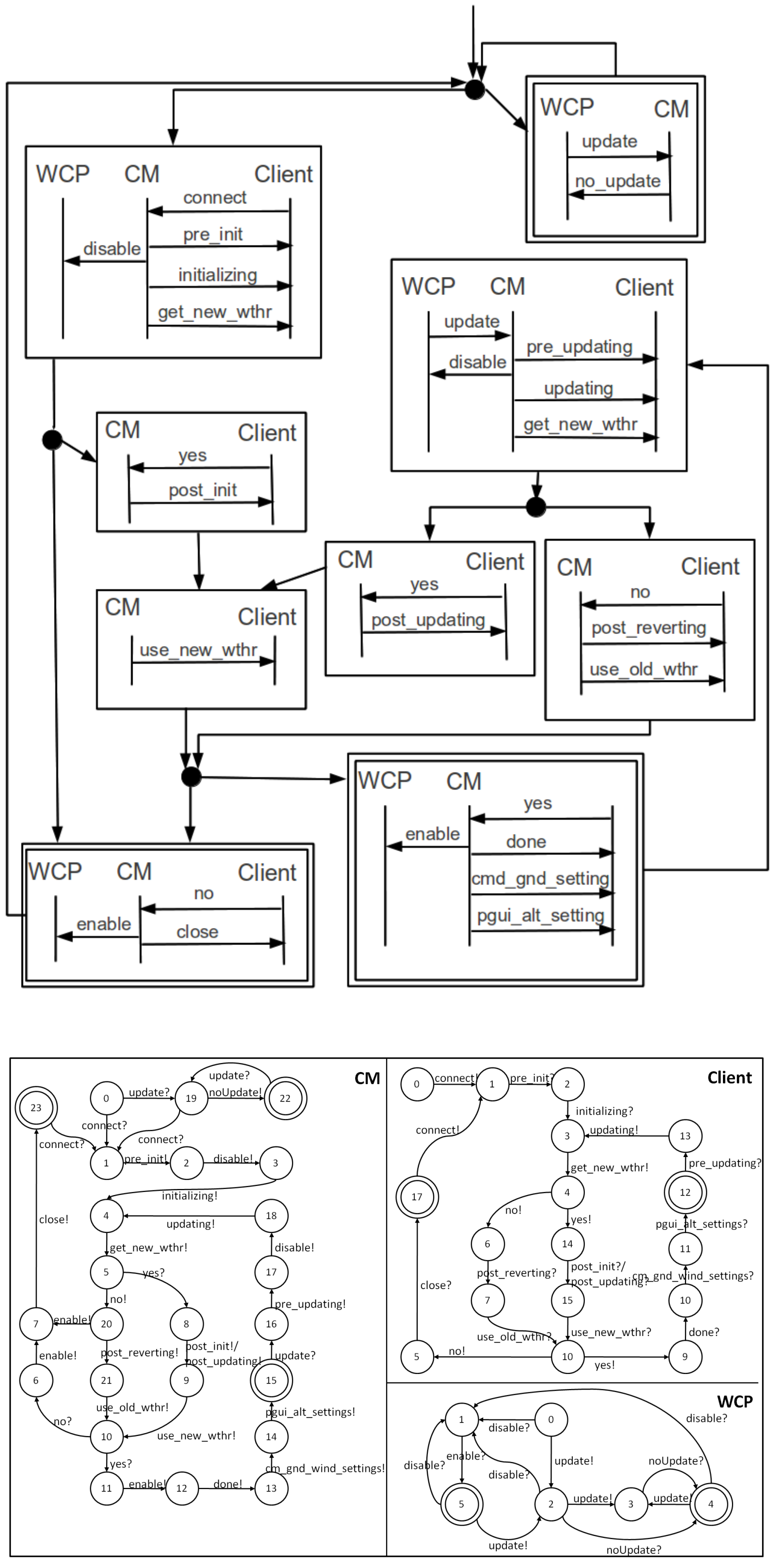


Figure 3.7: The Mined MSG for CTAS (top) and the learnt automata for individual processes

broadcast messages to multiple processes and await responses from its audience. We refer to such instances as “message broadcasts”. During message broadcasts, the order in which the messages are dispatched to individual recipients or that in which responses are received at the broadcasting lifeline is usually inconsequential. Furthermore, the actual order of events seen in traces may be different for each realization of such broadcasts. Without knowledge of “message broadcasts”, the mining procedure presented thus far fails to produce a succinct and comprehensible MSG. Instead it will interpret different ordering of events as distinct interactions and depict them using distinct basic MSCs.

MSC semantics [6] provide features such as *coregions* or the *par* inline expression to capture situations where there may be no specific logical ordering between some events within a lifeline. The *par* expression allow us to list a group of MSCs and imply that they are to be executed in parallel. With these constructs, a single basic MSC can explain all valid interactions during the message broadcast scenario.

Since situations like message broadcasts are specific to certain systems, the framework is extended to accept an additional input that declares specific behavior. This additional input is termed as an *oracle*. By designing the mining framework in this manner, the core mining methodology remains generic while domain specific information regarding the system being mined can be provided as input. The oracle for instance can inform the framework that certain events within a lifeline need not be ordered. Based on this information, the framework will construct customized dependency graphs and identify MCDs that capture such scenarios; the MSGs produced by the extended system become less cluttered and much more comprehensible.

While constructing a dependency graph, the framework can consult the oracle on whether a dependency edge must be created between a given pair of events from a lifeline. An oracle that returns true for all queries causes *MSGMiner* to behave as per our original description. To handle special cases like message broadcasts, the oracle can be customized based on the domain knowledge of users or automatically created based on external static or dynamic analyses. Algorithm 7 is a modified version of Algorithm 1 that converts traces to dependency graphs based on an oracle $\psi : \Sigma \times \Sigma \rightarrow \{\text{true, false}\}$ that answers queries regarding dependency between pairs of event labels. Algorithm 1, in lines 19 - 24 creates a total order of events in each lifeline. In Algorithm 7, edges between events within a lifeline are added only if the oracle answer with *true*.

Algorithm 7 $dgraph(t = (e_1, e_2 \ldots e_n), \psi)$

```
let $L \leftarrow V \leftarrow R \leftarrow \gamma \leftarrow \Sigma \leftarrow \emptyset$
/*Create Vertices */
...
/*Add ordering within lifelines to R */
for all $l \in L$ do
  let $(v_1, v_2 ... v_m) \leftarrow t_l$
  for $i \leftarrow 2 \ldots m$ do
    $j \leftarrow i$
    while $j > 0$ do
      if $\psi(v_j, v_i) = true \wedge \forall v_k \in V : (v_j, v_k) \notin R^+ \vee (v_k, v_i) \notin R^+$ then
        $R \leftarrow R \cup (v_j, v_i)$
      end if
    end while
  end for
end for
/* Add send receive pairs to R */
...
return $(L, V, R, \gamma, \Sigma)$
```

Figure 3.8 shows an example of broadcasts in the CTAS system (Section 3.6.1) with two clients connected to the CM. The CM, requests and receives responses from the two clients simultaneously. The figure also shows the dependence graph corresponding to this MSC. Although events

$\langle$*CM!Client1.get_new_wthr*$\rangle$ and $\langle$*CM!Client2.get_new_wthr*$\rangle$ belong to the same lifeline, there is no edge between their corresponding vertices in the dependency graph.

It can be tedious for the user to define the oracle by specifying the depen-

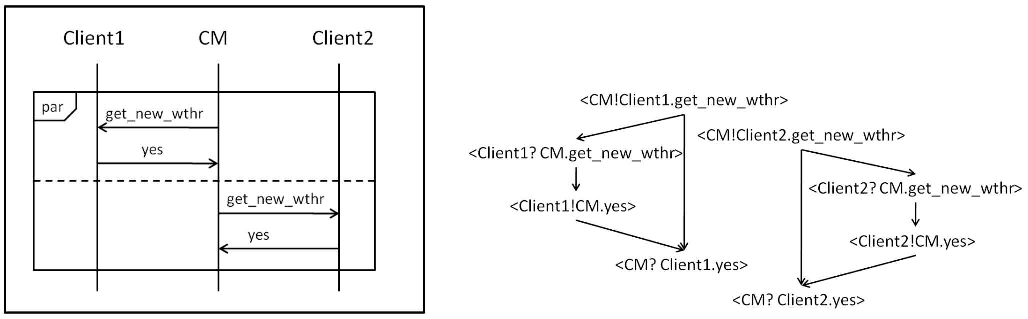


Figure 3.8: MSC and dependency graph describing broadcast message in CTAS system.

dency between every pair of events. It is easier to indicate event pairs which are exceptions to the default rule and for the oracle to be constructed automatically. For broadcast messages, it is sufficient for the user to specify a pair of the form (m_{req}, M_{resp}), where m_{req} is a broadcast message and M_{resp} is the set of response messages that m_{req} evokes ($M_{resp} = \emptyset$ when there are no responses). With this information, an oracle is constructed, to return true for all pairs (e_1, e_2) with the following exceptions:

1. $\gamma(e_1) = \langle p!q_1, m_{req}\rangle \wedge \gamma(e_2) = \langle p!q_2, m_{req}\rangle \wedge q_1 \neq q_2$
2. $\gamma(e_1) = \langle p?q_1, m_1\rangle \wedge \gamma(e_2) = \langle p?q_2, m_2\rangle \wedge q_1 \neq q_2 \wedge m_1, m_2 \in M_{resp}$
3. $\gamma(e_1) = \langle p!q_1, m_{req}\rangle \wedge \gamma(e_2) = \langle p?q_2, m_2\rangle \wedge q_1 \neq q_2 \wedge m_2 \in M_{resp}$

The first exception states that there is no dependency between two send events from the same lifeline p, if the message being sent is m_{req} and it is being sent to different lifelines. The second exception states that two receive events at a lifeline have no dependency if they arrive from different process and are both responses to a broadcast. The third exception enforces there be no dependency between a send of a broadcast message to a process and the receipt of one of its responses from some other process.

Using the dependency graphs created based on these rules and exceptions, MCDs are identified. Before automaton learning, it should be ensured that for each scenario given by $G = (V, R, \gamma)$, if two adjacent events e_1, e_2 belong to the same lifeline l, and they are not dependent i.e. $(e_1, e_2) \notin R^+$, then e_1 and e_2 must be grouped under the same basic MSC. This is because the definition of MSC concatenation dictates that every event in a lifeline from the first MSC should occur before the events of the same lifeline in the next MSC. Algorithm 6 can be modified to Algorithm 8 (in line 5 to account for user defined dependency relations. $Last_l(g)$ refers to the set of events in lifeline l that have no outgoing edges in dependency graph g. Similarly $First_l(g)$ refers to the set of events in lifeline l that have no incoming edges in dependency graph g. Note that besides Algorithms 1 and 6, none of the remaining algorithms for mining MSG Specifications need to be modified.

Algorithm 8 Convert to full MSCs

```
Input: $gList$ - A sequence of dependency graphs
Input: $\psi$ - User defined oracle
 1: Let $L$ - Set of lifelines appearing in $gList$
Output: $outputList$ - Corresponding sequence of MSCs
 2: outputList ← [ ]
 3: temp ← $gList[0]$
 4: for $i \leftarrow 1 \ldots gList.size()$ do
 5:     if temp has an unmatched send event $\vee$
        $\exists l \in L, v_1 \in Last_l(temp), v_2 \in First_l(gList[i])$ s.t.
        $\psi(\gamma_{\text{temp}}(v_1), \gamma_{\text{gList[i]}}(v_2)) = false$ then
 6:         temp ← $temp \circ gList[i]$
 7:     else
 8:         outputList.add(temp)
 9:         temp ← $gList$[i]
10:     end if
11: end for
12: return outputList
```

After automaton learning, the dependency graphs at the nodes of the MSG have to be converted to the visual formalism of MSCs. The ITU MSC standards documentation specifies the syntax of the "par" expression. Support for a simpli-

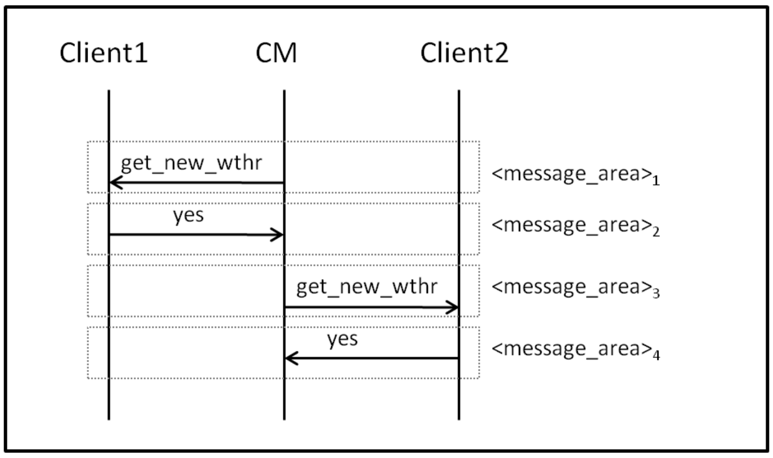


Figure 3.9: Message areas in the CTAS system example.

fied version of this has been implemented in the mining framework.

Let $\langle \mathit{message\ area} \rangle$ represent a visual region of the MSC that does not contain any par expressions. We can define an MSC containing par expressions $\langle \mathit{msc\ area} \rangle$ in the following manner.

$$\boxed{\begin{array}{ll} \langle \mathit{msc\ area} \rangle ::= & \langle \mathit{message\ area} \rangle \\ & \mid (\ \langle \mathit{msc\ area} \rangle\ ) \\ & \mid \langle \mathit{msc\ area} \rangle\ \langle \mathit{msc\ area} \rangle \\ & \mid \langle \mathit{msc\ area} \rangle \mid\mid \langle \mathit{msc\ area} \rangle \end{array}}$$

$\langle \mathit{msc\ area} \rangle\ \langle \mathit{msc\ area} \rangle$ represents one region above the other and $\langle \mathit{msc\ area} \rangle \mid\mid \langle \mathit{msc\ area} \rangle$ shows two regions that are in parallel. For example, the MSC in Figure 3.8 is syntactically equivalent to

$(\langle \mathit{message\ area} \rangle_1\ \langle \mathit{message\ area} \rangle_2) \mid\mid (\langle \mathit{message\ area} \rangle_3\ \langle \mathit{message\ area} \rangle_4)$

where $\langle \mathit{message\ area} \rangle_1$, $\langle \mathit{message\ area} \rangle_2$, $\langle \mathit{message\ area} \rangle_3$ and $\langle \mathit{message\ area} \rangle_4$ are the regions shown in Figure 3.9.

Let us assume that for a dependency graph g that has total ordering within its lifelines, we have function $msc(g)$ to determine the corresponding $\langle \mathit{message\ area} \rangle$

in a straightforward manner. The function *getEventArea()* in Algorithm 9 converts a dependence graph g to an $\langle$*msc area*$\rangle$ containing parallel regions. The algorithm identifies E_{max}, a set of events that have to be placed in distinct parallel regions as they are from the same lifeline but not dependent. If the set is a singleton, then there are no parallel regions and the graph is converted to $\langle$message area$\rangle$ as before. If there are non-dependent events in the same lifeline, then vertices of g are partitioned into sets. Each parallel block $\langle\text{message area}\rangle_i^{par}$ is formed from the events in the partition V_i^{par}. In the implementation of the algorithm, it is also ensured that if a send event belongs to a message area, then its corresponding receive event is also contained within the same message area.

Algorithm 9 getMSCArea(g)

```
Input: $(V, R, \gamma) \leftarrow g$
1: let $E_{max} = \{e_1, e_2 \ldots e_n\}$ be the largest set of events from the same lifeline s.t.
   $e_i \in E_{max} \wedge e_j \in E_{max} \Rightarrow (e_i, e_j) \notin R^* \vee e_i = e_j$.
2: if $n < 2$ then
3:     /*g has no parallel blocks */
4:     return $msc(g)$
5: else
6:     /* Split $V$ into $n + 2$ blocks*/
7:     let $V^{pre} = \{e | e \in V \wedge \forall e_i \in E_{max}, (e_i, e) \notin R^*\}$
8:     $\langle\text{msc area}\rangle^{pre} \leftarrow \text{getMSCArea}((V^{pre}, R, \gamma))$
9:     for all $e_i \in E_{max}$ do
10:        let $V_i^{par} = \{e | e \in V \wedge (e_i, e) \in R^* \wedge \forall e_j \in E_{max}(e_j = e_i \vee (e_j, e) \notin R^*)\}$
11:        $\langle\text{msc area}\rangle_i^{par} \leftarrow \text{getEventArea}((V_i^{par}, R, \gamma))$
12:    end for
13:    let $V^{post} = V - V^{pre} - (V_1^{par} \cup V_2^{par} \ldots V_n^{par})$
14:    $\langle\text{msc area}\rangle^{post} \leftarrow \text{getMSCArea}(V^{post}, R, \gamma)$
15:    return $\langle\text{msc area}\rangle^{pre}$ ($\langle\text{msc area}\rangle_1^{par}$ || $\langle\text{msc area}\rangle_2^{par}$|| ... $\langle\text{msc area}\rangle_n^{par}$)
       $\langle\text{msc area}\rangle^{post}$
16: end if
```

This method can be used to convert dependency graph to basic MSCs for the case of message broadcasts. For the CTAS system with two connecting clients, it was found that providing the list of broadcast messages reduced the number of states in the MSG from 60 to 36. There was no loss in precision or accuracy of the mined specification.

A formal grammar is envisioned in which users can contribute domain specific information about the system being studied. The information, can then be automatically passed on to the Mining framework as the oracle. The user may enter this information based on the results from one cycle of mining. Such an interface also entertains the possibility of feeding discoveries from other automated analyses into the MSG mining framework to improve overall comprehension.

3.9 Message Loss

MSC specifications also permit depiction of lost messages. Presently our algorithm requires perfectly matched send or receive events in traces. However it may be unreasonable to have this restriction in some systems, where system behavior in the case of message loss has to be specified. It is possible to encounter execution traces where a send message event occurs but the corresponding receive is not encountered. The existing framework can be made to tackle lost messages by preprocessing the traces and identifying scenarios where a send event does not have a corresponding receive event. In general, a send and receive pair from process p to process q can be modelled as an interaction between three processes p, q and c_{pq}, where c_{pq} is an imaginary intermediate process depicting the FIFO channel or buffer between p and q. A message event pair $\langle p!q.m \rangle$ and $\langle q?p.m \rangle$ can be represented by four events, $\langle p!c_{pq}.m \rangle$, $\langle c_{pq}?p.m \rangle$, $\langle c_{pq}!q.m \rangle$ and $\langle q?c_{pq} \rangle$. Once traces are represented in this way, a lost message can be depicted by the presence of the pair $\langle p!c_{pq}.m \rangle$, $\langle c_{pq}?p.m \rangle$ without the latter pair of events. The mining framework can proceed as before on the enlarged traces by taking the additional precaution to make sure all four message events derived from a message passed between two processes should be contained within a basic MSC. At the end, when the output is presented, the imaginary processes can be hidden and lost messages can be depicted using special symbols prescribed by the MSC syntax.

The frawework proposed in this chapter analyzes interactions between a set of processes and infers the full set of behaviors that those processes are likely to exhibit. This set of behaviors is presented in the form of an MSG. An important limitation of this approach is the restrictions places on the test executions and output model, such the number of processes present in the system and the role that each process plays. Chapter 4 discusses these limitations in greater detail and offers a solution this is based on the *MSGMiner* framework that is described here.

Chapter 4

Inferring Class Level Specifications

4.1 Introduction

Many real distributed systems contain a large number of processes running on several computers. Each process in such systems has its independent flow of control, thereby being programmed as an active object. Typically, these processes belong to one of a finite number of classes. As an example, consider a telecommunication system with many phones and switches. Depending on the level of sophistication of the telecommunications software - the phone and switch objects could exhibit many snippets of behavior such as three way calling, call forwarding and call waiting. However, the exact identities of the phone/switch objects participating in such behavior are not important for comprehending the overall system behavior. Instead, the system behavior can be understood at the class level - the behavior of the *class* of phones, and the *class* of switches. The processes belonging to the same class execute the same code or are various implementations of a generic object specification. In application domains such as telecommunications, when system behavior in the form of inter-process interaction is expressed using MSCs or sequence diagrams, class-level specifications are used [63, 40, 64].

In a class-level specification a lifeline may represent a single process or the "collective" behavior of an entire class of objects. Class level interaction is abstracted by describing them using *symbolic* actions. While concrete actions are performed by a specific concrete process, a symbolic action is performed by a process class. Here, an action involving a process class is specified using a symbolic formula that constraints the exact manner in which processes of that class participate. Abstracting specifications in this manner simplifies the global specifications significantly thereby making them more comprehendable. This is because a behavior specified at the class level summarizes a large set of corresponding concrete behaviors. Class level specifications are also easier to verify as it allows a large set of execution paths to be simultaneously explored in a symbolic manner.

4.2 Class Level Behavior

The inference of class level specifications requires a process of grouping observed concrete behavior based on behavioral similarity and then describing the behavior of these groups using symbolic actions. Ideally, the inferred symbolic specification will also accept additional concrete behavior that is similar to the observed behavior but not exactly the same. To appreciate how the presence of process classes entails similarity of concrete behavior, consider a simple system consisting of a server s and clients $c_1, c_2, \ldots c_n$. Consider the following informal description of the system:

"when client c_1 sends message *update* to server the server shall respond to c_1 with message *ack*".

If this were true of any client then n concrete specifications could be replaced with a single class level specification:

"when *any* client sends message *update* to server, the *same* client shall receive the response *ack* from server".

This statement specifies the class level behavior of the class of clients in the system. The term *any* is used to suggest that it applies to any client and *same* to suggest the exchange involves just one client at a time.

We can also have a class level specification even when more than one processes of the same process class are part of an interaction. For instance assume client c_2 presently controls a resource that client c_1 requests. We can envisage a concrete interaction of the form : "when client c_1 sends message *request* to server it shall forward *request* to c_2. When c_2 sends *release* to server, it shall send *grant* to c_1". As any two clients may be involved in such an interaction, there are n^2 concrete behaviors that are similar to the one described above [1]. We can represent the interaction using the following class level specification: "when *any* client sends *request* to server, it shall forward *request* to the client that controls resource. When the client controlling resource sends *release* to server, it shall send *grant* to the client that sent *request*". This class level specification specifies exactly the set of n^2 concrete interactions. Class level specification can therefore precisely describe large number of concrete behaviors in a simple manner. As can been seen in the example above, the class level specification contextualizes interactions using conditions such as *client that controls resource* and *client that requested resource* making it resemble informal descriptions.

Finally, symbolic actions can also be used to represent group actions performed by multiple members with a process class. Concrete behaviors of the form "If the client c_1 sends *change* to server, it shall send message *update* to $c_2, c_3, \ldots$ and c_n", can be replaced with the class level specification: "If any clients sends *change* to

[1]For simplicity we assume a client can request even if it already has control

server, it shall *broadcast update* to *all other* clients". The term broadcast suggests that the same action is repeated with respect to multiple clients in the process class. In all the class level specifications above, the number of clients in a class (n), is not explicitly specified. This is an important advantage as the specification is equally valid for a system with any number of clients.

4.3 Formal Specifications

In this chapter, the inference of class-level specifications in the formal language of Symbolic Message Sequence Graphs, a graph of symbolic Message Sequence Charts [79] is considered. As an example, Figure 5.1(a) shows a Message Sequence Chart (MSC) that describes interactions between multiple devices having a shared bus as is typical in a bus architecture like PCI (Peripheral Component Interconnect). The bus master broadcasts the address (*addr*) of the intended target device by placing it in the bus and all connected devices decode it. Only one of the devices responds by asserting a control signal (*ack*). This MSC description is specific in that it addresses a unique scenario in which there are exactly three connected devices and when the intended target device is $Target_2$. The specification in Figure 5.1(b) stands for a generic interaction between a Master device and the *class* of target devices and therefore is a parameterized version of the original specification. In this *Symbolic* Message Sequence Chart (SMSC) [79], message communication events are symbolic actions that have annotations specifying the exact nature of the interaction. The guard $\forall true$ signifies that the message "addr" is intended for all target devices. The guard $\exists_1 ends(addr)$ makes it a requirement that exactly one of the devices that have received "addr" will respond with "ack".

The major technical difficulty in the mining process is to infer the *guards* of the events involving several behaviorally similar processes (or active objects) in

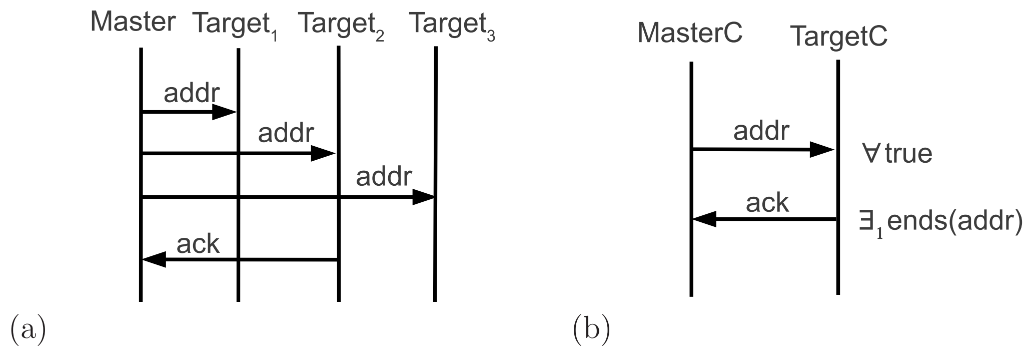


Figure 4.1: Concrete and Symbolic Message Sequence Charts describing interactions in a computer bus

a class. Such guards can be seen as "object selectors" — they select a subset of objects from the set of objects in a class of processes. Instead of specifying such an object selector (as one would do in distributed system modeling), object selectors are automatically inferred from the system execution traces. Mined object selectors are less general, easy to comprehend and accurately match the positive and negative observations as seen in the system execution traces.

The following subsections define the distinction between object-level concrete events and class-level symbolic events. The characteristics of symbolic events are also defined.

4.3.1 Concrete Events

It is assumed that the real system being analyzed has a finite set of processes – P. We shall refer to these processes as concrete processes of the system. The term *Concrete Event* is used to refer to an atomic action executed by any concrete process in the system. A concrete event is either an internal action $(\langle p, m\rangle, s_p)$ or an external action $(\langle p \oplus q, m\rangle, s_p)$ where,

- $p \in P$ is the *main* concrete process to which this event is associated.
- $\oplus \in \{!, ?\}$ is an action type: *send* (!) or *receive* (?).
- m is an action label,

- $q \in P$ is a counterpart process.
- s_p, the current state of process p,

In a message passing context, $\langle p!q, m\rangle$ can be used to depict the event in which p sends message m to q and $\langle q?p, m\rangle$ for the event in which q receives message m from p. The current state s_p is captured using $\{\ldots, (p.x_j, v_j), \ldots\} \bigcup \{(h_p, v_h)\}$. Here, $p.x_j$ refers to a process variable and v_j refers to its corresponding value. The variable h_p refers to the local *execution history* or simply history of p when it is at state s_p. It is the sequence of actions executed by p prior to reaching s_p. For example, the sequence of events $\big((\langle p, m_1\rangle, s_p^1), (\langle p!q, m_2\rangle, s_p^2),\ (\langle p?q, m_3\rangle, s_p^3)\big)$ represents an execution history of the concrete process p at state s_p.

4.3.2 Process Classes

The mining of class-level specifications relies on a classification of processes in the system being analyzed. Formally, process classification is a surjective function $\Gamma : P \rightarrow \mathcal{P}$, from a set of concrete processes to $\mathcal{P}$ which is a set of process class labels. For $\tilde{p} \in \mathcal{P}$, we shall use the notation $\Gamma^{-1}(\tilde{p})$ to refer to the set of concrete processes having class label $\tilde{p}$. We assume that our analysis has prior knowledge of the classification of concrete processes. It is of the case that the same source code is executed by behaviorally similar processes in a distributed system. Even in other cases it is usually possible to group processes in a system into classes of behaviorally similar processes such as group of clients or the group of devices.

4.3.3 Symbolic Events

Class level specifications contain actions that are attached to a process class without being specific about the concrete processes that perform it. We refer to such class level actions as *symbolic events*, and these are the subjects which we shall infer.

A symbolic event is of the form $(\langle \tilde{p} \oplus \tilde{q}, m\rangle, \mathcal{Q}.g)$ $((\langle \tilde{p}, m\rangle, \mathcal{Q}.g)$ for internal events). Here, $\tilde{p} \in \mathcal{P}$ is the process class to which the action is associated and $\tilde{q} \in \mathcal{P}$ its counterpart. A symbolic event signifies the abstraction of a set of concrete events at one or more concrete processes belonging to the same process class. The set of concrete events share the same label m and (external) action type $\oplus$. The manner in which concrete processes may collectively participate in a symbolic event is specified through a quantified predicate $\mathcal{Q}.g$ that is referred to as its *guard*. For a concrete process $p \in \Gamma^{-1}(\tilde{p})$, $g : S_{\tilde{p}} \rightarrow \{true, false\}$ is a predicate on $S_{\tilde{p}}$, the set of all states of a process in $\tilde{p}$.

Definition 4.3.1 (Process Selection) *For a process class $\tilde{p}$, a process selection is a predicate $\sigma : \Gamma^{-1}(\tilde{p}) \rightarrow \{true, false\}$ on the set of its concrete members.*

Definition 4.3.2 (Process Class Context) *The context of a process class $\tilde{p}$ is a function $\theta : \Gamma^{-1}(\tilde{p}) \rightarrow S_{\tilde{p}}$ that returns the state of each concrete member of that class.*

The quantifier $\mathcal{Q}$ in $\mathcal{Q}.g$ specifies the number of concrete processes satisfying the predicate g that may participate in the symbolic action. It takes the form of one of the following: $\exists$, $\forall$, $\exists_k$ or $\forall_k$. The interpretation of the guard, denoted by $\mathcal{Q}.g(\sigma, \theta)$, is as follows.

1. $\exists.g(\sigma, \theta) \Leftrightarrow \forall p \in \Gamma^{-1}(\tilde{p}) : \sigma(p) \Rightarrow g(\theta(p)) \wedge\ |\sigma^{-1}(true)| \geq 1$

2. $\forall.g(\sigma, \theta) \Leftrightarrow \forall p \in \Gamma^{-1}(\tilde{p}) : \sigma(p) \Leftrightarrow g(\theta(p))$

3. $\exists_k.g(\sigma, \theta) \Leftrightarrow \forall p \in \Gamma^{-1}(\tilde{p}) : \sigma(p) \Rightarrow g(\theta(p)) \wedge |\sigma^{-1}(true)| = k$

4. $\forall_k.g(\sigma, \theta) \Leftrightarrow \forall p \in \Gamma^{-1}(\tilde{p}) : \sigma(p) \Leftrightarrow g(\theta(p)) \wedge |\sigma^{-1}(true)| = k$

The number of processes selected by σ is given by $|\sigma^{-1}(true)|$. Informally, the guard $\exists.g$ permits any combination of one or more processes in the class that satisfy g to participate in the action. The guard $\exists_k.g$ allows combinations of exactly k processes that satisfy g to participate. The guard $\forall.g$ requires the participation of all processes satisfying g. Finally, $\forall_k.g$, requires that exactly k processes satisfy g and that all of them be involved in the action. In this work, we opt for selecting processes for participation in the action based on the histories of the processes. The format of g thus characterizes the histories of the selected processes. We defer the details to Section 2.7.

4.3.4 Process Class Constraints

In addition to using symbolic actions, class level specifications may assert how a process class should behave as a whole. We identify two such process class constraints: "$all(g)$" and "count(g) op k", where op can be either "=" or "$\geq$". We consider the following process class constraints: "$all(g)$" and "$count(g)\, op\, k$". These predicates over the set of contexts of a process class $\tilde{p}$ are interpreted as follows as follows:

1. $[\![all(g)]\!](\theta) \Leftrightarrow \forall p \in \Gamma^{-1}(\tilde{p}) : \; g(\theta(p))$

2. $[\![count(g)\, op\, k]\!](\theta) \Leftrightarrow \exists_{P' \subseteq \Gamma^{-1}(\tilde{p})}, \forall_{p \in \Gamma^{-1}(\tilde{p})} : \; |P'|\, op\, k \; \wedge g(\theta(p)) \; \Leftrightarrow p \in P'$

4.4 Discovering Class-Level Specification

The syntax of mined class level specifications closely resemble concrete specifications. The main difference lies in the primitive actions involved in both specifications (concrete events in concrete specifications, symbolic events in class-level specifications). The principles and heuristics that are used to discover state based

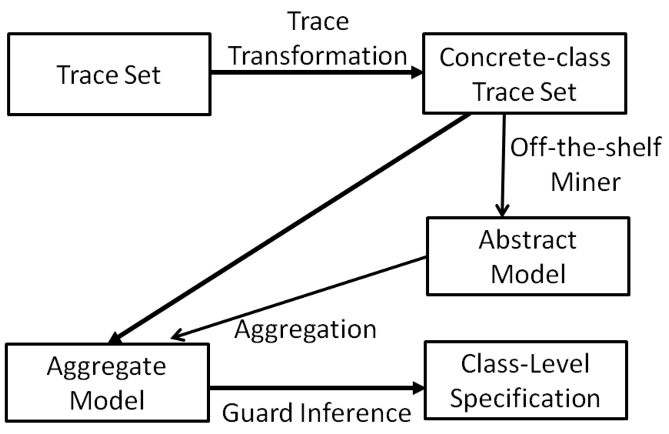


Figure 4.2: Overview of proposed mining procedure

specifications with object level events are reused to discover similar models containing class level events. This section describes how an existing state-based model miner can be combined with a guard inference mechanism to obtain class-level specifications. The entire process is depicted in Figure 4.2. The first step involves incorporating class-level information into concrete events of the trace. The transformed traces will be used to mine an abstract model via a state-based model miner. The transformed traces, together with the abstract model are then used to generate an aggregate model. Lastly, guard inference is performed for each event in the aggregate model to generate the class level specification.

4.4.1 Transforming Traces

The purpose of trace transformation is to incorporate process class information into the trace, and prepare it for eventual extraction of class-level information. To this end, the trace transformation performs the following tasks:

1. It translates concrete process labels to their corresponding class process labels.

2. It combines consecutive concrete events having identical action label and type into a single *concrete-class* event when those concrete events are part

of different processes of the same process class.

3. For each concrete-class event thus created it records the process selection (σ) and the state information of the entire process class (θ).

Specifically, for each trace t consisting of concrete events of the form (e_p, s_p) where $e_p = \langle p \oplus q, m\rangle$[1], the trace transformer produces an embellished trace $\tilde{t}$ consisting of *concrete-class* events of the form $(\tilde{e}, \theta, \sigma)$, such that:

1. $e = \langle \tilde{p}_{(n_{\tilde{p}})} \oplus \tilde{q}_{(n_{\tilde{q}})}, m\rangle$, where $\tilde{p} = \Gamma(p)$, and $\tilde{q} = \Gamma(q)$ and $n_{\tilde{p}}, n_{\tilde{q}} \in \{1, \star\}$. Here, $\tilde{p}_{(1)}$ indicates that only one concrete process participates in this event, whereas $\tilde{p}_{(\star)}$ indicates the participation of more than one concrete processes.

2. σ identifies the process selection corresponding to this class-level action. (Definition 4.3.1)

3. θ Is the context of $\tilde{p}$ prior to this class-level action. (Definition 4.3.2)

For example, if there is a sequence of adjacent actions $(\langle p_1 \oplus q_1, m\rangle, s_{p1})$, $(\langle p_2 \oplus q_1, m\rangle, s_{p2})$, $\ldots$, $(\langle p_l \oplus q_1, m\rangle, s_{pl})$, such that $p_1, p_2, \ldots, p_l(, \ldots p_n) \in \Gamma^{-1}(\tilde{p})$ are distinct concrete processes and $q_1 \in \Gamma^{-1}(\tilde{q})$, these concrete events will be transformed into the following concrete-class event: $(\langle \tilde{p}_{(\star)} \oplus \tilde{q}_{(1)}, m\rangle, \theta, \sigma)$, where $\forall_{p \in \Gamma^{-1}(\tilde{p})} : \theta(p) = s_p$ (s_p is the state of p, just prior to execution of the concrete events being combined) and $\sigma^{-1}(true) = \{p_1, \ldots, p_l\}$. The corresponding sequence of actions in q_1 – $(\langle q_1 \oplus p_1, m\rangle, s^1_{q_1})$, $(\langle q_1 \oplus p_2, m\rangle, s^2_{q_1})$, $\ldots$, $(\langle q_1 \oplus p_l, m\rangle, s^l_{q_1})$ will also be combined into a single class level action $(\langle \tilde{q}_{(1)} \oplus \tilde{p}_{(\star)}, m\rangle, \theta, \sigma)$, where $\forall_{q \in \Gamma^{-1}(\tilde{q})} : \theta(q) = s_q$ (s_q is the state of q, just prior to execution of the first concrete event being combined).

[1]The presence of internal action is ignored for ease of presentation. Traces containing internal actions can be processed in a similar manner

4.4.2 Mining Abstract State-based Model

The concrete-class trace set $\{\tilde{t_1}, \ldots, \tilde{t_k}\}$ is then used by an off-the-shelf miner to produce a state-based model. Such a model describes the system behavior in terms of abstract, class-level events. Section (4.5.1) discusses the specific mining approach used to generate the desired abstract MSC model.

Only an abstract view of the traces is presented to the mining tool. The process selection σ and context information θ are stripped from the concrete-class events in traces before using them to build the state-based model. The simplified *abstract* events are of the form $\langle \tilde{p}_{(n_{\tilde{p}})} \oplus \tilde{q}_{(n_{\tilde{q}})}, m \rangle$. The resulting model will contain states and/or transitions attached with *abstract* events.

4.4.3 Generating Aggregate Model

Creation of a state-based model typically requires merging similar concrete-class events occurring at different traces and "folding" several concrete-class events occurring at different time stamps within a trace into one. Consequently, an action in the state-based model will correspond to multiple concrete-class events in the traces. The generation of an aggregate model first determines these correspondences. It then aggregates the process selections (σ_j) and process class context (θ_j) from all these concrete-class events. Lastly, it replaces the abstract events in the abstract model by the aggregated information. Specifically, an abstract event $\tilde{e}$ will be replaced by an *aggregate* event $(\tilde{e}, \mathcal{C})$ where $\mathcal{C} = \cup_i \{(\sigma_i, \theta_i)\}$ and σ_i and θ_i are retrieved from the corresponding concrete-class events. We refer to $\mathcal{C}$ as a *configuration* of the process class $\tilde{p}$.

Most techniques that mine for state based models can be easily adapted to record the mapping of actions in the model to corresponding concrete-class events in the trace that support it. Alternatively the correspondences may be recovered by "executing" the state based model according to the sequence of concrete-class events in the trace and thereafter mapping each instance in the trace to the corresponding action executed by the model.

4.4.4 Inferring Symbolic Events

The last step of the discovery process is to derive symbolic events, of the form $(\langle \tilde{p} \oplus \tilde{q}, m\rangle, \mathcal{Q}.g)$, from the aggregate events, of the form $(\langle \tilde{p} \oplus \tilde{q}, m\rangle, \mathcal{C}_{\tilde{p}})$, in the aggregate model. This section describes how to infer the quantified guard $\mathcal{Q}.g$ from the configuration $\mathcal{C}_{\tilde{p}}$.

As we opt for guards that can characterize the history patterns of the participating processes, the inference algorithm aims to solve the following problem: “Find the most appropriate regular expression re that characterizes the history h_p of each participating process p belonging to the class $\tilde{p}$.” The corresponding quantified guard is of the form $\mathcal{Q}.g_{re}$. The predicate obtained from re, denoted by $g_{re}(\tilde{p})$, evaluates to True only when $h_p \in L(re)$ for all $p \in \tilde{p}$. The inference algorithm requires several inputs: The configuration $\mathcal{C}_{\tilde{p}}$; a library of regular expression templates from which the candidate regular expressions are constructed; and a threshold *min_sup* defining the mandatory minimum number of histories required to support a candidate regular expression.

Algorithm 10 describes how a regular-expression based guard can be inferred from an aggregate event of class $\tilde{p}$..

In line 1 the function *extractData* is used to extract relevant information from the configuration $\mathcal{C}_{\tilde{p}}$. Specifically, given that $\mathcal{C}_{\tilde{p}} = \{(\sigma_1, \theta_1), (\sigma_2, \theta_2), \ldots (\sigma_l, \theta_l)\}$ and $\Gamma^{-1}(\tilde{p}) = \{p_1, p_2, \ldots p_n\}$, we have $\mathit{extractData}(\mathcal{C}_{\tilde{p}}) = (H^+, H^-, k)$, where

$$\begin{aligned} H^+ &= \{\theta_i(p_j)(h_{p_j}) | i \in \{1, \ldots, l\} \wedge j \in \{1, \ldots, n\} \wedge \sigma_i(p_j)\} \\ H^- &= \{\theta_i(p_j)(h_{p_j}) | i \in \{1, \ldots, l\} \wedge j \in \{1, \ldots, n\} \wedge \neg\sigma_i(p_j)\} \end{aligned}$$

$$k = \begin{cases} r & \text{if } \exists r\ \forall_{i \in \{1,\ldots,l\}}(r = |\sigma_i^{-1}(true)|), \\ -1 & \text{otherwise.} \end{cases}$$

H^+/H^- refers to the set of execution histories of concrete processes when they had participated/not-participated in the action captured by the aggregate event. Moreover, k stores a positive constant r only if for every $(\sigma, \theta) \in \mathcal{C}_{\tilde{p}}$, the number of concrete processes which σ selects is r.

Line 2 in Algorithm 10 obtains R^+ and R^-, which are the sets of regular expressions accepting all histories in H^+ and H^- respectively, by invoking the function *getAccREs*. If there is no regular expression obtained in R^+, the algorithm will return $\exists.true$ (line 14).

Among the regular expressions in R^+, we select the most suitable one re, based on certain ranking heuristics (line 5) that will be discussed later. Lines 6 to 12 specify how the right quantifier to this re is chosen. The final output is the quantified expression $\mathcal{Q}.g_{re}$. The method used to obtain accepting regular expressions as well as the ranking heuristics are discussed below.

Finding Candidate Regular Expressions

A finite set of regular expression templates are chosen for guard inference. This set of templates may be modified as neither the inference technique nor the proposed algorithm rely on any feature of these templates. For all $p \in \Gamma^{-1}(\tilde{p})$, let Σ denote the alphabet from which execution histories for a process class $\tilde{p}$ are formed. The following set of regular expression templates are selected as they are found to be intuitive and sufficiently expressive.

1. ϵ: The process is in its initial state

2. $\Sigma^* A$: The last action taken by the process is A.

Algorithm 10 Guard Inference

```
Input: Configuration: $\mathcal{C}_{\tilde{p}}$ for aggregate event at process class $\tilde{p}$; Threshold: $min\_sup$
Output: $\mathcal{Q}.g$ - Inferred Guard
 1: $(H^+, H^-, k) \leftarrow extractData(\mathcal{C}_{\tilde{p}})$
 2: $R^+ \leftarrow getAccREs(H^+, \tilde{p})$
 3: $R^- \leftarrow getAccREs(H^-, \tilde{p})$
 4: if $R^+ \neq \emptyset$ then
 5:     Select $re \in R^+$ such that $rank(re)$ is maximal.
 6:     if $supp(re, H^+) > min\_sup \wedge \exists_{re' \in R^-} : L(re) = \overline{L(re')}$ then
 7:         if $k > 0$ then $\mathcal{Q} \leftarrow \forall_k$ else $\mathcal{Q} \leftarrow \forall$ end if
 8:     else
 9:         if $k > 0$ then $\mathcal{Q} \leftarrow \exists_k$ else $\mathcal{Q} \leftarrow \exists$ end if
10:     end if
11:     Let $g_{re}(p)$ represent the proposition $h_p \in L(re)$ for any $p \in \Gamma^{-1}(p)$
12:     return $\mathcal{Q}.g_{re}$
13: else
14:     return $\exists.true$
15: end if
```

3. Σ^*AB: The last two actions taken by the process is AB.

4. $\Sigma^*A(\Sigma - B)^*$: The action B has not occurred after the last execution of action A.

By substituting all pairs of events $e_1, e_2 \in \Sigma$ for variables A and B in these templates a library of basic regular expressions referred to as $RELib_{\tilde{p}}$ is generated.

The method, $getAccREs(H, \tilde{p})$ in Algorithm 11 returns a set of regular expressions accepting all elements of H. Here, every element of H has to be tested against each expression in $RELib_{\tilde{p}}$. In addition, more complex regular expressions obtained by combining the basic ones are also considered.

Algorithm 11 is designed to efficiently find all the accepting regular expressions through a single pass of each string $h \in H$. The approach used is adapted from the one used by Yang et. al. to detect temporal rules based on some fixed templates [86]. A method in which the process histories are tested for acceptance against an arbitrary library of regular expressions is described here. Each regular expression is represented by an automaton A_i (line 5). The current state of each A_i is maintained in $state[i]$. The algorithm traverses through (in line 10) each event e_j in the history h and apply the corresponding transition e_j to the current state of all automata. As $modList(e_j)$ maintains the set of relevant automata where state change must happen, the remaining automata need not be updated. When an automata is moved to a new state (line 12), $modList$ is updated as required in lines 15 and 17.

On reaching the end of string h, those regular expressions that are at their accepting states are added to the set R_h in line 23. The set of expressions is expanded to the set R'_h, which contains regular expressions formed by combining one or more regular expressions (line 25). For example for a pair $re_1, re_2 \in RELib_{\tilde{p}}$, if $re_1 \in R_h$ but $re_2 \notin R_h$, the function *combineREs* will include the regular expressions re', re'' and re''' in the expanded set R'_h, for which $L(re') = \overline{L(re_2)}$, $L(re'') = L(re_1) \cup \overline{L(re_2)}$ and $L(re''') = L(re_1) \cap \overline{L(re_2)}$.

Ranking Guard Conditions

Given a set of regular expressions R^+ we have to select the most appropriate re that can be applied as a guard for the symbolic event. For trace set T, let $H^T_{\tilde{p}}$ denote the set of all execution histories of class $\tilde{p}$ which the entire trace set T has witnessed. The following heuristics are employed to rank the list of potential guards.

1. **Ranking based on rejection:** If re_1 and re_2 accept all positive samples, but re_1 rejects more negative samples than re_2 then $\text{rank}_{rej}(re_1) > \text{rank}_{rej}(re_2)$. This ranking criterion evidently prefers regular expressions that accept all positive samples and rejects all negative samples. When such a regular expression is not found, one that rejects the largest number of negative samples is preferred.

Algorithm 11 *getAccREs*$(H, \tilde{p})$

```
Input: $\tilde{p}$: Process class
Input: $H$: Set of execution histories of concrete processes from $\tilde{p}$
Input: $RELib_{\tilde{p}} \leftarrow \{re_1, re_2 \ldots re_i \ldots re_n\}$: Regular expression library
Output: $R$: Set of regular expressions accepting history $h$, $\forall h \in H$
 1: Let $\Sigma$ represent set of all events of the form $\langle \tilde{p} \oplus \_, \_ \rangle$
 2: for all $h \in H$ do
 3:    Let $h = (e_1, e_2, \ldots e_j \ldots e_m)$
 4:    //Create automaton for each regular expression
 5:    Let $A_i \leftarrow (Q_i, \Sigma, \delta_i, q_{i0}, Q_{if})$ s.t. $L(A_i) = L(re_i)$
 6:    // $state[i]$ stores current state of $A_i$ (initialize to $q_{i0}$)
 7:    $state[i] \leftarrow q_{i0}$ (for $i = 1 \ldots n$)
 8:    // $modeList(e)$: set of regexes for which event $e$ effects a state change
 9:    $modList(e) \leftarrow RELib_{\tilde{p}}$ (for all $e \in \Sigma$)
10:    for $j = 1 \ldots m$ do
11:       for all $re_i \in modList(e_j)$ do
12:          $state[i] \leftarrow \delta_i(state[i], e_j)$
13:          for all $e \in \Sigma$ do
14:             if $\delta_i(state[i], e) \neq state[i]$ then
15:                $modList(e) \leftarrow modList(e) \cup \{re_i\}$
16:             else
17:                $modList(e) \leftarrow modList(e) - \{re_i\}$
18:             end if
19:          end for
20:       end for
21:    end for
22:    //Form $R_h$, the set of basic regexes accepting $h$
23:    $R_h \leftarrow \{re_i | re_i \in RELib_{\tilde{p}} \wedge state[i] \in Q_{if}\}$
24:    //Form $R'_h$, the set of basic and complex regular expressions accepting $h$
25:    Let $R'_h \leftarrow combineREs(R_h)$
26: end for
27: $R \leftarrow \bigcap_{h \in H} R'_h$
28: return $R$
```

2. **Ranking based on implication:** If re_1 and re_2 are candidate guards for an event belonging to process class $\tilde{p}$, if $\forall_{h \in H^T_{\tilde{p}}} h \in L(re_1) \Rightarrow h \in L(re_2)$ then $\text{rank}_{impl}(re_2) > \text{rank}_{impl}(re_1)$. If for every execution history h witnessed in the traces, if h is included in the language of re_1, then it is also included in the language of re_2 then re_2 is preferred. These heuristics are based on the intuition that in the given process class, when an execution history of an object belongs to $L(re_1)$ then it is also known to belong $L(re_2)$ then the regular expression re_2 enforces a *weaker* constraint on execution histories. As we rely only on histories found in $H^T_{\tilde{p}}$, it should be noted that the assumption of implication is not sound. It was found that when two expressions are equally powerful in separating positive from the negative samples (have equal rank_{rej}), then the weaker constraint is more intuitive. This is because in several cases, the set of actions that differentiate the role of processes within the same class are selected. For example, in the basic MSC M_1 of Figure 5.1(a), the send event $\langle MasterC!TargetC, addr\rangle$, the regular expression $ends(grant)$ and $bet(grant, rel)$ will have equal rank_{rej}. However, $bet(grant, rel)$ will accept more execution histories in any trace set from the system. For the same result, the regular expression $bet(grant, rel)$ will also be chosen at M_3, M_4 and M_5. Therefore specification consistently uses the expression $bet(grant, rel)$ to refer to the master divide that has presently been granted control.

3. **Ranking based on likelihood:** If $|L(re_1) \cap H^T_{\tilde{p}}| > |L(re_2) \cap H^T_{\tilde{p}}|$ then $\text{rank}_{lkl}(re_1) > \text{rank}_{lkl}(re_2)$. Here $|L(re_1) \cap H^T_{\tilde{p}}|$ refers to the number of strings in $H^T_{\tilde{p}}$ that are also part of language $L(re_1)$. If strings in $H^T_{\tilde{p}}$, the set of all execution histories witnessed in the trace, are more likely to be accepted by guard re_1 than by guard re_2 then re_1 is preferred. This a generalized version that includes rank_{impl}. The intuition is similar, but is able to rank guards

even when one does not appear to imply the other.

4. **Ranking based on simplicity of guards:** If re_1 is a guard formed directly from one of the templates and re_2 is a composite guard then, $\text{rank}_{spl}(re_1) > \text{rank}_{spl}(re_2)$.

These heuristics aim at an accurate regular expression that is also simple and easy to understand. By considering traces that are beyond the current historical data, the ranking criteria rank_{impl} and rank_{lkl} encourage the reuse of regular expressions across multiple events in the mined specification. This in turn improves the overall comprehensibility of class level behavior. We select the highest overall ranking guard as the inferred guard (line 5 in Algorithm 10). From our empirical studies the best results are obtained by finding overall ranking after applying the ranking methods in the following precedence order: $\text{rank}_{rej} > \text{rank}_{impl} > \text{rank}_{lkl} > \text{rank}_{spl}$, where a ranking criterion is used only to break a tie resulting from the application of higher ranking criteria. The rank_{rej} is given highest preference as it selects the guard that has the most distinguishing power (rejects most number of negative samples) and therefore likely to impact precision of mining. Apart from such automatic methods to discover guards, user assistance may be sought at this point to determine ideal guards from a shortlist. The user may also be able to assist in narrowing down the alphabet used for obtaining the basic regular expression library.

4.5 Mining SMSGs

The proposed class level specification mining approach can be used to mine SMSGs. The method described here is based on the method used to mine to mine concrete models in the MSG representation. The *MSGMiner* framework is used to mine abstract behavior and combine it with our method to infer symbolic events to produce an SMSG.

4.5.1 Mining Abstract Behavior

MSGMiner converts each trace in the trace set into a dependency graph whose vertices contain the events in the trace. The dependency graph captures the partial order of events from across processes. The cronological order of events within each process is maintained by a minimal set of directed edges. There is also a set of edges from send events to their respective receive events. The trace transformation operation discussed in Section 4.4.1, is performed to the dependency graphs (partially ordered set of events) instead of traces (fully ordered sequence of events). When a group of concrete events from different concrete processes can be combined into a concrete-class event, the corresponding vertices are merged and labelled with that concrete-class event. We use the dependency graphs with concrete-class events to discover class level behavior. The *MSGMiner* framework breaks down the dependency graphs obtained from the set of traces into sequences of smaller dependency graphs called basic MSCs. It then mines for an MSG using a variant of the *k-tails* algorithm [29]. From a finite set of sample strings of a language, the k-tails algorithm mines an automaton that approximately defines the full language. We feed the sequence of basic MSCs to this process to obtain an automaton whose transitions contain basic MSCs. This automaton, when converted to a Moore machine having basic MSCs as output at its states is an MSG representing the abstract behavior of the system.

4.5.2 Conversion to Symbolic MSG

The *MSGMiner* framework maintains the set of trace locations which support each action in the mined MSG. Using this information, the configuration for abstract actions can be derived and transformed into to aggregate events. Using the guard inference technique discussed in Section 4.4.4 a symbolic event is inferred from every aggregate event.

Process class constraints are also attached to edges of the output SMSG. An edge from a basic SMSC, say M_A, to another basic SMSC M_B is labelled with a set of contexts $\Theta_{\tilde{p}} = \{\theta_1, \theta_2, \ldots \theta_n\}$ for each process class $\tilde{p}$. Here, $\Theta_{\tilde{p}}$ is the set of contexts of $\tilde{p}$ from the trace set, in which, it has just finished execution of events in M_A and is about to execute of events in M_B.

A set of process class constraints, $G_{\tilde{p}}$, is inferred on $\tilde{p}$ at edges of the SMSG by first initializing it to a set of potential constraints of the form $[all(g_{re})]$, $[count(g_{re}) \geq k]$ and $[count(g_{re}) = k]$ (defined in Section 4.3.4) with each g_{re} from the set of regular expression templates ($RELib_{\tilde{p}}$). The value of k is initially chosen based on any one $\theta \in \Theta$. We then iterate over remaining $\theta_i \in \Theta_{\tilde{p}}$ and discard or modify the constraints in $G_{\tilde{p}}$ as necessary so that the final set of constraints are satisfied by all elements of $\Theta_{\tilde{p}}$.

Having identified a set of constraints $G = \cup_{\tilde{p} \in \mathcal{P}} G_{\tilde{p}}$ at edges in an SMSG, we now discuss how it can be further reduced to a smaller set of important constraints. If a basic SMSC has l outgoing edges, having set of constraints $G_1, G_2 \ldots G_l$ respectively, let $\hat{G} = G_1 \cap G_2 \cap \ldots G_l$ represent the set of conditions that are common to all edges. As constraints in $\hat{G}$ are valid at every outgoing edge and not critical to the choice of an edge, they are discarded from $G_1, G_2, \ldots G_l$. A set of constraints G can be further reduced to contain only those constraints that are not implied by any other constraint in G. In the mined SMSG, the conjunction of all constraints in G is imposed at the respective edge. To reduce the risk of over-fitting data, an edge constraint is imposed only if it has been inferred from a set of contexts $\Theta_{\tilde{p}}$ such that its size ($|\Theta_{\tilde{p}}|$) is greater than a specified threshold. This threshold is referred to as *ec_min_sup* and make it a parameter to the mining technique.

4.6 Evaluation

The mined models (both concrete and symbolic) are compared against the correct specification of the system expressed as an SMSG. An MSG generates partially ordered sets (rather than totally ordered sequences) of events, each expressed as an MSC, which are tested against the accepting model. In Chapter 3, we have tested if a generated MSC is accepted by an MSG. In order to test SMSCs (generated by an SMSG) against the accepting model in a similar fashion, we will have to quantify what portion of the behaviors expressed by each SMSC is valid according to the accepting model. This is challenging because guards in symbolic events may refer to an unbounded number of configurations. This challenge is overcome by transforming each generated SMSC to a finite number of concrete MSCs. This is done by producing all concrete realizations of the SMSC with each process class mapped to a finite set of concrete processes.

In practice, process classification (Γ) that is part of the input to the mining process is also used to generate concrete realizations. This ensures a fair comparison with the mined concrete model as the number of concrete processes and their labels are consistent with what is present in the trace set. The concrete realizations must also honor the edge constrains in the SMSG. For example consider the set of SMSCs formed by concatenation of basic SMSCs beginning with the following path (M_1, M_2, M_3, M_5, M_2, $\ldots$) from the SMSG in Figure 2.3. Any concrete MSC derived from these SMSCs, must be able to satisfy the constraint on edge from M_5 to M_2, *i.e.*, the concrete realizations of this SMSC must involve simultaneous requests from two or more master devices. As the number of concretizations of an SMSC can be exponentially high, we use a combination of a loop and path bound to generate the SMSCs. A path bound of 10 basic MSCSs and a loop bound of 2 is used for precision and recall calculations.

To test if a concrete MSC M_{conc} is accepted by an SMSG, we search the SMSG for a path that forms an SMSC M_{sym}, such that M_{conc} is one of the valid concrete realizations of M_{sym}. For evaluation in this chapter, precision and recall are redefined as follows.

$$\text{precision} = \frac{\text{\# of MSCs generated by MM and accepted by CM}}{\text{Total \# of MSCs generated by MM}}$$

$$\text{recall} = \frac{\text{\# of MSCs generated by CM and accepted by MM}}{\text{Total \# of MSCs generated by CM}}$$

Here CM refers to the $SMSG$ specification that is correct and MM the mined model is either the mined $SMSG$ (evaluating the proposed approach) or the mined concrete MSG (evaluation of existing mining approach). The F_1 score (the harmonic mean of precision and recall) that is typically used by the information retrieval community to measure accuracy is also computed.

4.7 Case Studies

We evaluate class-level mining on the same set of subjects considered in Chapter 4. In Chapter 4, the analysis is performed on traces collected from a specific instantiation of each system. For instance, we ensured that only a fixed number of processes would participate in any scenario. We also ensured that each process operated within the constraints of a specific 'role'. The benchmark specifications used for evaluation are also specific to the chosen instantiation of the systems. By assigning such roles to processes (roles such as *administrator* of a multi user chat conversation or *call originator* of a VoIP call), the person performing mining is able to ensure a simple and more meaningful output specification. However, the main disadvantage of this approach is that it assumes there is prior knowledge as the the set of roles that processes of a type may assume.

To evaluate class-level specifications we consider more realistic configurations

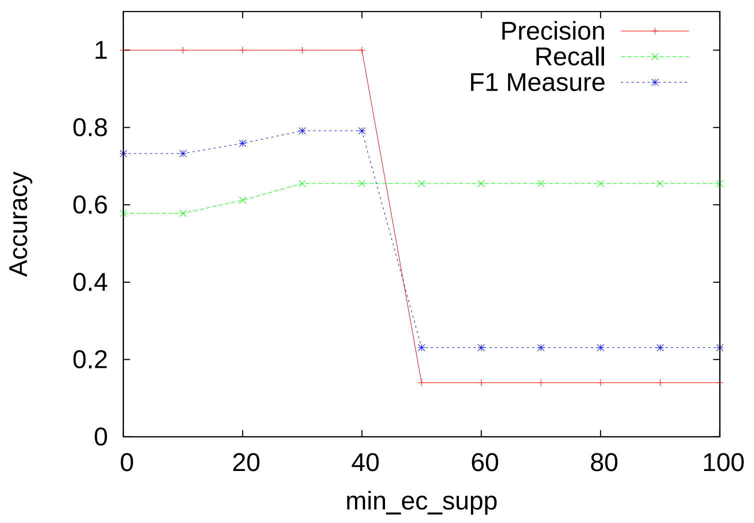


Figure 4.3: Plot showing impact of *ec_min_sup* on mining accuracy for the XMPP core protocol

of the system. In each of the examples, processes are permitted to assume any role that other processes in the same process class can assume under similar circumstances. For example, in a multi user chat scenario, any user may acquire the role of the chat administrator. The results discussed in this section are based on traces collected without instantiating the number of processes or roles of processes within certain process class.

Both symbolic and concrete methods employ a variant of the *k-tails* algorithm to mine finite state machines. The k parameter is set to 2 in both cases as is commonly used in most applications of the algorithm. It was observed that universally quantified guards can be accurately inferred even with a low minimum support (*min_sup* in Section 4.4.4). The threshold *ec_min_sup* was found to play a critical role in determining whether the constraints on edges are correctly effected. The core XMPP protocol example was found to benefit most in terms of precision from the presence of edge constraints. Figure 4.3 shows the impact of change in *ec_min_sup* to the accuracy measures.

Table 4.1 tabulates the results from the case studies. It shows the precision,

System	**# events in trace set**	**Mined Concrete MSG**					**Mined SMSG**				
		Prec	**Rec**	**F_1 Score**	**# events in MSG**	**Time (s)**	**Prec**	**Rec**	**F_1 Score**	**# events in SMSG**	**Time (s)**
SIP	3326	0.8	0.05	0.09	222	97.7	0.64	0.66	0.65	54	55.7
XMPP-Core	5522	1	0.19	0.32	288	94.6	1	0.66	0.79	46	44.3
XMPP-MUC	7938	0.61	0.36	0.45	186	131.7	0.67	0.63	0.65	82	83.6
CTAS	11814	0.25	0.43	0.31	752	466.15	0.88	0.9	0.89	134	338.5

Table 4.1: Accuracy of mined concrete MSG and SMSG

recall and F_1 measure of the mined concrete MSGs and the mined SMSGs for each of these systems that were studied. The column, "# events in trace set" indicates the total size of the trace set in each case. The columns "# events in MSG/SMSG" reflect the size of mined specifications in terms of the number of primitive actions they contain. It is seen that mined symbolic specifications have better accuracy when compared to the mined concrete specifications. The concrete specification mining approach gives poor recall as it does not consider similarity between processes. Concrete MSGs reflect only those process selections that were captured by the traces. In reality, the traces only capture a small fraction of all the possible configurations of the system. In certain cases, the mined SMSG has better precision. This can be attributed to the presence of guards and edge constraints due to which the set of actions a process is allowed to perform is determined by its full execution history. The selected set of regular expression templates were found to be sufficient to infer meaningful guards and edge constraints for the subjects that were considered.

Chapter 5

Mining Difference Specifications

Most state based specification mining techniques have focused on inferring the behavior of a *single software system*. In reality, software systems are not written from scratch — rather they gradually evolve over time. Software systems undergo an evolutionary process during which they adapt to changes in requirements, addition of features, bug fixes, performance enhancements or re-factoring of code. The evolution of software due to these factors is reflected in a series of incremental revisions made to the source code. These incremental revisions are often the root of difficulty in understanding program behavior. Understanding the software system is not simply understanding the current version - but also the major revisions it went through, and the main functionalities that were added. Usually not all code revisions get accurately described in the commit logs checked in by programmers, when they check in a new version. Thus, when a new developer takes over the maintenance of a large code-base, understanding the major differences between certain program versions can greatly enhance his/her understanding of the program behavior and its evolution. It can also help in understanding how bugs were introduced and possibly subsequently fixed in the evolution of a software system. Current methods for mining high-level state based specifications, including FSM based specifications do not seek to mine for specifications that highlight *differences* between program versions.

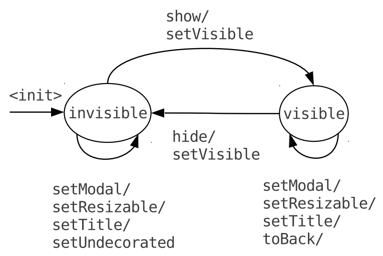
To infer the differences between program versions via model mining, one could envision a rather simple strategy. One could employ specification mining to obtain models for the individual program versions, and then subsequently perform model differencing [69] on the mined models. However, note that such an approach is open to several sources of loss of information. Since specification mining is an inherently lossy process (subject to generalizations for inferring loops in the mined model from the linear execution traces) — it is preferable to avoid repeated specification mining on the individual program versions.

In this chapter, we discuss a directed mining technique that infers differences between a given pair of program versions and presents them neatly in an extension of MSG notation. Thus, the output of the mining method can be used to understand, at a high level, the difference in the inter-object and inter-class behaviors across two versions of a program.

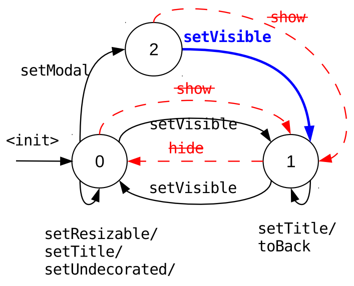
Since the mining method precisely seeks to summarize the differences across two versions, it can be useful for understanding the differences between two versions of a legacy software system. This can be particularly helpful for a new inexperienced developer taking over the maintenance of a software system. A difference mining method can be used by such an inexperienced developer to understand the changes between major versions checked-in in the past. Furthermore, if such a developer makes some changes to the software which leads to regressions (breaking some previously working functionality) - a summary of the differences with a previously working program version can give a hint of what went wrong.

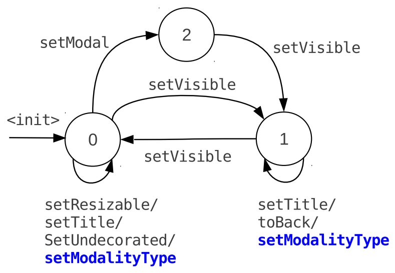
5.1 Overview of Approach

This chapter describes a generic mining based technique to highlight program differences on high-level state based behavioral specifications such as object usage specifications, statecharts and Message Sequence Graphs. Later, we shall look at specifics pertaining to the mining difference specifications based on MSGs. Consider the *java.awt.Dialog* class, a Java UI container, as an example to describe the general approach. Objects of the *Dialog* class are typically used to create UI windows to collect user input. Figure 5.1(a) shows a specification of correct usage of *Dialog* in Java version 1.4. Accessor methods and inherited methods are omitted for simplicity. All constructors create an invisible window and methods *show* or *setVisible(true)* have to be used to make the window visible. The proposed difference mining technique can be used to comprehend changes to the usage of *Dialog* class since Java 1.4 by observing how programs using dialogs that are written for Java 1.4 have been adapted for use with Java 1.5. Assuming such programs can be executed with test inputs providing reasonable coverage, one can generate two sets of execution traces (containing usage of Dialog objects) — $T_{1.4}$ and $T_{1.5}$ corresponding to each version. These trace sets are used to produce a difference specification of the form shown in Figure 5.1(b). In this specification, the method calls *show* and *hide* are shown as deprecated and only the *setVisible* method is now used for transitions between the visible and invisible states. Note that as the mining technique is imperfect, certain transitions are incorrectly left out (eg: from state 2 to state 0, and state 0 to itself). However, as the mined specification draws the user's attention to the changes between the two versions it serves a useful purpose in program comprehension. Figure, 5.1 (c) is the difference between java versions 1.5 and 1.6, which shows the introduction of new methods.



(a) Correct specification for v1.4





(b) Diff between v1.4 and v1.5 (c) Diff between between v1.5 and v1.6

Figure 5.1: Difference mining example of the java.awt.Dialog class

5.2 Problem Formulation

This section defines difference specifications and formalize the problem of mining such specifications. For simplicity of presentation, we shall define difference specification on automata and then extend those principles to mining Message Sequence Graphs.

5.2.1 Difference Specifications

In the remaining chapters, by difference FSA or DFSA, we shall refer to a tuple of the form $D = (Q, \gamma_{v0}, \gamma_{v1}, q_0, Q^f, \Sigma)$ where,

- Q is a set of states,
- v_0 is the original version label, v_1 is the changed version label.
- $\gamma_{v_0}, \gamma_{v_1} \subseteq Q \times Q \times \Sigma$ are transition functions for versions v_0 and v_1 respec-

tively,

- Q^f the set of accepting states,
- Σ the trace alphabet.

Semantically, the difference specification refers to two FSA specifications -
$D[v_0] = (Q_{v_0}, \gamma_{v_0}, q_0, Q^f_{v_0}, \Sigma)$ and
$D[v_1] = (Q_{v_1}, \gamma_{v_1}, q_0, Q^f_{v_1}, \Sigma)$.
Where,

- $Q_{v_0} = \{q : q \in Q \ \wedge \ q_0 \gamma^{\star}_{v_0} q\}$: the set of states in D, reachable from q_0 by γ_{v_0}.
- $Q_{v_1} = \{q : q \in Q \ \wedge \ q_0 \gamma^{\star}_{v_1} q\}$: the set of states in D, reachable from q_0 by γ_{v_1}.
- $Q^f_{v_0} = Q^f \cap Q_{v_0}, \quad Q^f_{v_1} = Q^f \cap Q_{v_1}$

The language $L(D[v_0])$ contains the set of correct behaviors executed by program with version v_0 and $L(D[v_1])$ contains the set of behaviors executed by program with version v_1.

DFSAs are directed graphs with the following syntax:

- Regular vertices denoted by labelled circles, and labelled arrows denoting regular edges.
- *Novel edges* denoted by bold arrows and bold labelled text, can be executed only in version v_1 ($\gamma_{v_1} - \gamma_{v_0}$).
- *Novel vertices* denoted by bold circles and bold labelled text, which are visited only in version v_1 ($Q_{v_1} - Q_{v_0}$).
- *Obsolete edges* denoted by dotted arrows and strike-through text, can be executed only in version v_0 ($\gamma_{v_0} - \gamma_{v_1}$).

- *Obsolete vertices* denoted by dotted circles which are visited only in version v_0 $(Q_{v_0} - Q_{v_1})$.

The difference specifications in our motivating examples of Section 5.1 were depicted as DFSAs in Figure 5.1 (Note: State q_0 is not depicted in the specifications).

Let P_0 be the reference program or the older software version and the P_1 the changed or new software version. Let I be a set of inputs or test cases that can be inputed to P_0 and P_1 to produce two execution trace sets, T_0 and T_1 respectively. We state the difference specification mining problem as follows:

Given trace sets T_0 and T_1 as inputs obtained from a set of test cases I, infer a DFSA D such that $D[0]$ is a specification of P_0 and $D[1]$ a specification of P_1.

In reality, it is impractical to infer a DFSA D that captures precisely the specification of P_0, that of P_1 and their differences, because of the following two reasons:

1. It is not feasible to obtain the set of test cases (I) that achieves full coverage for black box testing.

2. The mining technology is not advanced enough to generate perfect specification from a set of non-trivial traces.

Thus, our technical challenge is to infer a difference specification that enables the derivation of specifications for P_0 and P_1 respectively, as precise as possible. This naturally requires that the test cases used to generate T_0 and T_1 provide a good coverage of behaviors exhibited by the programs.

5.3 Mining Technique

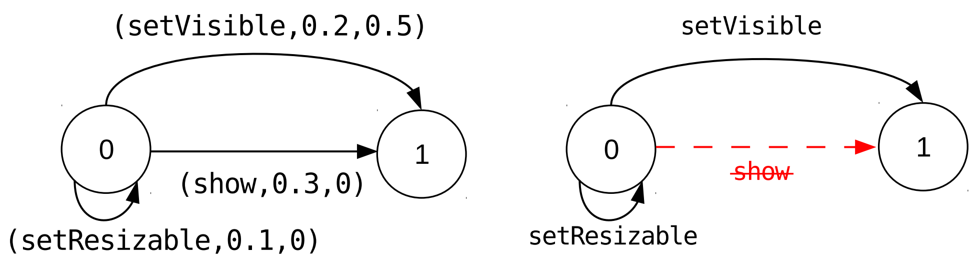
A methodology for mining difference specifications based on Finite-State Automata(FSA) is proposed in theis section. A description of the technique on a simple specification languages will help the reader to better appreciate the basic principles that we use to mine differences in MSG based languages.

5.3.1 Mining Difference Specification

Mining is performed on execution data from both program versions, T_0 and T_1. An automaton learning algorithm can be adapted to directly mine a difference specification from the two such sets of traces.

As discussed in earlier chapters, the *sk-string* algorithm has been popularly used to learn automata from a sample set of input strings [74]. The algorithm begins with a canonical automaton which accepts exactly the set of input strings. States in this automaton are merged iteratively based on certain heuristics to obtain a more general automaton that accepts additional strings which are not in the sample set, but likely to belong to the language from which the sample is derived. These heuristics are based on the probabilistic distribution of words that are generated by transitions originating from a given state. Retaining these heuristics, the algorithm is adapted to accept two trace sets (set of sample strings) T_0 and T_1 as input.

An initial automaton is formed to accept all strings occurring in $T_0 \cup T_1$. During the merging steps, the transition probabilities for each version are maintained separately. At the end, we output a probabilistic automaton $(Q, \rho, q_0, Q_f, \Sigma)$ with both T_0 and T_1 as the input trace sets. Here $\rho \subseteq Q \times Q \times \Sigma \times \mathbb{P} \times \mathbb{P}$, is a probabilistic transition function, where $\mathbb{P}$ is the interval $[0, 1]$ denoting the range of a probability. A transition from one state to another is labelled (e, p_0, p_1), where



(a) Probabilistic model (b) Difference model

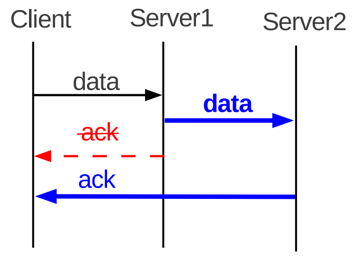
Figure 5.2: Converting probabilistic model to difference specification

e is the event executed by the transition, $p_0 \in \mathbb{P}$ represents the probability that the transition is taken in version 0 of the software and p_1 the probability that the transition is taken in version 1. From this output probabilistic automata, we derive a difference automaton $(Q, \gamma_{v0}, \gamma_{v1}, q_0, Q_f, \Sigma)$ where,

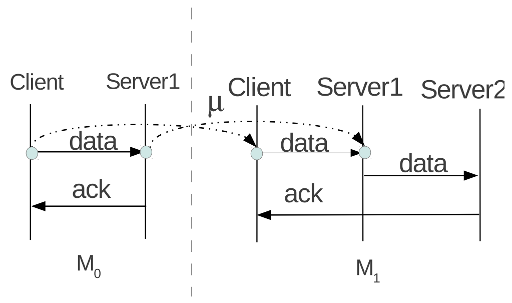
- $\gamma_{v0} = \{(q, q', e) : (q, q', e, p_0, p_1) \in \rho \wedge \; (p_0 \neq 0 \vee p_1 \leq \tau)\}$
- $\gamma_{v1} = \{(q, q', e) : (q, q', e, p_0, p_1) \in \rho \wedge \; (p_1 \neq 0 \vee p_0 \leq \tau)\}$

Intuitively, we include a transition (q, q', e) in γ_{v0} if either there is at least one trace in T_0, that has executed a sequence of events to reach state q and then executes event e to reach state q'. Alternatively, the probability that it is taken by traces in T_1 is less than a fixed threshold τ (indicating that we have insufficient evidence to conclude that the transition does not exist in version 0). Similarly for transitions included in γ_{v1}. The threshold τ is an additional parameter to the mining algorithm. When $\tau = 0$, transitions are excluded from a version when the transition probability in that version is 0. For higher values of τ, a transition is excluded from a version only if the other version has a high probability of executing the same action. When $\tau = 1$ transitions are never excluded from either versions.

Figure 5.2 describes how outgoing transitions from state 0 of a learnt probabilistic automaton is transformed into corresponding transitions in the difference model with $\tau = 0.2$. The transition *setResizable* is preserved, but the transi-



(a) Example of DMSC



(b) M_0, M_1 and μ

Figure 5.3: Syntax and Semantics of DMSC

tion *show* is marked as removed in version 1.5. The differences between program versions may involve a previously accepting state now becoming a non-accepting state. Such changes can be easily handled by the difference automaton mining algorithm if each input trace is marked with a special end of line character.

5.4 Difference Mining for MSGs

Automata learning techniques have been adopted to mine state based specifications of various kinds. In this section, we shall discuss how the skeletal approach used for FSAs can be combined with MSG learning to produce scenario-based difference specifications.

5.4.1 Difference MSGs

A DMSC D represents a triplet $\langle M_0, M_1, \mu \rangle$ in which M_0 represents a full or partial execution scenario in program P_0, and M_1 represents a full or partial execution scenario in P_1. Visually, the MSC M_0 can be derived from the syntax of D, by dropping message arrows in bold and reverting dotted arrows to regular lines. Similarly, dropping dotted arrows and reverting bold arrows give us the MSC M_1. Formally, MSCs M_0 and M_1 are represented by dependency graphs that record the permissible partial order in which events may be executed. If vertex v in the dependency graph represents a regular event (neither novel nor obsolete) in M_0, then $\mu(v)$ is the corresponding regular event in the dependency graph for M_1 which represents the same event.

Concatenation: An MSC M_B can be concatenated to another MSC M_A to form a new MSC $M \equiv M_A \circ M_B$ which contains events from both MSCs. The order of events from within each MSC have the same partial order in M as in M_A or M_B. However for any given lifeline, the events from M_B must strictly follow events of the same lifeline that come from M_A. The concatenation $(D \circ D')$ of two DMSCs $D = \langle M_0, M_1, \mu \rangle$ and $D' = \langle M'_0, M'_1, \mu' \rangle$ results in a new DMSC $D'' = \langle M''_0, M''_1, \mu'' \rangle$, where

$$M''_0 = M_0 \circ M'_0,\ M''_1 = M_1 \circ M'_1,\ \mu'' = \mu \cup \mu'$$

Figure 5.3(b) describes the semantic interpretation of the DMSC in Figure 5.3(a).

A Message Sequence Graph (MSG) is a high-level version of the MSC formalism that allows the specification of a collection of scenarios. An MSG's vertices are labelled with *basic* MSCs that represent fundamental interaction snippets. Directed arrows connecting the vertices represent valid transitions. An MSG represents the set of scenarios obtained by concatenating basic MSCs along its paths. We extend the syntax and semantics of Message Sequence Graphs (MSGs) and define Difference Message Sequence Graphs (DMSGs) for easily describing changes in a collection of system behaviors. DMSGs are directed graphs whose vertices are labelled with *basic* DMSCs. The edges in the DMSG are either a regular arrow, dotted lined arrow or bold arrow. As in the convention used within DFSAs, dotted arrows represent obsolete transitions in the specification and bold arrows represent novel transitions.

5.4.2 Mining DMSGs

Chapter 3 defined the concept of *Maximal Connected Dependency Graphs* (MCDs) to represent likely basic MSCs for a given trace set. An MCD is a dependency graph that represents a partially ordered set of events occurring in execution scenarios recorded by the traces. MCDs are maximal dependency graphs that occur in the trace set with the same frequency as all its constituent events. We also developed an algorithm to determine a set of weakly connected dependency graphs that are sufficient to describe (by concatenation) all the scenarios witnessed in the trace set.

A DMSG can be considered as a DFSA whose alphabet is a set of basic DMSCs. We can represent trace sets T_0 and T_1 as a two sets of sentences or strings formed out an alphabet of basic MSCs (represented by MCDs identified from $T_0 \cup T_1$). However, mining a DMSG in this manner limits our ability to represent minor changes within basic DMSCs of the output specification. Furthermore, as our learning algorithm relies on heuristics based on strings emitted after a state, minor changes can prevent the detection of similarity between identical states of different program versions which are reached immediately prior to the point of change. To avoid these disadvantages we propose to identify a set of basic DMSCs prior to applying the DFSA learning process.

Identifying Basic DMSCs

The set of basic DMSCs is constructed by first identifying the set of MCDs for T_0 and T_1 separately from $\mathcal{M}_0$ and $\mathcal{M}_1$ respectively. Algorithm 12, describes how the set of basic DMSCs are derived. In the initial for-loop, if an MCD from one trace set is a perfect prefix of an MCD from the other trace set, then the larger MCD is split into two. The second for-loop identifies the best match for each MCD in $\mathcal{M}_0$ from $\mathcal{M}_1$. Finally, when an MCD has no mapping to an MCD in the other program version, DMSCs of the form $(m, \_, \emptyset)$ or $(\_, m', \emptyset)$ are added.

Algorithm 12 Algorithm to identify *basic* DMSCs

```
Input: $\mathcal{M}_0$, $\mathcal{M}_1$
Output: $\mathcal{D}$ - The set of basic DMSCs
  $\mathcal{D} \leftarrow \emptyset$
  $W \leftarrow \mathcal{M}_0$
  for all $m \in \mathcal{M}_0 \wedge m' \in \mathcal{M}_1$ do
    if For some $m''$, $m \equiv m' \circ m''$ then
      $\mathcal{M}_1 \leftarrow \mathcal{M}_1 - \{m\}$;  $\mathcal{M}_1 \leftarrow \mathcal{M}_1 \cup \{m'\}$;  $\mathcal{M}_1 \leftarrow \mathcal{M}_1 \cup \{m''\}$
    else if For some $m''$, $m' \equiv m'' \circ m''$ then
      $\mathcal{M}_0 \leftarrow \mathcal{M}_0 - \{m\}$;  $\mathcal{M}_0 \leftarrow \mathcal{M}_0 \cup \{m'\}$;  $\mathcal{M}_0 \leftarrow \mathcal{M}_0 \cup \{m''\}$
    end if
  end for
  for all $m \in \mathcal{M}_0 \wedge m' \in \mathcal{M}_1$ s.t. $m$ and $m'$ share a common event do
    if $\forall m'' \in \mathcal{M}_1$: $dist(m, m') < dist(m, m'')$ then
      $\mathcal{D} \leftarrow (m, m', \mu_{m,m'})$
      $\mathcal{M}_0 \leftarrow \mathcal{M}_0 - \{m\}$; $\mathcal{M}_1 \leftarrow \mathcal{M}_1 - \{m'\}$
    end if
  end for
  for all $m \in \mathcal{M}_0$: $\mathcal{D} \leftarrow \mathcal{D} \cup \{(m, \_, \emptyset)\}$
  for all $m' \in \mathcal{M}_1$: $\mathcal{D} \leftarrow \mathcal{D} \cup \{(\_, m', \emptyset)\}$
```

Here, $dist(m, m')$ refers to the minimum edit distance required to convert MSC m into m'. The edit distance between two graphs for a given mapping between vertices from one graph to the other, is the total cost of adding/removing the remaining vertices and edges to make one graph identical to the other. The minimum edit distance for two MSCs is defined as a smallest edit distance of all possible mappings. We use $\mu_{m,m'}$ to represent a mapping between vertices of m and m' such that the edit distance is minimal. The problem of calculating the minimum edit distance between graphs is in NP-Hard. We adopt a solution which searches the space of all possible mappings to identify the mapping with the least edit distance. The search algorithm is bounded by pruning paths which exceed the minimum distance from mappings that have already been considered [36]. The search space is further pruned for dependency graphs corresponding to MSCs by only considering mappings between events from the same lifeline.

Once the set of basic DMSCs have been established, the trace set is represented as sequences from a unified alphabet of DMSCs. Each $(m, m', \mu) \in \mathcal{D}$, replaces occurrences of m in T_0 and occurrences of m' in T_1 . We eliminate some mappings, if $dist(m, m') > \tau_{dist}$ for some configurable threshold τ_{dist}.

With strings formed from DMSCs, the approach to obtain a DMSG specification is identical to the technique described for learning difference specifications in the form of automata. The Mealy model machine that is created is converted to a Moore model machine to be output as a DMSG.

5.5 Evaluation and Results

This section details experiments that employ our approach on various subject programs. For each pair of subject programs (P_0 and P_1) we derive a single difference specification D using our approach. In addition, we also derive two separate MSG specifications for each version. Subsequently, the mined models are compared using a structural model matching technique.

To the best of our knowledge, there is no existing method to structurally compare two MSG specifications. The work in [69] is a popular approach to compare statechart models and is representative of related techniques to compare state based models. Although this technique does not directly cater to the MSG syntax, it permits non-exact matching of labels on states. We use this feature to compare MSG models by modeling them as state machines with MSCs as state labels. We implement the same model comparison technique at a lower level to match MSCs (modelled as dependency graphs).

Two aspects are considered in evaluating difference models: (1) The accuracy with which the models describe correct behaviors of their respective program versions. (2) the relative quantity of editing performed to describe changes. These two aspects are discussed in greater detail:

Accuracy: The accuracy of mined FSAs have been evaluated by comparing the language they describe with that of a manually constructed correct specification. Precision and recall are derived by generating a bounded set of behaviors from one model and testing their acceptance on another model. All paths in the MSGs having a length of up to 20 vertices, with a loop bound of 2 are explored to generate MSCs to identify precision and recall by the language comparison method used previously. The accuracy of a difference specification D is expressed as precision and recall, (p_0, r_0), of $D[0]$ with respect to a correct specification of program version P_0 and (p_1, r_1) of $D[1]$ with respect to a correct specification of P_1.

Edit Ratio: The size of edits is quantified based on past attempts to quantify structural similarity between models [72, 23]. Intuitively, if according to a difference specification D, 2 out 10 edges in a specification S_0 have been deleted and 2 new edges added to form a new specification S_1, the similarity, sim between the two, as described by this edit, is 0.8 (as both models share 80% of their edges). We define *edit ratio* as the value $1 - sim$ to measure the relative amount of structural editing performed in a difference specification. In DMSG specifications, we also take into account the amount of edits needed within the basic DMSCs. Note that two difference specifications that effect the same semantic change may have different edit ratios. Although it is conceivable for a difference specification with a larger edit ratio to be more comprehensible, it is typically desirable to express the change in the simplest possible manner.

As subjects, the following systems described in [41] are considered:

- *MOST* – an embedded system for automobiles, *Shuttle* – an automated shuttle system that receives offers from and serves passengers.

- *RailCar* – an automated rail car system.

- *Weather* a part of NASA's CTAS air traffic control system.

We perform our analysis on Java code that is automatically generated from UML models of these systems. The experimental setup in [41] also uses a set of test inputs as well as multiple buggy versions of these systems, defined as mutations to the correct model. By executing the correct version we obtain trace set T_0 and and executing buggy versions gives us multiple sets of T_1. As each state of system components were implemented as a unique Java class in model generated code, we employ simple trace preprocessing to reflect the appropriate component names in trace events. We also considered three medium sized parsers/parser generator tools in Java: JLex [1], NanoXML [2] and JTidy [3]. Traces were generated from successive versions by using a set of documents as input to these programs. The bytecode of subjects are instrumented by load time weaving of tracing aspects using AspectJ [21]. In each case, only invocations of public methods of one class by another are recorded in the traces.

The results from quantitative evaluation of MSG specifications are tabulated in Tables 5.1 and 5.2. Correct specifications used for evaluation were manually constructed. The parameters for difference mining used were as follows: $\tau = 0.1, \tau_{dist} = 4$. The experiments demonstrate that changes between program versions could be accurately captured in a mined difference specification. In certain cases, in which changes do not affect the abstract behavioral specification and no corresponding change is reported. In most cases, the mined difference specifications have equal or better accuracy than individually mined specifications. The mined difference specifications were consistently found to have a lower edit distance. As fewer edits are made to effect the same semantic change, these specifications are easier to comprehend. Directly mining single difference specification was found to

[1]http://www.cs.princeton.edu/ appel/modern/java/JLex/
[2]http://nanoxml.sourceforge.net/
[3]http://sourceforge.net/projects/jtidy/

be faster as, in early stages of mining, identical traces from the two trace sets are combined thereby reducing the number of pairwise comparisons performed in the MSG construction phase. Such comparisons are performed twice when separate models are mined. In these experiments we were able to identify major changes in the mined global DMSG specification and confirm these changes by observing code level differences. The mined specification reveals only those changes where a new method invocation is introduced between objects of different classes. It was observed that only small changes result in the mined specification despite large code level differences. This enables faster comprehension of the change and a better understanding of the context of the change.

In NanoXML, a library in Java for parsing XML files, we were able to observe the behavioral impact of changes to the class architecture between versions 2.0 and 2.2. The *XMLElement* is modified in the same version to implement the *IXMLElement*. Existing code to build the document tree — *StdXMLBuilder* and write the tree to file — *XMLWriter* are also modified to support the newly defined interface. Our technique to mine for difference specifications allow us to determine what the collective impact of these changes are to the behavior of the program. In the difference specification, the transitions to the basic MSC which initializes an new *XMLElement* are removed and new transitions from the same set of basic MSCs now point to a new basic MSC that in which the *createElement* method, that is defined in *IXMLElement* and newly implemented by *XMLElement*, is invoked.

The behavior of the *XMLWriter* class is also seen to be modified to invoke the new methods exposed by the *IXMLElement* interface *getFullName* and *getNameSpace* before writing tree elements into the output file.

As these programs are small scale opensource projects, the documentation and change logs included limited information regarding the changes. By performing model level mining, it was possible to detect changes that were not documented.

Table 5.1: Evaluation Results for MSG based models

Prog	LOC	Versions	Structural Matching		Mined DMSG	
			Edit	Time(s)	Edit	Time(s)
RailCar	3144	Bug1	0.0	10.1	0.0	5.2
		Bug2	0.0	9.6	0.0	5.5
		Bug3	0.780	9.5	0.071	5.7
		Bug4	0.613	9.8	0.184	5.4
MOST	3989	Bug1	0.046	6.0	0.046	3.8
		Bug2	0.100	6.9	0.100	4.5
		Bug3	0.700	7.0	0.150	5.4
		Bug4	0.050	6.7	0.050	5.8
		Bug5	0.0	6.7	0.0	5.4
Shuttle	1854	Bug1	0.379	9.5	0.0417	6.0
		Bug2	0.111	9.8	0.059	6.3
		Bug3	0.111	10.1	0.059	8.1
		Bug4	0.0	9.3	0.0	6.1
		Bug5	0.0	10.5	0.0	7.7
Weather	3114	Bug1	0.035	24.0	0.035	17.5
		Bug2	0.672	24.3	0.098	16.6
		Bug3	0.036	25.7	0.036	16.7
		Bug4	0.0	23.9	0.0	15.4
		Bug5	0.529	25.6	0.056	15.0
JLex	5449	v1.1.1 - v1.1.2	0.119	26.4	0.119	26.9
NanoXML	5069	v2.0 - v2.1	0.938	6.5	0.348	4.4
		v2.1 - v 2.2	0.0	7.0	0.0	3.8
JTidy	18946	r820 - r918	0.351	19.6	0.282	15.6
		r918 - r938	0.048	19.1	0.048	16.7
Average			0.234	13.5	0.074	9.5

Table 5.2: Accuracy of Mined Models

Prog	Prog	Structural Matching		Mined DMSG	
		(p_0, r_0)	(p_1, r_1)	(p_0, r_0)	(p_1, r_1)
RailCar	Bug1	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
	Bug2	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
	Bug3	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
	Bug4	(1.00, 1.00)	(1.00, 0.75)	(1.00,1.00)	(1.00, 1.00)
MOST	Bug1	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
	Bug2	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
	Bug3	(1.00,1.00)	(1.00,0.22)	(1.00,1.00)	(1.00,1.00)
	Bug4	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
	Bug5	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
Shuttle	Bug1	(1.00, 0.41)	(1,0.41)	(1.00,0.48)	(1.00,0.48)
	Bug2	(1.00, 0.41)	(1.00,0.57)	(1.00,0.48)	(1.00, 0.89)
	Bug3	(1.00,0.41)	(1.00,0.57)	(1.00, 0.41)	(1.00,0.89)
	Bug4	(1.00,0.41)	(1.00,0.41)	(1.00,0.41)	(1.00, 0.86)
	Bug5	(1.00,0.41)	(1.00,0.41)	(1.00,0.41)	(1.00, 0.41)
Weather	Bug1	(0.21, 0.29)	(0.18,0.29)	(0.21, 0.29)	(0.18, 0.29)
	Bug2	(0.21, 0.29)	(0.39, 0.16)	(0.21,0.29)	(0.42,0.41)
	Bug3	(0.21, 0.29)	(0.21, 0.33)	(0.24, 0.29)	(0.20, 0.33)
	Bug4	(0.21, 0.29)	(0.36,0.31)	(0.21,0.29)	(0.36, 0.41)
	Bug5	(0.21, 0.29)	(0.24,0.25)	(0.21,0.29)	(0.24,0.25)
JLex	v1.1.1 - v1.1.2	(1.00,0.13)	(1.00,0.13)	(1.00,0.19)	(1.00,0.13)
NanoXML	v2.0 - v2.1	(1.00,1.00)	(0.84,0.50)	(1.00, 1.00)	(1.00,0.82)
	v2.1 - v 2.2	(0.84,0.50)	(0.84,0.50)	(0.84,0.50)	(0.84,0.50)
JTidy	r820 - r918	(1.00,1.00)	(1.00,0.50)	(1.00,1.00)	(1.00,0.50)
	r918 - r938	(1.00,0.50)	(1.00, 0.50)	(1.00, 0.50)	(1.00, 0.50)
Average		(0.83,0.65)	(0.84, 0.58)	(0.83,0.66)	(0.84,0.68)

Chapter 6

Adapting Specifications to Changes

Specification mining is a lossy and imprecise process and can only partially automate and assist the creation and maintenance of bona fide specifications throughout the software life cycle. Errors in the mining process are unavoidable, and mined specifications for each version will have to be subjected to human review and correction. Ideally, such corrections made on the specification of the previous software version should not have to be repeated over each program version. With this ideal case as motivation, this chapter processes an approach for managing and maintaining up-to-date specifications of programs. One of the common problems in software development comes from constant changes in the code-base (possibly due to demands of new functionality from various stake holders), and these changes not being reflected in the informal/formal specification document even if such a document exists. Exploiting the difference specification mining approached, a technique to update a existing correct specification of the earlier program version is proposed. Using the correct specification as a reference enables us to better understand changes and also obtain a more accurate specification of the new software version.

6.1 Overview

Revisiting the example of Java Dialog in 5, Figure 6.1(a) shows the correct specification for version 1.4 of Java. Let us assume that this version is available to the user, perhaps crafted manually or through semi-automatic means. The method proposed here propagates changes in the mined difference specification to the correct specification. Figure 6.1 (c) shows changes in the mined difference specification (Figure 6.1(b)) ported to correct specification of 1.4 (Figure 6.1(a)). Now, as the reference specification is the familiar and correct specification of version 1.4, the changes are easier to comprehend and verify. The meaningful labels attached to the states can be retained after propagation of changes. Moreover, when the changes are applied, i.e. deprecated transitions removed, we arrive at the correct specification for version 1.5. Figure 6.1(e) shows both difference specifications ported to the known correct specification, thereby allowing us to visualize the evolution of the Dialog class over three versions.

6.2 Technique

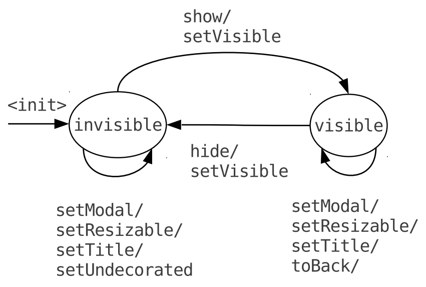
The approach for adapting difference specifications makes use of the difference specification identified from trace inputs from the previous software version and the current software version. Given such a difference specification D, derived through the methodology described in Chapter 5 we can define the problem of adapting specifications as follows:

Given an approximated difference specification D for P_0 and P_1, and a correct specification A_0 of P_0, derive an upgraded difference specification D' such that $D'[0] \equiv A_0$ and $D'[1]$ a more precise specification of P_1 than $D[1]$.

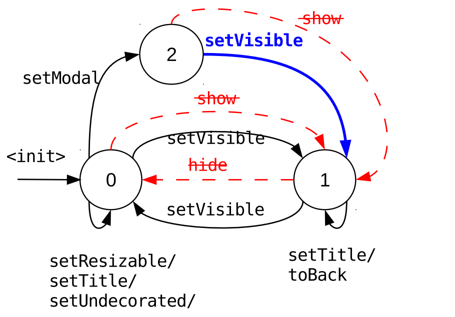
When a correct specification of P_0 is known, the difference specification D' is often easier to understand because it uses A_0 as its basis, *i.e.* edits (such as add and delete of transitions) are made on A_0 — a representation of P_0 that the user is already familiar with. Moreover, due to incompleteness in the test input set, certain behaviors common to P_0 and P_1 will be missing in both $D[0]$ and $D[1]$. Similarly, inaccuracies of the mining process, can lead to new behaviors to be added in the mined specifications. However, if such errors are not present in A_0, they will not be included in $D'[0]$ and may be avoided in $D'[1]$. It should be noted here, that the specification $D'[1]$ remains an approximation of program P_1 and as D' may not contain the full set of changes.

As seen in our motivating example of Figure 5.1, the mined specification provides an incomplete view of the system and incorrectly leaves out certain behaviors (eg: *setTitle* may be invoked after *setModal*, without changing to the *visible* state). These inaccuracies lead to a fragmented (and possibly inaccurate) understanding of the overall specification, as well the detected changes. After a specification is automatically generated it may have to be subjected to a review process whereby such errors are corrected. Unless the mining procedure and the set of test inputs are augmented to address these inaccuracies, they are bound to reappear in mined specifications of subsequent software versions.

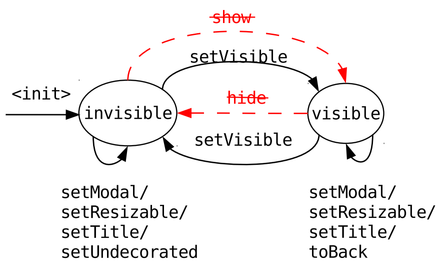
The proposed solution to this problem is as follows. We extract each change in D, identify the corresponding contexts in A_0 where it may apply and finally superimpose those changes onto A_0. At the end of this procedure, A_0, with changes superimposed is output as specification D'. The following sections will define changes in a difference specification as a set of *edits* and the concept of "contexts" in state based specifications D and A_0, with respect to a trace set T_0. Subsequently, the process of applying changes to a specification is discussed.



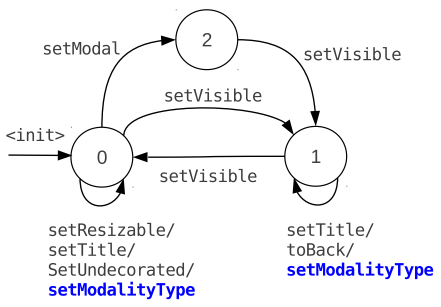
(a) Correct specification for v1.4



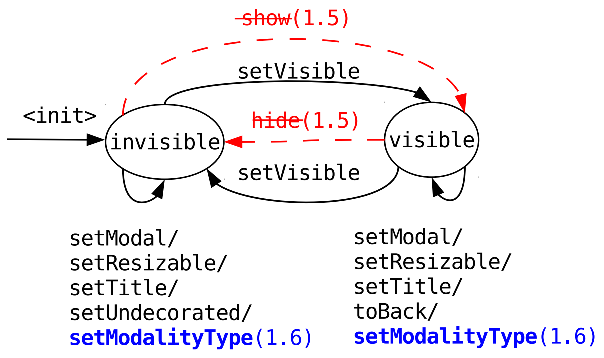
(b) Diff between v1.4 and v1.5



(c) Updated specification for v1.5



(d) Diff between v1.5 and v1.6



(e) All changes between v1.4 and v1.6

Figure 6.1: Difference mining example of the java.awt.Dialog class

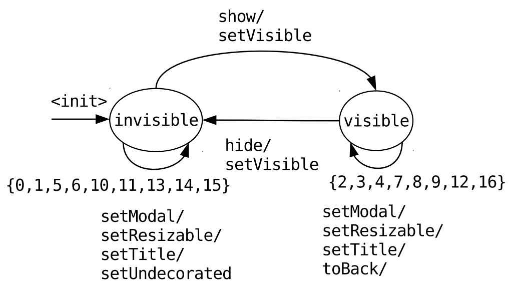
6.2.1 Edits and their Contexts

As in the previous chapter, we first discuss the process for automata based specifications before describing the additional steps required for adapting MSG based specifications. The DFSA syntax allows us to specify changes using novel and obsolete edges or states. We can extract the changes in a mined DFSA specification and represent them as a set of edits E. An edit represents a fundamental operation, to be performed in order to transform a specification of P_0 to a specification of P_1. For FSAs, the addition or removal of transitions can be represented as edits of the form $\langle e, \oplus, \psi_s, \psi_t \rangle$, where e is a transition label, $\oplus \in \{+, -\}$ specifies whether it is the addition or removal of the edge and ψ_s and ψ_t together form the context of the edit by specifying the pair of source and destination states where it was derived from.

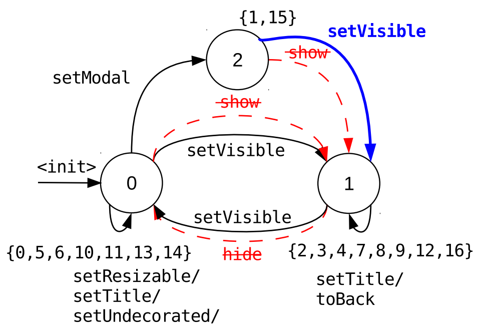
Ideally, the context specified in the edits should also be recognizable in specification A_0 to which we intend to propagate the edits. Since A_0 may hold an entirely different view of the system, with its own set of states, specifying edits that are applicable to both specifications is non-trivial. We assign a unique integer value to each occurrence of events in the trace set T_0 to symbolize the actual internal state of a program (shown in parentheses in Figure 6.2(a)). Thereafter, by executing T_0 against the deterministic FSA A_0, we can accumulate a dynamic *event record* at each state of A_0. For example, when trace $t1$ from Figure 6.2(a) is executed on the correct specification, the state *invisible* is reached by executing the first event *init (*0*)*. We therefore add 0 to the event record of the state. On executing the next event *setModal (*1*)*, we return to state *invisible* and add 1 to the same event record. Similarly, each state in the mined specification D can be associated with a corresponding event record. In practice we construct event records for states in D during the difference mining stages and assign unique event records to novel states in D to differentiate them from regular and obsolete states. Note that we have

t1		t2		t3	
`<init>`	(0)	`<init>`	(6)	`<init>`	(13)
setModal	(1)	show	(7)	setTitle	(14)
show	(2)	setTitle	(8)	setModal	(15)
setTitle	(3)	setTitle	(9)	show	(16)
toBack	(4)	setVisible	(10)		
hide	(5)	setResizable	(11)		
		show	(12)		

(a) Trace set T_0



(b) Correct spec with event records



(c) Mined spec with event records

Figure 6.2: Matching of states using event records

made two assumptions regarding the specification A_0. That it should faithfully execute traces from T_0 and that it should be deterministic. We believe that these are reasonable restrictions and likely to hold true for most specifications.

The changes in the difference specification example of Figure 6.2(c), can be expressed using the following set of edits:

δ_1: $\langle show, -, \{0, 5, 6, 10, 11, 13, 14\}, \{2, 3, 4, 7, 8, 9, 12, 16\}\rangle$

δ_2: $\langle show, -, \{1, 15\}, \{2, 3, 4, 7, 8, 9, 12, 16\}\rangle$

δ_3: $\langle setVisible, +, \{1, 15\}, \{2, 3, 4, 7, 8, 9, 12, 16\}\rangle$

δ_4: $\langle hide, -, \{2, 3, 4, 7, 8, 9, 12, 16\}, \{0, 5, 6, 10, 11, 13, 14\}\rangle$

6.2.2 Applying Edits

We take the list of edits from the difference specification D and apply them to the correct specification A_0. For every novel state in D, we update A_0 by introducing a corresponding new state having an identical event record. For two states q_u, q_v, in the updated A_0 having event records ψ_u and ψ_v, we apply a change transition (e) of type $(\oplus)$ between q_u and q_v if there exists a non-empty set of edits $\{\ldots \delta_i \ldots\} \subseteq E$, such that

- $\delta_i = \langle e, \oplus, \psi^i_{q_s}, \psi^i_{q_t} \rangle$ and,
- $\omega(\psi_u, \bigcup_i \psi^i_{q_s}) \leq \tau_\omega \wedge \omega(\psi_v, \bigcup_i \psi^i_{q_t}) \leq \tau_\omega$.

Where $\omega(\psi, \psi')$ is a measure of the **im**probability that a change affecting a state with event record ψ' in D also affects a state with event record ψ in A_0. A change is effected, when the ω-measure is less than τ_ω — a customizable maximum threshold parameter.

In our example, state *invisible* has event record $\psi_{inv} = \{0, 1, 5, 6, 10, 11, 13, 14, 15\}$ and state *visible* has event record $\psi_{vis} = \{2, 3, 4, 7, 8, 9, 12, 16\}$. Based on δ_1 and δ_2, we infer a deletion of transition *show* as there is an exact correspondence between the event records at source and terminal vertices. Similarly, δ_4 is propagated by to delete the edge *hide* between states *visible* and *invisible.* The edit δ_3 is not propagated as there already exists an transition *setVisible* from state *invisible* to *visible.* When there are new states in the mined difference specification, corresponding new states are added to the correct specification.

6.2.3 The ω-measure

As event records in $D[0]$ and A_0 are sub-sets of the same internal state identifiers assigned to T_0, we can view them as two different models for clustering the same set of event identifiers in trace set T_0. Such comparison of multiple clustering methods have been performed, outside the field of software engineering research, using the concept of conditional entropy in information theory [49]. In particular, two clusters — c_1 and c_2 from different clustering methods C_1 and C_2 respectively are considered proximate if there is a high conditional probability (or low conditional entropy) that an event occurs in c_1 when it is known to occur in c_2. We calculate conditional entropy as follows. Let N be the total number of event identifiers in trace T_0. Let X (or Y) denote a random variable which takes value 1 in the event that a randomly chosen event belongs to ψ_x from A_0 (or ψ_y from D_0) and has value 0 otherwise. The entropy of variable X is given as:

$$H(X) = -P(X=1)log(P(X=1)) - P(X=0)log(P(X=0))$$

The joint entropy $H(X,Y)$ is given by

$$H(X,Y) = \sum_{a=0,1;b=0,1} -P(X=a,Y=b)log(P(Y=a,Y=b))$$

where the probability values are obtained based on the event records as follows,

$$\begin{aligned} P(X=0) &= \frac{|\psi_x|}{N} & P(X=0,Y=0) &= \frac{N - |\psi_x \cup \psi_y|}{N} \\ P(X=1) &= \frac{|N-\psi_x|}{N} & P(X=1,Y=0) &= \frac{|\psi_x| - |\psi_x \cap \psi_y|}{N} \\ P(X=1,Y=1) &= \frac{|\psi_x \cap \psi_y|}{N} & P(X=0,Y=1) &= \frac{|\psi_y| - |\psi_x \cap \psi_y|}{N} \end{aligned}$$

The conditional entropy, i.e. the number of additional bits required to convey information about X given the value of Y is given as, $H(X|Y) = H(X,Y) - H(Y)$. Typically, if ψ_x and ψ_y are similar event records the conditional entropy will be low. We normalize the conditional entropy to obtain our ω-measure — $\omega(\psi_x, \psi_y) = \frac{H(X|Y)}{H(X)}$.

If $\omega(\psi_x, \psi_y) = 0$, then there is an exact match between the two records. Values close to 1 signify complete mismatch.

When the changes in the mined difference specification D is applied to A_0, the syntax of $DFSA$s can be maintained. An edit of type ($-$) is marked as an obsolete transition and an edit of type ($+$) is marked as a novel transition. States without an incoming transition can also be marked as obsolete. The resulting difference specification D' is the final output. The specification $D'[1]$ is likely to be a more accurate representation of the behavior of P_1 than the initially mined $D[1]$ as only portions of A_0 which are impacted by edits are modified. For our running example, after all the edits have been considered, the resulting D' is as shown in Figure 5.1.

6.3 Propagating changes from DMSGs

The process of propagating changes from a mined DMSG D to a correct MSG S_0 of P_0 is fundamentally similar to the process used for DFSA. The peculiarities of change propagation from mined DMSGs are described below.

6.3.1 MSG Event Records

While event records are associated with states of a DFSA, each send/receive event (at two ends of a message arrow) in a DMSG or MSG has its associated event record. For example, when a message *ack* is marked obsolete in a DMSC within D, it is represented as an edit whose context is provided by the event records of the send and receive events corresponding to the message. For a novel message, the edit context is provided by adjacent event records on the lifelines connected by the message arrow. The context for an edit involving the addition and removal of edges in the graph is set by event records of maximal events (which must precede all other events) of the source basic MSC and the event records of minimal events (which must follow all other events) of the destination basic MSC. As for DFSAs, each edit is propagated to all locations on S_0 that have a low ω-measures with respect to the event records in the edit.

6.3.2 Splitting Basic MSCs

A basic MSC in S_0 may be cut into two basic MSCs that are connected by an edge in order to accommodate a new incoming or outgoing transition. If the context in an edit specifying the source of a novel edge matches the event records of non-maximal events in a basic MSC in S_0, that MSC is then split to make the matching events maximal. Similarly a basic MSC is also split when the destination of a novel edge matches event records of non-minimal events.

After performing the necessary splitting, internal edits within basic MSCs and external edits between basic MSCs are imposed on S_0 to produce the difference specification D'. The specification $D[1]$ is the correct specification that is output.

6.4 Accuracy of Updated Specifications

For the set of test subjects used in Chapter 5, we migrate the changes on the the correct specification of program P_0 that is used for evaluation. A threshold of $\tau_\omega = 0.5$ is used for propagating changes. The precision and recall obtained for $D'[1]$ that is output as a result is compared with the correct specification of program P_1 and is shown in column (p'_1, r'_1). Since by design, $D'[0] = S_0$, the specification of P_0 therefore this portion of the specification need not be evaluated. The accuracy of mined specifications $D[0]$ and $D[1]$ are shown against these values for comparison. Our experiments show that precision and recall is substantially improved after changes are ported to the correct specification of program P_0, indicating that mined models convey sufficient information about the actual change.

Table 6.1: Accuracy of Mind and Adapted Specifications

Prog	LOC	Versions	(p_0, r_0)	(p_1, r_1)	(p'_1, r'_1)
RailCar	3144	Bug1	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
		Bug2	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
		Bug3	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
		Bug4	(1.00,1.00)	(1.00, 1.00)	(1.00,1.00)
MOST	3989	Bug1	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
		Bug2	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
		Bug3	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
		Bug4	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
		Bug5	(1.00,1.00)	(1.00,1.00)	(1.00,1.00)
Shuttle	1854	Bug1	(1.00,0.48)	(1.00,0.48)	(1.00,1.00)
		Bug2	(1.00,0.48)	(1.00, 0.89)	(1.00,1.00)
		Bug3	(1.00, 0.41)	(1.00,0.89)	(1.00,1.00)
		Bug4	(1.00,0.41)	(1.00, 0.86)	(1.00,1.00)
		Bug5	(1.00,0.41)	(1.00, 0.41)	(1.00,1.00)
Weather	3114	Bug1	(0.21, 0.29)	(0.18, 0.29)	(0.92, 1.00)
		Bug2	(0.21,0.29)	(0.42,0.41)	(0.647,1.00)
		Bug3	(0.24, 0.29)	(0.20, 0.33)	(0.45, 0.81)
		Bug4	(0.21,0.29)	(0.36, 0.41)	(0.53, 0.28)
		Bug5	(0.21,0.29)	(0.24,0.25)	(0.75,1.00)
JLex	5449	v1.1.1 - v1.1.2	(1.00,0.19)	(1.00,0.13)	(1.00,1.00)
NanoXML	5069	v2.0 - v2.1	(1.00, 1.00)	(1.00,0.82)	(1.00,0.82)
		v2.1 - v 2.2	(0.84,0.50)	(0.84,0.50)	(1.00,1.00)
JTidy	18946	r820 - r918	(1.00,1.00)	(1.00,0.50)	(1.00,0.50)
		r918 - r938	(1.00, 0.50)	(1.00, 0.50)	(1.00,1.00)
Average			(0.83,0.66)	(0.84,0.68)	(0.93,0.93)

Chapter 7

Threats to validity

In this chapter we discuss some of the threats to the validity of the research described in this dissertation. Several of these threats are common to related work in specification mining.

7.1 Trace Collection

Specification mining is a dynamic analysis technique that infers the general behavior of a system based on an input set of observed samples. The size of the sample has a significant impact on the accuracy of the mined result. The availability of comprehensive test inputs to generate execution traces poses a threat to validity. In our experiments, test execution of subject programs for trace generation was performed in different ways. The traces were obtained for the CTAS system using several executions in which the clients behave in a random and non-deterministic manner. In the SIP and XMPP systems, the traces were collected from several executions involving the usage of the graphical user interfaces of the clients in the system. During usage we actively tried to cover the use-cases that are part of the specifications. We rely on already available test drivers for trace generation from model-generated code for the embedded system examples (RailCar, Shuttle, Weather and MOST). While a good test suite is required to obtain sufficient data to mine a more accurate specification, trace collection from a limited test input set can also help to improve the understanding of system behavior. In future, the threat can be partially addressed by combining specification mining with test generation to generate new test inputs based on mined specifications [30]. The new test inputs can produce new test executions that can be used to enrich the mined specification. Another threat to validity is the availability of a message abstraction method that records observed communication using meaningful message names. In experiments involving implementations of SIP and XMPP protocols, we implemented simple regular expressions to parse the packets being exchanged between processes and automatically transform them into an abstract message labels. The parsers were written based on information available in informal documentations of these systems. We note that in practice, the mining process may have to be repeated multiple times during which the message abstraction method may be tweaked to refine or coarsen the model as desired.

7.2 Comparison with Correct Specifications

An internal threat to the validity is posed by the assessment method where the benchmark specifications have been derived by hand based on informal specifications. For most systems considered, the specifications were derived by the author to specify the configuration of the system that executes a pre-determined set of use-cases. To partly address the threat, the results have been presented in the context of corresponding results obtained from a baseline method. Both methods use the same set of input traces and their outputs are compared against the same benchmark specification. In addition, we inspect the set of behaviors specified by mined concrete and symbolic models but rejected by the correct model to ensure they are in fact incorrect behaviors.

7.3 Templates for Guards

In experiments to evaluate the mining of class-level specifications, we have only considered a small set of regular expression based templates. The selection of templates and may not result in accurate specifications in other kinds of distributed and embedded systems . We found that the selected set of templates were sufficient to specify the subjects considered. In these systems, the processes participating in a class-level interaction could be differentiated using an action it performed in the past and/or the most recent operation it performed. Another common factor of the systems considered in our experiments is that internal state changes affecting global behavior were explicitly communicated to other processes. For example, clients connect or disconnect through messages sent to the server. Additionally, many of the communication in these systems followed a request-response format in which the response messages are sent only by processes that have recently received a request. In general, regular expression based guards may not be sufficient to precisely define class-level behaviors in all systems.

7.4 Language of Difference Specifications

The difference specifications describe changes using a pre-defined set of edit operations that can be performed on MSG specifications. The evaluation is performed against the correct specifications of two versions of the program at the same level of abstraction. If the two correct specifications are different, we measure if the difference has been sufficiently captured using the set of edit operations. However, if two different versions of a program have the same correct MSG specification, then the difference specifications are not expected to describe any changes. In practice, difference MSGs may be insufficient to specify changes in a wide variety of cases. While such instances were observed in the subjects considered, most changes involved addition/removal of transitions or actions in the specification.

7.5 Subject Selection

The selection of subjects used in experiments raises an external threat to validity. We have considered Java programs emulating embedded systems, open source client-server programs and object-oriented programs as subjects for our evaluation. The subjects were chosen based availability of traces sets, the ease of constructing correct specifications and (for difference specifications) the availability of multiple versions. Although, our approach does not make assumptions regarding the nature of the systems, in practice, execution, instrumentation and dynamic analysis is challenging in many real life applications. We have considered significantly large subject programs in our evaluation (XMPP – 230KLOC, SIP –240KLOC). In practice, comprehending complex distributed systems by mining a single state-based specification can be challenging. We have evaluated our method on these complex subjects by limiting the scope of the analysis to specific features and system configurations.

The MSG and SMSG mining approach was seen to perform best in the CTAS system where processes collectively shift from one global state to another. As these global state changes were performed using broadcast messages, the class-level mining approach significantly reduces the size of the mined specifications. In the chat and VoIP systems, the class-level specification mining approaches were able to exploit redundancies among scenarios involving multiple processes of the same class. For example, a scenario in which client A calls client B is equivalent to the scenario in which client B calls client A. Another factor common to the subjects considered is that there are no pre-defined ordering or distinctions among these processes within a process classes. As a result, the class-level specification mining was able to exploit symmetries in the behaviors of processes within a process class and summarize scenarios effectively. As such features are common to a wide variety of Internet protocols, the approaches proposed in our method can help mine meaningful specifications for a large class of systems.

Chapter 8

Related Work

Existing work in specification mining involves both static and dynamic approaches and the discovery of specifications that are tailored to specific applications. Significant amount of research has also looked into methods for comprehending program evolution. These methods are organized based on the format or the language in which mined specifications are expressed.

8.1 Mining Finite State Machines (FSM)

Multiple techniques have independently emerged to discover common specifications in the form of finite state machines [17, 53, 60, 65, 31, 84, 71, 38, 15]. Many of these techniques are built upon the k-tails learner [22]. In mined state machines, the transition edges between program states are usually labelled with method calls. Ammons *et al.* propose the use of automaton mining on execution traces to infer state machine specifications for Application Programming Interfaces (API) [17]. The precision and recall of automaton mining is improved by a trace filtering and clustering method proposed by Lo and Khoo [53]. Lorenzoli *et al.* combine the work of Daikon[35] with mining finite state models [60]. Boolean invariants are attached to transitions among the nodes in the finite state machines to express guards. Walkinshaw et. al. in [84] use an alternative grammar inference algorithm to mine state machines that is interactive and need not rely on positive sample alone. The approach proposed here uses a similar automaton mining algorithm, but performs additional steps so as to mine state machines having MSCs at each node. It is possible to apply the techniques proposed in the past work on top of the method proposed here to improve the mining accuracy (e.g., by performing trace filtering and clustering) and enhance the expressiveness of the mined model (e.g., by the addition of guards).

Component Interaction: In [65], component interactions are analyzed so that compatibility can be tested when they are reused in new environments. Method invocations from one component to another constitute component interactions and they are characterized using two types of invariants; *interaction invariants* and *I/O invariants*. Interaction invariants capture, in the form of an FSM, valid interaction patterns between components. I/O invariants capture properties of the data being exchanged between components, for example the parameter $frac$ being passed during the interaction must satisfy $0 \leq x \leq 1$. Based on interaction characteristics learnt during the learning phase, conformance is verified when components are modified. The proposed mining of MSC based specifications can be adopted in capturing interaction invariants. The proposed MSC mining solution can be especially useful when the interacting components are autonomous units having independent control. The approach proposed here does not identify I/O invariants but can be easily extended using Daikon like invariant detection tools to infer properties regarding the messages being exchanged.

Object Behavior: Dallmeier *et. al.* in [31] discover state machines that model object behavior in Java. In this work object behavior is described in terms of state changes that result from the invocation of its methods. This requires classifying methods as those that modify the state of the object (*modifiers*) and those that keeps the state of objects intact (*inspectors*). For instance, the method *isEmpty*() and *size*() are inspectors of a $Vector$ object whereas *add*(), *remove*() or *clear*() are modifiers. The mined behavioral model of the $Vector$ object is then an FSM with the modifier methods describing transitions. The states of the FSM also capture the state of the object in terms of inspector methods. For instance the initial state in the FSM is labelled with *isEmpty*() as this inspector returns true when the $Vector$ object is empty. As the object behavior model is derived for a class, based upon multiple instances of that class it can be considered to be specifying the behavior of the class. However, this kind of behavior model is akin to the per-process view of a distributed system. As argued, the mined MSC based specifications that are argued for in this thesis are global specifications of the system and capture global state transitions. When the global specification is raised to the class level it specifies the "collective" behavior of a class of objects using symbolic actions. This is different from specifying all possible behaviors that an individual object of the class can exhibit. This fundamental shift from capturing individual behavior to collective or group behavior is an important step towards the comprehension of distributed systems through specification mining. Unlike in the work of Dallmeier *et. al.*, our mining of MSC based specifications does not recover object states using inspector methods and therefore can be used in systems having processes with autonomous control and other types of message passing.

Pradel and Gross in [71] also confront the problem of discovering object behavior models. The specification mined is similar to the object behavior model discussed above. Their focus is to achieve scalability by identifying small sets of related objects that can be analyzed separately. This paper adopts a different course where the problem being studied is "how to characterize the complete behavior of a system based on observations in a given trace set from a system having multiple autonomous components". The solutions proposed here involve, a) use of a specification language suited for concurrent systems, b) abstraction to class level. The class level behavioral specification mined is parameterized and therefore can be instantiated to a finite number of objects to define the complete behavior of a system having those many objects. In contrast, the object interaction specifications concentrate on a small set of objects. The methods that are used narrow down the candidate components and the set of interactions that should be analyzed from can be adopted to the MSG mining scenario.

Partial Order: In [15], Archaya et al. extract relevant API interaction scenarios out of static traces generated from program code. The scenarios are then summarized as compacted partial orders. A collection of work that attempts to infer frequent partial order from string databases is discussed in [34]. The generic partial order representation that is identified can be used to explain multiple sequences occurring in the database. Lou *et al.* in [61] construct workflow models from traces of concurrent systems by identifying dependency relationships between pairs of events in interleaved traces. Different from the above studies, the method proposed here expresses partial orders in the semantics of Message Sequence Charts (MSCs). MSC is a popular specification language and formally specifies the partial order constraints among messages sent between lifelines. At a technical level, the problem addressed here is substantially different. In distributed systems the partial ordering of events can easily be inferred based on the association of events to processes and the causal links between send and receipt of the same message.

The particular problem addressed here is to analyze multiple partially ordered scenario specifications and identify a simple MSG specification for those scenarios that also includes additional scenarios which are likely to be executed by the same system.

Global Automata: In [73], a library for automata learning is presented that uses domain specific properties of distributed systems to optimize the learning algorithm. Although some of the properties exploited are the ones identified for the symbolic mining approach, the L^* learning algorithm used is fundamentally different. For the L^* approach to identify the language, a series of membership and equivalence queries must be adequately answered. As the approach proposed here is based on the *sk-string* algorithm, it is sufficient to have execution traces from the system and active experimentation (to answer queries) is not required. Furthermore, the final model mined is a single global automaton containing concrete events, as opposed to the hierarchical and symbolic MSG model mined by the approach proposed here.

Automata Inference based on Templates: Yang et. al. in [86] propose an efficient algorithm to to detect temporal rules in API usage. This method is capable of checking long execution traces for a set of properties based on predefined regular expression templates. In contrast, we use regular expression based templates to identify quantified guards that can be applied for process selections or edge conditions within a behavioral specification. In our application, we found it fruitful to form more complex guards by combining those from the basic template using intersection, union and complement operations. Gabel and Su in [37] improves the performance of mining templates having three or more characters using a BDD based symbolic mining technique. It should be noted that the word "symbolic" applies to the mining technique rather than the mined class-level specifications which we have also referred to as being symbolic.

8.2 Frequent Patterns and Rules

Approaches that mine frequent patterns highlight statistically significant patterns in the execution of the system which can be interpreted as temporal rules [54, 80, 15, 86, 55]. While the mined set of rules and properties are valuable to processes like model checking, they provide a limited understanding of the system as a whole. We mine for MCDs based on a frequency criterion and use them along with automaton learning methods to provide a complete specification of the system.

Live Sequence Charts: The work of [59, 56] mine Live Sequence Charts (LSC) that represent rules of the format "If the execution described by the pre-chart occurs, the execution prescribed by the main chart must follow". These charts are derived by discovering statistically significant sequential patterns in execution traces and depicting them as rules in the LSC form. Figure 8.1 shows LSCs for the CTAS example considered in case studies. For example, if a client connects to the CM, then CM disables the weather control panel and at a later stage of execution re-enables it. These rules must be followed by all execution scenarios. The focus on mining for MSGs (a global system model) in the proposed research involves a fundamental conceptual shift from mining of LSCs (a collection of temporal properties). This is because LSCs are simply a visual description of temporal properties which must hold in every system execution. In contrast, MSGs can be a complete description of the global system behavior, that provides the full set of scenarios that the executing system can take. The mined MSG accounts for all execution scenarios witnessed in the traces and includes additional execution scenarios inferred by the mining approach based on the given trace set whereas mined LSCs provide a set of rules that hold for 'most' execution traces. Through the mined MSG model we highlight the interaction snippets or commonly executed protocols across the processes and these get captured as the nodes or basic MSCs in the mined MSG model.

In [57] Lo et. al. mine for LSCs that contain symbolic lifelines representing a class. However, the mined LSCs have very limited symbolic power - in rough terms, existential quantification of objects within a class can be mined, but universal

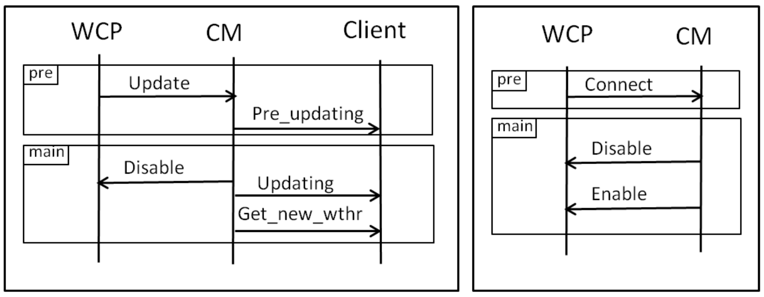


Figure 8.1: LSCs for the CTAS System

quantification involving all objects in a certain class satisfying a certain guard is not mined for. It is the combination of the existential/universal quantification, along with the inference of the guards which makes our mining method challenging.

8.3 Sequence Diagrams

Efforts have been made in program visualization by constructing UML sequence diagrams from dynamic executions [28, 70]. Such work constructs a sequence diagram from dynamic traces traces but does not produce graph-based models like MSG that include loops and branches. Rountev *et. al.* [77], perform a static interprocedural analysis to reverse engineer UML Sequence Diagrams from programs. Such an analysis requires the program source code, whereas the techniques proposed here, being dynamic, only needs execution traces. The proposed framework supports mining with synchronous/asynchronous message passing(within MSCs) and synchronous/asynchronous concatenation(across MSCs) — making it a fully general framework for mining MSC-based system models.

8.4 Invariant Detection

Property inferencing in a fixed logical language have been studied earlier, as evidenced by the work on Daikon [35]. However, Daikon attempts to infer potential invariants — properties that may hold in a certain control location of a program

— via dynamic analysis. The Daikon method has been has been combined with behavioral specification mining in [60, 58]. Boolean invariants regarding object variables or parameters are attached to transitions between states or to method calls to express guards. The conception of guards used in our class-level specifications is fundamentally different as it is a quantified expression that constrains the selection of processes from a process class. In our work, we are inferring guards or logical formulae which capture the set of processes/objects (each with their own independent flow of control) which execute a common action. Furthermore, our inferred guards involve reasoning about execution histories, as opposed to Daikon which only infers state-based potential invariants. While execution history is used to indirectly represent the state, it is easier to record only the history of actions in traces rather than state variables and their respective values. Alternatively, the guards on the execution history may in certain cases be easier to comprehend that constraints on state variables. A possible extension to our work is to consider a combination of both history based and state based dynamic analysis can help to infer a more accurate class-level specification. It should be noted that the method used to infer guards in class-level specifications was inspired by the dynamic analysis approach taken by Daikon.

8.5 Semantic Differencing

Potential applications in program debugging have inspired research into techniques for identifying differences between program versions. As syntactic differencing techniques have limited ability to capture the scope and impact of changes, techniques to identify semantic differences between program versions are proposed in [43, 44, 19]. These techniques perform a static comparison between the source code of two programs. Zhang et. al in [87] propose a dynamic technique for matching execution histories from program versions having dissimilar control flow graphs. The matching technique outputs relationships between instructions from the two versions using data recorded in the execution traces. These techniques highlight, in addition to syntactic differences, differences between program control flow or characterize the difference in the effect (output) of the program. Although they can differentiate the more interesting semantic differences from minor syntactic differences, the difference is described at the source-code level and therefore requires a good understanding of the program. Moreover, semantic differencing techniques are limited to the analysis of two versions of a single procedure or the program dependence graphs of two programs. Our difference specification mining method can describe version differences for distributed systems realized through multiple communicating processes.

8.6 Structural Differencing

Xing et. al. in [85] propose a technique to compare UML specifications such as class models through structural matching. Nejati et. al. propose a structural matching and merging technique for behavioral models such as statecharts [69]. Both these techniques presuppose that reliable specifications of two versions are already available. They match models using heuristics to identify structural similarity between nodes or states in the input models. The result of such differencing techniques are very similar to the output produced in the difference mining technique proposed here. They try to address the same need for change comprehension at the model level. However our technique is different in that it automatically infers a high-level model through specification mining and therefore does not require models for both versions as input. Instead we require that the two program versions have been implemented and can be executed with a comprehensive test suite. Secondly to identify similarities between models, we utilize actual dynamic execution data rather than only structural similarities and features of a static model.

8.7 Language Comparison

Several techniques have been proposed to automatically synthesize behavioral specifications [18, 61, 31, 60]. Subsequently, approaches have been proposed to compare and difference mined specifications. Lo et. al. propose a language based comparison between two models [52] to measure the proximity between two models. Although, this approach can provide a set a of sample sentences that are accepted by one model and rejected by the other, it can be difficult to comprehend change and assess its impact by looking at a set of such samples. Structural approaches to compare mined specifications have also been proposed [72, 23]. However, these techniques first use dynamic data to separately derive the models and then perform comparisons, purely based on structural matching heuristics, to obtain a structural difference model. In our approach, we utilize the dynamic execution data to directly infer a difference model. Here, matching between program states from the same version and from across program versions are both performed using dynamic trace data.

8.8 Discriminative Pattern Based Rules

Discriminative pattern mining, identifies patterns that discriminate the traces of one program version from traces of another version [51]. These patterns or rules point to the core differences (potential cause of bugs) between the two versions. Let us take the example of the Java *Dialog* class that we considered in Chapter 5 where methods *show* and *hide* were deprecated after version 1.4 (in version 1.5). A discriminative pattern mining approach will report the simplest discriminating pattern to distinguish traces from each version which in this case are sequences containing single events: $< hide >$ and $< show >$. These two sequences occur only in traces from version 1.4 and not in traces from version 1.5. A potential user who is not familiar with the Dialog class may gain only a limited understanding about the change. Specifically, it is not evident as to (a) what the function of these methods are (b) what are they replaced with. Difference specifications, in contrast, describe the removal of these methods within a complete behavioral specification (such as state machine or Message Sequence Graph), enabling better comprehension. One could argue that discriminative rules can be subsequently used to modify an existing specification. However, as rules are minimal, they are often insufficient to identify where they must be applied. In our approach for adapting specifications, we extract changes by identifying the full dynamic context in the form of event records as to where the changes must be applied.

Mileva et. al. in [66] introduce the LAMARCK tool to identify evolution of API usage patterns. The patterns identified are temporal rules on the invocation of API methods within a single function in the client programs. We identify evolution in terms of modifications required on the high-level state based specifications through a dynamic method based on execution traces that does not require program source code. The LAMARCK tool is also used to identify other client code which may have to be adapted in the wake of API changes. This points us towards future work, in which mined difference specifications can be utilized to automatically detect and adapt other code that utilize the evolving components.

Chapter 9

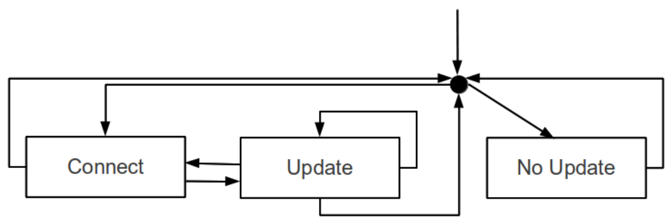
Future Work

There are multiple avenues by which the specification mining approach proposed here can be extended. We explore directions for future research in the following sections.

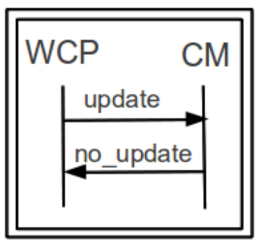
9.1 Expansion of Specification Language

The mining techniques studied here have targeted the discovery of specifications in formally defined specification languages. These languages are variants of the standardized MSC language. The mining tool can be extended to utilize the expressive power of other features defined by the MSC standards. One manner in which the *readability* of complete specifications can be improved is by representing them in a hierarchical fashion. The node of a High-level MSC is either a *basic* MSC or a nested HMSC. Figure 9.1 shows as an example a hierarchical specification of the CTAS system. The HMSC in Figure 9.1(a) contains two nested HMSCs (Figures 9.1(c) and (d)).

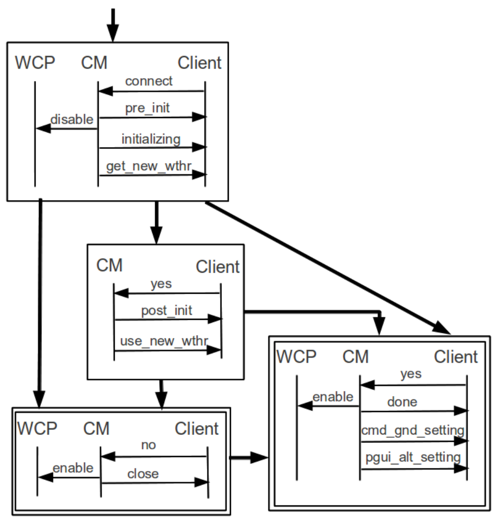
The automated or assisted discovery of such specifications faces interesting challenges. As there are several ways in which a flat graph can be transformed into a hierarchical graph, the properties that are desirable in hierarchical specifica-



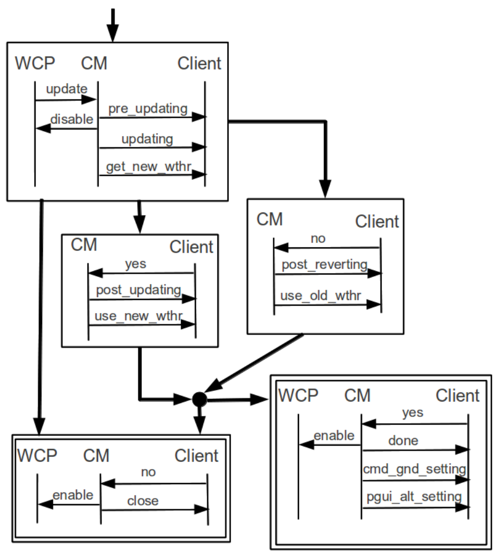
(a) Highlevel MSC



(b) No Update



(c) Connect



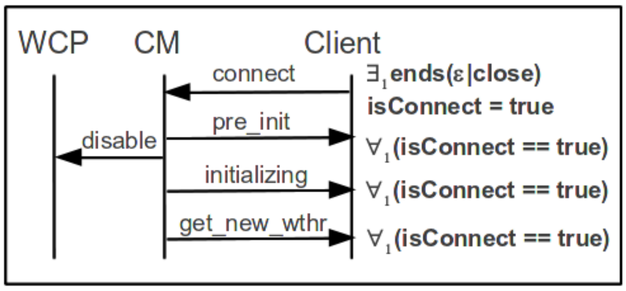
(d) Update

Figure 9.1: Hierarchical Specification of the CTAS system

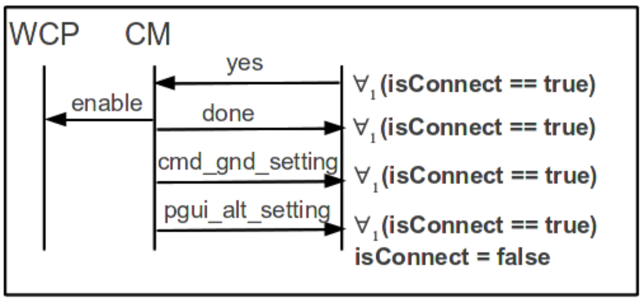
tions have to be identified and formally defined. From a program comprehension standpoint, the specification at the higher level should provide a broad overview of system behaviors and reveal details at lower levels of hierarchy. The mining procedure must therefore be able to determine the relative "interestingness" of nodes and transitions in the mined model so that less interesting characteristics can be suppressed.

The language of guards used in mined class level specifications can also be expanded. The guard language has already been defined to include constraints on the execution histories and states of processes. Figure 9.2 shows basic SMSCs containing both state and history based constraints are depicted. Figure 9.2(a) shows how a client initiates connection with the CM process. Figure 9.2(b) shows the sequence of interactions at the end of a successful connection. Figure 9.2(c) shows the sequence of interactions if connection failed and CM has decided to close the connecting client. The process history constraint $ends(\epsilon|close)$ refers to a client connecting for the very first time or one that has been closed. The condition $(isConnect == true)$ is used to refer to the unique object that is presently connecting ($isConnect$ here is a variable of the client process). The specification also enforces the postcondition $(isConnect = true)$ immediately after $connect$ and resets it to $(isConnect = false)$ at the end of a successful (after receiving $pgui\_alt\_setting$) or failed (after $close$) connection. The use of such a state based constraint is likely to be viewed as being a less tedious description than the use of an equivalent regular expression constraint such $bet(connect, close) \wedge bet(connect, pgui\_alt\_setting)$, which refers to execution histories in which the last occurrence of $\langle Client!CM, connect\rangle$ have not been followed by the $\langle Client?CM, pgui\_alt\_setting\rangle$ or $\langle Client?CM, close\rangle$ actions.

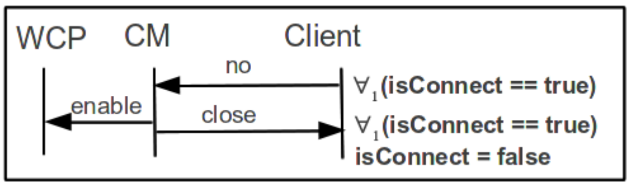
Constraints over process states can be derived from mined regular expressions. For example, for the regular expression $bet(connect, close)$ we can specify



(a) SMSC using regular expressions



(b) SMSC using state variable - Connect



(c) SMSC using state variable - Close

Figure 9.2: Class-Level Specification of the CTAS system

a boolean variable $isBetConnectClose$ at client processes. The variable has to be set to $true$ whenever $\langle Client!CM, connect\rangle$ is executed and set to $false$ after $\langle Client?CM, close\rangle$ is executed (enforced through post-conditions). In effect, the variable at any state of a concrete process keeps track of whether the execution history of that process satisfies $bet(connect, close)$. Occurrences of $bet(connect, close)$ can therefore be replaced with the equivalent constraint $(isBetConnectClose == true)$.

Apart from improving readability, state based constraints may be important to characterize class level behavior. This is because history based guard inferencing can fail when the set of histories for participating and non-participating concrete processes are indistinguishable or if their difference can not be characterized using regular languages alone. To account for such scenarios, constraints over process states (values of state variables) can be inferred directly from trace events. For this, the values of variables that are common to all processes within a process class must also be recorded in the traces events of those processes. As invariant detection based on program state can potentially produce a large number of invariants a method to rank and select invariants has to be developed. State based constraints can be discovered by adopting existing techniques for invariant detection (eg: Daikon [35]).

9.2 Traceability to Informal Specifications

MSC based specifications resemble the communication of system behavior in natural languages. This provides an opportunity to infer and maintain traceability links from mined specifications to existing informal documentation. Traceability links are mappings from requirements in documentations to code/design artifacts (or vice versa) that enable requirements traceability. These links from informal specifications to methods and snippets in code can play an important role in program understanding and maintenance.

The following excerpt is taken from requirements documentation in English for the CTAS weather control logic [68].

> 2.6.2 The CM should perform the following actions when a weatheraware client attempts to establish a socket connection to the CM:
> a) it should set the weatheraware clients weather status to "preinitializing" (i.e., Socket.wthr_status = WTHR_CLIENT_STATUS_PREINITIALIZING)
> b) it should set the Weather Cycle status to "preinitializing"(i.e., Weather_cycle.status = WTHR_STATUS_PREINITIALIZING)
> c) it should disable the F2 Weather Control panel "update" button so no manual changes can be made by the use

The external actions described in this section: set client status to "pre-initializing" and WCP to "disable" closely matches up with the interactions described in the basic SMSC considered in Figure 9.2(a). Automatic methods to establish traceability links from mined specifications which contain message names used by the system implementation to informal documentation will have to rely on techniques from areas such as natural language processing and information retrieval. The matching may be based on key-words (eg: "pre-initializing", "disable" etc.) or semantic similarities (eg: "first send message to Client and then send message to WCP").

9.3 Test-Suite Augmentation

The mined specifications reflect the set of behaviors that have been observed in traces. It also contains the set of additional behaviors that were inferred based on what is observed in traces. Additional behaviors may be a result of generalizations performed during the mining of state based models or guard inference for the creation of class-level specifications. If traces were generated during the execution of a test suite, then the test suite can be augmented to include test cases where the inferred behaviors are also tested. Furthermore, the mined MSGs can be utilized to identify likely failure points in each process of a system. For example, the mined specification of the CTAS system show that when CM broadcasts message *get_new_wthr* two alternative responses (*yes* or *no*) are anticipated from the clients. New tests, which ensure graceful handling by CM of incorrect responses (other than *yes* or *no*) or delayed responses, can be constructed. The MSG also reveals that the WCP component is indirectly impacted by the behavior of the clients and therefore these new behaviors should be included in tests of WCP as well.

9.4 Multi-threaded Systems

The proposed techniques have been targeted at systems in which there is a clear and known separation of processes and modes of interactions. Behavior in multi-threaded systems involving shared variables can also be specified in MSC like specifications. In such specifications, threads and shared memory are represented as lifelines and causal relationships between events from different threads (arising from synchronization operations or access shared memory) represented using message arrows [16, 78]. A significant challenge here is the recording of execution traces without impacting system behavior and subsequent reconstruction of a dependency graph from execution traces . Once dependency graphs are recovered from execution traces, techniques proposed in this paper for the identification of basic MSCs (Maximal Connected Dependency Graphs), construction of global state transition models (MSG) and the inference of class level specifications can be utilized to discover global models of multi-threaded systems.

9.5 Usability Evaluation

The importance of documented specifications in various software development phases is widely appreciated. Among these, UML sequence diagrams are recommended in the process of translating requirements to design. MSC based specifications have been used in the industry to specify embedded systems or telecommunication protocols. This is a good indicator that the proposed automated specification discovery methods can become a powerful tool for creating specifications that are useful during software engineering processes. User studies to evaluate the impact of UML based specifications (including sequence diagrams) have been performed in the past [20, 81]. A user study performed along similar lines could help to verify the usability of mined specifications in software engineering processes. The user study could also be set up to compare comprehensibility of two kinds of specifications [75]. In our case, mined class level MSG specifications can be compared to object level specifications mined using automata learning method. Some of the factors involved in the design of such a study are considered below:

- **Experimental Hypothesis:** Mined global behavioral specifications aid in the comprehension of overall design and properties of distributed systems as compared to per-process automata views of the same system.

- **Subject Selection:** Ideal subjects for user study on program comprehensibility are developers who have both a basic familiarity with concurrent programming as well as specification languages such as sequence diagrams. The competence of the subjects can be ensured through a basic screening test containing questions regarding these two topics.

- **Methodology:** A distributed system is to be selected for case study and MSG specifications as well as per-process specifications be mined from the execution of that system. Simple tasks involving global behavioral changes to the system have to be identified. In addition to such tasks, a set of questions regarding the architecture of the system can be designed and a quiz formulated in a multiple choice format. The subjects are divided into two groups A and B. Group A is provided with the source code [1], a compilation kit and mined MSG specifications. Group B which is the control, should be provided with the identical source code and compilation kit but specifications in the form of per-process automata.

- **Measured Variables:** The relative comprehensibility of different software specifications should be measured through by evaluating and scoring the quality of completed tasks, time taken to complete tasks as well as a quiz pertaining to the case studies. The completion times can be accurately measured if the tasks and quizes are administered through an automated mechanism online.

[1]It should be ensured that subjects have experience with the programming language as well as the message passing mechanisms used in the implementation

Chapter 10

Conclusion

In this thesis, a dynamic specification mining framework to mine Message Sequence Graphs from execution traces of distributed programs has been presented. The focus on Message Sequence Graphs is driven by the view that the mined specification will be used for program comprehension. Thus, the mining framework exploits the ease-of-use of MSCs/MSGs for understanding interactions in distributed software. As demonstrated by experiments, an MSG being a global graph of interaction snippets — provides a higher-level view of system behavior (and its interactions), as compared to mining the behavior of individual processes of a concurrent program as state machines.

The case studies show that the mining framework can be used to discover MSG specifications with good accuracy. The global picture presented by the mined MSG provides an intuitive way to understand system behavior when compared to local process automata. While the local view is important for implementing the individual components, the global view is desirable for understanding communication protocols and the distributed system as a whole. The evaluation techniques show that the mined MSG were found to provide precision and recall that is on par with or better than the model obtained by mining automata for each process separately.

Class level mining is particularly important for distributed systems having many behaviorally similar processes - as object-level specifications (with concrete processes/objects) are hard to comprehend. Since specification mining aims for behavior comprehension - arguably this makes for a strong case to mine succinct class level specifications. The specification depicts inter-class interactions and guards that behave as object selectors and allow for state-based as well as history based constraints, along with universal/existential quantification (capturing whether all or any one process satisfying the guard executes the event in question). The evaluation performed shows that such guards allow us to mine specifications for distributed systems that are more accurate than concrete models.

We have also extended the specification mining approach used to mine MSG based specifications to identify differences across program versions. Existing techniques for model-level comparison of program versions require independent creation (manually or automatically) of specifications of each version which are then subjected to structural matching techniques. By implicitly fusing the model creation/mining and difference identification processes into a single difference mining step, we have made it possible to control the mined specifications specifications using a single set of parameters. Furthermore, we have proposed a change porting technique, which in effect makes it possible to remember and retain human inputs and corrections to the mined specifications as the system evolves. Our experiments show that difference mining to identify high-level behavioral differences reveal important, undocumented program changes which are useful to understand software evolution.

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