Dynamic Slicing of Object-Oriented and Aspect-Oriented Softwares

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Dynamic Slicing of Object-Oriented and Aspect-oriented Softwares

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Certificate

This is to certify that the work in the thesis entitled ***"Dynamic Slicing of Object-Oriented and Aspect-Oriented Softwares"*** by ***Alina Mishra*** is a record of an original research work carried out under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology in Computer Science. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

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Acknowledgement

"No one walks alone on the journey of life. just where do you start to thank those that joined you, walked beside you, and helped you along the way....."
Thank you God for showing me the path...

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Abstract

Program slicing is a program analysis technique that uses program statement dependence information to identify parts of a program that influence or are influenced by an initial set of program points of interest (called the slice criteria). Slicing is generally based on program code. An alternative approach to compute the slice is from specifications developed using formalism such as Unified Modeling Languages(UML). Moreover in component based software development, only the specifications are available and the source code is proprietary. UML is widely used for object-oriented modeling and design. In our research, we focus on UML communication diagram to compute the dynamic slices because communication diagrams model the dynamic behaviour. We first develop a suitable intermediate representation for communication diagram named as Communication Dependence Graph (CoDG). Then, we propose two dynamic slicing algorithms. We have named the first algorithm edge-marking dynamic slicing algorithm for communnication diagram (EMACD) and the second node-marking dynamic slicing algorithm for communnication diagram (NMACD). To verify the correctness and preciseness of our algorithms, we have implemented our algorithms and also calculated the space and time complexity.
Aspect-oriented Programming (AOP) is a recent programming paradigm that focuses on modular implementations of various crosscutting concerns. In our research, we proposed a technique for dynamic slicing of aspect-oriented software based on the UML communication diagram. Next, we generate an intermediate representation from the communication diagram which we named as Communication Aspect Dependency Graph (CADG). Then, we proposed an edge marking dynamic slicing algorithm named as Aspect-Oriented Edge Marking Algorithm (AOEM). The novelty in our approach is that we present the communication diagram for the aspect-oriented software. We have implemented the algorithm and also found the space and time complexity of the algorithm.

Keywords: *UML, Communication Diagram, Communication Dependence Graph (CoDG), EMACD, NMACD,Communication Aspect Dependency Graph (CADG), AOEM.*

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Chapter 1

Introduction

Nearly every transactions carried out in today's world make use of different types of software solutions. These software solutions are becoming reasonably complex and their qualities have been largely bounded by cost and time factors. It has been established that approximately 60% of the software built at present goes unused due to their lack of ability to meet the above cited constraints, which in turn results in enormous loss of money, time and manpower. Therefore, software testing activities are extremely important for developing of reliable software. Object-oriented procedure modularizes the software, but simultaneously, it is extremely complex and difficult to test and debug for errors.

Program slicing is a reverse engineering technique that has been usually studied since it was first proposed in 1979 [38]. It is a significant method which has many applications in the field of software testing. Program slicing offers a innovative way to perform software maintenance and software understanding. Program slicing is defined as a decomposition strategy which removes program statements that are not applicable to a particular computation, known as slicing criterion. The residual statements form an executable program called a slice that outline a distinction of the original programs definition. It provides programmer the statements that are only relevant to computation of a given function. Essentially, program slicing is a technique for simplifying programs by giving emphasis on selected aspects of semantics. It is also a method of program analysis used to extract a set of statements from a program which is relevant for a particular computation.

Slicing of a program is done with respect to a *slicing criterion* . Usually, a slicing criterion defined as a pair $\langle S,V \rangle$, where S is the statement number and V defines the set of variables. A slice of a given program P with respect to a given slicing criterion $\langle S,V \rangle$, is the set of all the statements of the program P that might affect the slicing criterion for every possible input to the program. Various assumptions of program slices have been proposed [5, 38]. Also, a number of methods have been proposed to compute the slices. The main motivation for this large number of slicing techniques lies in the fact that different types of applications need different properties of slices.

Program slicing technique has been widely studied and applied deeply into all the phases of software engineering. In the requirement stage, we analyse the Software Requirement Specification (SRS) document dynamically and problem is discovered as soon as possible. In the design stage, slicing of architecture or UML models is used to create the module with low coupling and high cohesion, hence reducing complexity of the software. In applications like coding, testing, maintenance phase, program slicing techniques can be used to achieve code optimization and localisation of error.

As defined by *Weiser* [38] a program slice S is a reduced, executable program obtained from a program P by removing statements, in such a way that S replicate part of the behaviour of P. Executable does not mean that the slice is only a closure of statements, but it also can be compiled and run. The slicing technique initially proposed by Weiser [38–40] is currently called as static backward slicing because the slices that are obtained do not depend on the input values. It is considered as backward slicing because during computation of slices, the flow of control is in backward direction of the program. A forward slice [35] contains all statements depending on the slicing criterion, whereas backward slice contains all statements that slicing criteria may depend on. Another definition of a slice is that it is a subset of the statements and control predicates of the program which directly or indirectly affect the values computed at the slicing criterion, but which do not essentially form an executable program. Admirable surveys of program slicing are available in [5, 35, 42]

The high-level design configuration of object-oriented software is defined by its architecture. Architectural design models are more helpful as the size and complexity of software increases. The significant uses of architectural design models are assessment, understanding and testing a proposed solution [22]. Unified Modeling Language (UML) is most widely used for construction of architectural models of complex and large software [22]. It offers a broad collection of visual artifacts for modeling the various aspects of a system. As the software size and complexity tends to increase, UML models also become more complex which involves hundreds of objects and thousands of interactions among them. Hence, it becomes very difficult to handle, analyze and comprehend these models. Since the information regarding a system is scattered across a range of model views shown using various diagrams, evaluating the UML models is a challenge. Analysing the effect of a modification in one model on another model therefore becomes an imperative problem. For such vast architectures, it becomes tremendously demanding to analyse these models. Moreover, it turns out to be difficult on one hand and equally advantageous on the other to discover the consequence of a particular change to one model on other models.

With this motivation, different program slicing techniques are introduced to modularize huge architectural modules into smaller and manageable modules. However, considering the software architectures, a slicing technique should recognize different characteristics of UML diagrams such as use cases, classes and relationships among them, and objects and interactions between them, etc. In UML 2.0 models, interaction is represented using different diagrams like communication diagram, sequence diagram, interaction overview diagram and timing diagram. A communication diagram is comprised of objects and associations which shows how the objects are communicating. One advantage of using communication diagram is that it does not consider the timing aspect of the interaction, rather it focuses on objects and the communication between them. Also, communication diagram is compact in size compared to sequence diagram since timeline is not used in it. In a sequence diagram whenever we need to add any object it is added to the right of the diagram. Hence, sequence diagram sometimes becomes very unwieldy. Therefore, we have used the communication diagram for analyzing the dynamic behavior of the system. To perform architectural slicing, it is first required to transform architectural model into a appropriate intermediate representation which represent various relationship that is present among different elements within models. This intermediate representation is then evaluated by the slicing algorithms to compute the slices.

1.1 Categories of Program Slicing

Several categories of program slicing are found in literature. Program slicing is mainly classified into two categories, namely static slicing [40] and dynamic slicing [40]. Depending upon the application, slicing can also be classified as forward slice or backward slice [14], inter-procedural or intra-procedural slice [14]. Other categories of slicing includes quasi-static slicing, amorphous slicing and simultaneous dynamic slicing.

1.1.1 Static slicing

As defined by Weiser, a program slice includes the parts or components of a program that influence the values computed at some point of interest known as a slicing criterion [5].

Usually, a slicing criterion comprises of a pair ⟨S, V⟩, where S is defined as the statement number and V as a set of variables. Statistically obtainable information is utilised for slicing thus this type of slicing is called as static slicing.

Example:

(1) DataInputStream di = new DataInputStream (System.in);

(2) var= Integer.parseInt(di.readLine());

(3) prod=1;

(4) sum=0;

(5) for(count=1; count<=var; count++) {

(6) sum=sum+count;

(7) prod=prod*count; }

(8) System.out.println("The Sum is : "+sum);

(9) System.out.println("The Product is :" + prod);

Slice: with respect to the slicing criteria (8, sum).

(1) DataInputStream di = new DataInputStream(System.in);

(2) var= Integer.parseInt(di.readLine());

(4) sum=0;

(5) for(count=1; count<=var; count++) {

(6) sum=sum+count; }

(8) System.out.println("The Sum is : "+sum);

1.1.2 Dynamic slicing

In program slicing, the slicing criterion comprises of the variables that produce an unexpected result on some given input to the program [45]. But, a static slice may include statements which have no influence on the values of the variables of interest for the particular execution. Dynamic slicing takes the input given to the program during its execution and the slice contains only those statements that cause the failure while specific execution of interest. Dynamic analysis is used by dynamic slicing to find all and only the statements that have an effect on the variables of interest on particular execution trace [5]. The benefit of dynamic slicing is run-time handling of pointer variables and arrays.

Dynamic slicing will take care of each element of an array independently, while static slicing considers every definition or use of some array element as a definition or use of the complete array [19]. In the same way, dynamic slicing differentiates the objects that are pointed to by pointer variables in a program execution. A dynamic slicing criterion represents the input, and makes a distinction between dissimilar occurrences of a statement in an execution. Slicing criteria is defined as a triplet (input, statement number, variable). The difference between dynamic and static slicing is that dynamic slicing takes fixed input for a program, while static slicing does not make postulations regarding the input [7].

Example:

```
(1) DataInputStream di = new DataInputStream (System.in);
(2) p= Integer.parseInt(di.readLine());
(3) i=1;
(4) while (i<=p) {
(5) if (i mod 2==0) then
(6) a=17; else
(7) a=18;
(8) i=i+1; }
(9) System.out.println(a);
```

Slice: slice with criterion (p = 2, 9, a)

```
(1) DataInputStream di = new DataInputStream (System.in);
(2) p= Integer.parseInt(di.readLine());
(3) i=1;
(4) while (i<=p) {
(5) if (i mod 2==0) then
(6) a=17;
(8) i=i+1; }
(9) System.out.println(a);
```

1.1.3 Simultaneous dynamic slicing

Hall [12] proposed a different approach to the definition of a slice regarding a set of executions of the program. This innovative slicing method merges the use of a set of test cases with program slicing [6]. This method is known as simultaneous dynamic program slicing as it expands and at the same time applies to a set of test cases, the dynamic slicing technique which generates executable slices that are accurate on only one input.

1.1.4 Quasi-static slicing

Quasi static slicing method was first introduced by Venkatesh [37]. It is an amalgam or fusion of Static Slicing and Dynamic Slicing. Static slicing is observed during compile time, without using information regarding the input variables of the program. Dynamic slicing analyses the code by means of giving input to the program. It is created at run time corresponding to a particular input. Also, there is a trade-off between dynamic and static slicing methods. Static slicing requires more space and resources as well as performs all feasible execution of the program but dynamic slicing requires less space and is specific to a program execution. In addition, dynamic slices are smaller than static slice.
In case of quasi slicing the value of a few variables are fixed, while the value of other variables vary. Slicing criteria consists of the set of variables of interest and initial conditions and hence quasi slicing is called as Conditioned slicing. This technique is unsuccessful to establish consistent treatment of static and dynamic slicing. In addition, there is no algorithmic description for this technique.

1.1.5 Amorphous slicing

The slicing methods discussed formerly such as static and dynamic slicing, simultaneous dynamic slicing and quasi static slicing etc. are syntax preserving, while amorphous slicing is focused on preserving the semantics of the program. Syntax preserving slicing technique is based on deleting statements from the program based on the slicing criterion and thus the syntax of the program statements does not alter even after slicing is carried out. In case of amorphous slicing [13], slice is obtained using some program transformation technique that preserves the semantics of the program corresponding to the slicing criterion. The slices formed are not as large as obtained through other slicing techniques. The slice is significantly simplified form of the program based on the slicing criterion. The advantage of amorphous slicing includes program comprehension, analysis and reuse.

1.2 Motivation for Our Work

A most important intend of all the slicing techniques is to recognize as small a slice corresponding to a slicing criterion as possible because smaller slices are more useful. To a large extent of available literature on program slicing, it is observed that improving the algorithms for slicing is done in terms of improving the efficiency of the slicing algorithm and reducing the size of the slice.

Slicing is commonly based on program code. An alternative approach is to compute the slice from specifications created with the help of formalism such as UML models. In this approach, slices are computed during analysis or design stage itself, preferably at low-level design stage. Also, in component based software development, only the component specifications are available and the source code of components are proprietary. Computing the slice from design specifications adds the benefit of permitting slices to be obtainable early in the software development life cycle. It is therefore, enviable to compute slices from software design document besides computing slices from the code.

UML is extensively used for modelling and design of object-oriented software. In recent times, numerous techniques have been proposed to execute different UML models. Executable UML models permit model specifications to be efficiently converted into code. In addition to reducing effort in the coding stage, it too guarantees platform independence and evade obsolescence. This is so because the code frequently needs to change while software is ported to a new platform. Our computation of slice can also be employed on executable UML models.

With this motivation, we give attention to UML communication diagrams for computation of the slices. A major purpose of this technique is program debugging i.e. to search for the errors during the execution of software. Also, these errors are usually dynamic (behavioural) in nature. Customer comprehends software in terms of behaviour and not structure. Therefore, we choose the communication diagram for our work.

AOP is an emerging implementation level method which allows isolating pieces of behaviour into separate units called aspects. Much of the literature on slicing of AOP is based on code. Till now no work is done to develop a formal design specification for AOP based software and slicing of design models for the same. The main advantage of this technique is that it clearly modularises the crosscutting services. It also gives the benefit of platform independence and obtaining the slice at an early stage. With this motivation, we focus on developing a communication diagram for the Aspect-oriented software and also developing an algorithm for slicing of it.

The above reasons motivate us to identify the major goals of our thesis and for developing dynamic slicing algorithms for UML communication diagrams and aspect based communication diagram.

1.3 Objectives of Our Work

The foremost objective of our work is to develop dynamic slicing algorithms for object-oriented and aspect-oriented software. Our key goals are:

- We wish to compute dynamic slices of UML communication diagram for object-oriented software as fast as possible.
  To achieve this, we plan to develop:

  1. Suitable intermediate representations for UML communication diagram on which the slicing algorithm can be applied.
  2. Dynamic slicing algorithms for object-oriented software, using the proposed intermediate representation.

- Dynamic slicing of architectural models are valuable for debugging purposes and hence competent computation of dynamic slices is extremely significant to interactively impound bugs in an object-oriented program. Present techniques of dynamic slicing experience the difficulty of huge space and run-time overheads. Our goal would, thus, be to develop techniques that are more space and time efficient.

- Subsequently, we desire to expand this approach to compute dynamic slices of architectural models of aspect-oriented software. AOP helps to modularise the croscutting concerns in a software. Also, it enables more code reuse and reduce the costs of feature implementation. In this approach, slices are computed during analysis or design stage itself, preferably during low-level design stage. We have considered aspect based UML communication diagram to compute the slice.
  To achieve this, we plan to develop:

  1. Suitable aspect based communication diagram for representing the dynamic behaviour of aspect-oriented software.
  2. Suitable intermediate representations for aspect based communication diagram on which the slicing algorithm can be applied.
  3. Dynamic slicing algorithms for slicing of aspect based communication diagrams, using the proposed intermediate representation.

1.4 Organization of the Thesis

Our thesis is divided into chapters that are organized as follows:

Chapter 2 includes the background concepts used in the rest of the thesis. The chapter contains some graph-theoretic concepts which will be used afterwards in our algorithms. We illustrate some intermediate program representation concepts which are used in slicing techniques. Then, we discuss some applications of dynamic slicing. In the end, we discuss the concepts of *aspect-oriented software* and benefits of using AOP software.

Chapter 3 presents a concise review of the related work significant to our contribution. We initially consider the work on dynamic slicing of architectural models representing object-oriented software followed by description of the work on slicing of aspect-oriented softeware.

Chapter 4 deals with dynamic slicing of UML communication diagram for object-oriented software. We discuss how to develop a suitable intermediate representation for communication diagrams which we named *communication dependence graph*. Next, we explain two dynamic slicing algorithms i.e. *edge marking* and *node marking* dynamic slicing algorithm for communication diagram with example. We have implemented and proved that this algorithm computes correct dynamic slices.

Chapter 5 deals with dynamic slicing of aspect-based communication diagram for aspect-oriented software. We discuss the process to develop an appropriate intermediate representation for communication diagrams which we named *communication aspect dependency graph*. Next, we explain an *edge marking* dynamic slicing algorithm for aspect based communication diagram with example. We have also implemented and found the space and time complexities for our proposed algorithm.

Chapter 6 concludes the thesis by giving a summary of our contributions. We also discuss the achievable future extensions to our work.

Chapter 2

Background

Program slicing is very helpful in different applications like software testing, software measurement, software maintenance, program parallelization, program debugging, etc. since a slice is a supreme subset of the original program that guarantees to authentically demonstrate the particular behaviour of the original program within the specified domain. Since Weiser [38] initially proposed the notion of program slicing in 1979, different properties of slicing have been proposed to compute more accurate slices as well as to employ slice in different stages of SDLC (Software Development Life Cycle). This chapter deals with the essential concepts, definition and terminologies related with the slicing of object-oriented and aspect-oriented software at the design stage of the software development.

2.1 Basic Concepts

This section briefly describes some fundamental definitions and terminologies related with the intermediate representation.

Definition 2.1 Directed Graph: A directed graph G is a pair (N, E) where N represents a finite non-empty set of *nodes*, and $E \subseteq N \times N$ represents a set of directed *edges* between the nodes. Consider $G = (N, E)$ be a directed graph. If (x, y) is an edge of G, then x is called a *predecessor* of y and y is called a *successor* of x. The *predecessors* of a node adds up to give its *in-degree*, and the *successors* of a node adds up to give its *out-degree*. In this thesis, we use interchangeably the words *graph* and *directed graph*.

```
main(){
 int a, b, prod;
 cin>>a;
 cin>>b;
 prod=1;
 while(a<4){
   prod=prod*b;
   ++a;}
 cout<<prod;}
```

Figure 2.1: An Example Program

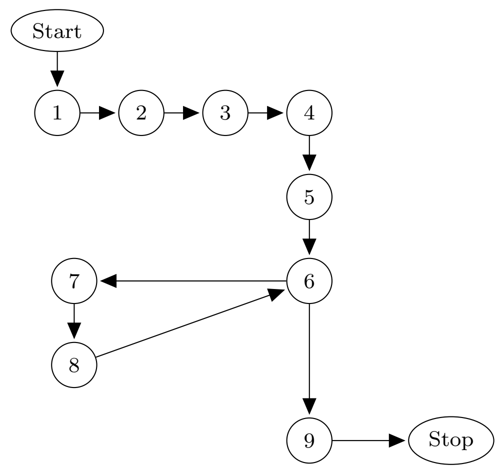


Figure 2.2: Control Flow Graph for the example given in Fig.2.1

Definition 2.2 Flow Graph: A *flow graph* is a quadruple $(N, E, Start, Stop)$ in which (N, E) is a graph, $Start \in N$ is a distinguished node of in-degree zero called the *start node*, $Stop \in N$ is a distinguished node of out-degree zero called the *stop node*, there exists a path from *Start* to every other node in the graph, and there exists a path from every other node in the graph to *Stop*.

Definition 2.3 Control Flow Graph: Let the set N represent the set of statements of a program P. The control flow graph of the program P is the flow graph $G = (N1, E, Start, Stop)$ where $N1 = N \cup (Start, Stop)$. An edge $(m, n) \in E$ indicates the possible flow of control from the node m to the node n. Note that the subsistence of an edge (x, y) in the control flow graph means that control *must* transfer from x to y during program execution. Fig.2.2 represents the CFG of the example program given in Fig.2.1. The CFG of a program P form the branching structures of the program, and it can be build while parsing the source code using algorithms that include linear time complexity in the size of the program.

2.2 Basic UML 2.0 concepts

Unified Modeling Language (UML) is defined as a graphical idiom for envisioning, identifying, creating and documenting the artifacts of a software system.UML is a blueprint of the actual system and helps in documentation of the system [4]. It makes any complex system easily understandable by the disparate developers who are working on different platforms. Another benefit is that UML model is not a system or platform specific. Modeling is an indispensable part of huge software projects, which as well facilitates in the improvement of medium and small projects. There are numerous explanations to use UML as a modeling language:

- The amalgamation of terminology and the consistency of notation escort to a considerable easing of communication in the software industry. It assists the swapping of models among different departments or companies.
- UML is widely supported and is platform independent, hence assists developers working in different platforms.
- UML-based software offers easiness for comparison among different software systems based on structure and behavior.
- Using UML helps new developers to understand the software more easily and also lowers the development cost.

UML 2.x has 14 types of diagrams divided into two categories. Seven diagram types represent structural information, and the other seven represents general types of behavior, including four that represent different aspects of interactions.

1. **Behavioural diagrams:** Diagrams which characterize the behavioral features of a software system. This category includes use case diagram, activity diagram and state-machine diagram in addition to four interaction diagrams.
2. **Interaction diagrams:** Interaction diagrams are subset of behavioural diagrams which emphasize interactions among objects. This category includes communication diagram, interaction overview diagram, sequence diagram, and timing diagram.

3. **Structured diagrams:** These diagrams show the constituent of a specification that does not depend upon time. This category includes class diagram, composite structure diagram, component diagram, deployment diagram, object diagram, and package diagram.

These diagrams can be categorized hierarchically as shown in the Fig.2.3

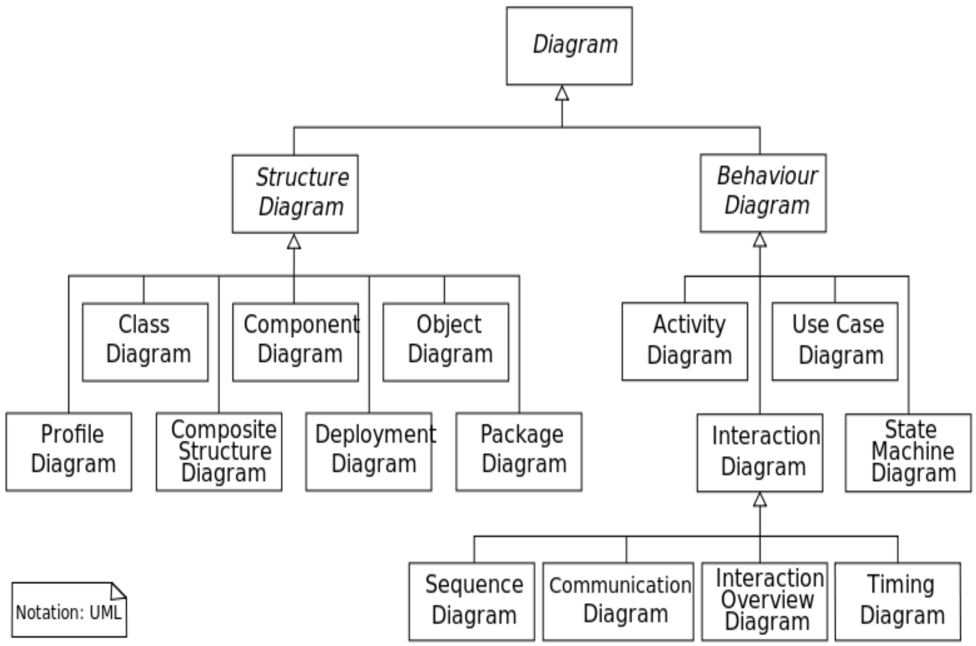


Figure 2.3: Classification of different types of UML diagrams

In our research, we give attention to UML communication diagram for computing the dynamic slice at the architectural level. UML communication diagrams are used to illustrate the flow of functionality during execution of a use case. A communication diagram is comprised of objects and associations which shows how the objects are communicating [1]. One advantage of using communication diagram is that it does not consider the timing aspect of the interaction; rather it focuses on objects and the communication between them. Also, communication diagram is compact in size compared to sequence diagram since timeline is not used in it. In a sequence diagram, whenever we need to add any object it is added to the right of the diagram. Hence, sequence diagram sometimes becomes very unwieldy. A communication diagram is a useful extension of the object diagram. Object diagram gives the snapshot of a system at any point of time, but communication diagram adds the dimension of time and gives the snapshot of the system at various points of time. Therefore, we have used the communication diagram for analyzing the dynamic behavior of the system. An example of UML 2.0 communication diagram is shown in Fig.2.4. In the

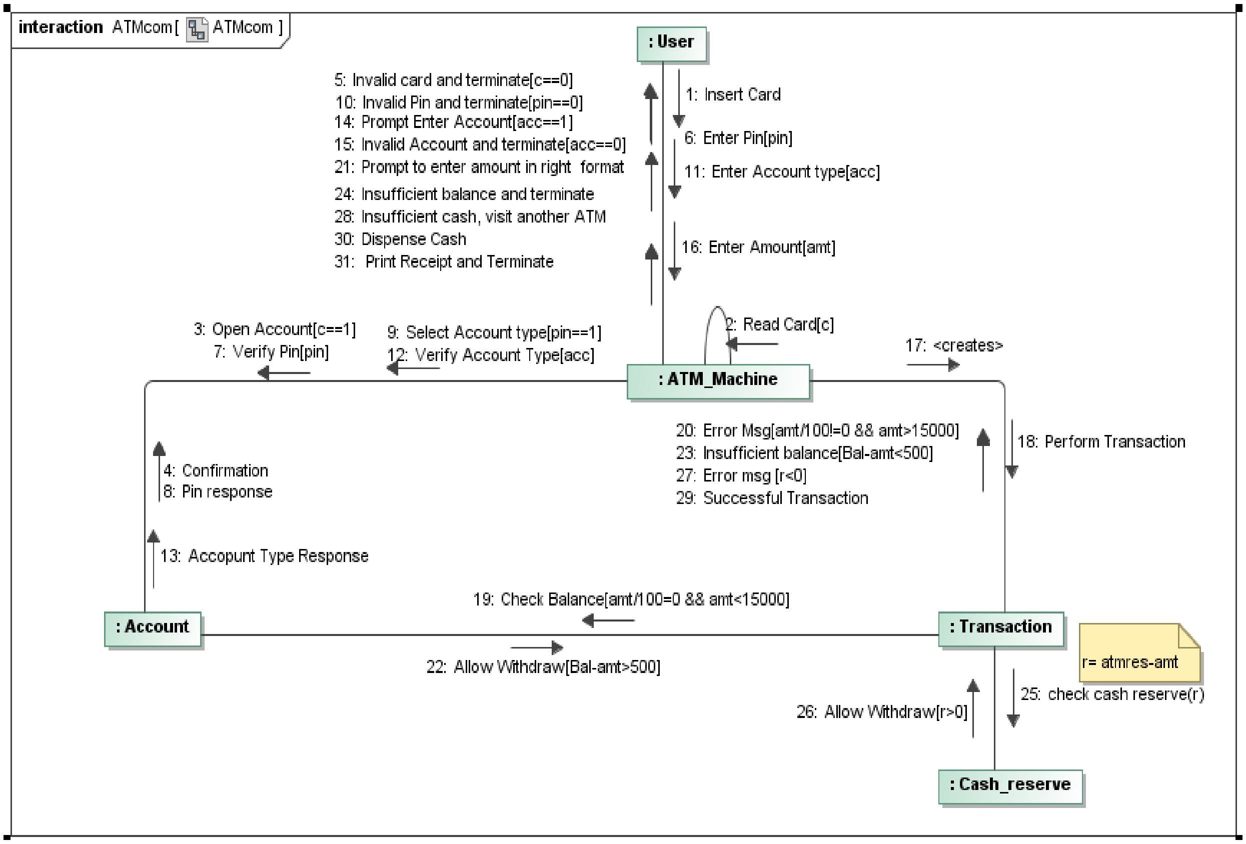


Figure 2.4: An example of communication diagram showing Withdraw() usecase of ATM

diagram, the rectangular box represents objects or lifeline in the communication diagram arranged in a free form. Messages in the communication diagram are shown as a line with sequence expression and an arrow above the line. The arrow specifies the direction of the communication. A message can be an operation call or initiation of execution or a sending or reception of a signal.

Based on the nature of action a message can be of several types like *asynchronous call, synchronous call, create, reply, delete. Synchronous call* messages are represented by filled arrow head. It symbolizes a function call, i.e. send message and defer execution while waiting for a response. Asynchronous call is revealed with open arrow head. In case of *asynchronous call*, a message is send and the next message is send without waiting for a response. *Create* message is sent to a lifeline or object to create itself. *Delete* message is sent to terminate another object or lifeline.

To represent extra information in the sequence diagram, *"notes"* are used. Notes are represented by symbol of dog-eared rectangle linked to the object lifeline through a dashed line. Notes are basically used for representing additional information like pseudo code, post condition, pre condition, text annotations, constraints etc.

2.3 Aspect-oriented programming concepts

Aspect-oriented programming (AOP): AOP is an emerging programming paradigm that focuses on modular implementation of cross-cutting concerns [9] such as exception handling, synchronization, security, data access, logging. This technique was first introduced by Gregor Kiczales et al. [17]. Aspect-Oriented Programming provides specific language mechanisms to explicitly capture the cross-cutting structure. Representation of such cross-cutting concerns by use of standard language constructs give poorly structured code because these concerns are tangled with the crucial functionality of the code. This increases the complexity and creates difficulty in maintenance considerably.

AOP intends to resolve this difficulty by allowing the programmer to build up cross-cutting concerns as complete stand-alone modules called aspects. The central idea behind AOP is to build a program by unfolding each concern separately. Aspect-oriented programming languages provide unique opportunities for program analysis schemes. For instance, to implement program slicing on aspect oriented software, definite aspect-oriented features such as *join-point, advice, aspect, and introduction* must be taken care of appropriately. Even though these features add great strengths to model the cross-cutting concerns in an aspect-oriented program, they also introduce difficulties to analyze the program.

Aspects: An aspect is an ordinary feature that's usually scattered across methods, classes, object hierarchies, or even whole object models. An aspect is a crosscutting type, defined by aspect declarations. Aspects may have methods and fields just like any other class. They may also contain pointcut, advice, and introduction (inter-type) declarations.

Advice: This is a method like construct that is required to define crosscutting behavior. Advice is classified into three types in AspectJ: *before, after, and around*. On a defined joinpoint *after advice* executes after the program proceeds with that joinpoint. Before the program proceeds with that joinpoint *before advice* executes. *Around advice* executes when the joinpoint is reached, and has a explicit control over the program whether or not the program proceeds with that joinpoint.

Crosscutting Concerns: Crosscutting concerns put a negative impact on the quality of the software developed which can be reduced to a great extent by using aspects [16]. Most of the classes in object-oriented programming perform a single, specific function, but many a times they share some secondary requirements with other classes. A concern is said to be crosscutting concern if it satisfies the two characteristics- *scattered and tangled*. When the design of a single requirement or functionality is inevitably scattered across several classes and operations in the object-oriented design, then we say that the functionality is scattered. When a single class or operation in the object-oriented paradigm encloses design details of multiple requirements, then it is tangled.

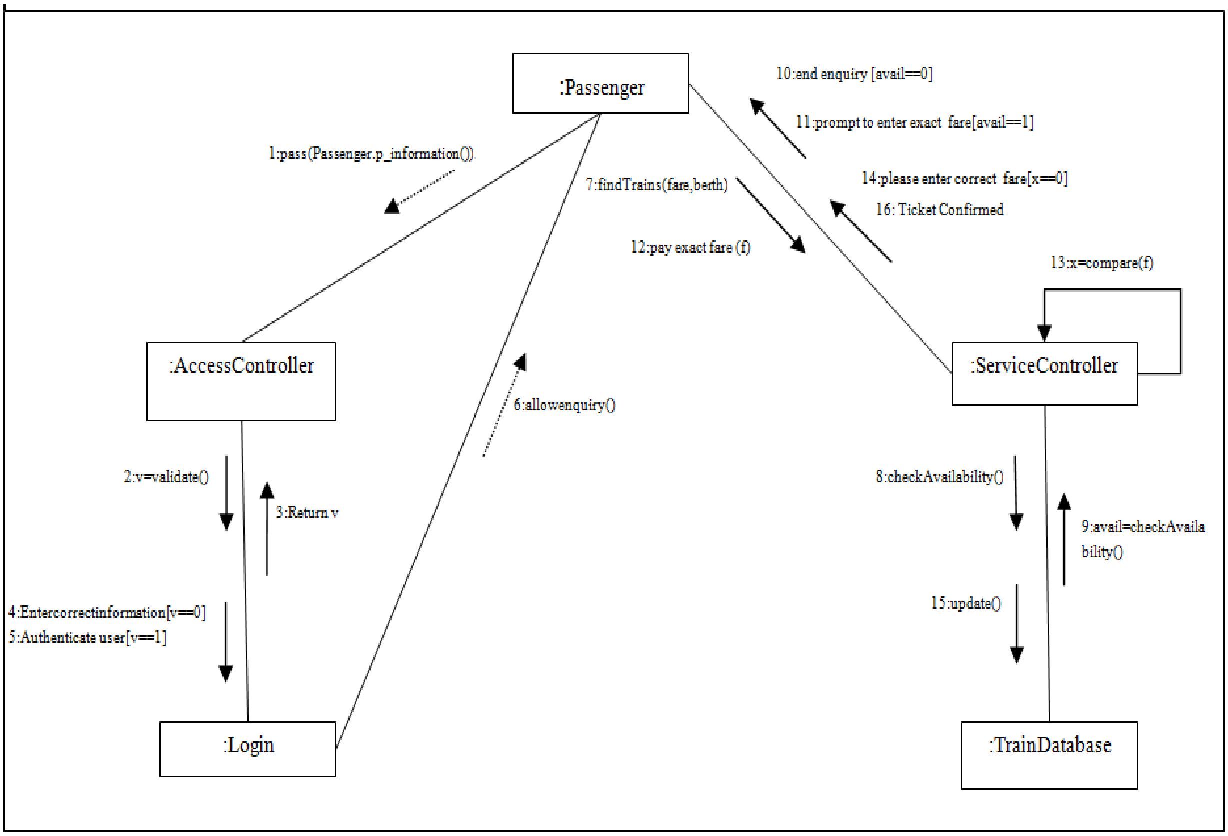


Figure 2.5: An example of communication diagram showing IssueTicket()usecase of Online Railway Reservation System

Aspect-based Communication Diagram: UML communication diagram is used to show the communications between different objects involved in a given problem scenario. The ordering of the messages is shown by the help of numbering technique. In order to draw the communication diagram, we identify the objects that are participating in the scenario. Then all the objects are connected using a link. Through the link the messages are sent between the objects to carry out the given scenario.

In our work, we have considered aspect-oriented based communication diagram to compute the dynamic slice at the architectural level. As we know, aspects in AOP are similar to classes in OOP; we have represented the objects of the aspects similar to OOP. In the example of aspect-oriented (woven) communication diagram shown in Fig.2.5, we have considered three base classes (Passenger, ServiceController and TrainDatabase), one Aspect (AccessController), and one Around advice (login).

The aspect in the scenario has a vital impact on the security of the system as it allows only the authenticated users for the enquiry process. The method p_information() of base class passenger act as joinpoint through pass pointcut designator. We have represented the pointcut i.e. the first message in dotted line from base class to aspect. At this point of time, the message is sent and the execution is temporarily stopped until acknowledgement is received. After the passenger informations are validated the control moves back to the suspended base class and the execution resumes for enquiring the train details.

2.4 Applications of Slicing

This section illustrates the utilization of program slicing techniques in different applications. The applications of program slicing techniques has now extended into a powerful set of tools for use in such various applications as program understanding and verification, automated computation of several software engineering metrics, software maintenance and testing, reverse engineering, parallelization of sequential programs, functional cohesion, software portability, compiler optimization, program integration, reusable component generation, software quality assurance, etc [10, 35, 39, 42]. Program slicing is exceptionally useful in abstracting the business rules from traditional systems. A complete study on the applications of program slicing is made by Binkley and Gallagher [5] and Lucia [26].

2.4.1 Program Differencing

Program differencing [25] is the task of analyzing an old and a new version of a program in order to establish the set of program components of the new version so as to represent semantic and syntactic changes. Such information is useful for the reason that only the program components reflecting changed behavior need to be tested [3]. There are two linked differencing problems:

1. Identify all the components of two programs which have dissimilar behaviour.

2. Fabricate a program that incarcerates the semantic differences among two programs.

For *old* and *new* programs, a clear-cut solution for the problem 1 is achieved by evaluating the backward slices of the vertices in *old* and *new*'s dependence graphs G_{old} and G_{new}. Here, the backward slice is computed regarding a given slicing criterion. Components whose vertices in G_{new} and G_{old} have isomorphic slices have the same behavior in *old* and *new*; therefore the set of vertices from G_{new} for which there is no vertex in G_{old} with an isomorphic slice approximates the set of components *new* with a change in behavior.
An explanation to the next differencing problem is achieved by taking the backward slice with regard to the set of affected points (i.e., the vertices in G_{new} with different behavior than in G_{old}). For programs with method calls, two modifications are essential: First, inter-procedural slicing techniques are required to be used to ensure that the resulting program slice is executable. Second, this result is overly negative: Let a component c in method P be invoked from two call-sites c_1 and c_2. If c is identified as an affected point by a forward slice that enters P through c_1 then we will include c_1 but not c_2 in the program that captures the differences. However, the backward slice with respect to c would include both c_1 and c_2.

2.4.2 Regression Testing

Regression testing [11,44] is the method of testing changes to software in order to ascertain that the older programming still works with the new changes. Any adverse behavior that can result due to a small change in the program needs to be tested which might include running a large number of test cases. Program slicing is very helpful to split tests cases into those that require to be repeated, since they have been affected by a change, and those which can be avoided, as their behaviour can be assured to be unaffected by the change.

2.4.3 Program Debugging

Debugging becomes a complicated task when one comes across with a large program and small solution concerning the location of a bug. The method to find a bug typically entails running the program repeatedly, learning more and lessening down the search each time, until the bug is finally located [26]. Program slicing was formerly proposed by examining the operation naturally carried out by programmers while debugging a piece of code.
Even after several improvements to the fundamental slicing techniques, program debugging remains a chief application area of slicing techniques. Program slicing is useful for debugging, since it potentially allows one to overlook many statements in the process of localizing the bug. If a program determines a flawed value for a variable a, then the statements in the slice that includes the variable a have added to the result of that value, other statements which are not present in the slice can be ignored.

2.4.4 Reverse Engineering

Reverse engineering addresses the problem of understanding the existing design of a program and the method this design differs from the original design [27]. This includes abstracting out of the source code the design decisions and motivation from the initial development and understanding the algorithms chosen. Program slicing offers a tool set for this type of re-abstraction. For example, a program can be demonstrated as a pattern of slices structured by the *is-a-slice-of* relation. Evaluating the original lattice and the lattice after (years of) maintenance can lead an engineer towards places where reverse engineering should be used. Since slices are not essentially adjoining blocks of code they are suitable to identify differences in algorithms which may cover multiple blocks or procedures.

2.4.5 Software Maintenance

To preserve huge software system is a demanding task. Majority of the software system splurge about 70% or more of their lifetime in the phase of software maintenance where they are enhanced and enlarged. The most important problem in software maintenance is to determine whether a change at one place in a program will affect the behaviour of other parts of the program. It is a expensive procedure as each modification to a program must take into account various composite dependence relationships in the existing software.

Chapter 3

Review of Related Work

This chapter provides an outline of the fundamental program slicing techniques and concise history about their development. We give a short survey that reviews majority of the existing slicing techniques including the *static slicing, dynamic slicing, slicing of object-oriented architectural models*, and *slicing of aspect-oriented software.*

3.1 Slicing of Procedural and Object-oriented Programs

This section discusses the related work on static and dynamic slicing of the procedural and object-oriented programs based on the source code. *Program slicing*, which was originally established by Weiser in 1979 [38], is a decomposition method that remove from program those statements significant to a particular computation. Weiser defined program slicing as a type of executable backward static slicing. A *backward slice* contains all statements that the computation at the slicing criteria may depend on, whereas a forward slice comprises all statements depending on the slicing criterion. The intra-procedural static slicing algorithm [39] used Control Flow Graph (CFG) as the intermediate representation of the program. In Weiser's algorithm [39, 40], slices are designed from scratch i.e. information obtain through any preceding calculation of slices are not considered. This is a foremost shortcoming of their approach.

Ottenstein and Ottenstein [30] employ the *Program Dependence Graph (PDG)* as the intermediate representation for computing intra-procedural slices. Horowitz et al. [14] enhanced the PDG representation to the *System Dependence Graph (SDG)* for computing inter-procedural static slicing. Since 1979, several alternatives of slicing, which are not static, have been proposed.

Korel and Laski [18] extended Weiser's CFG based static slicing algorithm and introduced the notion of *dynamic slicing*. A dynamic slice is different from static slice in the fact that dynamic slice is computed with regard to only one execution of the program. It does not include the statements that have no significance with the slicing criteria for some particular input. The dynamic slice computed by Korel and Laski may be *imprecise*, if a program consists of loops, because in that case N may be unbounded where N is the number of statements executed (length of execution) during run time of the program. This is a major shortcoming of their approach.
Agrawal and Horgan [2] introduced the algorithm for computing dynamic slices of procedural programs using dependence graphs. They introduced the notion of*Dynamic Dependence Graph (DDG)* to compute precise dynamic slices. The number of nodes in a DDG is same as the number of statements executed, which may be unbounded for programs containing loops. Then Agrawal and Horgan [2] tried to reduce the number of nodes by the concept of *Reducing Dynamic Dependence Graph (RDDG)*.
Mund et al. [29] enhanced their approach and proposed three intra-procedural dynamic slicing algorithms. Two of the three proposed algorithms compute dynamic slices of *structured program* using PDG as an intermediate representation and to compute dynamic slice of unstructured programs, they introduce the idea of *Unstructured Program Dependence Graph (UPDG)* as the intermediate representation. Their algorithm is based on marking and unmarking the dependence *edges* as and when the dependence arises and cease respectively.Mund et al. [29] proposed a new algorithm for inter-procedural dynamic slicing of structured programs.

When slicing object-oriented programs, representation of the programs is a major problem. Various object-oriented features such as classes, inheritance, and polymorphism need to be taken care of while slicing of object-oriented programs. The presence of polymorphism and dynamic binding raise the difficulty in process of tracing dependencies in OOPs. Larsen and Harrold [24] enhanced the SDG of Horwitz et al. [14] to compute slicing of object-oriented programs. After developing the SDG, Larsen and Harrold used the *two-phase algorithm* to compute the static slice of an object-oriented program.
Zhao [45] extended the DDG of Agrawal and Horgan [2], as *dynamic object-oriented dependence graph (DODG)* to represent different types of dynamic dependencies among statement instances for a particular execution of an object-oriented program. The DODG is based on dynamic analysis of control flow and data flow of the program. The chief drawback of this approach is that the number of nodes in a DODG is equal to the number of executed

statements, which may be unbounded for programs having many loops. Song et al. [33] proposed a technique to compute forward dynamic slices of object-oriented programs by the help of *dynamic object relationship diagram (DORD)*. In this process, they computed the dynamic slices for each statement immediately after the statement is executed. Xu et al. [41] extended their earlier method to dynamically slice object-oriented programs. Their method employs *object program dependence graph (OPDG)* and other static information to reduce the information to be traced during execution. Based on this model, they have proposed algorithms to dynamically slice methods, objects and classes.
Mohapatra et al. [28] extended Mund's edge marking algorithm to compute dynamic slice of object-oriented programs. They used an *extended system dependence graph (ESDG)* as the intermediate program representation. Their dynamic slicing algorithm is based on marking and unmarking of the *edges* of ESDG as and when the dependencies arise and stop at runtime. Their algorithm is named as *Edge Marking Dynamic Slicing Algorithm (EMDS)*. This algorithm does not require any new nodes to be created and added to the ESDG at the runtime nor does it require any execution trace in a file.

3.2 Slicing of Object-oriented Architectural Models

This section briefly reviews the related work on slicing of object-oriented softwares models. Zhao [45] examined a novel dependence analysis technique, called architecture dependence analysis, to support software architecture development. Zhao extended his work and introduced a static architecture slicing technique, which work by removing irrelevant components and connectors, and assures that the behaviour of a sliced system remains unaltered.

Kim [36] proposed an architectural model slicing algorithm known as dynamic software architecture slicing (DSAS) . Kim's work is capable of generating a smaller number of components and connectors in every slice as compared to [36]. This is mostly correct in conditions where a large number of ports are present and their invocation can alter the values of some variables, or the execution of some events.

Korel et al. [19] proposed a technique of slicing state-based models, like EFSMs (Extended Finite State Machines). They proposed two types of slicing - deterministic and non-deterministic slicing. Their method also involves a slice reduction technique to reduce the size of a resulting EFSM slice. Korel et al. [20] also present a tool which implements their slicing technique for EFSM models.

Lallchandani et al. [22] proposed an algorithm for static slicing of UML diagrams. They created a model dependency graph (MDG) by combining UML class diagram and UML sequence diagram. For a given slicing criterion, their algorithm traverses the constructed MDG to identify the relevant model elements. But our algorithms compute dynamic slices as compared to their algorithms.

3.3 Slicing of Aspect-oriented Softwares

In this section, we discuss few related work on slicing of aspect-oriented softwares. Aspect-oriented softwares differ from procedural or object-oriented based softwares in many ways. For example, the concepts of advice, join points, aspects, and their associated constructs shows some major differences. These aspect-oriented features may have an impact on the computation of slices for aspect-oriented softwares and thus should be taken care of appropriately.

Zhao [46] was the first to develop the aspect-oriented system dependence graph (ASDG) to represent aspect oriented programs. The ASDG is constructed by combining the SDG for non-aspect code, the aspect dependence graph (ADG) for aspect code and some additional dependence arcs used to connect the SDG and ADG. Then, Zhao used the two-phase slicing algorithm proposed by Larsen and Harrold [24] to compute static slice of aspect-oriented programs.

Mohapatra et al. [8] proposed a dynamic slicing algorithm for aspect-oriented programs, using a dependence-based representation called Dynamic Aspect-Oriented Dependence Graph (DADG) as the intermediate program representation. They have used a trace file to store the execution history of the program.

Mohapatra et al. [31] proposed a node marking technique for dynamic slicing algorithm for aspect-oriented programs using an Extended Aspect-Oriented System Dependence Graph (EASDG) as an intermediate program representation. Ishio et al. [15] proposed an application of a call graph generation and program slicing to assist in debugging. A call graph visualizes control dependence relations between objects and aspects and supports the detection of an infinite loop.

Y.Zhuo et al. [43] extended previous dependence-based representations called system dependence graphs (SDGs) to represent aspect-oriented programs and presented an SDG construction algorithm. After the construction, the result is the complete SDG. The SDGs capture the additional structure present in many aspect-oriented features such as join points, advice, introduction, aspects, and aspect inheritance, and various types of interactions between aspects and classes. They also correctly reflect the semantics of aspect-oriented concepts such as advice precedence, introduction scope, and aspect weaving. SDGs therefore provide a solid foundation for the further analysis of aspect-oriented programs.

Chapter 4

Dynamic Slicing of Communication Diagram

There is an ever increasing importance being put on design models to support the evolution of large software systems. Design models are being maintained and updated from initial development as well as being reverse engineered to more accurately reflect the state of evolving systems. Generally, program slicing is based on the source code for a software. Alternatively, we can compute the slice from the design specification. Program slicing technique is used to debug any errors in the design document at an earlier stage of software development. A major goal of any dynamic slicing technique is efficiency since the slicing results may be used during interactive applications such as program debugging. With this motivation, in this chapter, we propose new dynamic slicing algorithms for computing slices of UML models for object-oriented softwares. An increasing amount of resources are being spent in debugging, testing and maintaining these products. Slicing techniques promise to come in handy at this point. We have considered the UML 2.x Communication Diagram for analysing the dynamic behaviour of the system. For our research, we have taken the example of *Library Management System (LMS)* and considered the *IssueBook* usecase. In the first step, we have identified the objects involved in the *IssueBook* scenario. Next, we have drawn the Communication Diagram for the scenario using the MagicDraw tool.
After obtaining the Communication Diagram, we identified the flow of control and derived the Control Flow Graph(CFG). To draw the CFG, each message that is communicated between the involved objects is considered as a node of the graph. An edge between two nodes is drawn if there exists any dependencies between the flow of the messages. From the CFG, we identified the dependencies between the nodes of the graph. Dependencies

are of two types: *data dependency* and *control dependency*. Then, we developed a new intermediate representation from the CFG. This new representaion we named as Communication Dependency Graph (CoDG). Then we proposed two dynamic slicing algorithms called as *Edge Marking Dynamic Slicing Algorithm for Communication Diagram (EMACD)* and *Node Marking Dynamic Slicing Algorithm for Communication Diagram(NMACD)* . The EMACD algorithm is based on the marking and unmarking of the edges of the CoDG as the dependencies rises and ceases. The NMACD algorithm is based on the marking and unmarking of the nodes of the CoDG as the dependencies rises and ceases. For each given set of input our algorithm traverse the CoDG and finds the corressponding slice based on the slicing criterion. We have analytically calculated the correctness and preciseness of the algorithm. Also we have calculated the time complexity and space complexity of both the algorithm.

4.1 Basic Concepts And Definition

To calculate a slice it is first required to transform a model into a suitable intermediate representation. In this section, we present a few basic concepts, notations and terminologies associated with the intermediate representation of dependence graph based slicing algorithm. In our algorithm, we have named the intermediate representation as Communication Dependence Graph (CoDG) which captures the notion of data dependency and control dependency.

Definition1 RecentDef(var): For each variable var, RecentDef(var) represents the pointer to the node (label number of the node) corresponding to the most recent definition of the variable *var*.

Definition2 Communication Dependence Graph (CoDG): We define Communication Dependence Graph (CoDG) as a directed graph with (N,E), where N is a set of nodes and E is a set of edges. CoDG shows the dependency of a given node on the others. Here a node represents either a message or a note in the communication diagram and edges represent either control or data dependency among the messages.

Definition3 dynslice(m): For each node m of the CoDG C_G (message m of the communication diagram), dynslice(m) represents the dynamic slice with respect to the most recent execution of the node m.

4.2 Dynamic Slicing of UML Communication Diagram

In this section, we present dynamic slicing algorithms of architectural models. In our approach, we have considered communication diagram to generate the dynamic slice. We have used communication diagram to capture the dynamic interactions among objects. A communication diagram comprises of objects and associations which shows how the objects are communicating. One advantage of using communication diagram is that it does not consider the timing aspect of the interaction, rather it focuses on objects and the communication between them. Also, communication diagram is compact in size compared to sequence diagram since timeline is not used in it. Also, in sequence diagram whenever we need to add any object it is added to the right of the diagram. Hence, sequence diagram sometime becomes very unwieldy. A communication diagram is a useful extension of the object diagram. Object diagram gives the snapshot of a system at any point of time, but communication diagram adds the dimension of time and gives the snapshot of the system at various point of time. Therefore, we have used the communication diagram for analysing the dynamic behaviour of the system.

4.2.1 Edge Marking Dynamic Slicing Algorithm for Communication Diagram

We now provide an overview of our EMACD algorithm. We first construct the CoDG from the communication diagram as an intermediate representation. Consider the example of communication diagram given in Fig.4.1. Its corresponding CFG is shown in Fig.4.2.

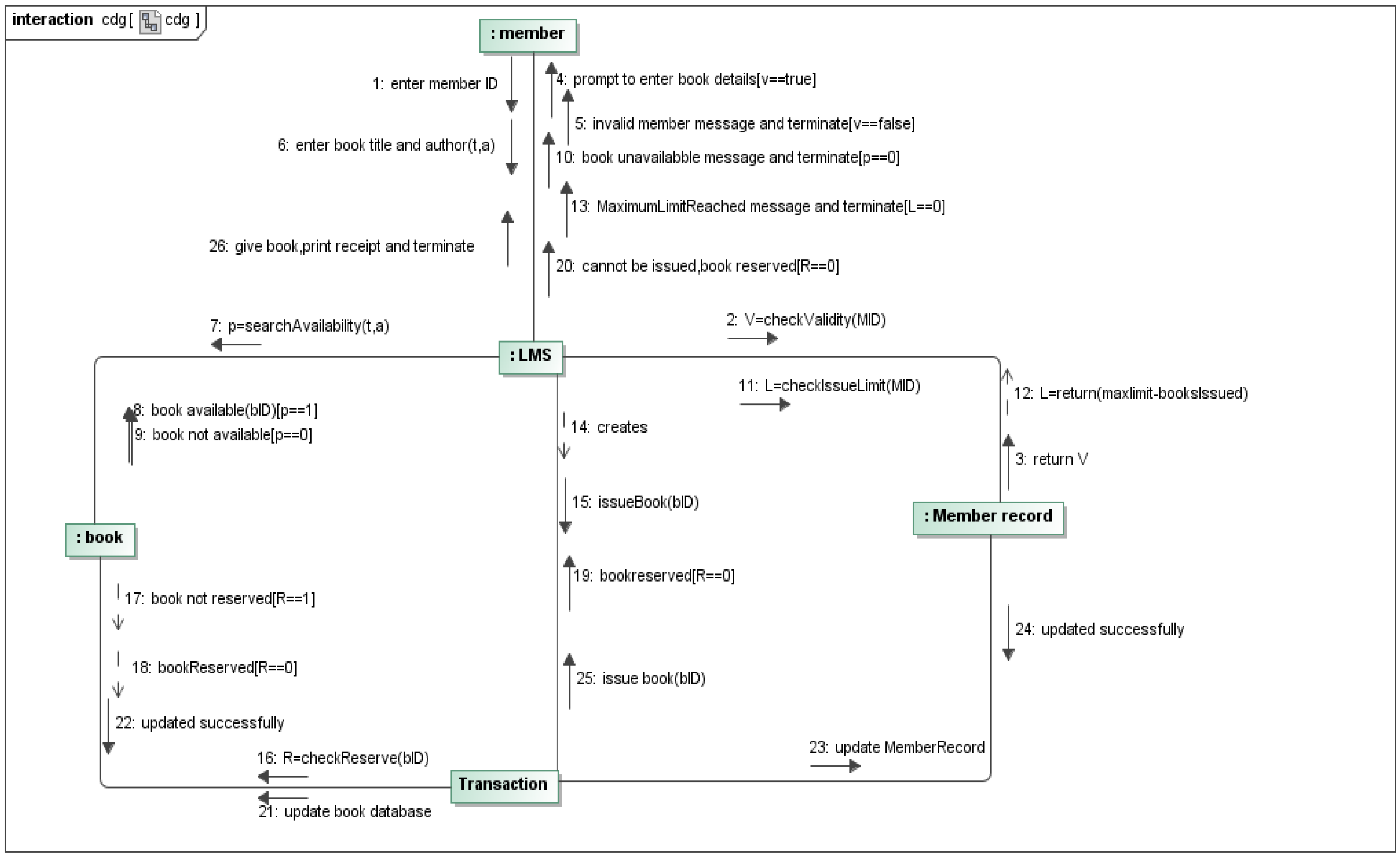


Figure 4.1: Communication Diagram for IssueBook usecase of Library Management System

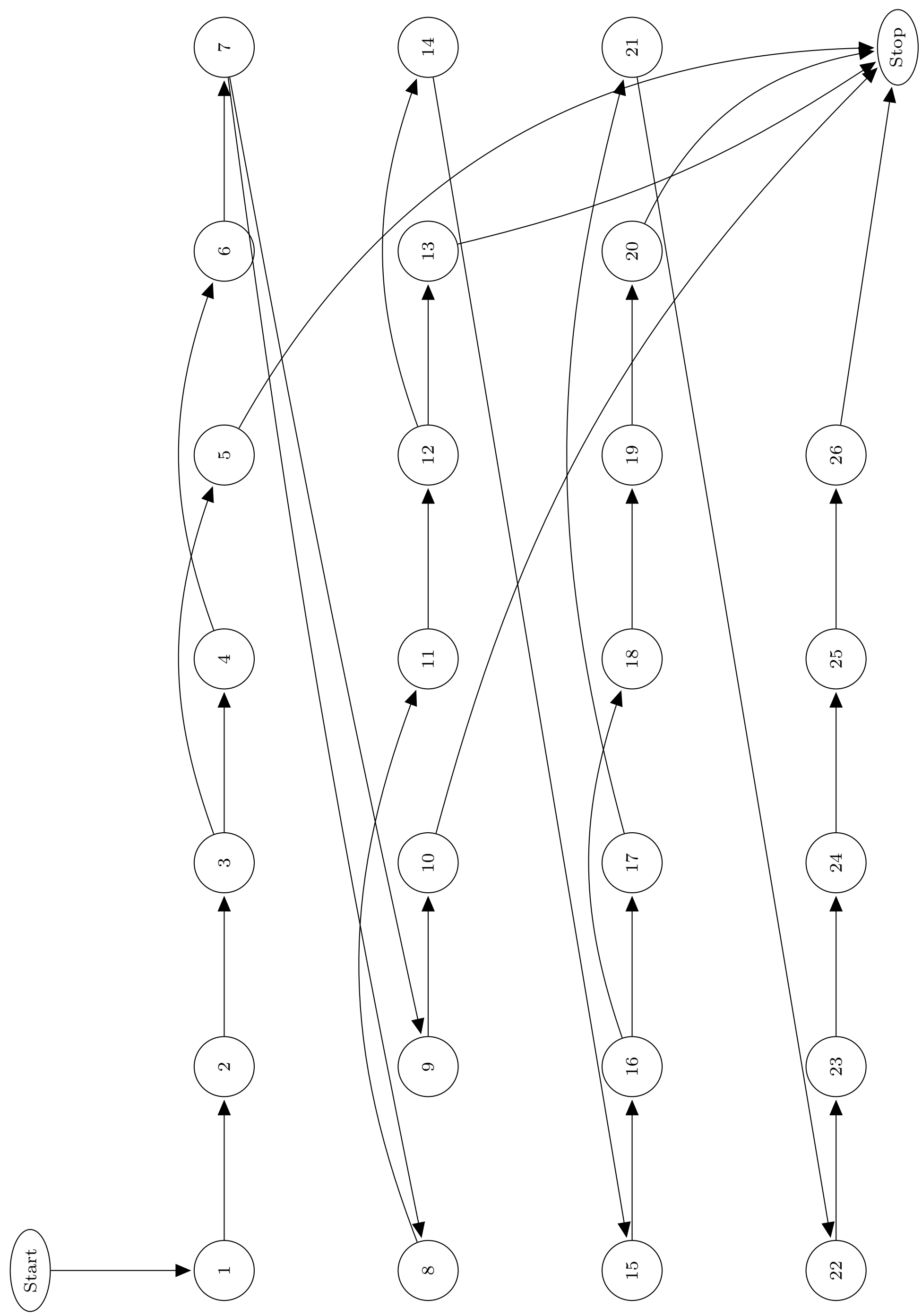


Figure 4.2: Control Flow Graph of IssueBook example shown in Fig.4.1

4.2.2 Communication Dependence Graph

In this section, we define our CoDG representation of UML 2.0 Communication diagrams. CoDG represents the dependency among the messages that are passed between various objects in a given scenario. Two types of dependencies are considered in the CoDG- data dependency and control dependency. These are represented by different types of edges in the Communication Dependence Graph. CoDG captures only the dynamic dependencies among objects in the system. Dynamic dependencies vary with time viz. data dependencies. Data dependence edges of CoDG represent the flow of data among the messages that are passed between objects in a communication diagram. In addition, it also shows the effect of the calling messages on the return value of that call. Control dependence edges of CoDG show flow of control in communication diagram. To draw CoDG, we follow the following steps:

1. Draw the communication diagram for the given scenario in the system.
2. Construct the Control Flow Graph (CFG) from communication diagram by identifying the various dependencies among the messages that are passed from one object to another.
3. From the CFG, construct the CoDG by classifying the dependency as- data dependence or control dependence edges.

An Example of CoDG

To explain the construction of CoDG, we have considered the IssueBook() scenario of Library Management System(LMS) system. In the first step, we identify the objects involved in the scenario and the communication among them. Then we used the MagicDraw tool to draw the communication diagram as shown in Fig.4.1. From the communication diagram, the CFG is drawn as shown in Fig.4.2. All the messages are represented by a node. The node number is equal to the label of the messages in the communication diagram. The edges of the graph represent the dependency among the nodes. From the CFG, we have classified the edges that are control dependent and data dependent. The control dependent edges are represented by solid edges and data dependent edges are represented by dashed edges. After each execution of a message the graph is updated to find the recent dependencies. In the graph, the previous execution dependencies are unmarked in order to get precise slices.

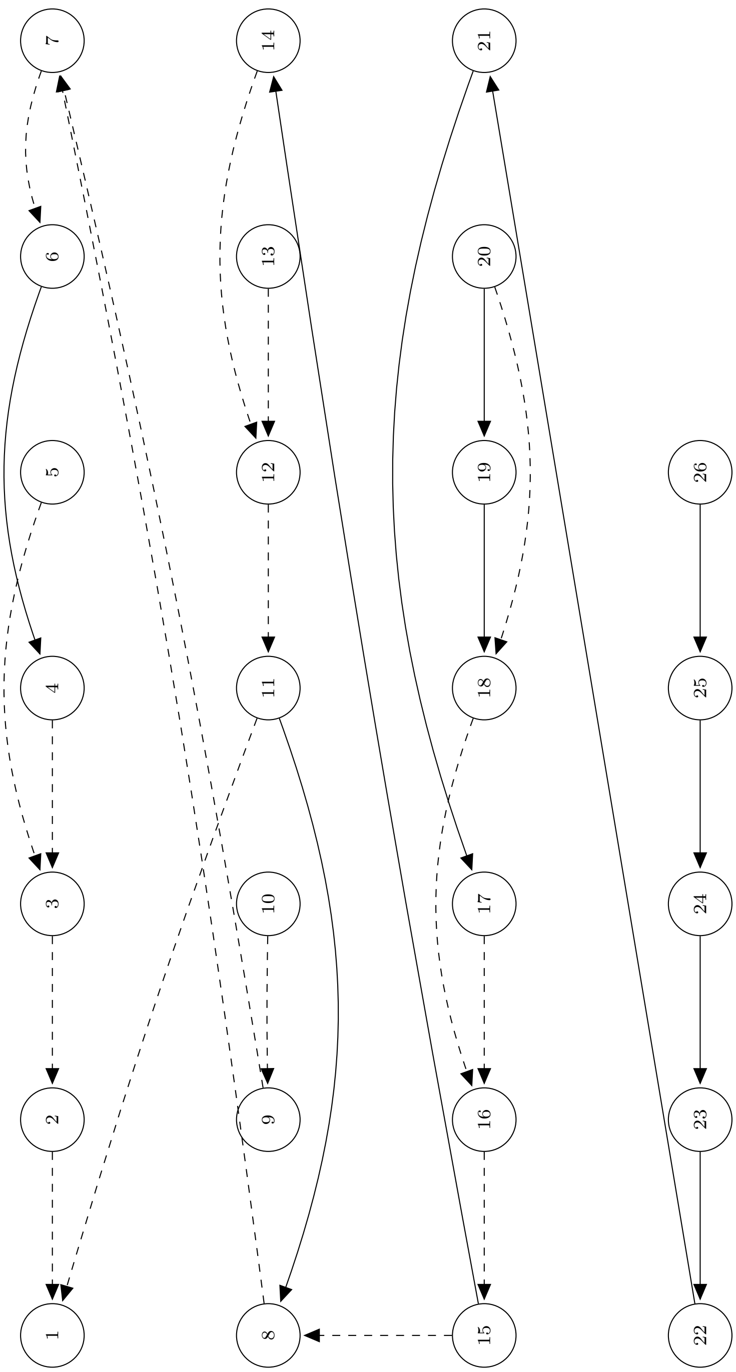


Figure 4.3: Communication Dependence Graph of IssueBook example shown in Fig. 4.1

The CoDG constructed from the CFG in Fig.4.2 is shown in Fig.4.3. In the figure the solid line represent the control dependency and the dashed lines represent the data dependency among the messages. This graph is traversed using EMACD algorithm to find the corressponding slice.
Let the node n in CoDG corresponds to the message m in communication diagram C_d. During execution of C_d, let dynSlice(m) denotes the dynamic slice with respect to the node m. Let (m, u_1), (m, u_2),$\cdots$,(m, u_k) be all the marked dependence edges of m in the updated CoDG.
Then, dynSlice(m) = $\{u_1, u_2, \cdots, u_k\}$ $\cup$ dynSlice(u_1) $\cup$ dynSlice(u_2) $\cup$ dynSlice(u_k).

4.2.3 Working of EMACD algorithm

We illustrate the working of the algorithm with the help of an example. Consider the communication diagram of LMS IssueBook function in Fig.4.1 and its CoDG shown in Fig.4.3. During the initialization step, EMACD algorithm first unmark all the dependence edges and set dynSlice(m) = ϕ, for every node of CoDG. Now, consider the input values Mid = 433 (let it be a valid id), (t, a) = (available book), BookIssued=2, reserved=false and Issuelimit = 5. For this input values, program will execute the statements 1, 2, 3, 4, 6, 7, 8, 11, 12, 14, 15, 16, 17, 21,22, 23, 24, 25, 26. Let us assume that a slicing command (16, r) is given at message number 16. This command requires us to find the backward dynamic slice for the variable r at node 16. According to the EMACD algorithm, the dynamic slice at statement 16 is given by the expression dynSlice(16) = 15 $\cup$ dynSlice(15). By evaluating the expression in a recursive manner, we can get the final dynamic slice at statement 16. During run-time, the slice for each statement is computed, immediately after the execution of the statement. The updated CoDG is shown in Fig.4.4. The required slice is shown by shaded nodes.

Algorithm 1 Edge Marking Dynamic Slicing algorithm of Communication Diagram (EMACD)

1: CoDG Construction

(a) CFG = constructCFG(C_G) //Call a procedure for CFG construction

(b) CoDG = constructCoDG(CFG) //Call a procedure for CoDG construction

2: Initialisation: Before execution do the following:

(a) Unmark all the data and control dependence edges of CoDG.

(b) Mark every control dependence edge (y, x) for current execution of variable *var*.

(c) Set dynSlice(n)=ϕ for every node *n* of CoDG.

(d) Set RecentDef(var)=ϕ for each variable *var* of the communication diagram.

3: RunTime Updation: With the given set of input values we traverse the communication diagram sequentially and after each message *m* of the communication diagram is processed do the following steps:

(a) For every variable *var* used at n do the following:

1. Unmark the marked data dependence edge associated with the variable *var* corressponding to previous execution of message *m*.
2. Mark the data dependence edge (n,u) where u = RecentDef(var)

(b) Let (n, u_1),(n, u_2),$\cdots$,(n, u_k) be all the marked dependence edges of *m* in updated CoDG.

(c) Update the dynSlice(n)={u_1, u_2,$\cdots$, u_k} $\cup$ dynSlice(u_1) $\cup$ dynSlice(u_2) $\cup$ dynSlice(u_k).

(d) If *n* is a Def(var) message, then update RecentDef(var)=*n*

(e) Exit if terminate message is encountered.

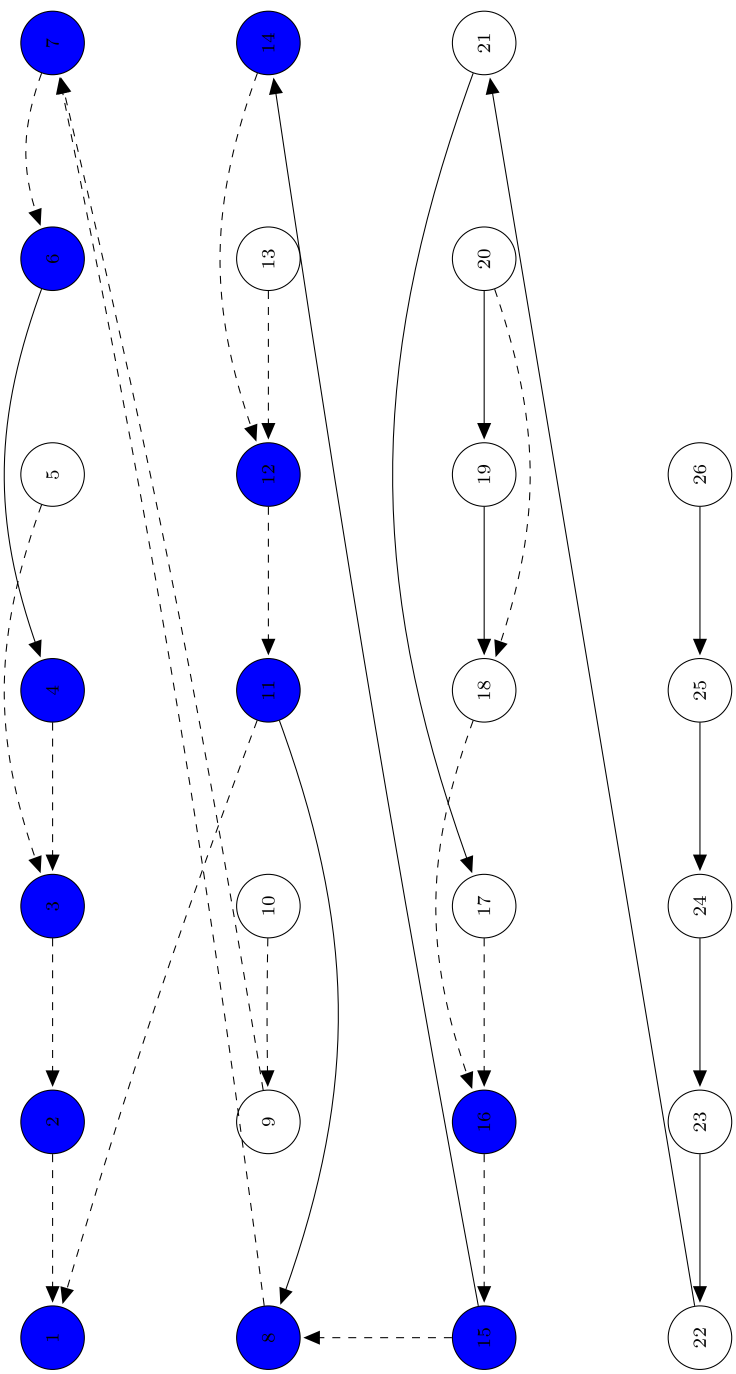


Figure 4.4: Updated CoDG of communication diagram in Fig. 4.1showing dynSlice(16)for EMACD algorithm

4.2.4 Correctness of EMACD Algorithm

In this section, we sketch the proof of correctness of our algorithm.

EMACD algorithm always finds a correct dynamic slice with respect to a given slicing criterion.

***Proof*.** The proof is given through mathematical induction. Let C_d be a communication diagram for which we want to compute the dynamic slice using EMACD algorithm. For any set of input values, the dynamic slice with respect to the first executed message is certainly correct, according to the definition. Using this argument, we establish that the dynamic slice with respect to the second executed statement is also correct. During the execution, assume that the EMACD algorithm has produced correct dynamic slice prior to the present execution of a node s. Let var be a variable used at s, and Dynamic Slice(s, var) be the dynamic slice with respect to the slicing criterion (s, var) for the present execution of the node s. Let the node d = RecentDef(var) is the reaching definition of the variable var for the present execution of the node s. Note that the node d is executed prior to the current execution of the node s and dynSlice(d) contains all those nodes which have affected the current value of variable var used at s. Our EMACD algorithm has marked all the incoming edges to d only from those nodes on which d is dependent. If a node has not affected the variable var, then it will not be included in dynSlice(d). So, dynSlice(s) = $\{d_1, d_2, \cdots, d_k\}$ ∪ dynSlice(d_1) ∪ dynSlice(d_2) ∪ $\cdots$ ∪ dynSlice(d_k). Since dynSlice(d_1), dynSlice(d_2), $\cdots$, dynSlice(d_k) are all precise, then dynSlice(s) computed by the algorithm must also be precise. This establishes the correctness of the algorithm.

4.2.5 Complexity Analysis of EMACD Algorithm

Space Complexity

Let C_d be a communication diagram having m messages. Each message is represented by a single vertex in CoDG. A graph with n number of nodes requires $O(n^2)$ space. Thus, the space require for the CoDG is $O(n^2)$. We also need the following additional run-time space to manipulate the CoDG.

1. To store the dynSlice(m) for each message of the communication diagram C_d, at most O(n) space is necessary, because the maximum size of the slice is equivalent to number of messages in the communication diagram. Therefore, for n messages, the space requirement of dynSlice(m) becomes $O(n^2)$.

Table 4.1: Updated Dynamic Slice Of Each Node

NODE No.	Resulting Dynamic Slice
dynSlice(1)	0
dynSlice(2)	2,1
dynSlice(3)	3,2,1
dynSlice(4)	4,3,2,1
dynSlice(5)	5,3,2,1
dynSlice(6)	6,4,3,2,1
dynSlice(7)	7,6,4,3,2,1
dynSlice(8)	8,7,6,4,3,2,1
dynSlice(9)	9,7,6,4,3,2,1
dynSlice(10)	10,9,7,6,4,3,2,1
dynSlice(11)	11,8,7,6,4,3,2,1
dynSlice(12)	12,11,8,7,6,4,3,2,1
dynSlice(13)	13,12,11,8,7,6,4,3,2,1
dynSlice(14)	14,12,11,8,7,6,4,3,2,1
dynSlice(15)	15,14,12,11,8,7,6,4,3,2,1
dynSlice(16)	16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(17)	17,16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(18)	18,16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(19)	19,18,16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(20)	20,19,18,16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(21)	21,17,16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(22)	22,21,17,16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(23)	23,22,21,17,16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(24)	24,23,22,21,17,16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(25)	25,24,23,22,21,17,16,15,14,12,11,8,7,6,4,3,2,1
dynSlice(26)	26,25,24,23,22,21,17,16,15,14,12,11,8,7,6,4,3,2,1

2. Consider v number of variables are present in the communication diagram C_d. To store the RecentDef(var) for each variable var of C_d, at most O(n) space is necessary. Assuming that the number of variables exist is less than number of messages, EMACD algorithm will require $O(n^2)$ space to store RecentDef(var) of all variables.

Therefore, the space complexity of the EMACD algorithm is $O(n^2)$, where n is the number of messages in the communication diagram C_d.

Time Complexity

Let C_d be a communication diagram having n number of messages. The total time complexity of EMACD algorithm is because of two components. The first one is result of the execution time required for the run-time maintenance of CoDG. The second one is the time required to calculate dynSlice(n). The time necessary to store the required information at every node is O(n), where n is the number of messages in communication diagram. The time needed to traverse the CoDG and reach the specified nodes is $O(n^2)$, where n is the number of messages in communication diagram. So, run-time complexity of the EMACD algorithm for computing the dynamic slice is $O(n^2S)$, where S is the length of the execution.

4.2.6 Comparison with the related work

Korel et al. [21] has proposed an algorithm for slicing state-based models. The architectures used in their techniques do not differentiate between the structural and behavioral aspects of a system. This does not permit the computed architectural slices to completely uncover the dependencies existing among different model elements. They compute static model slices of EFSM models and then apply a slice reduction step after the computation of the slice. Our algorithm computes the slice for the behavioural aspects of the system.
The worst case time requirement and space complexity for the architecture slicing algorithms reported by Zhao [46] is quadratic in the number of components, connectors and the attachments. The DSAS algorithm of Kim et al. [36] needs $O(N^2)$ space in the worst case and O(N) time to extract architecture slices, where N is the total number of event occurrences. Note that N may be unbounded for large systems containing event cycles. Our EMACD algorithm has the space complexity of $O(n^2)$ and a time complexity of $O(n^2S)$, where n is the number of messages in the communication diagram and S is the length of execution. Our EMACD algorithm requires no additional space overhead at run-time as no new nodes are added during the process of slice computation. Samuel et al. [32] proposed

an algorithm to generate test case using slicing of sequence diagram. They create a message dependence graph (MDG) from the sequence diagram and then applied edge marking dynamic slicing algorithm to compute the slice. They did not differentiate between the data dependence edge and control dependence edges while constructing the MDG. Instead, they used the concept of stable and unstable edges to compute the dynamic slices of a sequence diagram. Their edge marking algorithm requires at most $O(n^2)$ space to store the MDG, at most $O(n^2)$ space to store the dynamic slices of the executed nodes and at most $O(n^2)$ space to store the all other information, where n is the number of messages in the sequence diagram. So, the worst case time complexity of their algorithm for computing and updating information corresponding to an execution of node is $O(n^2)$. Thus, worst case time complexity of their algorithm for the whole execution of the MDG in an actual run is $O(n^2N)$, where N is the length of execution. Our proposed algorithm requires at most $O(n^2)$ space to store the CoDG, at most $O(n^2)$ space to store the dynamic slice of the executed nodes and at most O(n) space to store the other information. The time spent for calculating and updating the information corresponding to an execution of node u is O(kn), where k is the number of variables used at node u. Thus the worst case time complexity of our algorithm for the entire execution in an actual run is O(knN), where N is the length of the execution. Lallchandani et al. [22] proposed an algorithm for static slicing of UML diagrams. They create a model dependency graph (MDG) by combining UML class diagram and UML sequence diagram. For a given slicing criterion, their algorithm traverses the constructed MDG to identify the relevant model elements. But our algorithms compute dynamic slices as compared to their algorithms.

4.2.7 Node Marking Dynamic Slicing Algorithm for Communication Diagram

We now provide an overview of our NMACD algorithm. We first construct the CoDG from the communication diagram as an intermediate representation. Consider the example of communication diagram given in Fig.4.1 for the IssueBook usecase in LMS software. Its corresponding CFG is shown in Fig.4.2. Let the node u in the CoDG corresponds to the message m in the communication diagram C_d. During execution, let dynSlice(m) denote the dynamic slice with respect to the variable x for the most recent execution of the message corresponding to the node u. Let v_1, $v_2 \cdots v_k$ be all marked predecessor nodes of u in the CoDG after execution of node u. Then, dynamic slice with respect to the node u is given by, dynSlice(n)=$\{v_1, v_2 \cdots v_k\} \cup$ dynSlice(v_1) $\cup$ dynSlice(v_2) $\cup$ dynSlice(v_k). We now present

the steps of our NMACD algorithm for communication diagram.
The CoDG constructed from the CFG in Fig.4.2 is shown in Fig.4.3. In the figure the dashed lines represent the data dependency and the solid lines represent the control dependency among the messages. This graph is traversed using NMACD algorithm to find the corressponding slice.

4.2.8 Working of NMACD algorithm

We illustrate the working of the algorithm with the help of an example. Consider a communication diagram of LMS IssueBook function in Fig.4.1 and its CoDG shown in Fig.4.3. During the initialization step, NMACD algorithm first unmark all the appropriate nodes and set dynSlice(m) = ϕ, for every node of CoDG. Now consider the input values Mid = 433 (let it be a valid id), (t, a) = (available book), BookIssued=2, reserved=false and Issuelimit = 5. For this input values, program will execute the statements 1, 2, 3, 4, 6, 7, 8, 11, 12, 14, 15, 16, 17, 21,22, 23, 24, 25, 26. Let us assume that a slicing command (16, r) is given at message number 16. This command requires us to find the backward dynamic slice for the variable r at node 16. According to the NMACD algorithm, the dynamic slice at statement 16 is given by the expression dynSlice(16) = 15 $\cup$ dynSlice(15). By evaluating the expression in a recursive manner, we can get the final dynamic slice at statement 16. During run-time, the slice for each statement is computed, immediately after the execution of the statement. So, we are able to get the final dynamic slice at statement 16 by performing a table look up on dynSlice(16). Fig.4.5 shows the updated CoDG of communication daigram in Fig.4.1 for dynSlice(16). The shaded nodes constitutes the required slice.

Algorithm 2 Node Marking Dynamic Slicing algorithm of Communication Diagram (NMACD)

1: CoDG Construction

(a) First construct the Control Flow Graph of the communication diagram C_d.

(b) From CFG, construct the corresponding Communication Dependence Graph (CoDG).

2: Initialisation: Before execution do the following:

(a) Unmark all the nodes of CoDG.

(b) Set dynSlice(n)=ϕ for every nodes n of CoDG.

(c) Set RecentDef(x)=ϕ for every variable x of the communication diagram.

3: RunTime Updation: With the given set of input values we traverse the communication diagram sequentially and after each message m of the communication diagram is processed do the following steps:

(a) Let (n,v_1),(n,v_2)$\cdots$(n, v_k) be all the marked successor nodes of n in CoDG, then Update the dynSlice(n)=$\{v_1,\ v_2\ \cdots\ v_k\}$ $\cup$ dynSlice(v_1) $\cup$ dynSlice(v_2) $\cup$ dynSlice(v_k).

(b) If n is a Def(x) message, then

(i) Unmark the node RecentDef(x).

(ii) Update RecentDef(x)=n.

(c) Mark the node n

(d) Exit when encounter the terminate message.

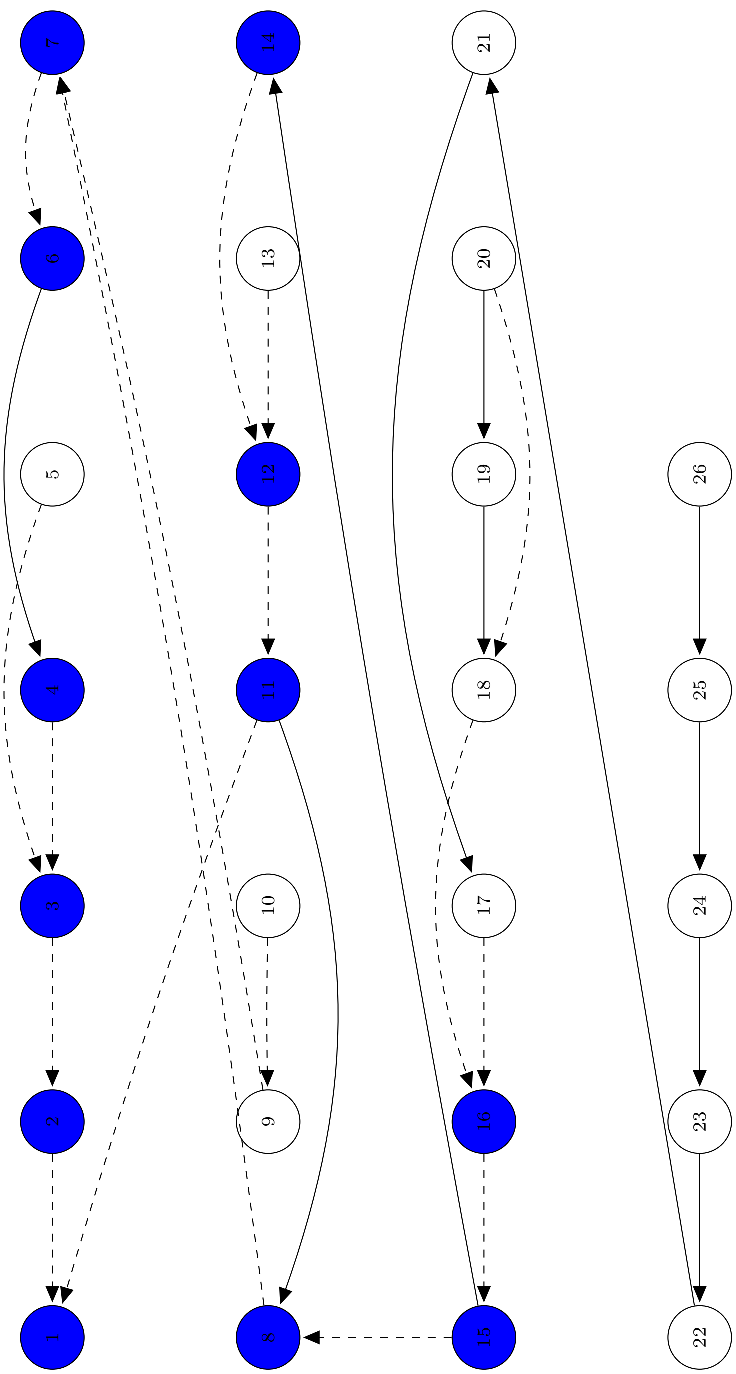


Figure 4.5: Updated CoDG of communication diagram in Fig. 4.1 showing dynSlice(16) for NMACD algorithm

4.2.9 Correctness of NMACD Algorithm

In this section, we sketch the proof of correctness of our Algorithm2.

NMACD algorithm always finds a correct dynamic slice with respect to a given slicing criterion.

Proof . A formal proof of the theorom and correctness of the algorithm can be constructed through mathematical induction by following an approach similar to the given in the proof of Algorithm1.

4.2.10 Complexity Analysis of NMACD Algorithm

Space Complexity

Like EMACD algorithm, it can be shown that the space complexity of the NMACD algorithm is $O(n^2)$, where n is the number of messages in the communication diagram.

Time Complexity

Let C_d be a communication daigram having m messages. The total time complexity of our NMACD algorithm is due to two components. The first one is due to the execution time requirement for the run-time maintenance of CoDG. The second one is due to the time requirement to look up the data structure dynSlice(m) for extracting the dynamic slice, once a slicing command is given. Like EMACD algorithm, it can be shown that, the run-time complexity of the NMACD algorithm for computing the dynamic slice, for the entire execution is $O(n^2S)$, where S is the length of execution of the communication diagram. Each vertex of the CoDG is annotated with its most recent dynamic slice during execution. Thus, slices can be extracted in constant time i.e., in O(1) time.

4.2.11 Comparison Between EMACD and NMACD

Both EMACD and NMACD algorithms use CoDG as the intermediate representation, and compute the correct dynamic slice. The EMACD algorithm is based on marking and unmarking the edges of CoDG as and when dependencies arise and cease at run-time whereas, the NMACD algorithm is based on marking and unmarking the nodes of CoDG appropriately at run-time. For marking and unmarking the dependence edges of CoDG corresponding to an execution of a message n, the EMACD algorithm needs $O(n^2)$ time in the worst case. For marking and unmarking the appropriate nodes, the NMACD algorithm always takes the constant time. Thus, NMACD algorithm is more efficient than the EMACD algorithm.

4.3 Implementation

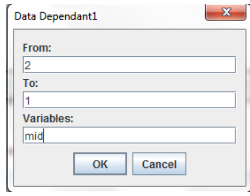
In this section, we briefly explain the implementation for our algorithms. The key stimulus for implementing algorithms is to check the preciseness and the correctness of both the algorithms. We have tested our algorithm through different slicing criterion. We have coded our algorithm in Java. First we are generating the Control Flow Graph (CFG) of the communication diagram. From CFG, we are developing the Communication Dependence Graph (CoDG). We have taken a node in the CoDG for each message in the UML communication diagram. These nodes are interconnected by the help of dependency edge.
The dependency edge represents two types of dependencies: data dependency and control dependency. We are storing the whole information about the CoDG in a file. While storing the different information about the CoDG, we store the data in structure data type. This data structure contains various information about each node in the CoDG like control dependency, data dependency, status- marked or unmarked. The communication dependency graph is given as input to our algorithm dynamically. The GUI for taking the input of data dependent edges, control dependent edges, number of variables used and node number at which slice is to be found is shown in Fig.4.6a, Fig.4.6b, Fig.4.6c and Fig.4.6d respectively. In addition to it, we are computing information related to each node and variable like:

1. The set def(var) and Use(var) for every variable *var* in the communication diagram.

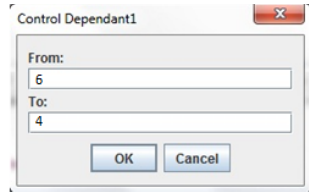
2. For every variable *var*, pointer to the node corresponding to its most recent definition at run-time, i.e. RecentDef(Var).

3. For every node *n* in the CoDG, the dynamic slice, dynSlice(n) corresponding to its most recent definition.

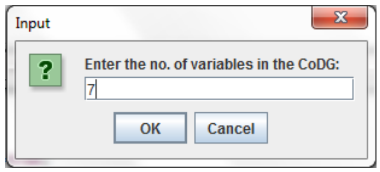
Structure is used to store the sets def(Var), Use(Var), RecentDef(Var) and dynSlice(u). The state of the variable is used in marking and unmarking the edges of CoDG after each statement is executed. After constructing the CoDG statically, we invoke the algorithm for execution. After execution of every message, the status field is marked and unmarked reasonably, and dynamic slice is updated. The dynamic slice is stored in a table created at the run-time. When the user inputs slicing criterion i.e. message number the algorithm outputs the slice along with the computation time with respect to that slicing criterion.



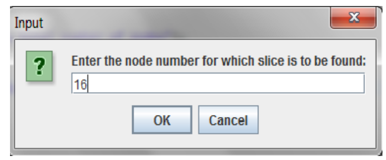
(a) Input for data dependent edges



(b) Input for control dependent edges



(c) Input for variables used in the communiation diagram



(d) Input for node number at which slice to be found

Figure 4.6: Snapshots of GUI to give input to both EMACD and NMACD algorithm

The snapshot of the dynamic slice obtained at node number 16 of EMACD algorithm and NMACD algorithm is shown in Fig.4.7 and Fig.4.8 respectively.

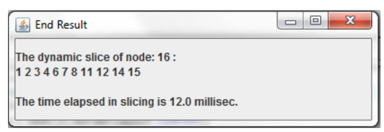


Figure 4.7: Screenshot of the EMACD algorithm showing dynSlice(16)

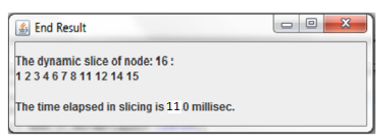


Figure 4.8: Screenshot of the NMACD algorithm showing dynSlice(16)

4.3.1 Experimental Results

This section briefly discuss our experimental results with reference to the run-time requirement for EMACD algorithm and NMACD algorithm. Table 4.2 gives the summary for the average run-time requirements of these algorithms for different communication diagram. Fig.4.9 shows the graphical representation for the comparison of the average run-time requirements of these algorithms. We have computed the average run-time requirements of

Table 4.2: Average run time of EMACD and NMACD algorithm

Sl.No.	No.of Messages	Avg. run-time for EMACD (in msec)	Avg. run-time for NMACD (in msec)
1	15	8.6284	7.8654
2	26	12.0235	11.0305
3	39	16.0087	15.0035
4	54	21.5658	20.2945

both the algorithms because we computed the dynamic slices at different messages of the communication diagram. It can be observed from Table 4.2, that the run-time requirement increases marginally with increse in program size. In addition to it, it can be observed that the average run-time of NMACD algorithm is less as compared to EMACD algorithm. As per the analysis presented in subsection 4.2.11, for marking and unmarking the nodes of the CoDG during run-time NMACD algorithm takes constant time while EMACD algorithm requires O(n^2) time for marking and unmarking the edges of CoDG, where n represents the order of number of messages in communication diagram. Therefore, the NMACD algorithm is marginally more efficient than the EMACD algorithm.

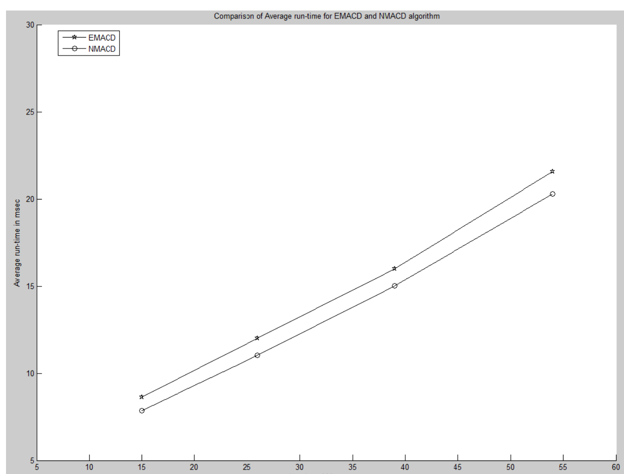


Figure 4.9: Comparison of Average run-time for EMACD and NMACD

Chapter 5

Dynamic Slicing of Aspect-oriented UML Communication Diagram

Aspect-oriented programming (AOP) is an emerging programming paradigm that focuses on modular implementation of cross-cutting concerns such as exception handling, synchronization, security, data access, logging. This technique was first introduced by Kiczales et al. Representation of such cross-cutting concerns by use of standard language constructs gives poorly structured code because these concerns are tangled with the crucial functionality of the code. This considerably increases the complexity and creates difficulty in maintenance. AOP intends to resolve this difficulty in maintenance by allowing the programmer to build up cross-cutting concerns as complete stand-alone modules called aspects. The central idea behind AOP is to build a program by unfolding each concern separately. Aspect-oriented programming languages provide unique opportunities for program analysis schemes. For instance, to implement program slicing on aspect-oriented software, definite aspect-oriented features such as join-point, advice, aspect, introduction must be taken care of appropriately. Even though these features adds great strength to model the cross-cutting concerns in an aspect-oriented program, they also introduce difficulties to analyse the program.

Traditional programming paradigms like procedural and object-oriented (OO) techniques can facilitate programmers in the mechanism of Separation of Concerns to some extents. Taking the example of procedural programming languages (such as C and Pascal) grant separation of concerns into procedures whereas object-oriented programming languages (such as Java and C++) allow software developers to separate the concerns into methods and classes. However, AOP languages such as AspectJ, carry a step forward and help developers to separate crosscutting concerns which are scattered across different procedures (or various classes) of a software into modular units called Aspects. One of the potentiality of the aspect-oriented programming languages is aiding the defining, designing, specifying, and constructing aspects and imposing a better coding style. However, few errors that are generated by the untrained programmers or by the poor understanding of requirements during development cannot be avoideded. Also, in AOP paradigm the behavior of the system is changed due to weaving the aspects into the original programs.

In this chapter, we use a communication diagram to capture the dynamic interactions between objects of a system. A communication diagram is the combination of objects and associations between them that corressponds to communication between objects. Here, we have considered the aspect-oriented UML communication diagram for representing the system dynamic properties. For a given problem scenario, we first draw the communication diagram. Once the diagram is done,it is converted into an intermediate representation, which we named *Communication Aspect Dependency Graph (CADG).* In the next step, the CADG is traversed according to the algorithm proposed on the basis of marking and unmarking of the dependence edges in the graph. The algorithm is named *Aspect-Oriented Edge Marking Algorithm (AOEM).* The traversal of the graph is based on the slicing criterion. As a result, we obtained the required slice from the architectural model at a higher level of abstraction.

5.1 Basic Concepts and Definition

This section gives a brief overview about some basic definitions, notations and terminologies related to the intermediate representation and the working of the algorithm.

UML Communication Diagram: UML communication diagram is used to show the communication between the different objects involved in a given problem scenario. The ordering of the messages is shown with the help of numbering technique. In order to draw the communication diagram, we identify the objects that are participating in the scenario. Then all objects are connected using a link. Through the link the messages are sent between the objects to carry out the given scenario. In our work, we have considered aspect-oriented based communication diagram to compute the dynamic slice at the architectural level. As we know, aspects in AOP are similar to classes in OOP, we have represented the objects of the aspects similar to OOP. In the example of aspect-oriented (woven) communication diagram shown in Fig.5.1, we have considered five base classes (Member, LMS, MemberRecord, Transaction and Book), one Aspect (AccessController), and one Around advice (Login).

The aspect in the scenario has a vital impact on the security of the system as it allows only the authenticated users for the enquiry process. The method pass_id() of base class *Member* act as joinpoint through pointcut designator. We have represented the pointcut i.e. the first message in dotted line from base class to aspect. At this point of time, the message is sent and the execution is temporarily stopped until acknowledgement is received. After the memberId (MId) is validated, control moves back to the suspended base class and the execution resumes for enquiring the book details.

Communication Aspect Dependency Graph (CADG): We define Communication Aspect Dependency Graph (CADG) as a directed graph with (N, E), where N is a set of nodes and E is a set of edges. CADG demonstrates the dependency of a node under consideration on the others. In this case, a node represents either a message or a note in the communication diagram and edges represent either control or data dependency among nodes. The CADG is used to represent the dynamic dependencies among the messages in the aspect-oriented communication diagram for *IssueBook* usecase in *Library Management System*. The communication diagram of IssueBook usecase as shown in Fig.5.1, is considered to construct the CADG as shown in Fig.5.2.

RecentDef (x): For all variable x, RecentDef (x) gives the pointer to the node or label number of the node equivalent to the latest definition of the variable under consideration. Each time a variable in the message is redefined, the RecentDef(x) for the variable changes.

dynSlice(n): For every node n of the CADG i.e. message m of the communication diagram, dynSlice(n) stores the dynamic slice with respect to the most recent execution of the node n. This is calculated at the run-time of the algorithm. We define the dynamic slice *dynSlice* as follows: dynSlice(n) = $\{v_1, v_2 \cdots v_k\} \cup$ dynSlice(v_1)$\cup$ dynSlice(v_2) $\cup \cdots \cup$ dynSlice(v_k).

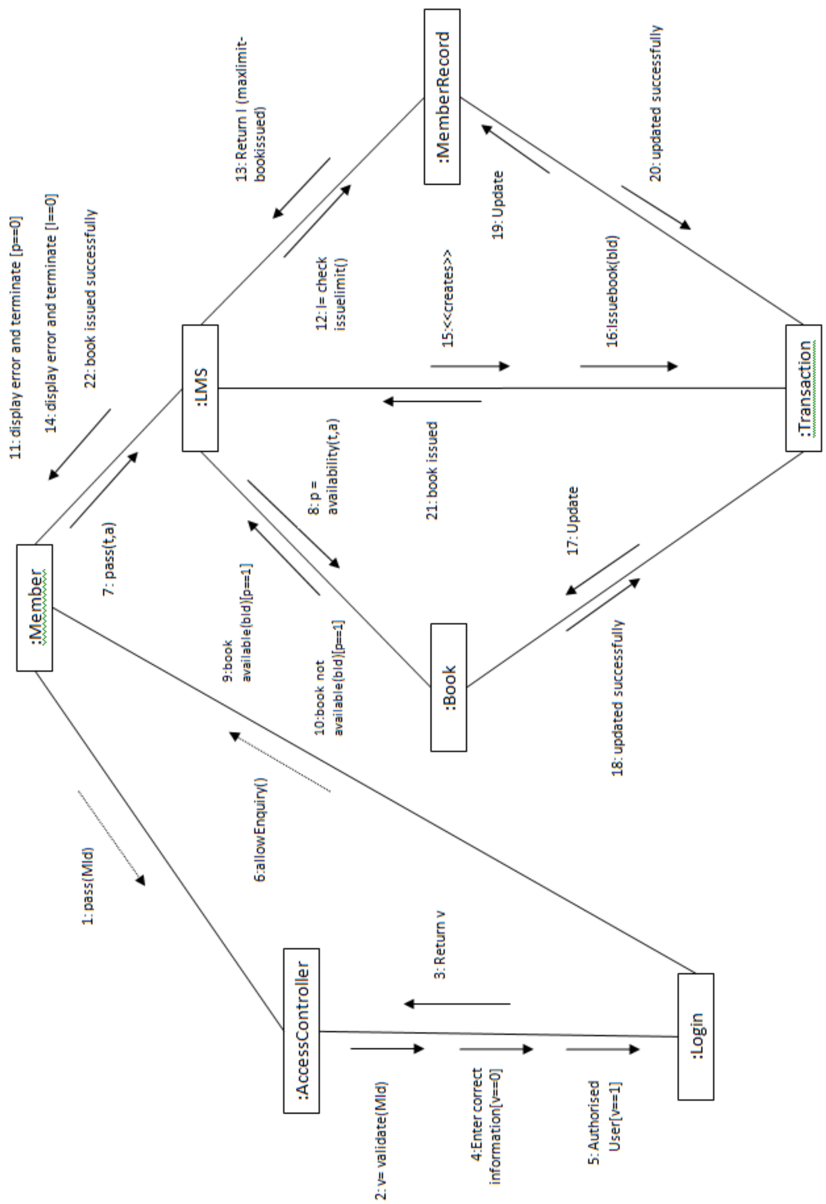


Figure 5.1: Aspect-oriented communication diagram for IssueBook scenario of Library Management System

5.2 Dynamic Slicing of Aspect-oriented UML Communication Diagram

In this section, we present the dynamic slicing algorithm for aspect-oriented (woven) communication Diagram. The communication diagram is used to capture the dynamic properties of the system. The communication diagram gives the snapshots of the system at various point of time. The important benefit of using communication diagram is that it represent the interaction among the objects involved in a particular scenario. Also, the size of communication diagram is small compared to other interaction diagrams such as sequence diagram and interaction overview diagram. We proposed a dynamic slicing algorithm based on marking and umarking of edges as the dependencies arises and ceases during run time. The algorithm is named as *Aspect-Oriented Edge Marking Algorithm (AOEM)*.

5.2.1 Aspect-Oriented Edge Marking Algorithm (AOEM)

We now provide an overview of our AOEM algorithm. We first construct the Communication Aspect Dependency Graph (CADG) from the communication diagram as an intermediate representation. Then we traverse the CADG by the AOEM algorithm to find the dynamic slice of the aspect-oriented communication diagram. Consider the example of communication diagram given in Fig.5.1. Its corresponding CFG is shown in Fig.5.2.

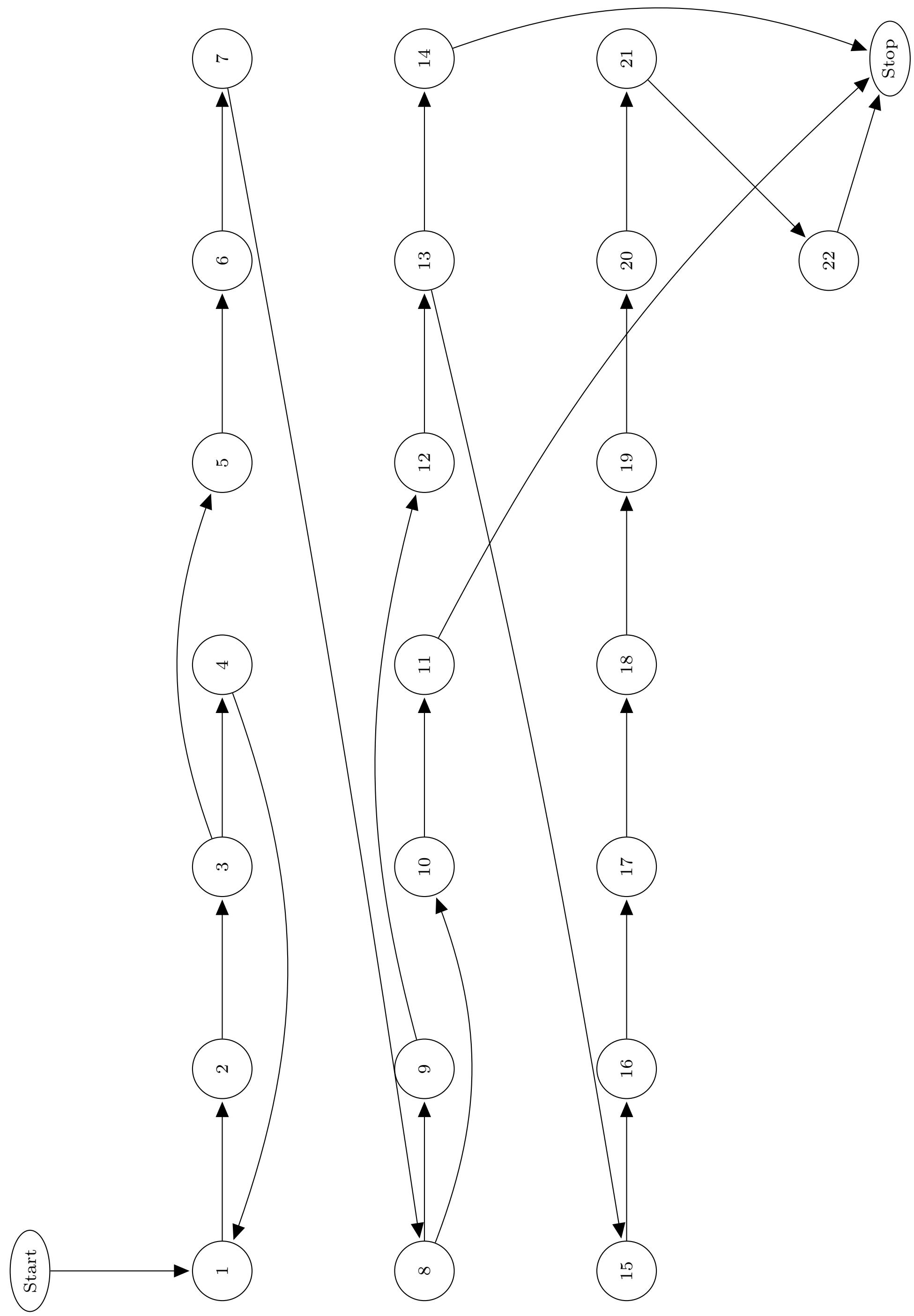


Figure 5.2: Control Flow Graph of IssueBook example shown in Fig.5.1

5.2.2 Communication Aspect Dependency Graph

In this section, we present our CADG representation of UML 2.0 Communication diagrams for aspect-oriented software. CADG demonstrates the dependency between the messages that are passed linking various objects in a given problem scenario. Dependencies considered in the CADG are classified into two different types namely data dependency edges and control dependency edges. We have used different notations to represent the different types of edges in the Communication Aspect Dependency Graph. CADG is confined to represent only the dynamic dependencies existing among various objects concerned in the scenario. Dynamic dependencies show a discrepancy with time (example data dependencies). The flow of data among the messages that are passed between objects in the communication diagram are represented by data dependence edges of CADG. Additionally, it shows the effect of the calling messages on the return value of that call. Control dependence edges of CADG represents flow of control in the communication diagram. We follow the steps mentioned below to construct CADG from communication diagram:

1. Draw the communication diagram for the given scenario in the system.
2. Represent each message of the communication diagram as node in CADG and label it with the message number.
3. Identify the different control dependencies and data dependencies existing between the messages passed among the objects in the communication diagram and represent them as edges in CADG.

An Example CADG

To explain the construction of CADG, we have considered the IssueBook() scenario of Library Management System. In the first step, we identified the objects concerned with the scenario and the communication among them. Then we draw the communication diagram as shown in Fig.5.1. From the communication diagram, the CFG is drawn as shown in Fig.5.2. From the CFG, the different dependencies are identified and shown in Fig.5.3. Each message is represented by a node. The label of the messages in the communication diagram is identical to the node number in CADG. The edges of the graph represent the dependencies among the nodes. The control dependence edges are represented by solid edges and data dependence edges are represented by dashed edges. After each execution of a message the graph is updated to find the recent dependencies.

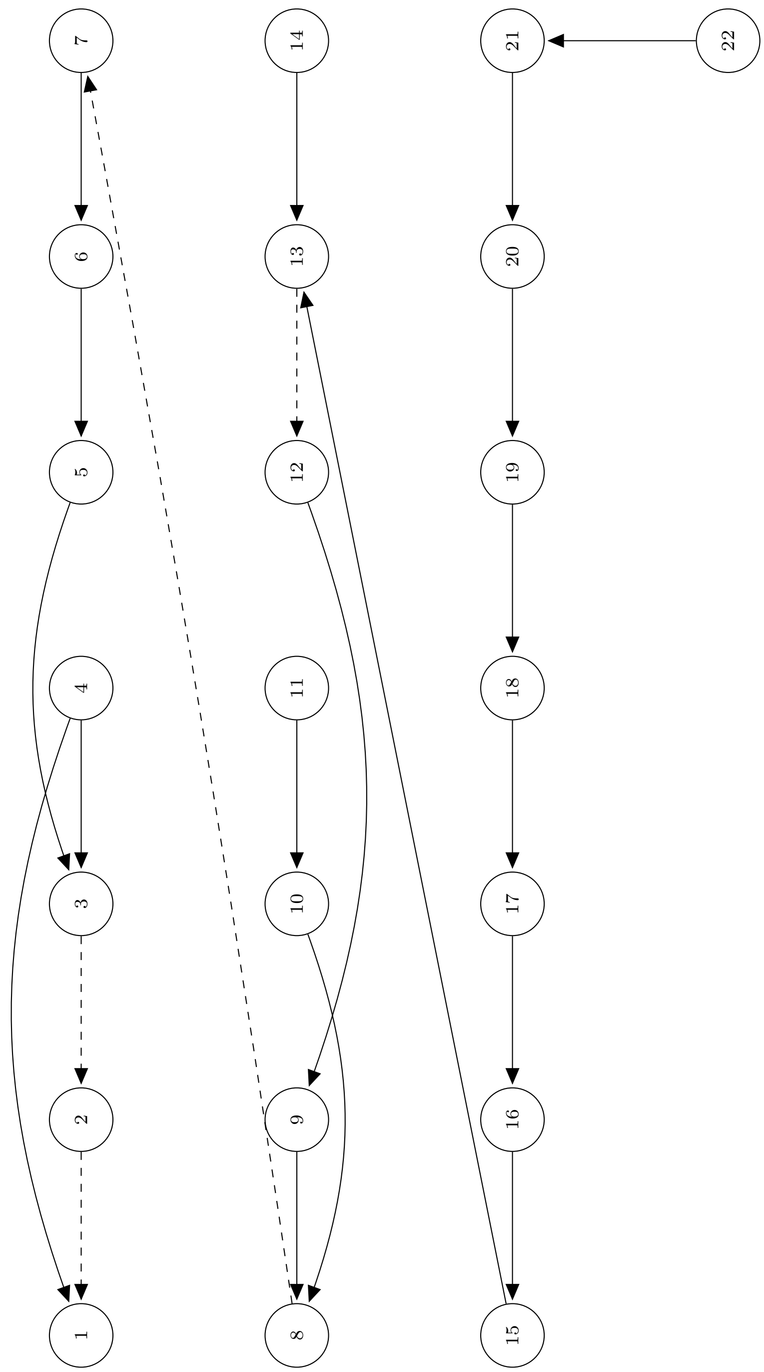


Figure 5.3: Communication Aspect Dependency Graph of IssueBook example shown in Fig. 5.1

5.2.3 Working of AOEM algorithm

We now demonstrate the working of AOEM algorithm with the help of our previously discussed example. Consider the communication diagram of IssueBook scenario in Fig.5.1 and the corressponding CADG shown in Fig.5.3. While execution of the initialization step, AOEM algorithm first unmarks all the dependence edges and set dynSlice(n) = ϕ, for every node of CADG. Now consider the following set of values: MId = valid, v = 1, p = 1 and l = 1. For these set of given values, the model will have the execution trace as 1, 2, 3, 5, 6, 7, 8, 9, 12, 13, 15, 16, 17,18, 19, 20, 21, 22. Let us assume that a slicing command (19, bId) is given. This command requires us to find the backward dynamic slice for the bId variable at node 19. According to the AOEM algorithm, the dynamic slice at statement 19 is given by the expression dynSlice(19) = 18 $\cup$ dynSlice(18). By evaluating the expression in a recursive manner, we can get the final dynamic slice at statement 19. The shaded vertices in Fig.5.4 represents the dynamic slices with respect to bId variable at node 19.

Algorithm 3 Aspect-Oriented Edge Marking Algorithm (AOEM)

1: CADG Construction

(a) CFG = constructCFG(C_G) //Call a procedure for CFG construction

(b) CADG = constructCADG(CFG) //Call a procedure for CADG construction

2: Initialisation: Before execution do the following:

(a) Unmark all the data and control dependence edges of CoDG.

(b) Mark all control dependence edge (y,x) where x is not a loop control node.

(c) Set dynSlice(n)=ϕ for every node n of CADG.

(d) Set RecentDef(var)=ϕ for each variable *var* of the communication diagram.

3: RunTime Updation: With the given set of values, we traverse the communication diagram sequentially and after each message m of the communication diagram is processed do the following steps:

(a) For every variable *var* used at n do the following:

1. Unmark the marked data dependence edge associated with the variable *var* corressponding to previous execution of message m.
2. Mark the data dependence edge (n, u) where u = RecentDef(var)

(b) Let (n, u_1),(n, u_2),$\cdots$,(n, u_k) be all marked dependence edges in updated CoDG.

(c) Update dynSlice(n) = {u_1, u_2,$\cdots$,u_k} $\cup$ dynSlice(u_1) $\cup$ dynSlice(u_2) $\cup$ dynSlice(u_k).

(d) If n is a Def(var) message, then update RecentDef(var)= n

(e) If n is a loop control node, then do -

1. Mark every control dependence edge (x, n), for which this execution of n corressponds to entry of loop in CADG.
2. Unmark every incoming dependence edge (x, n), for which this execution of n corressponds to exit of loop in CADG.

(f) Exit if terminate message is encountered.

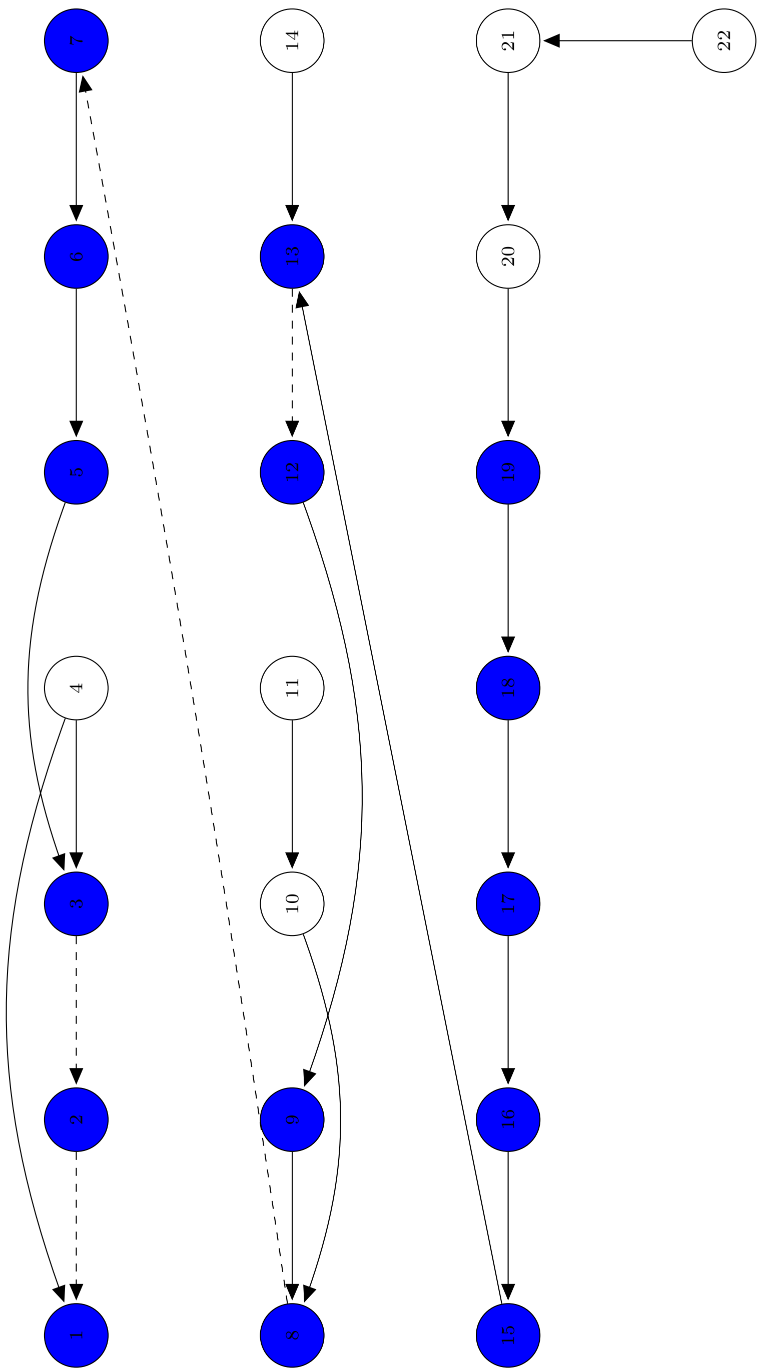


Figure 5.4: Updated CADG of IssueBook example shown in Fig. 5.1 showing dynSlice(19) for AOEM algorithm

5.2.4 Complexity Analysis of AOEM algorithm

Space Complexity

Let C_d be a communication diagram having m messages. Each message is represented by a single vertex in CADG. A graph with n number of nodes requires $O(n^2)$ space. Thus, the space require for the CADG is $O(n^2)$. We also need the following additional run-time space to manipulate the CADG.

1. To store the dynSlice(m) for each message of the communication diagram C_d, at most O(n) space is necessary, because the maximum size of the slice is equivalent to number of messages in the communication diagram. Therefore, for n messages, the space requirement of dynSlice(m) becomes $O(n^2)$.

2. Consider v number of variables are present in the communication diagram C_d. To store the RecentDef(var) for each variable var of C_d, at most O(n) space is necessary. Assuming that the number of varaibles exist is less than number of messages, AOEM algorithm will require $O(n^2)$ space to store RecentDef(var) of all variables.

Therefore, the space complexity of the AOEM algorithm is $O(n^2)$, where n is the number of messages in the communication diagram C_d.

Time Complexity

Let C_d be a communication diagram having n number of messages. The total time complexity of AOEM algorithm is because of two components. The first one is result of the execution time required for the run-time maintenance of CADG. The second one is the time required to calculate dynSlice(n). The time necessary to store the required information at every node is O(n), where n is the number of messages in communication diagram. The time needed to traverse the CADG and reach the specified nodes is $O(n^2)$, where n is the number of messages in communication diagram. So, run-time complexity of the AOEM algorithm for computing the dynamic slice is $O(n^2S)$, where S is the length of the execution.

5.2.5 Comparison with the related work

To the best of our knowledge no one has done slicing of aspect based UML communication diagram. In the absence of any directly related work, we compare our work with the work based on slicing of object-oriented UML models and code based slicing of aspect-oriented software. Korel et al. [21] proposed an algorithm for slicing of statebased models. The architectures used in their procedures do not make a distinction between the structural and behavioral aspects of a system. Also, it was designed for OOP. In our approach, we have considered the dynamic nature of the aspect-oriented system.

Mohapatra et al. [8] proposed an algorithm called Trace Based Dynamic Slice TBDS algorithm. This algorithm computes the dynamic slice from the code of aspect-oriented programs using a dependence based graph called Dynamic Aspect-Oriented Dependence Graph DADG. Our algorithm intends to find the dynamic slice from the design stage using communication diagram at architectural level.

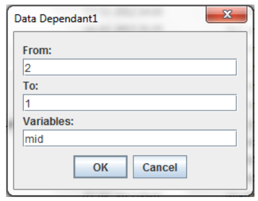
Zhao [46, 47] initially proposed a static slicing algorithm for AOP through aspect mining technique. Then, it was extended by constructing Sequence Dependence Graph for aspect-oriented programs. But this technique was unable to handle the pointcut. In our approach, CADG is able to find the dynamic slice as well as considers the pointcut feature of aspect-oriented programming.

Braak [34] extended the technique proposed by Zhao [46, 47] by including the Inter-type declarations in the graph. Then the two phase algorithm proposed by Horwitz et al. [14] was used to find the static slice of the aspect-oriented program. But our algorithm finds the dynamic slice for aspect-oriented programs at the architectural level.

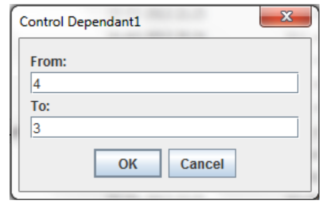
Lallchandani et al. [23] proposed an algorithm to find the dynamic slice combining class diagram and sequence diagram. The representation is named as Model Dependency Graph (MDG) for object-oriented programs. Whereas we have considered the communication diagram for aspect-oriented programs.

5.3 Implementation

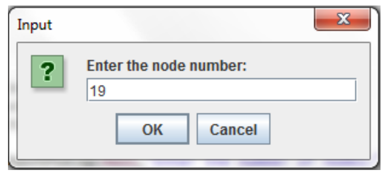
In this section, we discuss the implementation of our AOEM algorithm. The motivation for our implementation is to validate the correctness and the preciseness of our algorithm. We have tested our algorithm on different aspect-based communication diagram and different slicing criterion. We have coded our algorithm in JAVA. First we are generating Communication Aspect Dependency Graph (CADG) from the communication diagram. We have taken a node in the CADG for each message in communication diagram. These nodes are connected with the help of dependency edge. The dependency edge represents two types of dependencies: data dependency and control dependency. We are storing the whole information about the CADG in a file. While storing the different information about the



(a) Input for data dependent edges



(b) Input for control dependent edges



(c) Input for node number at which slice to be found

Figure 5.5: Snapshots of GUI to give input for AOEM algorithm

CADG, we store the data in structure data type. This data structure contains various information about each node in the CADG like control dependency, data dependency, status: marked or unmarked. We have also calculated various attribute of each variable like def(var), use(var)and RecentDef(var). We have developed a dynamic GUI (Graphical User interface) for providing the input to our algorithm. The GUI for taking the input of data dependent edges, control dependent edges and node number at which slice is to be found is shown in Fig.5.5a, Fig.5.5b and Fig.5.5c respectively.

The snapshot for dynSlice(19) is shown in Fig.5.6.

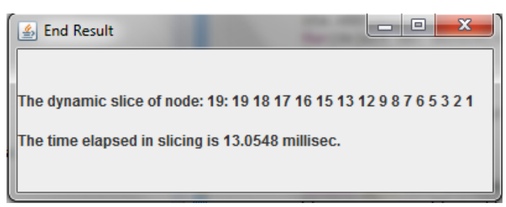


Figure 5.6: Snapshot of the AOEM algorithm showing dynSlice(19)

5.3.1 Experimental Results

In this section, we discuss our experimental results regarding the run-time requirement for the AOEM algorithm. Table 5.1 summarizes the average run-time requirement of AOEM

Table 5.1: Average run time for AOEM algorithm

Sl.No	Number of messages	Avg. run-time for AOEM algo.(in msec)
1	16	12.0045
2	22	14.0876
3	39	18.0004
4	48	20.2213

algorithm for different aspect-based communication diagram. for this, we have considered four different scenarios and drawn the communication diagram for it. Then we applied our AOEM algorithm at different node number for each communication diagram. Next, we have computed the average run-time taken by our algorithm for each of the communication diagram. The result shows the overall trend of the performance of our AOEM algorithm. Fig.5.7 shows the graphical representation of average run-time of AOEM algorithm. It can be observed from the figure that the run-time of the algorithm only increases marginally with increase in number of messages in the communication diagram.

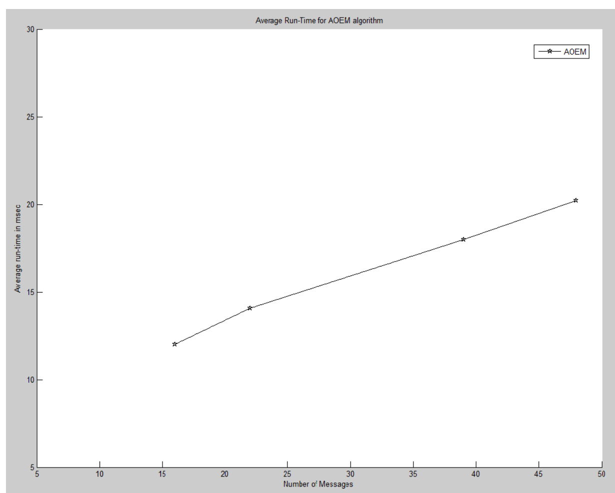


Figure 5.7: Average run-time of AOEM algorithm for different communication diagram

Chapter 6

Conclusions and Future Work

The major aim of our research was to develop efficient dynamic slicing algorithms for object-oriented and aspect-oriented softwares. Below, we summarize the important contributions of our work. At the end, some suggestions for future work are given.

6.1 Contributions

In this section, we summarize the important contributions of our work. There are two important contributions, *Dynamic Slicing of UML communication Diagram* and *Dynamic Slicing of Aspect-oriented UML Communication Diagram*.

6.1.1 Dynamic Slicing of UML communication Diagram

We first developed a communication diagram with the help of MagicDraw tool. In the next step, we generated an intermediate representation for the communication diagram which we named Communication Dependency Graph (CoDG). Then we proposed two dynamic slicing algorithm called as *Edge Marking Dynamic Slicing Algorithm for Communication Diagram(EMACD)*and *Node Marking Dynamic Slicing Algorithm for Communication Diagram(NMACD)*. We have computed that the space complexity of both the algorithm is $O(n^2)$, where n is the number of messages in the communication diagram. The time complexity of both the algorithm is $O(n^2S)$, where S is the length of the execution. We have also shown that our algorithm is more efficient than the exisitng algorithms. We have also proved that our algorithm computes the correct dynamic slices. We have implemented both the algorithm in Java to demonstrate their correctness.

Future work

We now briefly outline the possible extensions to our work.

- Our work can be extended to compute the dynamic slices using other UML diagrams like activity, class and statechart diagrams.
- The work can also be extended to compute dynamic slices by combining two diagrams like activity diagrams and class diagrams, class diagrams and sequence diagrams.

6.1.2 Dynamic Slicing of Aspect-oriented UML Communication Diagram

We have used UML 2.0 aspect-oriented based communication diagram to compute the dynamic slices. We have developed a Communication Aspect Dependence Graph (CADG) as an intermediate representation. Then, we propose an algorithm Aspect-Oriented Edge Marking Algorithm (AOEM). We have shown that the time complexity of our algorithm is $O(n^2S)$, where S is the length of the execution. The space complexity of our algorithm is $O(n^2)$, where n is the number of messages in the communication diagram. We have also proved that our algorithm computes the correct dynamic slice. We have implemented the algorithm to demonstrate their correctness.

Future Work

We briefly outline the following possible extensions to our work.

- Our current work can be extended to compute dynamic slices of other UML 2.0 diagrams like activity diagrams, state-chart diagrams, interaction overview diagrams.
- Computing dynamic slices of a combination of two or more UML 2.0 diagrams like communication diagram and class diagram, communication diagram and activity diagram etc. is another direction for extension.

Dissemination of Work

Dynamic Slicing of Communication Diagram [Chapter #4]

1. Dynamic Slicing of UML Communication Diagram, In *3rd IEEE International Advance Computing Conference* , Pages- 1394 - 1399, February 2013.

2. A Node Marking Algorithm for Dynamic Slicing of UML Communication Diagrams, In *Accepted for Publication International conference on Advanced Computing, Networking and Informatics (ICACNI)*, Raipur, June 2013.

Dynamic Slicing of Aspect-oriented Communication Diagram [Chapter #5]

1. Dynamic Slicing of Aspect-oriented UML Communication Diagram, In *6th National Workshop on Recent Trends in Software Testing (RTST)*, Published in International Journal of Computer Science and Informatics, 3(2), pages- 58-63, May 2013

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