

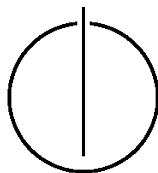
FAKULTÄT FÜR INFORMATIK

DER TECHNISCHEN UNIVERSITÄT MÜNCHEN

Master's Thesis

**Semi-Automated Detection of Sanitization,
Authentication and Declassification Errors in UML
State Charts**

Md Adnan Rabbi





FAKULTÄT FÜR INFORMATIK

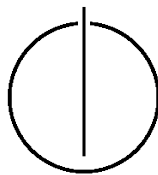
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Semi-Automated Detection of Sanitization, Authentication and Declassification Errors in UML State Charts

Halbautomatische Erkennung von
Sanitisierungs,Authenifizierungs und Deklassifizierungsfehlern
in UML-Zusantsdiagrammen

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Date: October 10, 2015



I assure the single handed composition of this masters thesis only supported by declared resources.

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München, den 10 October 2015

Md Adnan Rabbi

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Abstract

Information flow vulnerabilities detection with static code analysis techniques is challenging because code is usually not available during the software design phase and previous knowledge about what should be annotated and tracked is needed. To detect information flow errors in UML state charts and C code are not easy task as they can cause data leakages or unexpected program behavior. In this research it is proposed that textual annotations used to introduce information flow constraints in UML state charts and code which are afterwards automatically loaded by information flow checkers that check if imposed constraints hold or not. The experimental results on selected sample scenarios shows that this approach is effective and can be further applied to other types of UML models and programming languages as well, in order to detect different types of vulnerabilities.

The contributions of this thesis is the development of a system for semi-automated detection of sanitization, authentication and declassification errors in UML state Charts. A novel light-weight security annotation language used in order to define information flow constraints regarding authentication, declassification and sanitization function errors in UML state charts and source code. Annotation language editors designed as Eclipse plug-ins which is used to edit UML state charts and source code files. Developed Source code generator as Eclipse plug-in which is used to generate C code with header files from UML State chart. And finally experimented automatic loading and usage of textual annotations inside 3 new checkers.

Contents

Acknowledgements	vii
Abstract	ix
Outline of the Thesis	xiii
I. Introduction and Theory	1
1. Introduction	3
2. Literature Review	5
2.1. Sanitization	5
2.2. Declassification	6
2.3. Authentication	7
2.4. Detecting Information Flow Errors During Design	8
2.5. Detecting Information Flow Errors During Coding	8
II. The 2nd Part	11
3. Challenges and Annotation Language Extension	13
3.1. Challenges and Idea	13
3.2. Annotation Language Tags	14
3.3. Language Implementation Process	15
4. Implementation	17
4.1. Overview of System Architecture	17
4.2. The Grammar of Annotation Language	18
4.3. UML State Chart Editor	19
4.4. Source Code Editor	21
4.5. C Code Generator	22
4.6. Three Checkers in Static Analysis Engine	26
4.7. View Buggy Path in Sequence Diagram	26
5. Experiments	29
5.1. Authentication Scenario	29
5.2. Declassification Scenario	30
5.3. Sanitization Scenario	31
5.4. Checkers in Static Analysis Engine	32
6. Related Work	35
7. Conclusion and Future Work	37
Appendix	41

A. Appendix	41
Bibliography	43

Outline of the Thesis

Part I: Introduction and Theory

CHAPTER 1: INTRODUCTION

This chapter presents an overview of the thesis and its purpose. Furthermore, it will discuss the sense of life in a very general approach.

CHAPTER 2: BACKGROUND INFORMATION

This chapter describes the background and the essential theory to establish the research.

Part II: Implementation and Analysis

CHAPTER 3: CHALLENGES AND ANNOTATION LANGUAGE EXTENSION

This chapter presents the challenges and annotation language extension for the system.

CHAPTER 4: IMPLEMENTATION

This chapter presents the implementation of the system.

CHAPTER 5: EXPERIMENTS

This chapter presents the different application areas of the system.

Part III: Conclusion and Future Work

CHAPTER 6: CONCLUSION AND FUTURE WORK

This chapter presents the conclusion of the whole research along with future work intentions.

Part I.

Introduction and Theory

1. Introduction

Security is one of the important factor in software development. To develop a secure system is not an easy task. Only adding some information flow restrictions is not sufficient. Information flow vulnerabilities detection in code and UML state charts is not well known. It is particularly one of the challenging issue now-a-days. Actually there is no common annotation language for annotating UML state charts and source code with information flow security constraints such that errors can be detected also when code is not available. Also there are no automated checking tools which can reuse the annotated constraints in early stages of software development phase to check for information flow errors. It is important to specify security constraints as early as possible in the software development phase in order to avoid later costly repairs or exploitable vulnerabilities.

A solution for tagging sanitization, declassification and authentication in source code is based on libraries which contain all needed annotations attached to function declarations. This approach plays an important role mainly for static analysis bug detection techniques where the information available during program run-time. Detection of information flow vulnerabilities uses dynamic analysis techniques , static analysis techniques and hybrid techniques which combine static and dynamic approaches. The static techniques need to know when to use sanitization , declassification and authentication functions. Data sanitization has been studied in the context of architectures for high assurance systems, language-based information flow controls and privacy-preserving data publication [20]. A global policy of noninterference which ensures that high-security data will not be observable on low-security channels. Because noninterference is typically too strong a property, most programs use some form of declassification to selectively leak high security information [26]. Declassification is often expressed as an operation within a given program. Authentication is the way through which the users get access to a system. In this research main focus are these three types of functionalities which are sanitization, declassification and authentication errors in UML state charts.

Web applications are often implemented by developers with limited security skills and that's why they contain vulnerabilities. Most of these vulnerabilities come from the lack of input validation. That is, web applications use malicious input as part of a sensitive operation, without having properly checked or sanitized the input values prior to their use. Another function is declassification. We all know that computing systems often deliberately release (or declassify) sensitive information. A main security concern for systems permitting information release is whether this release is safe or not. Is it possible that the attacker compromises the information release mechanism and extracts more secret information than intended? Now-a-days computing systems release sensitive information by classifying the basic goals according to what information is released, who releases information, where in the system information is released and when information can be released. in case of authentication, it is the mechanism actually which confirms the identity of users trying to access a system(application, login verification into a system, database access etc.).

It is important to develop techniques and tools which can detect information flow type of errors before software developers or programmers develop their production code. Information flow errors in UML models and code are introduced by software developers or programmers who are sometimes unaware or blind while developing software. This type of vulnerabilities are hard to detect because static code analysis techniques need previous knowledge about what should be considered a security issue. Code annotations which are added mainly during software development [6] can be used to provide additional knowledge regarding security issues. On the other hand code annotations can increase the number of source code lines by 10%. In order to detect information flow vulnerabilities software artifacts have to be annotated with annotations attached to public data, private data and to

system trust boundaries. Next, annotated artifacts have to be made tractable by tools which can use the annotations and check if information flow constraints hold or not based on information propagation techniques.

Static Checking is a promising research area which tries to cope with the shortage of not having the program run-time information. During extended static analysis additional information is provided to the static analysis process. This information can be used to define trust boundaries and tag variables. Textual annotations are usually manually added by the user in source code. At the same time annotations can be automatically generated and inserted into source code. Static Checking can be used to eliminate bugs in a late stage of the software project when code development is finished. Tagging and checking for information exposure bugs during the design phase would eliminate the potential of implementing software bugs which can only be removed very costly afterwards. Thus security concerns should be enforced into source code right after the conceptual phase of the project.

It can be said that annotations can cover design decisions and enhance the quality of source code. Annotations are necessary in order to do Static Checking and the user needs a kind of assistance tool that helps selecting the suited annotation based on the current context. At the same time adding annotations to reusable code libraries reduces even more the annotation burden since libraries can be reused, shared and changed by software development teams.

In summary the contribution for this research are:

- A novel light-weight security annotation language used to define information flow constraints regarding authentication, declassification and sanitization function errors in UML state charts and source code.
- Annotation language editors designed as Eclipse plug-ins which is used to edit UML state charts and source code files.
- Source code generator developed as Eclipse plug-in which is used to generate C code with header files from UML State chart.
- Experiments are presented in experiments section based on automatic loading and usage of textual annotations inside 3 new checkers.

2. Literature Review

2.1. Sanitization

Sanitization is the process of removing sensitive information from a document or other message or sometimes encrypting messages, so that the document may be distributed to a broader audience. Sometimes sanitization can be called as an operation that ensures that user input can be safely used in an SQL query. Web applications use malicious input as part of a sensitive operation without having properly checked or sanitized the input values from the user. Previous research on vulnerability analysis has mostly focused on identifying cases which web applications directly uses external input for critical operations. It is suggested that always use proper sanitization method to validate external input values from the user for any application. For example, user inputs must always flow through a sanitizing function before flowing into a SQL query or HTML, to avoid SQL injection or cross-site scripting vulnerabilities.

Reflection of security breaches are very significant for high assurance system. For examples of this type of systems are aircraft navigation, where a fault could lead to a crash, various control systems which has critical infrastructure, where an error could cause toxic waste to leak, and weapons targeting, where an inaccuracy could result in severe collateral damage. In such operational environments, the impact is virtually irreversible and must therefore be prevented even if it is likely to occur with low probability. It's always good that transforming information to a form which is suitable for release or sanitize the information by redacting some portions of it.

Three of the top five most common website attacks are SQL injection, cross-site scripting (XSS), and remote file inclusion (RFI). The root cause of these attacks is common: input sanitization. All three exploits are leveraged by data sent to the web server by the end user. When the end user is a good guy, the data he sends the server is relevant to his interaction with the website. But when the end user is a hacker, he/she can exploit this mechanism to send the web server input which is deliberately constructed to escape the legitimate context and execute unauthorized actions.

Input sanitization describes cleansing and scrubbing user input to prevent it from jumping the fence and exploiting security holes. But thorough input sanitization is hard. While some vulnerable sites simply don't sanitize at all, others do so incompletely, lending their owners a false sense of security.

Some basic purpose of sanitization are given below:

- Remove malicious elements from the input.
- To identify the set of parameters and global variables which must be sanitized before calling functions.
- It is acceptable to first pass the untrusted user input through a trusted sanitization function.
- Any user input data must flow through a sanitization function before it flows into a SQL query.
- Confidential data needs to be cleansed to avoid information leaks.
- Most paths that go from a source to a sink pass through a sanitizer.
- Developers typically define a small number of sanitization functions in libraries.

- Prevent web attacks using input sanitization.

2.2. Declassification

Information security has a challenge to address: enabling information flow controls with expressive information release (or declassification) policies. In a scenario of systems that operate on data with different sensitivity levels, the goal is to provide security assurance via restricting the information flow within the system. Practical security-typed languages support some form of declassification through which high-security information is allowed to flow to a low-security system or observer.

United States Federal Trade Commission reveals the damage that is continually caused by electronic information leakage. In protecting sensitive information, including everything from credit card information to military secrets to personal, medical information, there is a highly need for software applications with strong, confidentiality guarantees. Security-typed languages promise to be a valuable tool in making provably secure software applications. In such languages, each data item is labeled with its security policy. In practical security-typed languages support some form of declassification, in which high-security information is permitted to flow to a low-security receiver/observer

To declassify information means lowering the security classification of selected information. Sabelfeld and Sands [49] identify four different dimensions of declassification, what is declassified, who is able to declassify, where the declassification occurs and when the declassification takes place.

Myers and Liskov introduced the decentralized label model [42], describing how labels could be applied to a programming language and then used to check information flow policy compliance in distributed systems. The framework includes a declassify function for downgrading data if the owners policies allow. The model allows principals to define their own downgrading policies.

Dimensions of declassification: Classification of the basic declassification goals according to four axes: what information is released, who releases information, where in the system information is released and when information can be released.

- **What:** Selective or Partial information flow policies [9, 10, 29, 21] regulate what information may be released. Partial release guarantees that only a part of a secret is released to a public domain. Partial release can be specified in terms of precisely which parts of the secret are released. This is useful, for example, when partial information about a credit card number or a social security number is used for logging.
- **Who:** In a computing system it is essential to specify who controls information release . Ignoring the issue of control opens up attacks where the attacker hijacks release mechanisms to launder secret information. Myers and Liskov decentralised label model [41] security labels with explicit ownership information. According to this approach, information release of some data is safe if it is performed by the owner who is explicitly recorded in the data security label. This model has been used for enhancing Java with information flow controls [40] and has been implemented in the Jif compiler [43].
- **Where:** In a system information Where is an important aspect of information release. One can ensure that no other part can release further information. by delegating particular parts of the system to release information. Declassification via encryption is not harmful as long as the program is, in some sense, noninterfering before and after encryption. A combination of “where” and “who” policies in the presence of encryption has been recently investigated by Hicks et al. [27]
- **When:** The fourth dimension of declassification is “when” information should be released. The work of Giambiagi and Dam [22] focuses on the correct implementation of security protocols.

Here the goal is not to prove a noninterference property of the protocol, but to use the components of the protocol description as a specification of what and when information may be released. Chong and Myers security policies [8] address when information is released. By annotating variables this is achieved.

For a given model, the “what” and “when” dimensions seem relatively straightforward to define formally. The “what” dimension abstracts the extensional semantics of the system; the “when” dimension can be distinguished from this since it requires an intensional semantics that (also) models time, either abstractly in terms of complexity or via intermediate events in a computation. The “who” and “where” dimensions are harder to formalize in a general way, beyond saying that they cannot be captured by the “what” and “when” dimensions.

2.3. Authentication

Authentication is the mechanism which confirms the identity of users trying to access a system. For a user to be granted access to a resource, they must first prove that they are who they claim to be. Generally this is handled by passing a key with each request (often called an access token, User verification using user id and password). The system or server verifies that the access token or user id and password is genuine, that the user does indeed have the required privileges to access the requested resource and only then the request granted.

Also authentication can be defined as it is the process by which the system validates a user’s logon information. A user’s name and password are compared to an authorized list and if the system detects a match then access is granted to the extent specified in the permission list for that user.

One familiar use of authentication and authorization is access control. A computer system that is supposed to be used only by those authorized must attempt to detect and exclude the unauthorized. Common examples of access control involving authentication include:

- A computer program using a blind credential to authenticate to another program.
- Logging in to a computer.
- Using an Internet banking system.
- Withdrawing cash from an ATM and more
- Assurance of identity of person or originator of data.

A variety of authentication technologies have hit the market over the years. To better understand what they are and how they compare to the user name/password combination, it helps to be familiar with the standard authentication factors something you know, something you have and something you are and how each technology leverages them to power its authentication capabilities.

- Something you know is a bit of knowledge committed to memory, such as a password or an answer to a secret question.
- Something you have is an item that is owned or carried, such as a smart card or similar hardware device.
- Something you are is a physical attribute that can be identified, such as a fingerprint or voice.

According to the networkworld [44] now-a-days seven strong authentication methods are:

- Computer recognition software.
- Biometrics
- E-mail or SMS one-time password (OTP).

- One Time Password (OTP) token.
- Out of band.
- Peripheral device recognition.
- Scratch-off card.

2.4. Detecting Information Flow Errors During Design

If a step of function call like authentication, sanitization or declassification is missing inside the program then this can lead to software vulnerabilities. In the figure 2.1 left side picture depicted that it has three functions. Among them func2() is named either sanitization/declassification/authentication function. Which means in this scenario there will be no error regarding sanitization/declassification/authentication function. On the other hand the right side picture represents there is a missing function of sanitization/declassification/authentication function. That's why it is the buggy path of UML state charts during design stage of software life cycle.

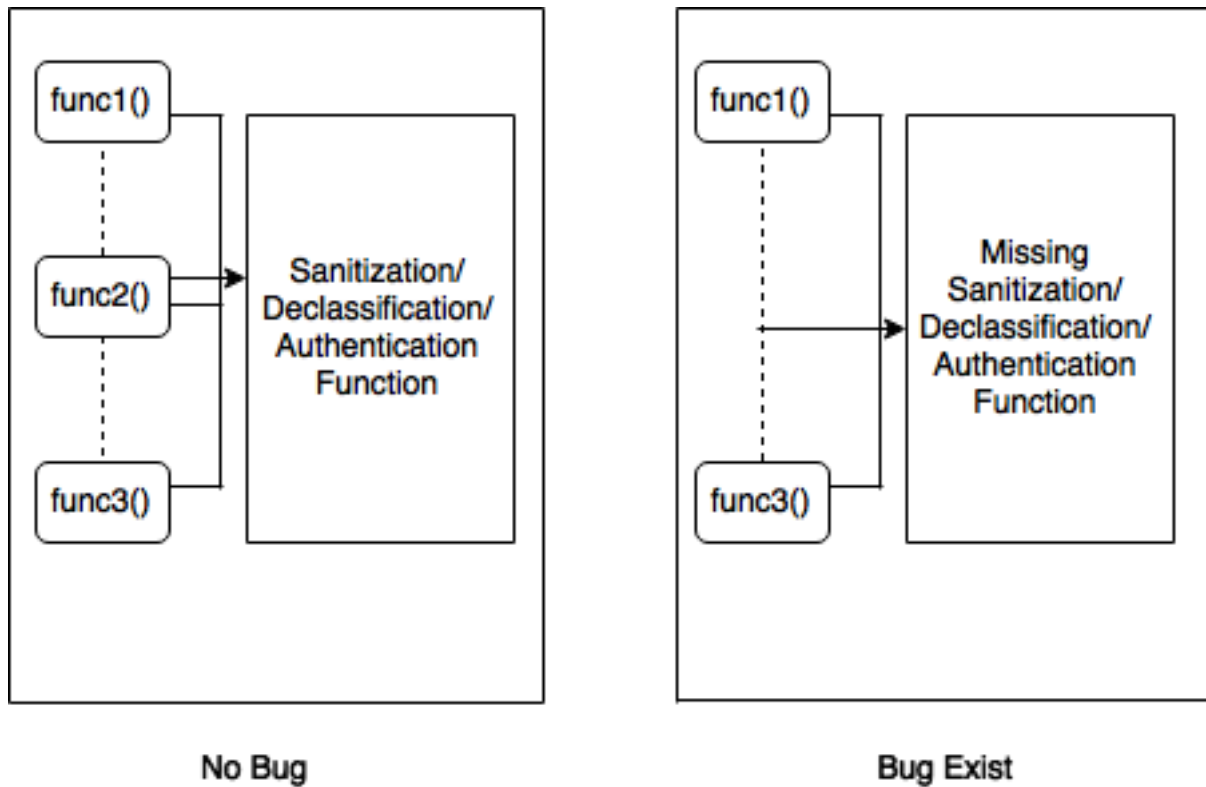


Figure 2.1.: Information flow errors during design

2.5. Detecting Information Flow Errors During Coding

Figure 2.2 depicts two explicit information flows according to A lattice model of secure information flow of Denning [12] contained in two systems (system 1) and (system 2) where each of the flows starts with statement variable a and ends with leaving the system. The the variable declaration up to outside the system represent C language statements. System 1 is depicted in left side containing the flow from the source to the sink and leaving the system indicated with circles at the top and bottom of each of the two information flows. A source is any function or programming language statement which provides private information through a system boundary. A sink can be a function call or programming language statement which exposes private information to the outside of the system

through a system boundary. A system boundary can be a statement, function call, class, package or module. In figure 2.2 the source and sink represent C language statements where information enters and respectively leaves system 1 or system 2. The variable *a* was tagged with label “H” (confidential) as it inserts confidential information into system 1. The arrows represent the passing of the confidential label “H” between the program statements. When a variable labeled with “H” is about to leave system 1 or system 2 without passing through either authentication/declassification/sanitization function then a bug report should be created. In figure 2 right side system has a bug because it passes a secured/confidential information without passing through authentication/declassification/sanitization function. These functions either authenticated, declassified or sanitized secured/confidential information and makes the variable label as “L” to leave the system. But in the left part of the picture there is no bug as in this system, secured/confidential information and the variable which is labeled with “H” passes through either authentication/declassification/sanitization function.

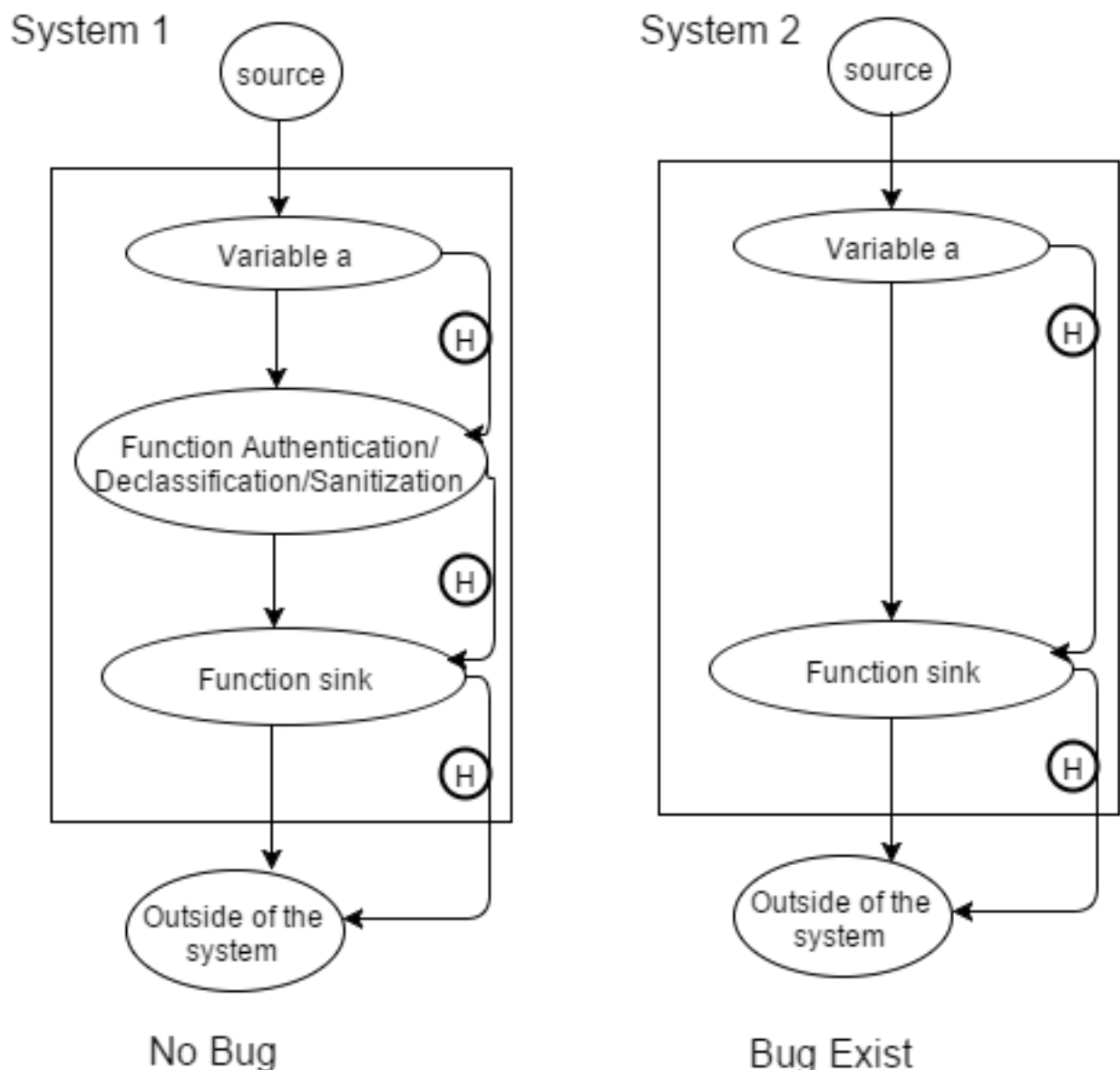


Figure 2.2.: Information flow errors during coding

Part II.

The Second Part

3. Challenges and Annotation Language Extension

3.1. Challenges and Idea

To develop the system eclipse.xtext, eclipse.xtend and static analysis engine named smtcodan(which is developed in Java to detect C and C++ vulnerabilities) are used. For building the source code annotation editor eclipse.xtext is used. Modeling the source as UML Statechart opensource platform YAKINDU SCT editor is used. Inside YAKINDU sct editor to generate the .c(c file) and .h(header file) eclipse.xtend is used mainly for generating code files from statechart. Let's see in briefly what is.xtext, .xtend and how it works.

- **Xtext** : Xtext is a framework for development of programming languages and domain specific languages. According to the "eclipse.org/Xtext", it covers all aspects of a complete language infrastructure, from parsers, over linker, compiler or interpreter to fully-blown top-notch Eclipse IDE integration. It comes with great defaults for all these aspects which at the same time can be easily tailored to your individual needs. Here is an example of Xtext file:

```
grammar org.xtext.example.mydsl.MyDsl with
org.eclipse.xtext.common.Terminals

generate myDsl "http://www.xtext.org/example/mydsl/MyDsl"

Model:
messages+=Message*;

Message:
'Hello' name=ID '!' ;
```

This language allows to write down a list of messages. The following would be proper input messages which are allowed to write:

```
Hello User!
Hello World!
```

- **Xtend** : According to the "eclipse.org/Xtend", Xtend is a statically-typed programming language which translates to comprehensible Java source code. Syntactically and semantically Xtend has its roots in the Java programming language but improves on many aspects such as- Extension methods, Lambda Expressions, Active Annotations, Operator overloading, Powerful switch expressions, Multiple dispatch, Template expressions etc. Xtend has zero interoperability issues with Java: Everything you write interacts with Java exactly as expected. At the same time Xtend is much more concise, readable and expressive. Its small library is just a thin layer that provides useful utilities and extensions on top of the Java Development Kit (JDK). Here is an example of Xtend file:

```
package example
import java.util.List
class A {
def greetToAll(List<String> names) {
    for(name: names) {
```

```
        println(name.sendMessage)
    }
}

def helloMessage(String name) {
    'Hello ' + name + '!'
}
}
```

Xtend provides type inference, the type of name and the return types of the methods can be inferred from the context. Classes and methods are public by default, fields private. Semicolons are optional.

The example also shows the method `helloMessage` called as an extension method, like a feature of its first argument. Extension methods can also be provided by other classes or instances.

Previous annotation language grammar has been extended more to detect implicit and explicit information flow bugs in UML state charts and C code. The purpose of the same annotation language can be used to add information flow constraints to UML state charts and code in order to detect information flow errors.

The challenge was addressed by extending the annotation language containing textual annotations which can be used to annotate source code and UML state charts which are backward compatible. The single-line annotations have the same as previous consisting start tag `///` and the multi-line annotations have the start tag `/**/` and the end tag `@*/`.

Some challenges throughout the approach are- converting textual comments into annotations objects, introducing syntactically correct annotations into files, how to use the same annotation language in order to annotate UML state charts and source code, dealing with scattered annotations and attaching annotations to the right function declaration or variable.

The eclipse xtext based grammar is used to parse the whole C/C++ language. The C/C++ source code file extensions (.h, .hh, .hhh, .hxx, .c, .cpp) and UML state chart annotation box (graphical boxes which can be attached to different parts of a UML state chart diagram) can be annotated with policy language restrictions. The obtained CORE model (a one to one mapping from xtext grammar to the ECORE grammar representation) that can be reused for integrating the policy language into an UML state chart editor. Treating the annotation tags as EObjects created new possibilities for annotating UML models. The policy language grammar has about 420 lines of code with code comments included. Source code generation is also supported by using eclipse xtend, ANTLR and .mwe2 files. To parse other programming languages as well this annotation language parser can be used. The result is an extensible policy language and a highly reusable source code implementation as well as source code generator that can easily be used for annotating models and source files.

3.2. Annotation Language Tags

Table 3.1 contains in this section: the annotation language target types, the annotation tags which can be used in combination with the tag `@function`, the tag `@parameter` can be used to annotate the function parameter as authenticated/declassified/santized H/L and the tag `@variable` used to annotate the variable of C/C++ code with confidential H/L which are used to tag public and private variables. The tag `@variable` which can be used only inside single line annotations whereas `@parameter` is used only in multi line annotations. The tags were defined and implemented iteratively based on the work flow presented in figure 3.1 and by using the eclipse xtext [15] language definition grammar.

For detecting of authentication, declassification and sanitization errors new function tags included like authentication, declassification and sanitization function type. Also for parameter new tag type

Annotation Type	Annotation Tag	Description
@function	sink	uses information
	source	source provides information
	authentication	authentication authenticates information
	declassification	declassification declassifies information
	sanitization	sanitization sanitizes information
@parameter	trust_boundary	trust_boundary is a trust-boundary
	authenticated H/L	authenticated High/Low tags
	declassified H/L	declassified High/Low tags
	sanitized H/L	sanitized High/Low tags
@variable	confidential H/L	confidential High/Low tags
	source H/L	source High/Low tags

Table 3.1.: Security language annotation tags

of parameter included such as authenticated, declassified and sanitized. Still H/L tags for parameter exists in the annotation tags for parameter to define that which type of parameter is this either “High” or “Low”. High means that this parameter is highly confidential or secured and low means that this parameter is not highly secured. In Table 3.1 the new tags for annotation language grammar has given.

3.3. Language Implementation Process

The process depicted in figure 3.1 was used in order to implement annotation language. Figure 3.1 depicts the annotation language implementation process. The process is comprised of the following steps: At first, the .xtext file containing the language grammar was extended following the requirements. Next the grammar file is compiled and software artifacts are generated. After editing the .mwe2 file then compile it. The result of compiling is: a parser, a lexer and class bindings between these two (lexer and parser) and the grammar ECore model. The generated parser, lexer and the bindings were reused inside static analysis engine and in the UI source file editor. After opening and editing a source file with the editor, the file can be parsed and the annotations can be automatically loaded and used inside checkers.

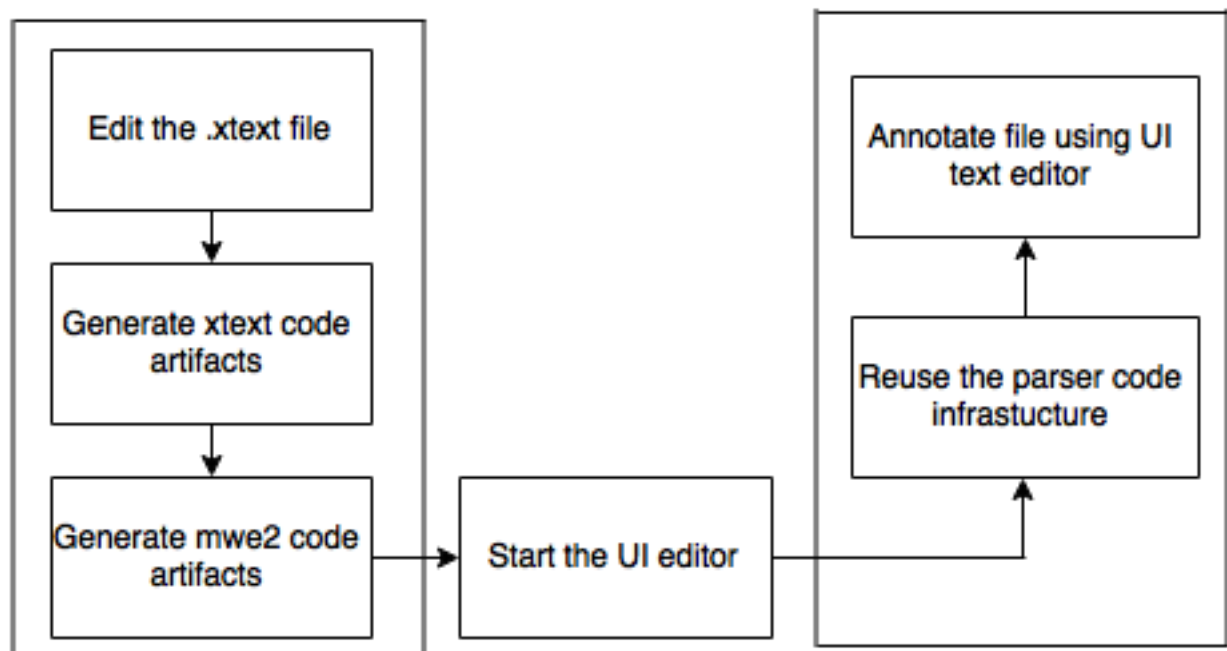


Figure 3.1.: Annotation language design process

4. Implementation

This chapter focus mainly about the software implementation for semi-automated detection of sanitization, authentication and declassification errors in UML state Charts. Used Eclipse xtext to develop source code editor, Eclipse xtend to develop source code generator, YAKINDU SCT editor for modeling C/C++ programs as UML statchart and extended static analysis engine named smtcodan using Java, Graphics2D and JFrame.

4.1. Overview of System Architecture

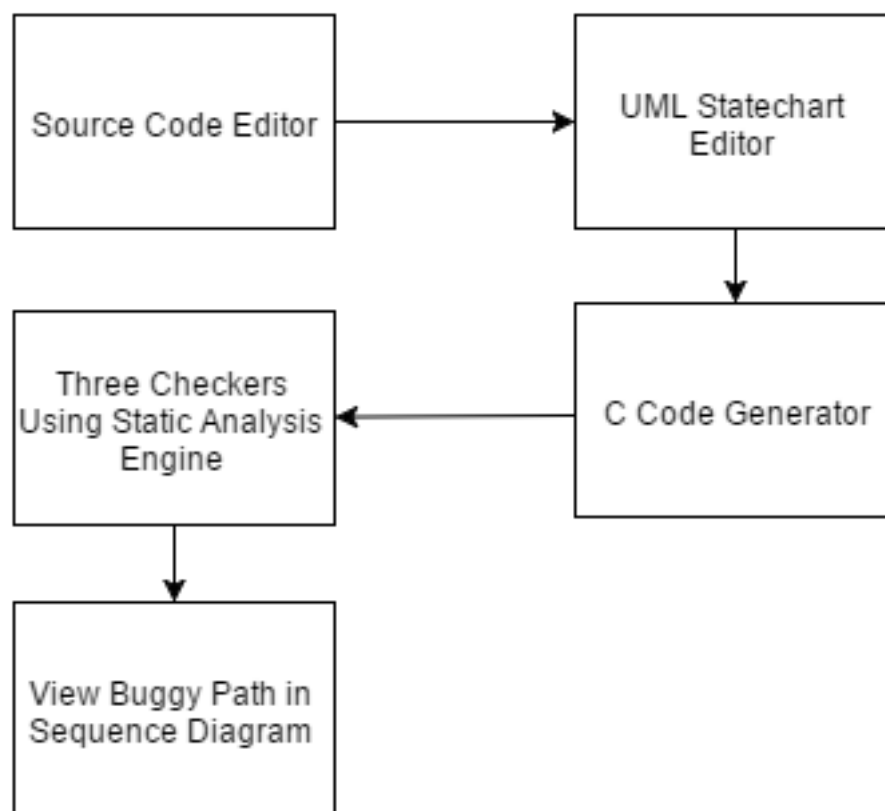


Figure 4.1.: System Overview

Figure 4.1 depicts the complete system architecture. First, the source code editor is developed using Eclipse Xtext. By this editor one can easily annotate the source code of C/C++. Even it is possible to annotate C/C++ header files. For information flow vulnerabilities detection in C/C++ code annotation technique has chosen which is easy to extend and backward compatible. Then for modeling purpose Yakindu SCT editor [1] has chosen to model the C/C++ code into state charts to detect the bug during design stage of software development life-cycle. Inside the Yakindu SCT editor the annotation language grammar has also included using Eclipse Xtext. So, that user can easily annotate the state charts to detect the information flow vulnerabilities. Afterwards the C code generator has extended inside the Yakindu SCT editor using Eclipse Xtend. After modeling the C code files in Yakindu SCT editor user can easily generate the code using C code generator. Through this generator two files will be generated. One file has .c extension and another file has .h extension. Inside those files annotation has also included. Those annotations are helpful to detect the information flow

errors. After generating the code files using static analysis engine named “smtcodan” three checkers have included to detect authentication, declassification and sanitization function missing vulnerabilities. Then to view the buggy path in sequence diagram a sequence diagram generator has created. That is the end of complete system architecture of this system.

4.2. The Grammar of Annotation Language

The grammar of annotation language is represented as in Extended Backus Naur Form (EBNF) in Figure 4.2. The following type face conventions were used: *Italic font* for non-terminals, **bold type-writer font** for literal terminals including keywords.

<i>Ann_Lang</i>	::=	HeaderModel*;	
<i>H_Model</i>	::=	<i>S_L_Anno</i> ;	;single line comment rule
		<i>M_L_Anno</i> ;	;multi line comment rule
		<i>Func_Decl</i> ;	;function declaration rule
		<i>Attr_Def</i> ;	;variable declaration rule
<i>S_L_Anno</i>	::=	"//@ @function ", Func_Type, [H L];	
		"//@ @parameter ", p_Name, Sec_Type, Var_Type, [H L];	
		"//@ @variable ", v_Name, Sec_Type, [H L];	
		"//@ @preStep ", pr_s_Name, [H L];	
		"//@ @postStep ", po_s_Name, [H L];	
<i>M_L_Anno</i>	::=	[/*@ "], [* "], Func_Ann, (@* "/")	
		(/* "), [* "]*, (@* "/");	
<i>Func_Ann</i>	::=	@function ", Func_Type, [H L];	
		@parameter ", p_Name, Sec_Type, Var_Type, [H L];	
		@preStep ", pr_s_Name, [H L];	
		@postStep ", po_s_Name, [H L];	
<i>Func_Type</i>	::=	authentication ;	
		declassification ;	
		sanitization ;	
		sink ;	
		source ;	
		trust_boundary ;	
<i>Sec_Type</i>	::=	confidential ;	
		source ;	
<i>Var_Type</i>	::=	authenticated ;	
		declassified	
		sanitized ;	

Figure 4.2.: Light-weight annotation language grammar excerpt

Annotation language grammar has two grammar rules *S_L_Anno* and *M_L_Anno* used for defining security annotations. The *Func_Decl* and *Attr_Definition* rules are used to recognize C or C++ function declarations and variable. The *Var_Type* rule is used for variable type which is either for authenticated or declassified or sanitized variable. *Sec_Type* rule is used for type of security

whether a variable is confidential or not. In `Func_Decl` rule the type function is declared. A function can be either one of this like authentication, declassification, sanitization, source or sink.

4.3. UML State Chart Editor

A set of formal representation of UML statecharts is presented in this section. The state identifier and event are represented as *S* and *Event* respectively both as set types. For simple specification, the basic set types are used. In the definition of a transition from one state to another the guard is defined as a Boolean type. According to F Alhumaidan state based static and dynamic formal analysis of UML state diagrams [2], a state can have three possible values that are active, passive or null represented as *Active*, *Passive* and *null* respectively. The type of state can be simple, concurrent, non-concurrent, initial or final.

```
[S, Event]
Boolean    ::=  True | False;
Status     ::=  Active | Passive | Null;
Type       ::=  Simple | Concurrent | Nonconcurrent | Initial | Final;
```

Figure 4.3.: UML Statechart Formal Representation

In modeling using sets, it's not imposing any restriction upon the number of elements and a high level of abstraction is supposed. Further, it's not insist upon any effective procedure for deciding whether an arbitrary element is a member of the given collection or not. As a consequent, sets *S* and *Event* are sets over which cannot define any operation of set theory. For example, cardinality to know the number of elements in a set cannot be defined. Similarly, the subset, union, intersection or complement operations over the sets are not defined.

The state diagram is a collection of states related by certain types of relations. In the definition of a state, state identifier, its type, status and set of regions is required. Region is defined as a power set of sequence of states. The state is represented by a schema which consists of four components described above. All these components are encapsulated and put in the Schema State given below. The invariants over the schema are defined in the second part of schema.

```
State
name : S
type : Type
status : Status
regions : seq Regions
regions = 1   type= Simple
# regions = 1   type= Nonconcurrent
# regions = 1   type= Concurrent
```

Figure 4.4.: UML statechart some other formal representation

Invariants:

- If there is no region in a state inside the state diagram, then it is a simple state.
- If there is exactly one region in a state then it is termed as non-concurrent composite state.
- If there are two or more regions in a state then it is concurrent composite state.

The collection of states is represented by the schema *States* which consists of four variables. The mapping substates from *State* to power set of *State* describes type of a state.

Invariants:

```

States
start : State
states : State
states : State
substates : State State;
target : State
start : states
start : target
start : dom substates
states
s : State s dom substates s states
s : State s states s start s target s.typ
Simple s dom substates
target states
target dom substates

```

Figure 4.5.: UML Statechart Formal Representation some parts

- The start state is not in the collection of states.
- The start state is not the target state.
- The start state does not belong to domain of substates mapping that is it has no sub-state.
- The set of states is non-empty.
- For any state, s, if it is in the states and is not the start or target state and not the simple state then it belongs to domain of sub-states.
- The target state does not belong to states.
- The target state of the state diagram does not belong to domain of the sub-states.

UML state chart editor has been extended based on the open source Yakindu SCT [1] framework. The existing language grammar with annotation language grammar has extended in order to support new set of tags. Furthermore, an annotation proposal filter implemented which was used to filter out the annotation language tags of the Yakindu SCT language grammar.

To extend the Yakindu SCT editor here it has been decided to represent the statements like variable declaration, function calling as state and transitions are represent as move from one statement to another. A rectangular box can be attached with transitions where annotation can be written as per requirements. So for the developed system the UML statechart formal representation is as like this:

```

States
start : State
states : State
states : State
substates : State State;
target : State
start : states
start : target
transition : annotation*
target : states

```

Figure 4.6.: UML Statechart Formal Representation for this System

4.4. Source Code Editor

The source code editor has extended which offers annotation language proposals which are context sensitive with respect to the position of the currently edited syntax line. Editor suggestions work only if the whole file is parsed without errors. Editor was developed using Eclipse Xtext [15].

As per requirements previous annotation language grammar which is written in xtext language has been extended. Extra annotation have included like “authenticated”, “declassified”, “sanitized”, “sanitization”, “declassification”, “authentication”. Some part of the code snippet of extended xtext grammar is given below.

```

/**
 * @FunctionAnnotation :used for function annotations
 */
FunctionAnnotation returns FunctionAnnotation:
{FunctionAnnotation}{
result += '@function ' functionType=FunctionType ( ' ')? (level
= ('H'|'L'))? ((name0=ID))? ((nameComment=ID))? ('\n' | '\r')?
// supported without space before confidential and sensitive
| '@parameter ' parameter=ID (name0=ID)? (securityType=SecurityType)? (' ')?
(level = ('H'|'L'))? ('True'|'False')? (variableTyp=VariableType)?
((name1=ID))? ((nameComment=ID))? ('\n' | '\r')?
;

/**
 * @SingleLineAnnotation :used for adding single line annotations
 */
SingleLineAnnotation returns SingleLineAnnotation:
{SingleLineAnnotation}{
result+= '//@ @function ' functionType=FunctionType ( ' ')? (level = ('H'|'L'))?
((name0=ID))? ((nameComment=ID))? ('\n' | '\r')*
// supported without space before confidential and sensitive
| '//@ @parameter ' parameter=ID (securityType=SecurityType)? (' ')? (level
= ('H'|'L'))? ('True'|'False')? (variableTyp=VariableType)?
((nameComment=ID))? ('\n' | '\r')?
| '//@ @variable ' variable=ID (securityType=SecurityType)? (' ')? (level
= ('H'|'L'))? ('True'|'False')? ((nameComment=ID))? ('\n' | '\r')?

;

/**
 * @FunctionType :annotaions types for functions
 */
enum FunctionType: declassification
| sanitization
| authentication
| sink
| source
| trust_boundary
;

/**
 * @Variable Type :annotaions types for function parameters
 */
enum VariableType: declassified
| sanitized
| authenticated
;

```

4.5. C Code Generator

C code generator has extended based on Eclipse EMF and xTend which is used to generate the state chart execution code containing the previously added security annotations from UML state charts. The code generator outputs two files per UML state chart (one .c and one .h file). Generated annotations can reside in both header file and source code file. Previously annotated UML state chart states are converted to either C function calls or C variables declarations, both have been previously annotated. We use the available state chart execution flow functionality which is responsible for traversing the UML state chart during state chart simulation. The UML state chart will be traversed by the code generation algorithm and code is generated based on the mentioned state chart execution flow. The generated code will contain at least one bad path (contains a true positive) and a good path (contains no bug) per UML state chart if those paths were previously modeled inside the UML state chart.

The algorithm is given below how the C code generator has been created. The input of the algorithm for code generator is UML statechart. In eclipse xtend [14] function can be declared as “def”. Here the generateTypeH function requires the input of UML statechart. The plug-in named “MyC” uses eclipse xtend to parse the UML statechart. Inside this function there another two functions named “typesHAnnotationContent” to generate header file of c(extension .h) and “typesCAnnotationContent” to generate source code file of c(extension .c).Function typesHAnnotationContent generate the required contents for C header file mostly function signature and annotation of the function which exist in the UML statechart. One sample example of a header file is given below-

```
/*@ @function authentication
* @parameter a L @*/
void authentication(char *a);

/*@ @function source
* @parameter a L @*/
void logIn(char *a);
```

Function typesCAnnotationContent generate the required contents for C source file. This file contains the annotation only for variable declaration. The function annotation is normally located at header file. In this file other code is as normal as C syntax. All functions, statements, variable declaration are similar to C programming language syntax. Some of the contents of the C file comes from another xtend file named “Naming.xtend” which contains in “MyC” project folder of YAKINDU Sct Editor. some part of code snippet from “Naming.xtend” file is given below:

```
def HashMap<String, String> getFileContent(Statechart sc) {
    var fileContent = <String, String>newHashMap
    for( region : sc.regions){
        for(vertex : region.vertices) {
            if (!(vertex.name.nullOrEmpty)){
                for(transition : vertex.incomingTransitions) {
                    fileContent.put(transition.specification, vertex.name)
                }
            }
        }
    }
    return fileContent
}

def HashMap<String, String> getFunctionContent(Statechart sc) {
    var functionContent = <String, String>newHashMap
    for( region : sc.regions){
        for(vertex : region.vertices.filter[eClass.name.contentEquals('State')])
```

Algorithm 1 C code generator**Input:** Statechart**Output:** .c and .h files

```

1: function GENERATEYPESH(sc) ▷ Where sc - statchart
2:   defgenerateFile1(testModule.h, typesHAnnotationContent(sc)) Where def - function decla-
   ration in xtend
3:   defgenerateFile2(testModule.c, typesCAnnotationContent(sc))
4: end function
5: function TYPESHANNOTATIONCONTENT(sc)
6:   for s : getFileContent(sc).entrySet do
7:     if !s.key.contains('//@@variable') then
8:       s.key
9:     else if s.value.contains('(') then
10:      void < s.value >;
11:    end if
12:  end for
13: end function
14: function TYPESCANNOTATIONCONTENT(sc)
15:   for s : getFunctionContent(sc).entrySet do
16:     if (!s.value.contains('authentication')and(!s.value.contains('declassification'))
17:   and(!s.value.contains('sanitization')))) then
18:       void < s.value >
19:     end if
20:   end for
21:   for region : sc.regions do
22:     if region.name.equalsIgnoreCase('badpath()') then
23:       void < region.name >
24:       for s : getBadPathContent(sc).entrySet do
25:         if s.key.contains('//@@variable') then
26:           s.key
27:           s.value
28:         end if
29:         if s.value.contains('(') then
30:           s.value;
31:           s.value
32:         end if
33:       end for
34:     end if
35:     if region.name.equalsIgnoreCase('goodpath()') then
36:       void < region.name >
37:       for s : getGoodPathContent(sc).entrySet do
38:         if s.key.contains('//@@variable') then
39:           s.key
40:         end if
41:         s.value;
42:       end for
43:     end if
44:   end for
45: end function

```

```

    {

        if ( (vertex.name.contains('(') && !(vertex.name.nullOrEmpty))) {
            functionContent.put (vertex.name, vertex.name)
        }
    }
}
return functionContent
}

def HashMap<String, String> getBadPathContent(Statechart sc) {
    var badfunctionContent = <String, String>newHashMap
    var String newName

    for( region : sc.regions){

        if(region.name.equalsIgnoreCase('bad_path()')){
            for(vertex :
                region.vertices.filter[eClass.name.contentEquals('State')]){

                if(!(vertex.name.contains('(') && !(vertex.name.nullOrEmpty))) {
                    for(transition : vertex.incomingTransitions) {
                        badfunctionContent.put (transition.specification, vertex.name)
                    }
                }
                if((vertex.name.contains('(') && !(vertex.name.nullOrEmpty))) {
                    if ( (vertex.name.contains('char '))) {
                        newName=vertex.name.replaceAll('char *', '')
                        if(newName.contains('*'))
                            newName=newName.replaceAll('\\*', '')
                        badfunctionContent.put (newName, newName)
                    }
                    else
                        badfunctionContent.put (vertex.name, vertex.name)
                }
            }
        }

    }

    return badfunctionContent
}

def String getVariableName(Statechart sc){
    var String variablename
    for( region : sc.regions){
        for(vertex :
            region.vertices.filter[eClass.name.contentEquals('State')]) {

            if (!(vertex.name.contains('(') && !(vertex.name.nullOrEmpty))) {
                for(transition : vertex.incomingTransitions) {
                    variablename= vertex.name.replaceAll('char *', '')
                    if(variablename.contains('*'))
                        variablename=variablename.replaceAll('\\*', '')
                }
            }
        }

    }

    return variablename
}

```

```

def HashMap<String, String> getGoodPathContent(Statechart sc) {
    var goodfunctionContent = <String, String>newHashMap
    var String newName

    for( region : sc.regions){
        if(region.name.equalsIgnoreCase('good_path()')){

            val choiceState=0;
            val increment=1;

            for(vertex :
                region.vertices.filter[eClass.name.contentEquals('Choice')]){
                val sum=choiceState+increment;
                for(transition : vertex.incomingTransitions) {
                    System.out.println("*****"+"if\n"+sum);

                }
            }

            for(vertex :
                region.vertices.filter[eClass.name.contentEquals('State')]) {

                for(invertex :
                    vertex.parentRegion.vertices.filter[eClass.name.contentEquals('State')]) {
                    {
                        if(!(vertex.name.contains('(') &&
                            !(vertex.name.nullOrEmpty))) {
                            for(transition : vertex.incomingTransitions) {
                                goodfunctionContent.put(transition.specification, vertex.name)
                            }
                        }
                        if((vertex.name.contains('(') &&
                            !(vertex.name.nullOrEmpty))) {

                            if ( (vertex.name.contains('char '))) {

                                newName=vertex.name.replaceAll('char *', '')
                                newName=newName.replaceAll('\\*', '')
                                goodfunctionContent.put(newName, newName)
                            }
                            else
                                goodfunctionContent.put(vertex.name, vertex.name)
                        }
                    }
                }
            }
        }
    }

    return goodfunctionContent
}

```

Here from the code snippet it can be seen that from the statechart xtend can easily access the contents of the statechart which is designed in the modeling stage. For example in case of the function

“getFunctionContent” it parses the function names and put it inside a hash map. It parses those as a function who is a state and contains first bracket like “(”. In case of the function “getBadPathContent” which returns the content for the bad path. From the content of state chart there is a region which named is “bad_path()”. From that region this function parses the comments from each transition and gets the name of each state. Then it puts those contents into a hash map. Through iterating that map according to the algorithm it puts some part of contents in C header file and some part in source code file. The purpose of function “getGoodPathContent” is to get all the required content from the good path(which is not buggy path). The parameter of this function is the state chart. In the modeling phase it has been declared a region as “good_path()”. This “getGoodPathContent” function starts parsing the contains from good path then traverse the whole good path and get all the required contents. After that this function puts the content into a hash map. Then according to the algorithm by iterating through the hash map generates the required files by putting the contents in proper place.

4.6. Three Checkers in Static Analysis Engine

Static analysis refers analyzing code without executing it. Generally it is used to find bugs or ensure conformance to coding guidelines. The classic example is a compiler which finds lexical, syntactic and even some semantic mistakes. Static analysis tools should be used when they help maintain code quality. If they’re used, they should be integrated into the build process, otherwise they will be ignored. Some characteristics of static analysis tools are:

- Identify anomalies or defects in the code.
- Analyze structures and dependencies.
- Help in code understanding.
- To enforce coding standards.

For this system static analysis engine “smtcodan” has been used. Inside the engine to detect the information flow vulnerabilities required classes like AuthenticationFunctionChecker.java, DeclassificationFunctionChacker.java, SanitizationFunctionChecker.java, Authentication_gen.java, Declassification_gen.java, Sanitization_gen.java files are included. These files are included in order to detect authentication, declassification and sanitization function missing bug detection in C code. For these three types of function detection here it has been used as library functions in C programming language. In order to detect the information flow vulnerabilities three models have been included such as Authentication_gen.java, Declassification_gen.java, Sanitization_gen.java. In the generated .c file there exist these three kinds of methods without signature which is given in figure . As they have no method body that’s why they are acting as library function in “smtcodan” static analysis engine. Inside the engine three function signature will act as keyword like authentication, declassification and sanitization function.

From C code generator generated .c and .h file with annotation should act as input for “smtcodan” static analysis engine. Engine parses the code with annotation. The authentication, declassification and sanitization function all makes the high secured variable or confidential variable as low and according to the policy they passes the information from the sender to the receiver in a secured way. While implementing the checkers, information flow restriction has followed. If any of the C files are not following the secure information flow then bug should be triggered as either authentication , declassification or sanitization function missing function.

4.7. View Buggy Path in Sequence Diagram

Through the static analysis engine buggy path can be found as a list of string. Inside the list there are function calls, separate statements like if statements, switch-case statements, variable declaration,

assignment of variables etc. of programming language (like C,C++). Then to view the path using java a sequence diagram is generated. now it easier to trace the buggy path by viewing generated sequence diagram.

One sample example of the buggy path is given in figure 4.7.

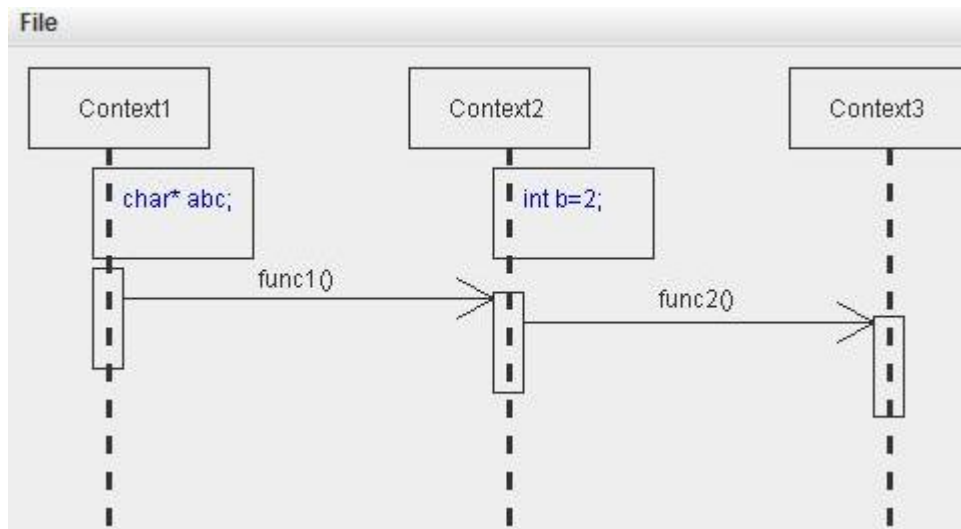


Figure 4.7.: Error trace path in UML sequence diagram

Algorithm 2 Sequence diagram generator

Input: List of statements and function call**Output:** Sequence diagram in a JFrame

```
1: function GENERATEYPESH(sc) ▷ Where sc - statchart
2:   defgenerateFile1(testModule.h, typesHAnnotationContent(sc)) Where def - function decla-
   ration in xtend
3:   defgenerateFile2(testModule.c, typesCAnnotationContent(sc))
4: end function
5: function TYPESHANNOTATIONCONTENT(sc)
6:   for s : getFileContent(sc).entrySet do
7:     if !s.key.contains('//@@variable') then
8:       s.key
9:     else if s.value.contains('(') then
10:      void < s.value >;
11:    end if
12:  end for
13: end function
14: function TYPESCANNOTATIONCONTENT(sc)
15:   for s : getFunctionContent(sc).entrySet do
16:     if (!s.value.contains('authentication') and (!s.value.contains('declassification'))
17:   and (!s.value.contains('sanitization'))) then
18:       void < s.value >
19:     end if
20:   end for
21:   for region : sc.regions do
22:     if region.name.equalsIgnoreCase('bad_path()') then
23:       void < region.name >
24:       for s : getBadPathContent(sc).entrySet do
25:         if s.key.contains('//@@variable') then
26:           s.key
27:           s.value
28:         end if
29:         if s.value.contains('(') then
30:           s.value;
31:           s.value
32:         end if
33:       end for
34:     end if
35:     if region.name.equalsIgnoreCase('good_path()') then
36:       void < region.name >
37:       for s : getGoodPathContent(sc).entrySet do
38:         if s.key.contains('//@@variable') then
39:           s.key
40:         end if
41:         s.value;
42:       end for
43:     end if
44:   end for
45: end function
```

5. Experiments

In this chapter experimental results are presented for semi-automated detection of sanitization, authentication and declassification errors in UML state Charts. For three separate problems such as authentication, declassification and sanitization three sample programs selected in C language. Then according to the system these three scenarios are modeled in YAKINDU SCT editor. After this source code file generated and analyzed using static analysis engine. Detailed process how the system works and what is the outcome of the system are given below.

5.1. Authentication Scenario

To understand the authentication scenario a simple example has chosen. The scenario contains a user account creation inside database to access the contents of the database. In the following Java example the method `createUser` is used to create a `DBAccess` object for a database management application.

```
public DBAccess createUser(String userName, String userType,
    String userPassword) {

    DBAccess access = new DBAccess();
    access.setUserName(userName);
    access.setUserType(userType);
    access.setUserPassword(userPassword);

    return access;
}
```

However, there is no authentication mechanism to ensure that the user creating this database user account object has the authority to create new user access. Some authentication mechanisms should be used to verify that the user has the authority to create database access objects. The following Java code includes a boolean variable and method for authenticating a user. If the user has not been authenticated then the `createUser` will not create the database access object.

```
private boolean isUserAuthentic = false;

// authenticate user,
// if user is authenticated then set variable to true
// otherwise set variable to false
public boolean authenticateUser(String username, String password) {
    ...
}

public DBAccess createUser(String userName, String userType,
    String userPassword) {
    DBAccess access = null;

    if (isUserAuthentic) {
        access.setUserName(userName);
        access.setUserType(userType);
        access.setUserPassword(userPassword);
    }
    return access;
}
```

To model this kind of scenario in UML statechart considering that for C/C++ application. Figure 5.1 represents an authentication scenario. In this scenario a user *A* wants to access a database. At first he/she has to provide his/her user id, password, account number. Then he/she sends request to access database. The database administrator creates a user using his/her id, name and password based on their policy. According to the policy user can either view or access the database or not. If database server doesn't have some secured policy like validation, encryption, decryption or authentication methodology then hacker may easily break the application and receives the confidential information or data from the database server. In Figure 5.1 depicts a highly secured variable "char *a" which is initially annotated as H. It passes through a function named authentication. This authentication function is represented as a state in the statechart as like "void declassification(char *a)". This function makes the high secured variable as low by following the policy language. After passing these function the variable "char *a" is annotated with L and authenticated. Now it can be passed to other system or release information to the authenticated user.

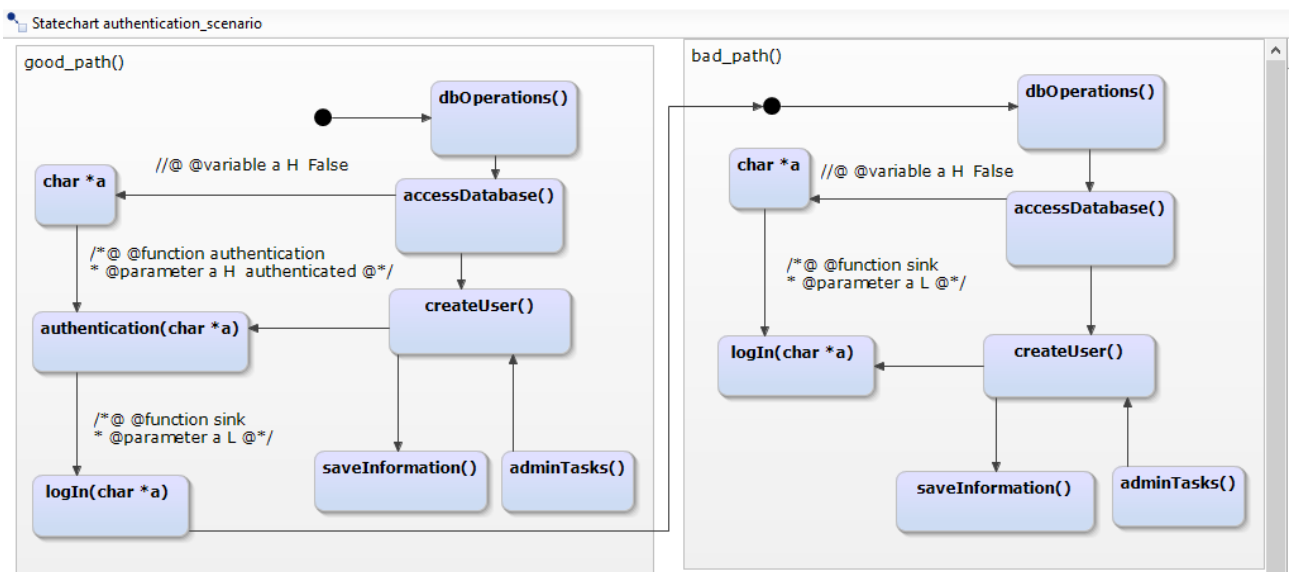


Figure 5.1.: UML Statechart Modeling for Authentication Scenario

5.2. Declassification Scenario

Noninterference is typically too strong a property, most programs use some form of declassification to selectively leak high security information when performing a password check or data encryption. Unfortunately, such a declassification is often expressed as an operation within a given program, rather than as part of a global policy, making reasoning about the security implications of a policy more difficult. For application programmers need to prevent a range of problems, from SQL injection and cross-site scripting, to inadvertent password disclosure and missing access control checks. Adding declassification function is one of the possibility for an application to detect information flow vulnerabilities. It requires few changes to the existing application code and an assertion of functions such as declassification, sanitization and authentication can reuse existing code and data structures.

For the declassification scenario, a user *A* wants to access his bank account. Every bank has their own policy to their customer who can access their account information. After giving the password, account number, user name user *A* send his request to the bank server to view the account information. The bank server has his own policy according to their requirements. Through that policy

bank server verifies the user *A* may be by following the basic declassification goals according to four axes like what information is released, who releases information, where in the system information is released and when information can be released.

Figure 5.2 represents a declassification scenario. In this scenario a user *A* wants to access his bank account. At first he/she has to provide his/her user id, password, account number. Then he/she sends request to access his/her account. The bank server has their own policy who can access the account details. According to the policy user can either view his account details or not. If bank server doesn't have some secured policy like encryption, decryption or declassification methodology then hacker may easily break the application and receives the confidential information or data. In Figure 5.2 depicts a highly secured variable "char *a" which is initially annotated as H. It passes through a function named declassification. This declassification function is represented as a state in the state-chart as like "void declassification(char *a)". This function makes the high secured variable as low by following the policy language. After passing these function the variable "char *a" is annotated with L and declassified. Now it can be passed to other function or release information to the verified user.

After finishing the modeling of declassification scenario then through the C code generator C code files are generated which consist two files(.c and .h file). Inside those files annotations are exist. Then through static analysis engine named "smtcodan" analyze the code and detect the information flow vulnerabilities if they exist inside the generated files.

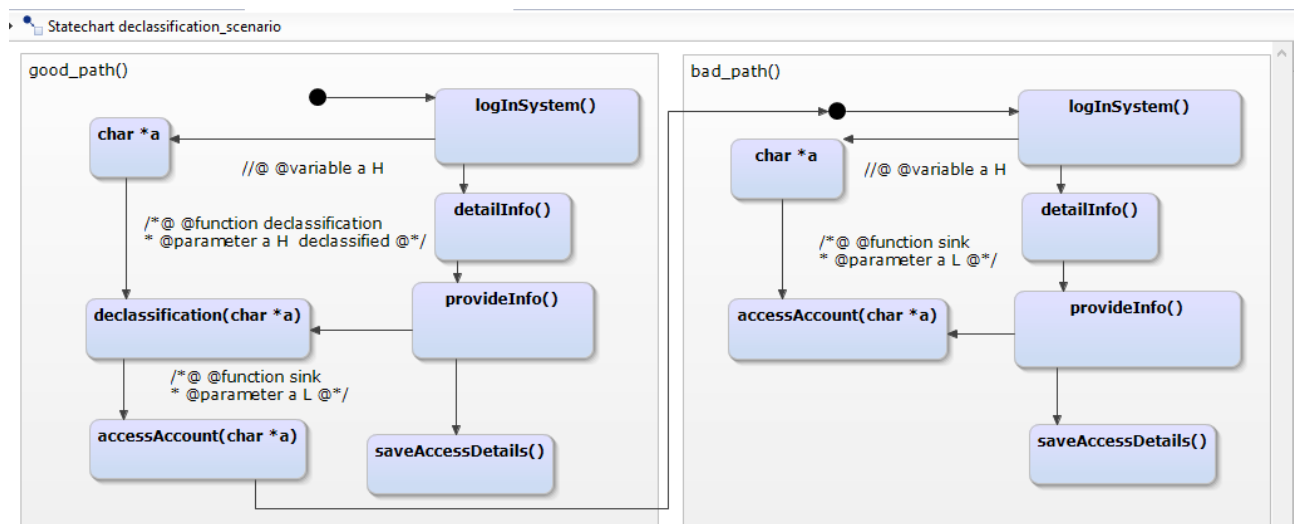


Figure 5.2.: UML Statechart Modeling for Declassification Scenario

5.3. Sanitization Scenario

Web applications are often implemented by developers with limited security skills. As a result, they contain vulnerabilities. Most of these vulnerabilities stem from the lack of input validation. That is, web applications use malicious input as part of a sensitive operation, without having properly checked or sanitized the input values prior to their use. In the past research on vulnerability analysis has mostly focused on identifying cases in which a web application directly uses external input in critical operations. However, little research has been performed to analyze the correctness of the sanitization process. Secured web application helps to prevent the bad guys from gaining unauthorized access to your application or website data. It helps you keep your data's integrity and ensures availability as needed. Sql injection and XSS attacks are common attacks now-a-days. to prevent this kind of attacks need to use sanitization methods and validate user input properly.

This example code intends to take the name of a user and list the contents of that user's home directory. It is subject to the first variant of OS command injection. Example language is in PHP.

```
$userName = $_POST["user"];  
$command = 'ls -l /home/' . $userName;  
system($command);
```

The `userName` variable is not checked for malicious input. An attacker could set the `userName` variable to an arbitrary OS command such as:

```
;rm -rf /
```

Then that would produce a result like this-

```
ls -l /home/;rm -rf /
```

Since the semi-colon is a command separator in Unix, the OS would first execute the `ls` command, then the `rm` command, deleting the entire file system.

The previous example was given for PHP language. In C language here it has been selected that user "A" wants to access some file from server pc. So, he needs to give the file name. If he wants to access some exe file then bug should be triggered or if he inserts some OS command injection type of statement then bug should be triggered. That's why the user input should pass through a sanitization method to sanitize the input parameter.

Figure 5.3 depicts a sanitization scenario. In this scenario a user *A* wants to access file from a server. At first he/she has to provide file name. Then he/she sends request to access his/her desire file. The server has their policy who can access the file. According to the policy if the server has proper sanitization methods then by sanitizing the user input server either allow or disallow the user to access the file. If bank server doesn't have some secured policy like encryption, decryption or sanitization methodology then hacker may easily break the application and receives the confidential information or data, even execute the .exe files or may do some OS command injection. In Figure 5.3 shows a highly secured variable "char *a" which is initially annotated as H. It passes through a function named sanitization which also represented as a state named "void sanitization(char *a)". This function makes the high secured variable as low by following the policy language. After passing these function the variable "char *a" is annotated with L and sanitized. Now it can be passed to other function or release information from the system.

5.4. Checkers in Static Analysis Engine

Figure 5.4 depicts the bug reports obtained by running the checkers in parallel on the generated programs. The circled numbers in figure 5.4 indicate the following: number 1 indicates the analyzed programs (generated programs), number 2 presents three bug reports (each generated by one of the checker for the analyzed programs) and number 3 shows the bug location (line number 18) in source code file `scenario3.c` by clicking on the second bug report (Missing Sanitization function Bug Detected). The bug reports depicted in figure 5.4 with number 2, confirm that all bugs were successfully detected and no false positives and false negatives were generated.

6. Related Work

There are many annotation languages proposed until now for extending the C type system [11], [16], [35], [36], [57] to be used during run-time as a new language run-time for PHP and Python [61] to annotate function interfaces [16], [35], [57] to annotate models in order to detect information flow bugs [31] to annotate source code files [46], [47], [56] or to annotate control flows [16], [18], [35]. The following annotation languages have made significant impact: Microsoft's SAL annotations [35] helped to detect more than 1000 potential security vulnerabilities in Windows code [4]. In addition, several other annotation languages including FlowCaml [51], Jif [7], Fable [55], AURA [28] and FINE [54] express information flow related concerns.

UMLSec [30] is a model-driven approach that allows the development of secure applications with UML. Compared with our approach, UMLSec does neither automatic code generation nor the annotations can be used for automated constraints checking.

The detection of information flow errors can be addressed with dynamic analysis techniques [3], [19], [48], static analysis techniques [23], [38], [52], [58], [60] (similar to our approach with respect to static analysis of code and tracking of data information flow) and hybrid techniques which combine static and dynamic approaches [37]. Also, extended static checking [13] (ESC) is a promising research area which tries to cope with the shortage of not having certain program run-time information. The static code analysis techniques need to know which parts of the code are: sinks, sources and which variables should be tagged. A solution for tagging these elements in source code is based on a pre-annotated library which contains all the needed annotations attached to function declarations. Leino [34] reports about the annotation burden as being very time consuming and disliked by some programming teams.

The studies rely on manually written annotations while our annotation language is integrated into two editors which are be used to annotate UML state charts and C code by selecting annotations from a list and without the need to memorize a new annotation language.

Recently taint modes integrated in programming languages as Caml-based FlowCaml [53], Ada-based SPARK Examiner [5] and the scripting. However, none of these annotation and programming languages have support for introducing information flow restrictions in both models and the source code. Splint [17], Flawfinder [59] and Cqual [50] are used to detect information flow bugs in source code and come with comprehensive user manuals describing how the annotation language can be used in order to annotate source code. iFlow [32] is used for detecting information flow bugs in models and is based on modeling dynamic behavior of the application using UML sequence diagrams and translating them into code by analyzing it with JOANA [33]. In comparison with our approach these tools do not use the same annotation language for annotating UML models and code. Thus, a user has to learn to use two annotation languages which can be perceived to be a high burden in some scenarios.

Heldal et al. [24], [25] introduced an UML profile that incorporates a decentralized label model [40] into the UML. It allows the annotation of UML artifacts with Jif [39] labels in order to generate Jif code from the UML model automatically. However, the Jif-style annotation already proved to be non-trivial on the code level [45], while [25] notes that the actual automatic Jif code generation is still future work. These approaches can not be used to annotate both UML models and code. Moreover, these approaches lack of tools for automated checking of previously imposed constraints.

7. Conclusion and Future Work

A keyword-based annotation language that can be used out of the box for annotating UML state charts and C code in two software development phases by providing two editors for inserting security annotations in order to detect information flow bugs automatically. It's evaluated on some sample programs and showed that this approach is applicable to real life scenarios.

It's a light-weight annotation language usable for specifying information flow security constraints which can be used in the design and coding phase in order to detect information flow bugs.

In future it can be extended for source code editor as a pop-up window based proposal editor used to add/retrieve annotation to/from a library. The definition of new language annotation tags should be possible from the same window by providing two running modes (language extension mode and annotation mode). The envisaged result is to reduce the gap between annotations insertion/retrieval and the definition of new language tags. This would help to create personalized annotated libraries which can be collaboratively annotated if needed.

Appendix

A. Appendix

Here come the details that are not supposed to be in the regular text.

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